Bathymetric and geophysical surveys of the southern end of Kluane Lake, Yukon

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ABSTRACT

Initial observations of lakebed geomorphology and morphodynamic processes operating at the southern end of Kluane Lake are presented here. In August 2013, multibeam and parametric echo sounders were used to map, with high resolution, the bathymetry and sub-bottom stratigraphy of the lakebed, and an acoustic Doppler current profiler and laser grain size analyser were used to measure flow and sediment transport over the Slims River delta. A series of low-angle asymmetric sediment waves were observed on the delta top, as well as buried within the delta sediments. These older bedforms were buried as the delta prograded into the lake over the past three centuries. Other delta surface features include small scarps and channels. Drowned terraces observed on the eastern margin of the lake indicate that lake level was stable and lower than present at least four times during the Holocene, to a maximum of 47 m below present datum.

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INTRODUCTION

Glacier-fed Kluane Lake, the largest lake in Yukon, has undergone significant hydrological changes in the past 1000 years. The most dramatic change resulted from the Little Ice Age advance of Kaskawulsh Glacier, south of Kluane Lake. Throughout most of the Holocene, Kaskawulsh Glacier terminated far short of the Slims River valley, which formerly drained south from Kluane Lake. However, during the Little Ice Age the glacier advanced into this valley and blocked the southerly drainage of the lake. As a result, Kluane Lake water levels rose to 12 m above current levels and a new drainage was created out the north end of the lake via the Kluane River (Bostock, 1969; Clague *et al*., 2006). Discharge of high volumes of fine-grained sediment and meltwater from Kaskawulsh Glacier over the past three centuries has caused the Slims River delta to extend north into Kluane Lake. The high suspended sediment load in the Slims River generates continuous turbidity currents and upstream-migrating sediment waves on the delta clinoform, which is currently prograding north at a rate of 18 m a^{-1} into the lake (Gilbert and Crookshanks, 2009). Despite some recent work (Brahney *et al*., 2008; Crookshanks and Gilbert, 2008; Gilbert and Crookshanks, 2009; Brahney *et al*., 2010), the detailed dynamics of water level variation through the Holocene and the morphodynamic processes of the delta clinoform advance into the lake remain poorly understood.

In August 2013, geoscientists from University of Victoria (Dan Shugar), Simon Fraser University (John Clague and Ray Kostaschuk), University of Illinois, Urbana-Champaign, USA (Jim Best), and University of Hull, UK (Dan Parsons) completed field studies to further investigate sedimentary dynamics operating at the Slims River delta and examine late Holocene lake-level fluctuations via quantification of detailed bathymetry, subsurface sediment characteristics, and flow over the delta. This report describes the datasets collected, methods applied, and some preliminary results from this study.

STUDY AREA

Kluane Lake (Fig. 1) lies within the Shakwak Trench, a Cenozoic fault-bounded basin at the east margin of the St. Elias Mountains in southwestern Yukon. The lake has a surface area of approximately 432 km^2, is 65 km long, averages 4 km in width, and is up to about 78 m deep (Clague *et al*., 2006). The Denali fault crosses the southern end of the Lake (Fig. 1). The Duke River fault crosses the Slims River valley south of Kluane Lake. Between 1897 and 2009, many earthquakes have occurred in the region, including a moment magnitude (M_w) 4.9 event on the Denali fault in 2009, a M_w5.1 event on the Duke River fault in 1995, and a M_w5.7 event between the Denali and Duke River faults in 1956 (Bird, 2004).

The watershed of Kluane Lake is approximately 5400 km^2 and, with the exception of Kaskawulsh Glacier which covers approximately 1100 km^2 (Foy *et al*., 2011), is currently largely ice-free. However, the watershed was covered by glaciers at the maximum of the Late Wisconsinan Kluane (McConnell) Glaciation (Rampton, 1981). Kaskawulsh Glacier is one of the large outlet glaciers flowing from the Icefield Ranges of the St. Elias Mountains. Many small streams flow into the lake, but the main source of water is the Slims River. Only a portion of the meltwater flowing from Kaskawulsh Glacier reaches Kluane Lake via the Slims River; the remainder discharges to the south via the Kaskawulsh River to the Pacific Ocean (Gilbert and Crookshanks, 2009).

METHODS

A suite of instruments was deployed to document high resolution bathymetry, three-dimensional flow and sediment transport, and sub-bottom stratigraphy of the southern part of Kluane Lake. Bathymetric surveying was conducted with a RESON 7125 multibeam echo sounder (MBES) coupled to a POS-MV inertial motion sensor. We used the MBES to produce bathymetric elevation maps with 25-cm resolution. We measured 3D flow velocity with a Teledyne 1200 kHz RDInstruments RioGrande acoustic Doppler current profiler (aDcp), with a bin spacing of 0.25 m over the full water column. Time series of suspended sediment concentration and particle size were determined with a Sequoia laser *in situ* scattering transmissometer (LISST-SL). The LISST-SL data can also be used to calibrate the acoustic backscatter from the aDcp, effectively providing concurrent 3D flow and suspended sediment flux information from the same instrument and for the entire water column (*e.g.*, Shugar *et al*., 2010). Sediment samples were also collected at the bed and at various depths in the water column using a a small Van Veen type grab and a Van Dorn sampler respectively.

