Quaternary Science Reviews 138 (2016) 62–75

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Deglaciation and postglacial environmental changes in the Teton Mountain Range recorded at Jenny Lake, Grand Teton National Park, WY

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ARTICLE INFO

Article history:
Received 21 September 2015
Received in revised form
19 February 2016
Accepted 22 February 2016
Available online xxx

Keywords:
Holocene climate change
Lake sediment
Western U.S.
Deglaciation
Grand Teton National Park
Glacier Peak tephra
Teton fault

ABSTRACT

Sediments contained in lake basins positioned along the eastern front of the Teton Mountain Range preserve a continuous and datable record of deglaciation and postglacial environmental conditions. Here, we develop a multiproxy glacier and paleoenvironmental record using a combination of seismic re ection data and multiple sediment cores recovered from Jenny Lake and other nearby lakes. Age control of Teton lake sediments is established primarily through radiocarbon dating and supported by the presence of two prominent rhyolitic tephra deposits that are geochemically correlated to the widespread Mazama (~7.6 ka) and Glacier Peak (~13.6 ka) tephra layers. Multiple glacier and climate indicators, including sediment accumulation rate, bulk density, clastic sediment concentration and ux, organic matter (concentration, ux, $\delta^{13}C$, $\delta^{15}N$, and C/N ratios), and biogenic silica, track changes in environmental conditions and landscape development. Sediment accumulation at Jenny Lake began centuries prior to 13.8 ka and cores from three lakes demonstrate that Teton glacier extents were greatly reduced by this time. Persistent ice retreat in Cascade Canyon was slowed by an interval of small glacier activity between ~13.5 and 11.5 ka, prior to the end of glacial lacustrine sedimentation ~11.5 ka. The transition to non-glacial sediments marks the onset of Holocene conditions at Jenny Lake and re ects a shift toward warmer summers, increased vegetation cover, and landscape stability in the Tetons. We discuss the Teton lake sediment records within the context of other regional studies in an effort to construct a comprehensive overview of deglaciation and postglacial environmental conditions at Grand Teton National Park.

1. Introduction

Mountain ranges in the western U.S. contain a legacy of periodic Quaternary glaciations (e.g. Blackwelder, 1915; Porter et al., 1983; Pierce, 2003 and references therein), which have either directly or indirectly in uenced the topography, environmental conditions, and sedimentary systems that exist today (e.g. Hallet et al., 1996; Brozovic et al., 1997; Zhang et al., 2001; Pierce, 2003; Egholm et al., 2009; Foster et al., 2010; Mitchell and Humphries, 2015). These landscapes are characterized by relatively high environmental gradients and are considered particularly sensitive to external disturbances related to climate change and human impacts (Beniston, 2003; Settele et al., 2014). For example, recent atmospheric warming, dryer conditions, and human activity in mountainous regions of the western U.S. have led to numerous environmental changes, including increased glacier recession (Arendt et al., 2002; Gardner et al., 2013), wild re occurrence (Westerling et al., 2006), and ecological shifts (Walther et al., 2002), and both decreased alpine snowpack (Mote et al., 2005) and variable water resources (Nelson et al., 2011) . Reconstructions of past mountain environments derived from sedimentary deposits are important for placing such changes within the context of longer-term geomorphic and ecologic development, and may improve projections of future changes and the ef cacy of natural resource management. Here, we target sediments contained in glacially scoured lake basins at Grand Teton National Park, WY to reconstruct the timing and pattern of deglaciation and subsequent (postglacial) environmental history of the Teton Mountain Range.

The Teton Range in northwest Wyoming is a rectangular (~65 km by ~15 km; roughly north-south trending) fault-block

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http://dx.doi.org/10.1016/j.quascirev.2016.02.024
0277-3791/

mountain range located within the Middle Rocky Mountain physiographic province (Fenneman, 1931, Fig. 1). The bedrock geology of the Range consists primarily of a Precambrian crystalline core (e.g. quartz monzonite and gneisses) unconformably overlain by a sequence of westward-tilting Cambrian and Paleozoic sedimentary units (Love et al., 1992, 2003; Pierce and Good, 1992; Smith et al., 1993). During the most recent (Pinedale) glaciation, the Tetons and adjacent Yellowstone region contained one of the largest mountain glacier ice complexes in the western U.S (Porter et al., 1983) and glacier deposits (e.g. moraines, till, outwash) are common, particularly in the broad low-lying basins that ank both sides of the range (Fig. 1). The dramatic topography and geomorphic asymmetry of the Tetons is attributed to uplift along the Teton fault, a major range-bounding, eastward-dipping normal fault that extends for ~70 km along the base of the mountains (Love et al., 1992, 2003; Smith et al., 1993; Byrd, 1994; Byrd et al., 1994). Well-preserved fault scarps up to ~30 m tall displace Pinedale-age glacier deposits and provide evidence for recent fault activity (Fig. 1; Smith et al., 1993; Machette et al., 2001; Foster et al., 2010; Thackray and Staley, 2014). The active tectonic setting and glacial