An Innomar SES-2000 Parametric Echo Sounder (PES) was used to image and quantify the internal sedimentary structure of Slims River delta clinoform sediments. The instrument is uniquely suited for fine-grained sediments (Sambrook Smith *et al*., 2013), making it ideal for use in Kluane Lake, and decimeter resolution of subsurface

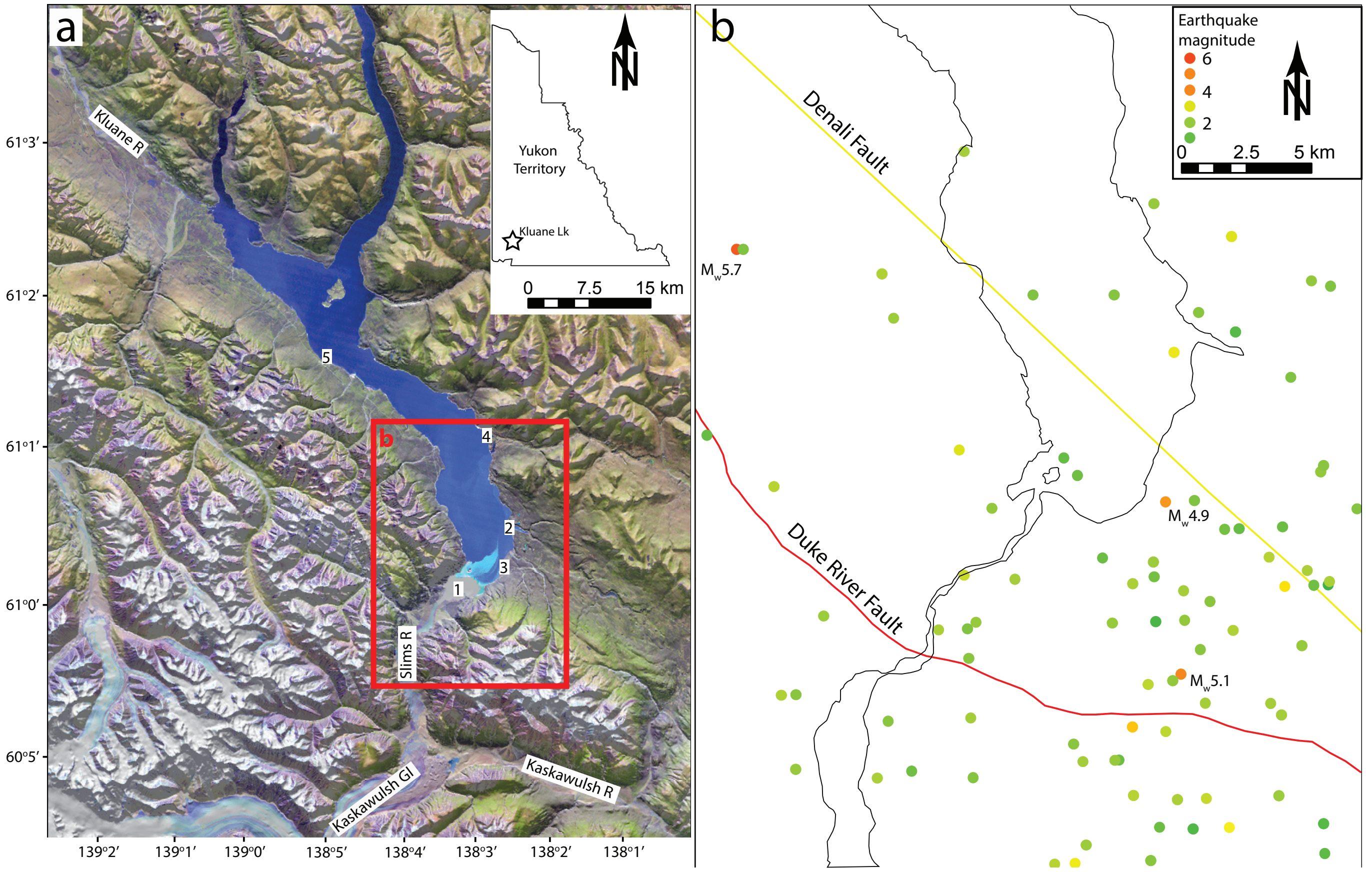

Figure 1. *(a) Map of the study area, showing Kluane Lake and its watershed; red box indicates extent of panel (b). Yukon Landsat mosaic with shaded relief underlay (Geomatics Yukon, 2004). Numbered locations refer to Slims River delta (1); Christmas Bay (2); Kluane Lake Research Station (3); Cultus Bay (4); and Destruction Bay (5). (b)Major faults and earthquake epicenters (1897-2009; Bird, 2004).*

sedimentary structure was achieved to depths of approximately 4x the water depth. For example, in 20 m of water, approximately 80 m of sediment could be imaged.