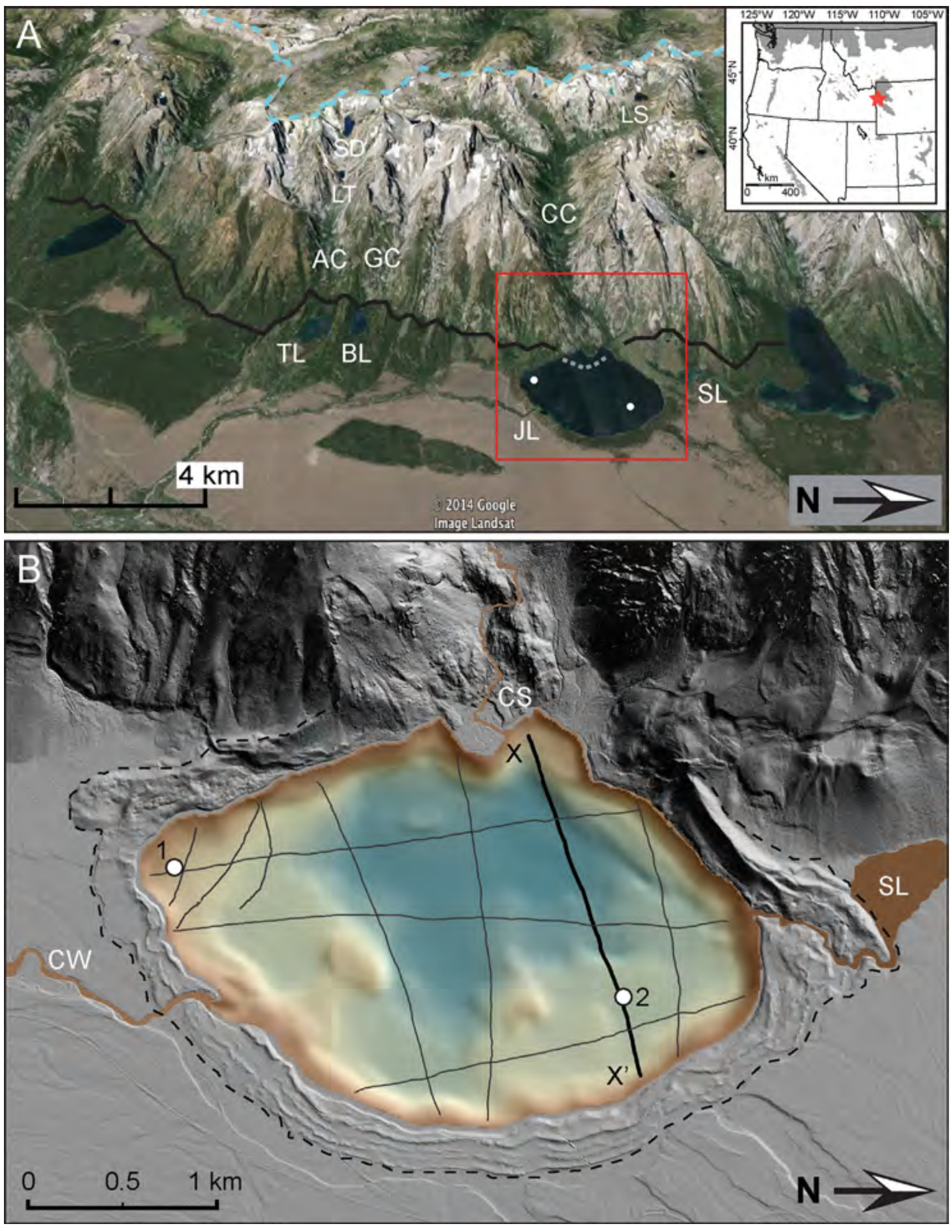

Fig. 1. Overview maps and geologic setting of study region. (A) Oblique aerial view of eastern ank of the Teton Mountain Range. Note the series of glacially carved valleys and moraine-impounded piedmont lakes located at their base. The three valleys and their respective lakes mentioned in the text are Cascade Canyon (CC), Jenny Lake (JL), Lake Solitude (LS), Garnet Canyon (GC), Bradley Lake (BL), Avalanche Canyon (AC), Taggart Lake (TL), Lake Taminah (LT), and Snowdrift Lake (SD). The Teton fault trace is marked with a black line (approximate location of the fault trace below Jenny Lake is marked by dashed grey line). The drainage divide is located near the top of the frame (dashed blue line). Inset map highlights location of Tetons (star) on map of western U.S. glaciers during Pinedale time (from Porter et al., 1983). Red square delineates area enlarged in panel B. (B) Lidar hillshade map of area surrounding Jenny Lake highlighting the mouth of Cascade Canyon and the position of the lake behind a Pinedale-age moraine complex (dashed black line). The locations of seismic pro les are shown along with lake bathymetry (cooler colors represent greater water depth; raster map provided courtesy of NPS) and core sites JEN13-1 and JEN13-2 (white dots). Seismic pro le X-X is presented in Fig. 2. In ows to Jenny Lake are Cascade Creek (CS), which drains Cascade Canyon, and a stream that emanates from String Lake (SL) to the north. Lake out ow occurs through Cottonwood Creek (CW) to the south. (For interpretation of the references to colour in this gure legend, the reader is referred to the web version of this article.)

geomorphic history of the Tetons have created a series of roughly parallel glacial valleys carved into the steep eastern front of the range (Fig. 1). Many of the valleys drain into moraine-dammed piedmont lakes positioned along the Range front. Sediment fill in each lake marks the timing of glacier retreat at the end of the Pinedale glaciation and preserves a continuous and datable record of subsequent upstream glacier activity and landscape evolution related to environmental conditions in the catchment.

We develop an integrated record of glacier variations and environmental changes using a combination of seismic profiles and sediment cores from Jenny Lake, and supportive information contained in cores from nearby Taggart and Bradley Lakes (Fig. 1). Numerous previous studies have investigated the tectonic (Roberts and Burbank, 1993; Smith et al., 1993; Byrd et al., 1994; Love et al., 2003; Hampel et al., 2007; Hampel and Hetzel, 2008; Pickering White et al., 2009), geomorphologic (Pierce, 2003; Foster et al., 2008, 2010; Tranel et al., 2011, 2015), glacier geologic (Pierce and Good, 1992; Love et al., 2003; Licciardi and Pierce, 2008; Pierce et al., 2011), and ecologic (Whitlock, 1993; Whitlock and Bartlein, 1993; Millspaugh et al., 2004; Whitlock et al., 2008, 2012; Krause and Whitlock, 2013; Krause et al., 2015) history of the Tetons and nearby Yellowstone region. We discuss the Jenny Lake sediment record within the context of these and other relevant studies in an effort to construct a comprehensive overview of deglaciation and postglacial environmental conditions in the Tetons.

2. Geologic setting

Jenny Lake (43.76°N, 110.73°W; 2070 m asl) is a large piedmont lake located at the base of Cascade Canyon in the central part of the Teton Range (Fig. 1). The lake has an area of ~5 km^2, a maximum depth of ~73 m, and an average depth of ~43 m. Two main inflows are Cascade Creek, which drains Cascade Canyon, and a stream that emanates from String Lake to the north (Fig. 1). Catchment areas of the two inflows are each ~45 km^2 and they span the full elevation gradient of the Tetons, reaching altitudes of nearly 4200 m asl. Jenny Lake is classified as slightly oligotrophic (Dustin and Miller, 2001). Mean annual temperature and precipitation measured 10 km south of Jenny Lake at Moose, WY (~1970 m asl) are 3.1 °C and ~550 mm, respectively (Fig. S1; NOAA; reference period: 1981–2010 CE). Precipitation is dominated by winter snowfall (Fig. S1), particularly at higher elevations within the catchment. Cold winters and thick snowpack result in prolonged lake ice cover, which commonly persists from November to May. Soils in the catchment are generally thin and poorly developed. Modern vegetation varies according to moisture availability and elevation, and ranges from sagebrush steppe communities at low elevations to alpine tundra (Shaw, 2000). Mixed conifer forests cover the moraines immediately surrounding Jenny Lake and occur in patches in Cascade Canyon, primarily in areas of low slope and those protected from mass movement events. Hillslope failures affect large portions of the canyon and are considered to be important agents of erosion, sediment transport, and long-term landscape evolution (Foster et al., 2010; Marston et al., 2011; Tranel et al., 2015).

The primary sediment source to Jenny Lake is via Cascade Creek. Sediment transported by this stream has created a small delta at the mouth of Cascade Canyon along the western lakeshore (Fig. 1). The absence of a delta to the north indicates that String Lake is presently not an important source of sediment. Lake outflow occurs to the south via Cottonwood Creek, a broad shallow overflow channel that transects a relatively subdued segment of the impounding moraine complex. Relict meltwater channels and outwash deposits from the Yellowstone glacial system are clearly visible in Lidar (light detection and ranging) data and suggest drainage patterns in the vicinity were substantially different during Pinedale times (e.g. Pierce and Good, 1992; Licciardi and Pierce, 2008, Fig. 1).