The MBES, PES, and aDcp were mounted, using pivoting brackets, to the side of a small aluminum-hulled research vessel (*RV Matthews*). The brackets allowed the instruments to be rotated out of the water when not in use. The LISST-SL was lowered into the water on a cable and trailed behind the vessel. All the instruments were tied spatially and temporally to a dGPS system, with a temporary RTK base station located at Kluane Lake Research Station during the entire survey. The RTK rover unit on the vessel was linked to the base unit via PDL radio for real-time corrections. Surveys were completed from Aug 7-13, 2013, during stationed moorings and while the vessel was under way. Significant volumes of data, totaling 1.8 TB were collected. At the time of writing, data processing was in progress.

RESULTS AND DISCUSSION

Approximately 12 km^2 of the floor of Kluane Lake was mapped using the MBES and a total of 48 km of PES line collected in three areas: the subaqueous portion of the Slims River delta; west of Christmas Bay; and west Cultus Bay (Fig. 2). Below, we discuss the historic (1899-present) evolution of the Slims River delta, describe the stratigraphy and bedforms on the delta, and examine drowned lake terraces off Christmas and Cultus bays.

HISTORIC DELTA MORPHOLOGY, 1899-PRESENT

The Slims River flows 19 km from the terminus of Kaskawulsh Glacier to Kluane Lake, where it is currently rapidly extending its delta. Historic rates of delta growth are high compared to other glaciolacustrine deltas in western Canada (Gilbert and Crookshanks, 2009).Rates have been decreasing steadily over the past century, from

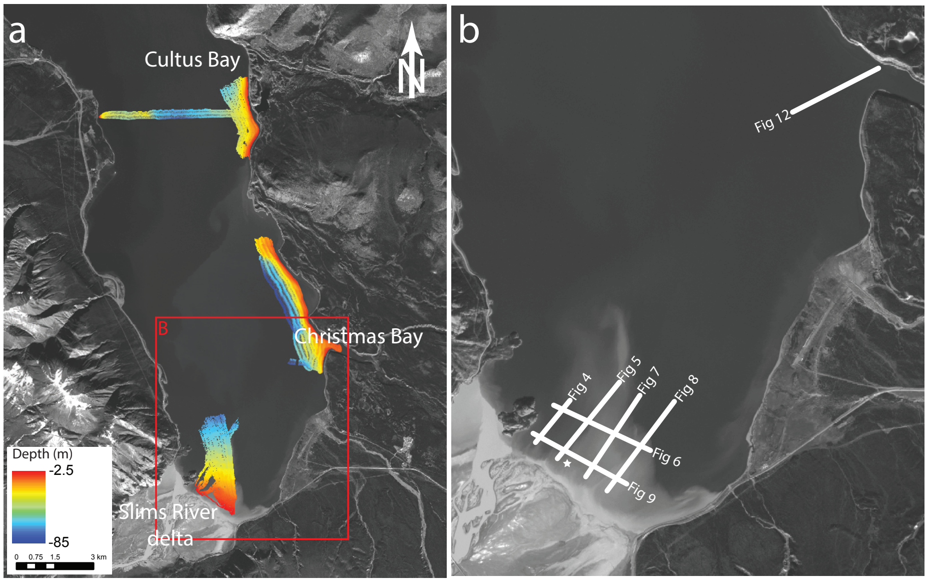

Figure 2. *(a) Multibeam echo sounding coverage; red box indicating extent of panel (b). (b) locations of PES survey lines and corresponding figure numbers. White star indicates location of sediment samples shown in Fig. 10, and aDcp profiles shown in Fig. 11.*

a high of 74 m a-1 between 1899 and 1914, to 48 m a-1 between 1914 and 1947, to 27 m a-1 between 1947 and 1970, and to about 18 m a-1 between 1970 and 2006 (Gilbert and Crookshanks, 2009). The decreasing rate of delta growth is due, in part, to construction of the Alaska Highway across the outwash plain in 1942 and relocation of the road and bridge in 1956. These engineering works confined flow to a single channel, trapping much of the coarser sediment upstream of the structures. Only the finer sediment fraction (silt and fine to very fine sand) is currently transported into the lake. Another factor in the decreasing rate of delta growth may be the greater width of the valley where Slims River is currently discharging into the lake. This assertion however, remains to be tested. As the delta progrades into the lake, it also aggrades vertically. Between 1970 and 2004, the delta aggraded approximately 15 m (0.45 m a-1, Fig. 3) in thickness.