Similar to other piedmont lakes in the Tetons, Jenny Lake formed in the late Pleistocene following regional deglaciation (Love et al., 2003). The lake occupies a terminal basin excavated by a major valley glacier during its Pinedale advance and was developed in part by outwash buildup outside the area covered by the glacier terminus (e.g. Pierce and Good, 1992). The relatively narrow terminal moraine complex encircling the lake contains multiple closely nested ridges and likely contains outer segments that are buried by outwash (Licciardi and Pierce, 2008, Fig. 1). 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 ~4 m on the southern margin. Bathymetric data indicate the steep backslope of the inner moraine continues below the lake surface before intercepting a relatively flat shelf that surrounds a central overdeepened basin (Fig. 1).

3. Methods

3.1. Seismic survey, sediment cores, and sedimentary indicators

A seismic survey of Jenny Lake was conducted to map the spatial distribution of sediment and to identify optimal coring locations (Fig. 1). The survey was performed in a gridded manner using an EdgeTech 3100 compressed high intensity radar pulse (CHIRP) subbottom profiler operated at frequencies of 4–20 kHz. Sediment thickness was estimated using the velocity of sound in freshwater (~1500 m s^{-1}). Two core sites (JEN13-1 and JEN13-2; Fig. 1; Table 1) were selected for their locations in the distal shelf region of the basin, where seismic profiles indicate regular undisturbed horizontal stratigraphy and sediment deposition occurs predominantly through suspension settling. The influences of past disturbances (e.g. landslides, sediment gravity flows, flood events) at these sites were considered minimal. Multiple sediment cores were collected from both locations using a percussion-driven piston corer deployed on cables from the frozen lake surface in April 2013. Sediment cores were also collected from nearby Bradley and Taggart Lakes using the same methods (Fig. 1). All cores were packaged in the field and transported to the University of Wyoming and the National Lacustrine Core Facility (LacCore) at University of Minnesota for initial core processing and description. Core sections were split longitudinally and core halves photographed using a Geotek Geoscan linescan core imager. The cores were subsequently transported to the Department of Geology and Environmental Science at the University of Pittsburgh for sub-sampling and additional analyses.

We measured sediment dry bulk density on all cores at continuous 1 cm intervals by weighing 1 cm^3 samples after drying in a low temperature oven (~60 °C). Total organic matter content (TOM) was measured at continuous 1 cm intervals using loss on ignition (LOI) at 550 °C for 4 h following Heiri et al. (2001). Samples for total organic carbon (TOC), total nitrogen (TN), and stable carbon and nitrogen isotopes ($\delta^{13}C$ and $\delta^{15}N$), were taken from core JEN13-1C at continuous 2 cm intervals ($n = 127$) and processed at the University of California, Davis using a PDZ Europa ANCA-GSL elemental analyzer interfaced with a PDZ Europa 20-20 isotope ratio mass spectrometer (IRMS). Prior to analyses, samples were pretreated with 1 M HCl and rinsed back to neutral with purified water. Samples were then freeze dried, homogenized, and combusted at 1020 °C, and N_2 and CO gas were separated on a Carbosieve GC column (65 °C, 65 mL/min) before entering the continuous-flow IRMS for isotope measurements. The $\delta^{13}C$ and $\delta^{15}N$ values are reported as ‰ values relative to Vienna Pee Dee

Table 1
Teton lakes sediment core metadata.

Lake name	Core ID	Latitude	Longitude	Water depth (m)	Spliced core length (m)	Approx. core age (cal yr BP)
Jenny	JEN13-1C	43.75054	110.73428	25.4	2.56	14,200
Jenny	JEN13-2A	43.77172	110.72578	45.2	1.06	9200
Jenny	JEN13-2B	43.77172	110.72578	45.2	1.49	11,400
Jenny	JEN13-2D	43.77172	110.72578	45.2	1.56	11,500
Jenny	JEN13-2E	43.77172	110.72578	45.2	2.09	13,900
Taggart	TAG13-2A	43.70492	110.75282	6.4	0.77	14,100
Bradley	BRA13-1D	43.71348	110.75286	15.3	2.71	13,300

Belemnite and atmospheric nitrogen, respectively. LOI and TOC concentrations ($LOI_{\%}$ and $TOC_{\%}$) were converted to fluxes (LOI_{Q} and TOC_{Q}) using bulk density values and calculated sediment accumulation rates (SAR).

Biogenic Silica was measured at continuous 2 cm intervals ($n = 127$) in core JEN13-1C and processed at the University of Pittsburgh following procedures adapted from Mortlock and Froelich (1989). Wet samples were freeze-dried, homogenized to a fine powder, and treated with 30% H_2O_2 and 1 M HCl. Biogenic silica (BSi) was extracted with 0.5 M reagent grade Na_2CO_3 solution and determined by molybdate blue spectrophotometry at 812 nm using a Thermo Scientific Evolution 60s UV–Visible Spectrophotometer. Replicate measurements of internal sediment standards from Harding Lake, AK (Finkenbinder et al., 2014) and Twin Lakes, MT run during sample analysis yielded a precision error <0.2%. Clastic sediment concentration ($Clastic_{\%}$) was measured in core JEN13-1C at 2 cm intervals by calculating the residue of sediment after subtracting organic matter and biogenic silica components using: $Clastic_{\%} = 100 \times (1 - (TOM + BSi))$. $Clastic_{\%}$ and BSi concentration ($BSi_{\%}$) were converted to fluxes ($Clastic_{Q}$ and BSi_{Q}) using bulk density values and SAR.

3.2. Chronology

Age control of Teton lake sediments was established using Accelerator Mass Spectrometry radiocarbon (AMS ^{14}C) dating and tephrochronology. Samples of wood, charcoal, conifer needles, and plant macrofossils selected for AMS ^{14}C analyses were pretreated at the University of Pittsburgh using standard acid-base-acid treatments (Abbott and Stafford, 1996) and subsequently combusted, graphitized, pressed in Al targets, and measured at the W.M. Keck Carbon Cycle AMS Laboratory, University of California, Irvine. AMS ^{14}C results were calibrated and converted to calendar years before 1950 CE (cal yr BP) using CALIB v. 7.0 with the INTCAL13 calibration curve (Stuiver et al., 2005; Reimer et al., 2013). Two prominent rhyolitic tephra layers were visually observed in Teton lake cores and analyzed for major element geochemical composition at the GeoAnalytical laboratory, Washington State University, using electron probe microanalysis (EPMA). The geochemical composition of multiple size fractions from each tephra layer was compared to reference glass chemistry and combined with stratigraphic information to identify source volcano and eruption. Age-depth models for Jenny Lake cores were constructed using a smooth spline interpolation between control points and the classical age modeling (CLAM) code version 2.2 developed for the statistical software program R (Blaauw, 2010).

4. Results and interpretations

4.1. Seismic survey

Seismic profiles of Jenny Lake reveal high spatial variation in sediment distribution associated with complex lake floor morphology (Fig. 2). Bathymetric data and seismic imagery define two primary depositional zones that comprise a broad outer shelf region and a central deep basin in front of the canyon mouth (Figs. 1 and 2). Sediment thickness is generally uniform across the broad shelf, with a consistent thickness of ~4 m blanketing a relatively flat but undulating plane. The sediment fill is greatest in the central deep basin where it reaches at least ~8 m in thickness. Prominent topographic highs in this region protrude above the lake floor and are visible in seismic profiles as acoustically opaque mounds, some partially draped with sediment. We hypothesize these features are related to the glacier and/or tectonic history of the basin (e.g. recessional moraine complexes, landslide deposits, and/or uplifted terrain associated with activity of the Teton fault). However, improved bathymetric data acquisition and further geophysical analyses are underway to securely identify these landforms.

The lowermost surface imaged by the CHIRP data is the acoustic basement (Fig. 2). We infer that the Cascade Canyon glacier was in contact with the acoustic basement during its Pinedale advance and that all sediment above this surface was deposited subsequent to the final retreat of the glacier from the lake basin during regional deglaciation (e.g. Maloney et al., 2013). Based on acoustic properties, we identify three seismic units above the acoustic basement. These are referred to as the basal unit, glacial unit, and non-glacial unit, and described briefly in chronostratigraphic order beginning with the oldest (Fig. 2). The basal unit is spatially discontinuous and more commonly observed in the central basin where it in fills hollows and depressions in the basement surface. Unlike the overlying sediment packages, this unit contains irregular reflectors or is otherwise semitransparent. Its wavy upper surface and chaotic stratigraphy indicate non-uniform deposition of coarse-grained sediments and a lack of strong internal structure. The acoustic character and distribution of this unit suggest rapid deposition and we interpret it to be glacial till and/or diamict deposited in a subglacial or proximal proglacial setting.

Resting conformably on the basal unit or draped over the acoustic basement lies another sediment package that smoothens the uneven topography of the lower surface and is defined by a series of relatively high-amplitude reflectors that are parallel and continuous and that separate more transparent layers. The observed thickness of this unit varies from approximately 4 m in the central basin to approximately 2 m along the outer shelf. We interpret this sediment package to represent fine-grained, dense glacial lacustrine sediments that were transported by glacial meltwater. Above this lies the uppermost sediment package, which ranges in thickness from approximately 3 m in the central depocenter to approximately 1.5 m on the shelf (Fig. 2). It contains semitransparent layers separated by parallel and continuous reflectors that are generally thin and low-amplitude. The acoustic properties of this homogenous sediment unit suggest it was formed after glaciers were largely absent from the catchment. Occasional discontinuous high-amplitude reflectors in portions of this unit in the central deep basin are suggestive of discrete high-energy sedimentation events that may be related to mass movements or floods (e.g. Maloney et al., 2013).