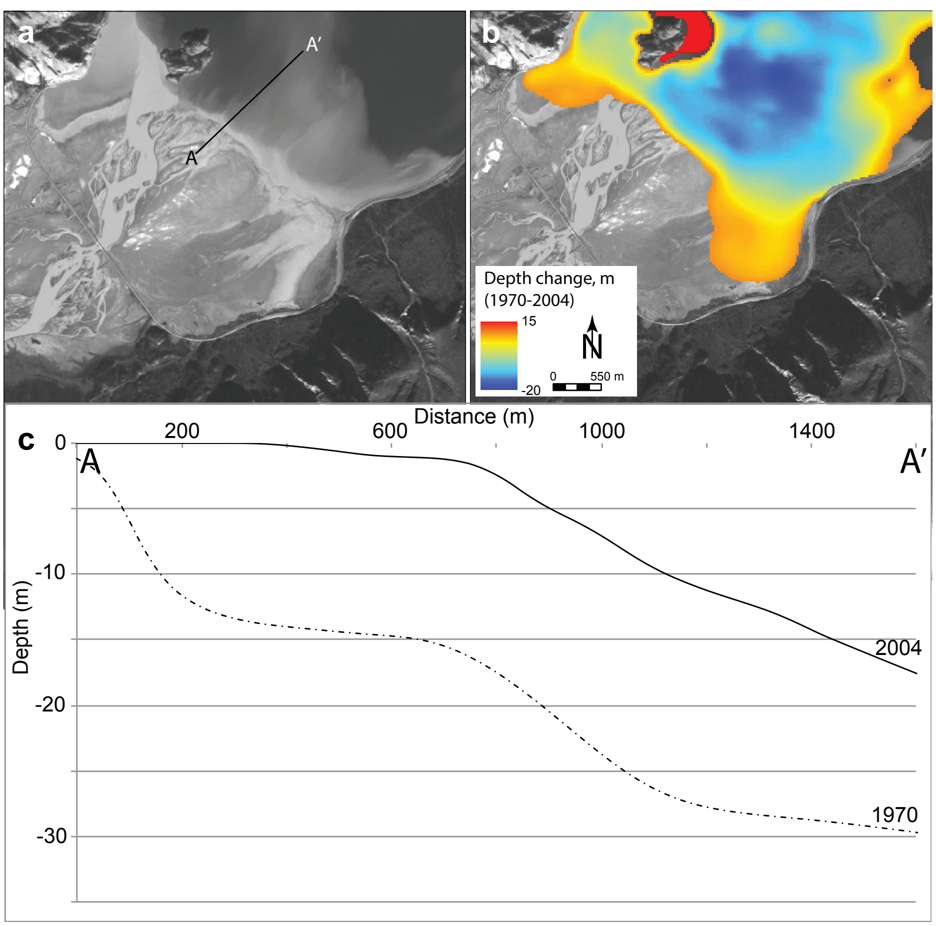

Figure 3. *(a) Orthophoto of southern Kluane Lake and Slims River delta with location of transect shown in panel C. (b) Lake depth difference map between 1970 (Bryan, 1970) and 2004 (Gilbert and Crookshanks, 2009), based on digitized bathymetric contours. Cool colours indicate a decrease in lake depth (e.g., sediment aggradation) while hot colours indicate an increase (e.g., erosion). Note that apparent scour in lee of the island may be a data artefact. (c). Change in depth of Kluane Lake along transect A-A′ between 1970 and 2004.*

DELTA STRATIGRAPHY

The Parametric Echo Sounder (PES) profiles from the Slims River delta show a range of surface and subsurface features that typify sedimentation in a fine-grained, actively prograding delta. The features identified in our survey support the earlier work of Gilbert and Crookshanks (2009), who found the delta surface to be populated by a series of large sediment waves that migrate upslope (*e.g.*, Fig. 4). Those authors also describe small, buried sediment waves, which initially formed at the distal end of the advancing sediment wedge. The sediment waves are seen in several of the PES profiles (Figs. 4, 5, and 6) that extend from the delta top into deeper water to the north. They are low-angle (1-2°) asymmetric features with heights of 1-3 m. The delta topset also appears to be cut by a number of small scarps (Fig. 7), which were interpreted by Gilbert and Crookshanks (2009) to be the result small sediment gravity flows from the delta top. Potential evidence for larger scale instabilities is shown by several large scarps that appear to cut through the delta sediment package (Figs. 7 and 8). These scarps are associated with underlying disturbance of sediment and appear to be products of longer-term gravitational instability and soft-sediment deformation on the delta slope. In addition to these larger scarp features, our surveys also reveal small channels, 1-3 m deep, that are cut into the delta top (Figs. 4 and 9).