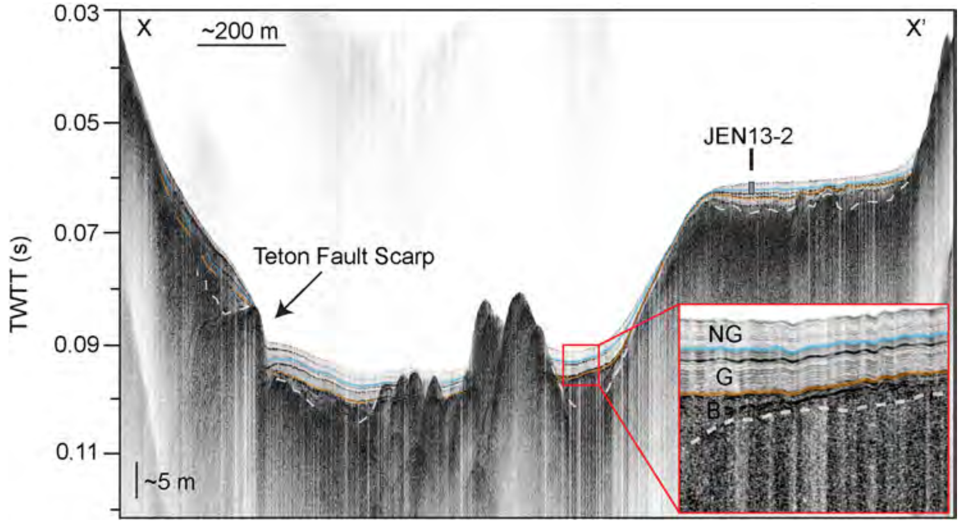

Fig. 2. Seismic pro le (transect X-X in Fig. 1) extending from canyon mouth across the central deep basin toward the distal eastern shore, showing lake oor morphology, sub-bottom stratigraphy, and sediment distribution in Jenny Lake. The approximate location of core site JEN13-2 is identi ed along with the Teton fault scarp, which is visible on the left (western) side of pro le. Inset image highlights seismic stratigraphy and primary seismic units. Colored blue and tan lines mark the bottom of the non-glacial unit (NG) and glacial unit (G), respectively. Dashed white line marks the bottom of the basal unit (B). TWTT two-way travel time (For interpretation of the references to colour in this gure legend, the reader is referred to the web version of this article.)

4.2. Sediment cores

Sediment cores were collected from two sites in Jenny Lake (Fig. 1; Table 1). We focus our analyses on the longest core from each site, JEN13-1C (256 cm-long) and JEN13-2E (209 cm-long). The lithostratigraphy of both cores is similar and consists of a two-part sequence of a relatively organic-rich olive brown homogenous unit that overlies denser light grey minerogenic silt- and clay-rich sediments (Fig. 3). The depth to the contact between the two units corresponds to a change in character of acoustic re ectors observed in seismic pro les. This transition separates the non-glacial and glacial seismostratigraphic units and we apply the same nomenclature to the two primary lithostratigraphic units identi ed in core section (Fig. 2). Seismic pro les reveal >2 m of glacial lacustrine sediment exists below our sediment cores.