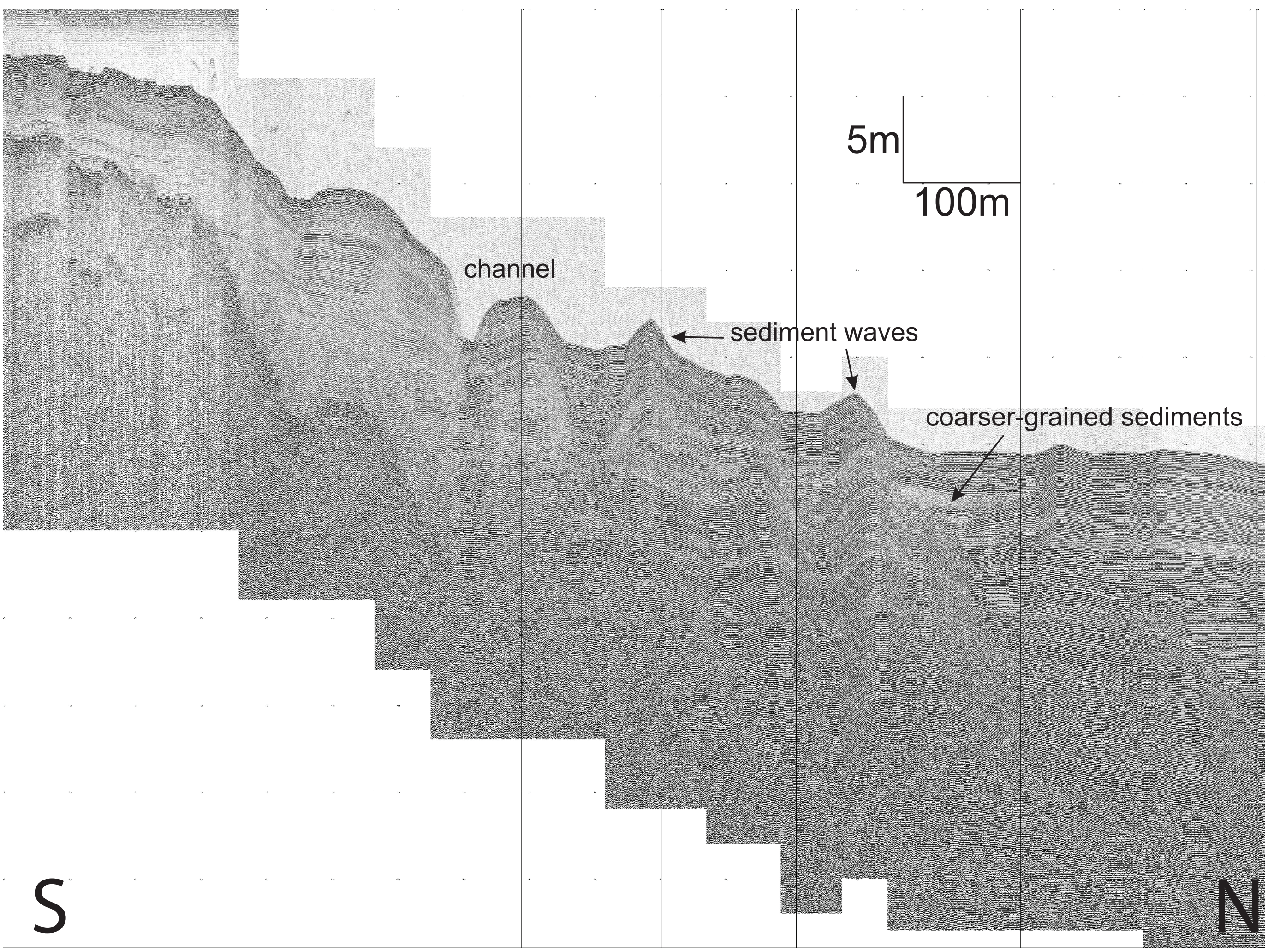

Figure 4. *Parametric echo sounder (PES) profile of Slims River delta showing lake bottom morphology and sediment stratigraphy; see Figure 2 for location.*

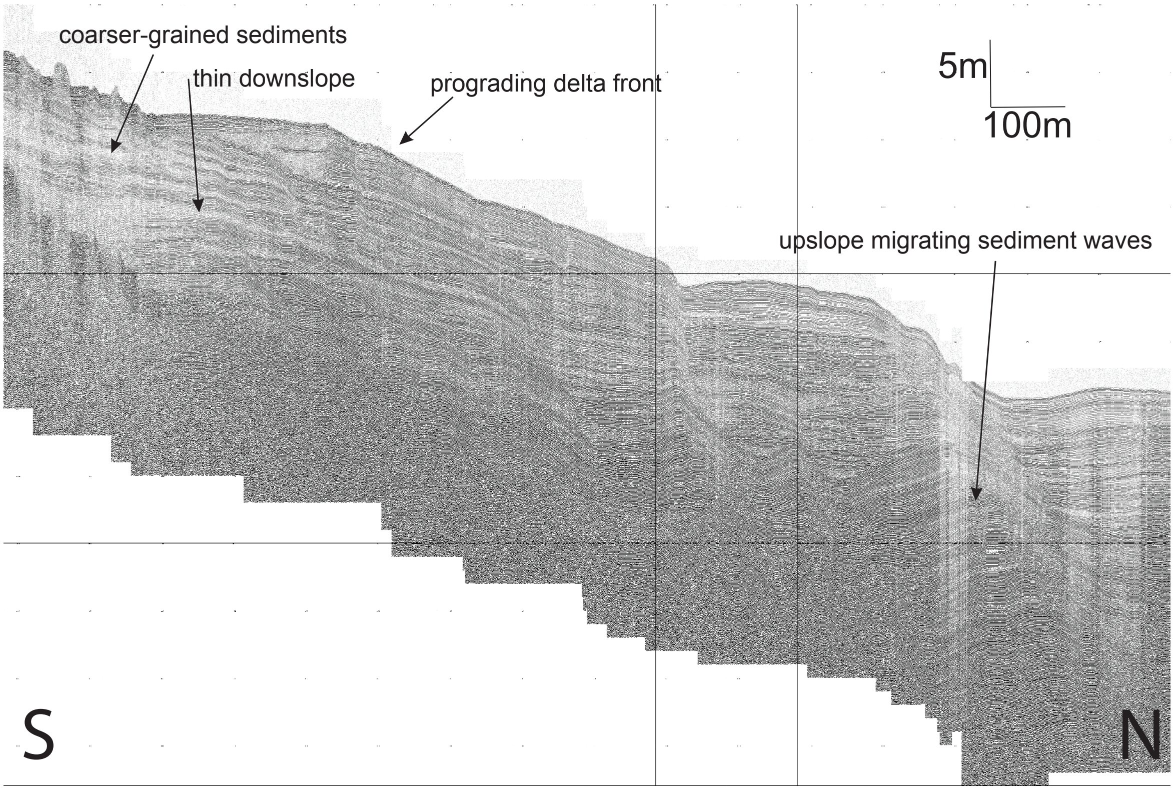

Figure 5. *Parametric echo sounder (PES) profile of Slims River delta showing lake bottom morphology and sediment stratigraphy; see Figure 2 for location.*

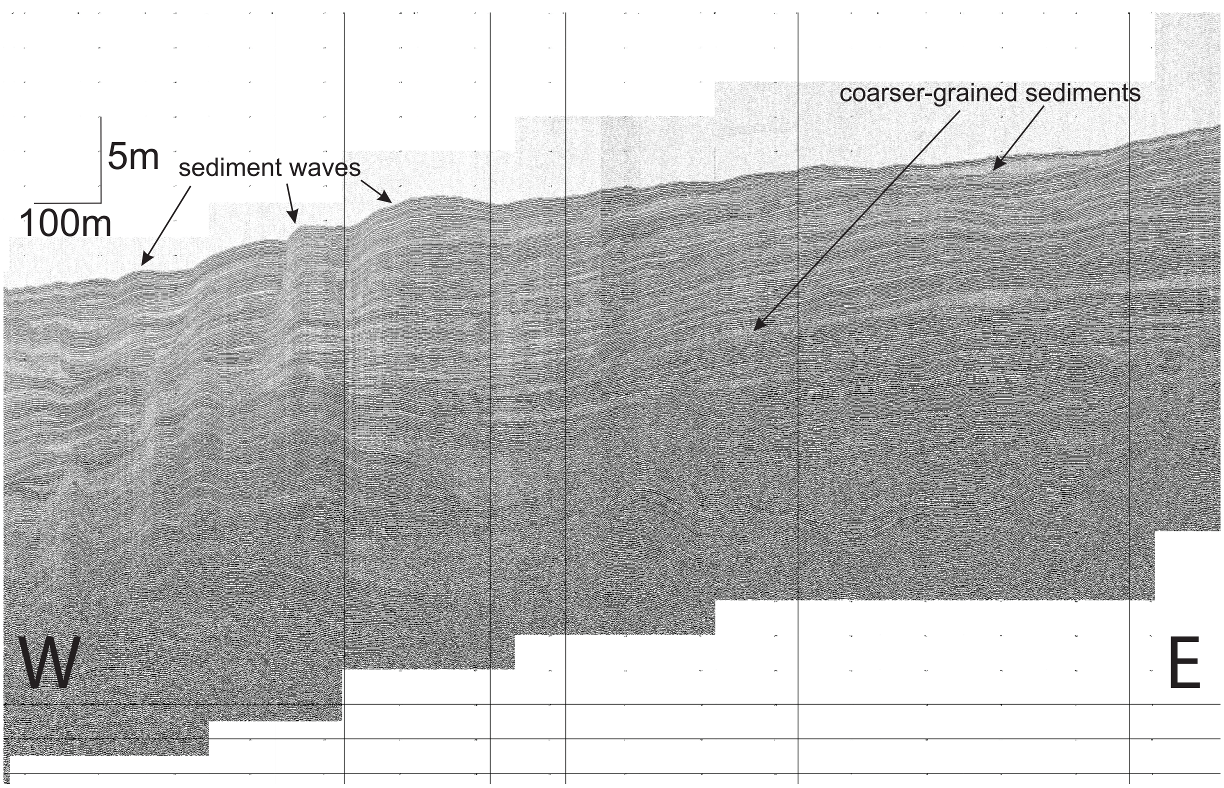

Figure 6. *Parametric echo sounder (PES) profile of Slims River delta showing lake bottom morphology and sediment stratigraphy; see Figure 2 for location.*