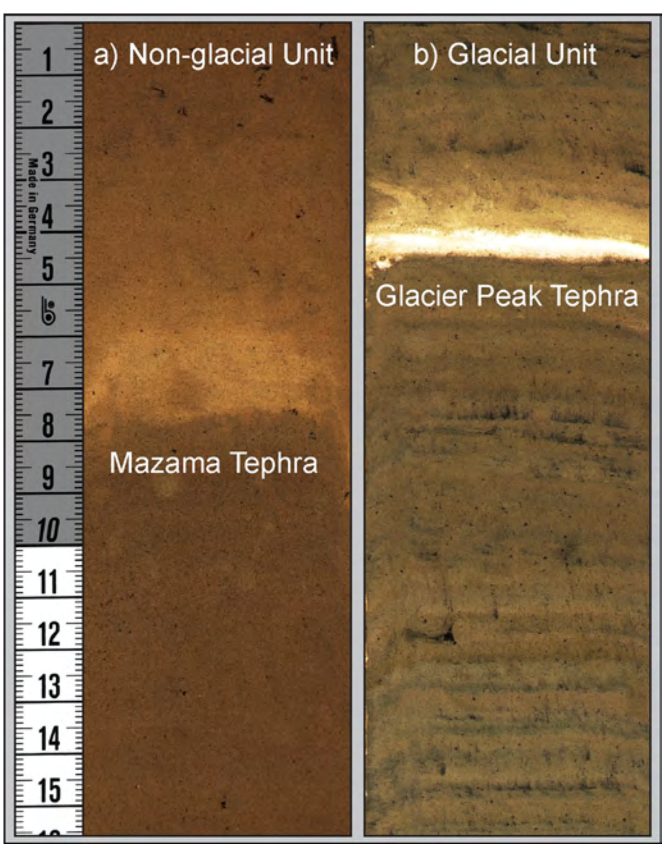

Fig. 3. Images of Jenny Lake sediments showing examples of (a) non-glacial and (b) glacial lithostratigraphic units. The Mazama tephra layer is visible in non-glacial panel at 7 cm depth and the Glacier Peak tephra layer is visible in glacial panel at 4 cm depth.

4.2.1. Geochronology

Thirteen macrofossil ages and two diagnostic tephra layers de ne the core age-depth models (Fig. 4; Table 2). Terrestrial plant remains suitable for radiocarbon dating are relatively abundant in the non-glacial unit and toward the top of the glacial unit. One radiocarbon sample in JEN13-1C (UCIAMS#141227) yielded an anomalously old age when compared with adjacent dates and was omitted from the age model (Fig. 4; Table 2). This sample was picked from woody plant fragments interbedded in a prominent sand horizon, which we interpret to be reworked clastic and organic material delivered from the landscape and/or littoral zone during a high-energy depositional event such as an earthquake-triggered landslide and/or seiche wave. The age of this disturbance layer in cores from both sites is ~9000 cal yr BP (Fig. 4).

Major element composition of the two tephra layers observed in the sediment sequence con rms their correlation with the Mazama (~7.6 ka; Hallett et al., 1997; Zdanowicz et al., 1999) and Glacier Peak (~13.6 ka; Kuehn et al., 2009) tephra beds (Fig. 3; Table 3). These important and widespread tephra layers have been previously noted in lake records from around the region (e.g. Whitlock, 1993). In addition to Jenny Lake, we identify the Glacier Peak tephra in a core from nearby Taggart Lake (43.70 N, 110.75 W; Fig. 1; Table 3) where it is found in non-glacial sediments, approximately 5 cm above transitional sediments and 25 cm above well-laminated silt-rich minerogenic sediments. The calibrated radiocarbon age of a macrofossil positioned ~7 cm below the tephra (i.e. near the top of