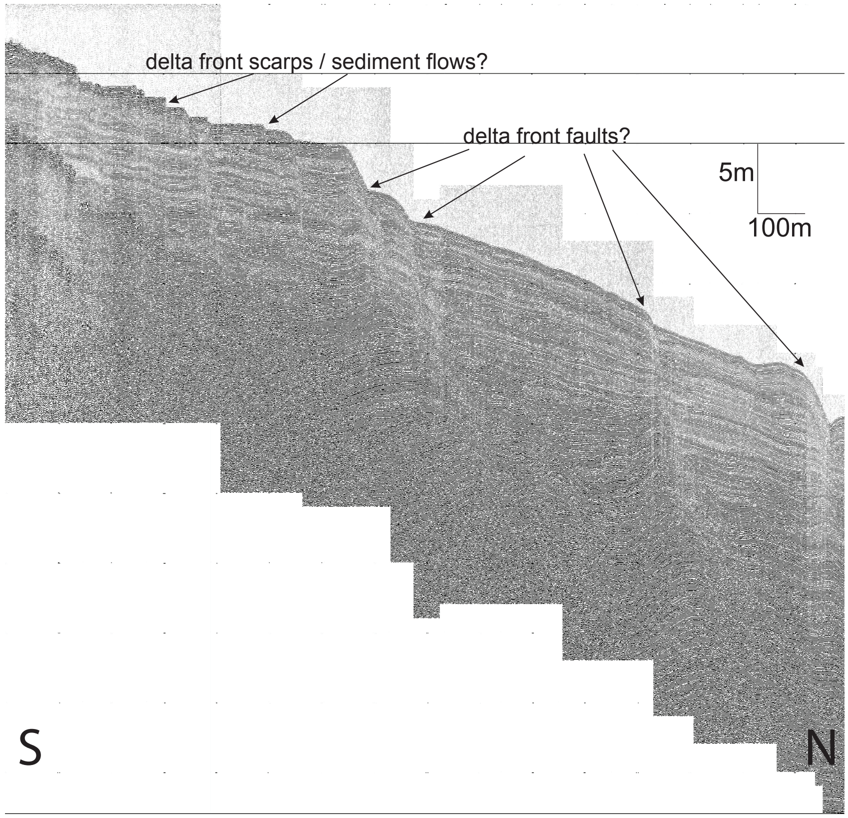

Figure 7. *Parametric echo sounder (PES) profile of Slims River delta showing lake bottom morphology and sediment stratigraphy; see Figure 2 for location.*

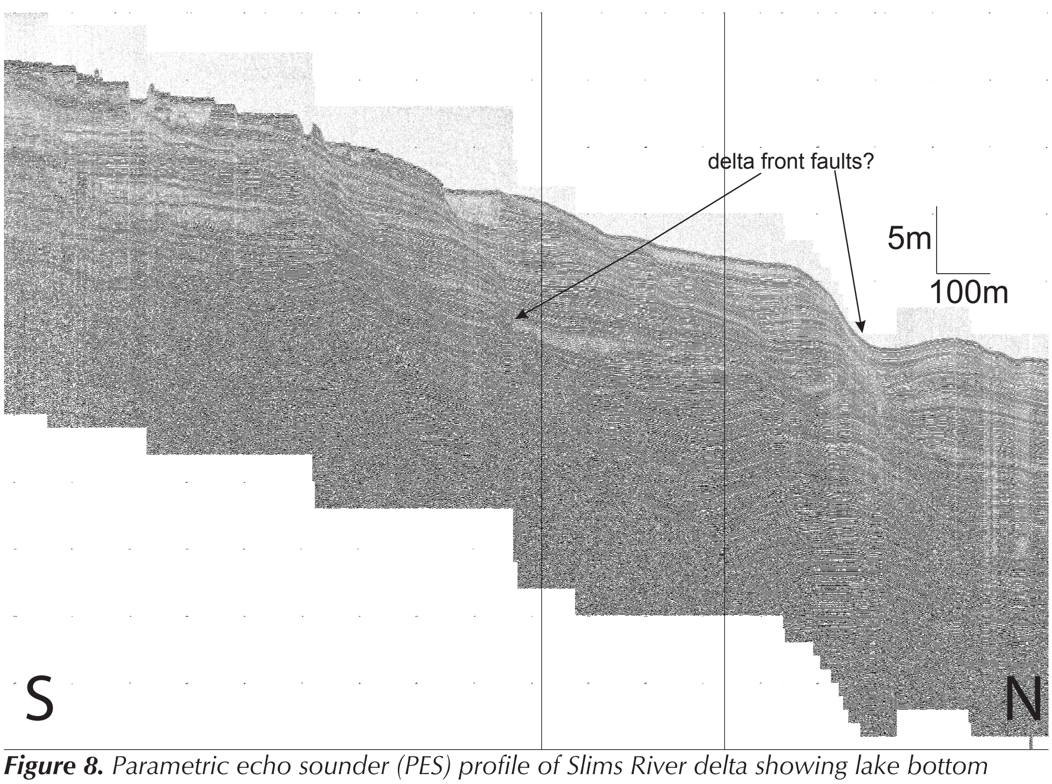

Figure 8. *Parametric echo sounder (PES) profile of Slims River delta showing lake bottom morphology and sediment stratigraphy; see Figure 2 for location.*

The strong reflections in the PES data indicate that most of the deltaic sediment sequence is fine-grained (silt to fine sand) (*e.g.*, Sambrook Smith *et al.*, 2013). Opaque structureless reflectors (Figs. 4, 5, 6, and 9) likely record episodic transport and deposition of coarser sand. Figure 5, for example, shows packets of sandy sediment that thin down the delta front and are bounded by strong reflectors that represent finer grained sedimentation. Coarser sediment is more abundant in the proximal region of the delta (Figs. 5 and 6) and is gradually replaced downslope by finer grained sediments. In other sections (*e.g.*, Figs. 8 and 9), lenses of opaque structureless sediment are nested within finer sediments. These may be evidence of occasional transport of coarser sediment during periods of high river discharge onto the delta slope, whereby the coarser sediments accumulate in depressions or swales and are then later covered by fine-grained sediments transported during lower velocity flows. Delta-front faults are evident (*e.g.*, Figs. 7, 8) although it is not clear whether or not these are co-seismically triggered.