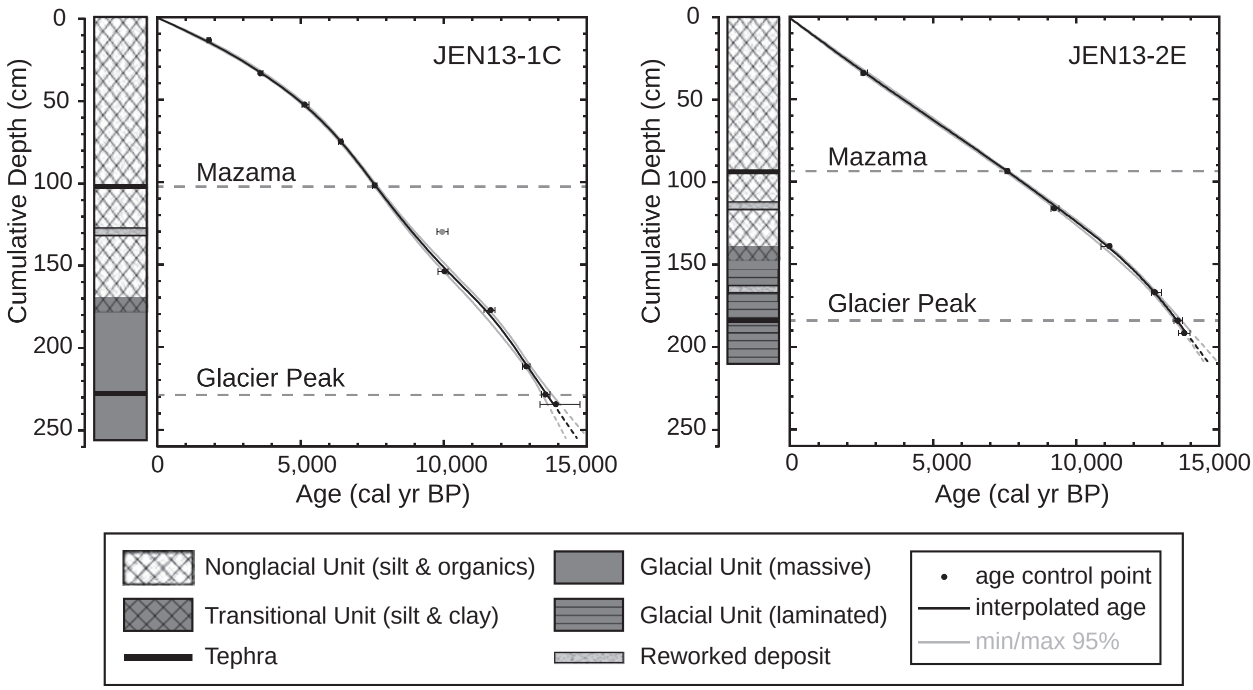

Fig. 4. Stratigraphy and age models for cores JEN13-1C and JEN13-2E. Core age models were generated with a smooth spline interpolation of AMS radiocarbon and tephra control points using CLAM code for R software (Blaauw, 2010). Note: one radiocarbon sample picked from a reworked disturbance deposit at 130 cm depth in JEN13-1C yielded an anomalously old age and was omitted from the age model.

Table 2
Sediment core AMS radiocarbon dates and tephra ages with calibrated 2 sigma error ranges.

Sample ID (UCIAMS#)	Core	Cumulative depth (cm)	Material dated	Uncalibrated age (^{14}C yr BP)	Error (yr)	Calibrated age (cal yr BP) (2sigma)
141223	JEN13-1C	14.0	plant material	1865	15	1812 (1736–1866)
141224	JEN13-1C	34.0	plant material	3360	20	3603 (3563–3681)
141225	JEN13-1C	53.0	plant material	4515	20	5152 (5053–5299)
141226	JEN13-1C	75.5	wood	5630	20	6414 (6322–6467)
na	JEN13-1C	102.0	tephra	6730	40	7597 (7514–7666)
141227	JEN13-1C	130.0	wood	8845	25	9951 (9772–10,152)
141228	JEN13-1C	154.0	plant material	8865	25	10,032 (9795–10,159)
141229	JEN13-1C	177.5	charcoal	10,075	30	11,645 (11,402–11,798)
141230	JEN13-1C	211.5	charcoal	11,025	35	12,888 (12,754–13,014)
na	JEN13-1C	228.5	tephra	11,600		13,560 (13,410–13,710)
151998	JEN13-1C	234.5	plant material	12010	230	13,916 (13,367–14,764)
141220	JEN13-2E	34.0	needle	2495	20	2582 (2490–2720)
na	JEN13-2E	93.5	tephra	6730	40	7597 (7514–7666)
141221	JEN13-2E	116.0	needle	8260	35	9246 (9125–9404)
151999	JEN13-2E	139.0	plant material	9710	40	11,161 (10,881–11,227)
152000	JEN13-2E	167.0	plant material	10,850	90	12,752 (12,632–12,979)
na	JEN13-2E	184.0	tephra	11600		13,560 (13,410–13,710)
141222	JEN13-2E	191.5	plant material	11945	35	13,771 (13,580–13,979)
152001	TAG13-2A	13.0	plant material	10,880	130	12,795 (12,590–13,050)
na	TAG13-2A	34.5	tephra	11600		13,560 (13,410–13,710)
141231	TAG13-2A	42.0	wood	11,920	210	13,787 (13,283–14,417)
152002	BRA13-1D	245.0	plant material	11,425	30	13,266 (13,167–13,339)

Table 3
Major element chemistry of the two tephra layers identi ed in Jenny Lake sediment cores. The data are normalized to 100 wt percent and the standard deviation for each major element is shown in parentheses. Results are consistent with Mazama (Hallett et al., 1997) and Glacier Peak (Kuehn et al., 2009) tephra layers.

Core ID	Depth (cm)	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Na_2O	K_2O	MgO	CaO	Cl	# shards analyzed	Tephra ID
JEN13-2E	93.5	73.11 (0.34)	14.63 (0.17)	2.1 (0.07)	0.43 (0.04)	4.76 (0.22)	2.74 (0.06)	0.46 (0.05)	1.59 (0.08)	0.18 (0.02)	17	Mazama
JEN13-2E	184.0	77.25 (0.37)	12.79 (0.17)	1.2 (0.06)	0.21 (0.04)	3.67 (0.22)	3.04 (0.15)	0.27 (0.03)	1.35 (0.07)	0.22 (0.10)	21	Glacier Peak
TAG13-2A	34.5	77.34 (0.24)	12.79 (0.14)	1.16 (0.04)	0.20 (0.02)	3.68 (0.14)	3.05 (0.13)	0.27 (0.02)	1.31 (0.07)	0.20 (0.02)	18	Glacier Peak

the transitional sediments) at Taggart Lake yields a median age of ~13,800 cal yr BP (two sigma range: 13,283–14,417 cal yr BP; Table 2; Fig. S2). Plant material picked from non-glacial sediments near the base of a core recovered from neighboring Bradley Lake