FLOW AND SEDIMENT TRANSPORT OVER THE SLIMS RIVER DELTA

The mean grain size of suspended sediment reaching the Slims River delta is 5-10 μm (very fine to fine silt), with little difference from the lake floor to the water surface. Time-averaged suspended sediment concentrations (SSC), however, decrease logarithmically from a maximum of 0.96 g L^{-1} near the bed (0.85 m above the bed), to only 0.02 g L^{-1} near the surface (7.13 m above the bed; Fig. 10). These values are at the lower end of the "normal" range of 1-2 g L^{-1} reported by Crookshanks and Gilbert (2008). Those authors recorded a maximum SSC of 4.8 g L-1 during a flood on June 30-July 1, 2007. Bed sediments (based on one sample) have a median grain size (D_{50}) of approximately 78 μm (Fig. 10). Bryan (1970) observed somewhat finer bed sediments (D_{50} 3-30 μm) in samples further from the Slims River delta than ours.

An aDcp was used to quantify 3D velocity and backscatter (proxy for suspended sediment concentration) within the turbidity current on the Slims River delta. A 180-minute moored-station aDcp measurement obtained on the delta clinoform starting at 14:00hrs on August 12, 2013, indicates that flow plunges to the bed, with velocities up to 0.3 m s^{-1}, and is internally stratified. Flow was relatively steady through the period of measurements with variation in both velocity (0.1 to 0.3 m s^{-1}) and thickness of the underflow (varying in thickness by about 1.5 m) evident (Fig. 11). Previous work on turbidity driven flow dynamics have identified large variations in velocity (*e.g.*, Best *et al.*, 2005). However, the variations identified in Figure 11 indicate lower frequency pulsing of the current on the Slims River delta. Crookshanks and Gilbert (2008) found no dominant frequency in their velocity records from Kluane Lake in the summer of 2007. The backscatter record (Fig. 11) indicates a positive correlation of suspended sediment concentration with streamwise velocity. Calibration of the backscatter to suspended sediment concentrations is ongoing (see below).

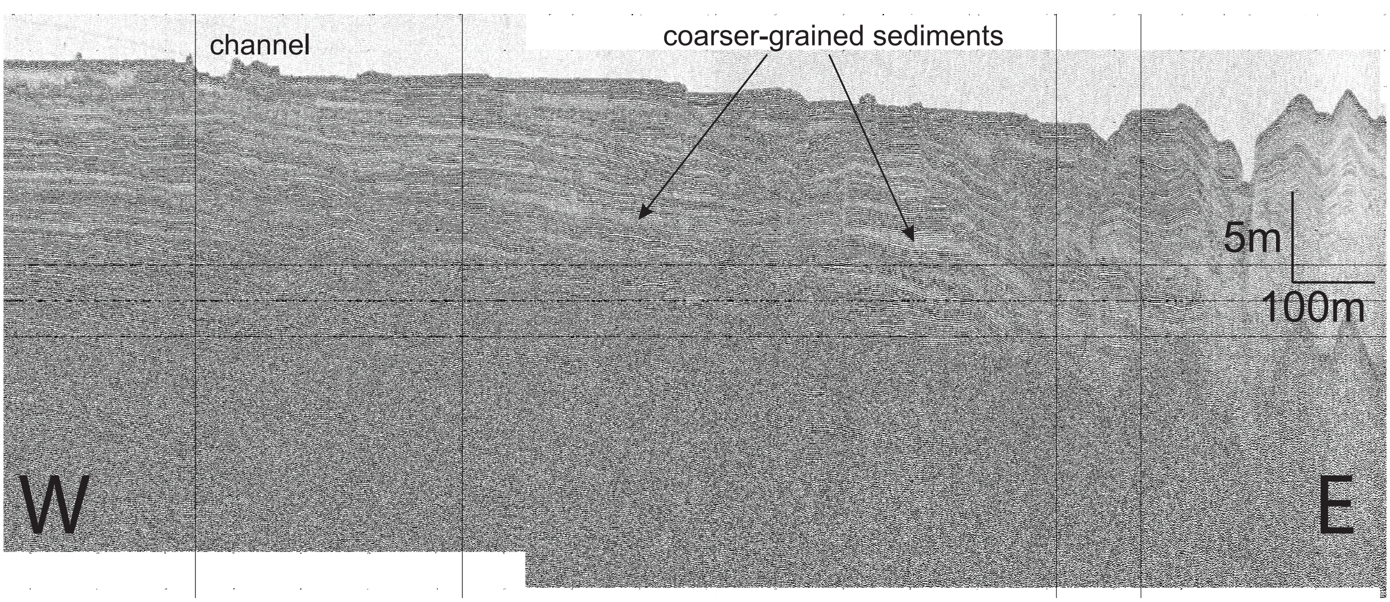

Figure 9. *Parametric echo sounder (PES) profile of Slims River delta showing lake bottom morphology and sediment stratigraphy; see Figure 2 for location.*

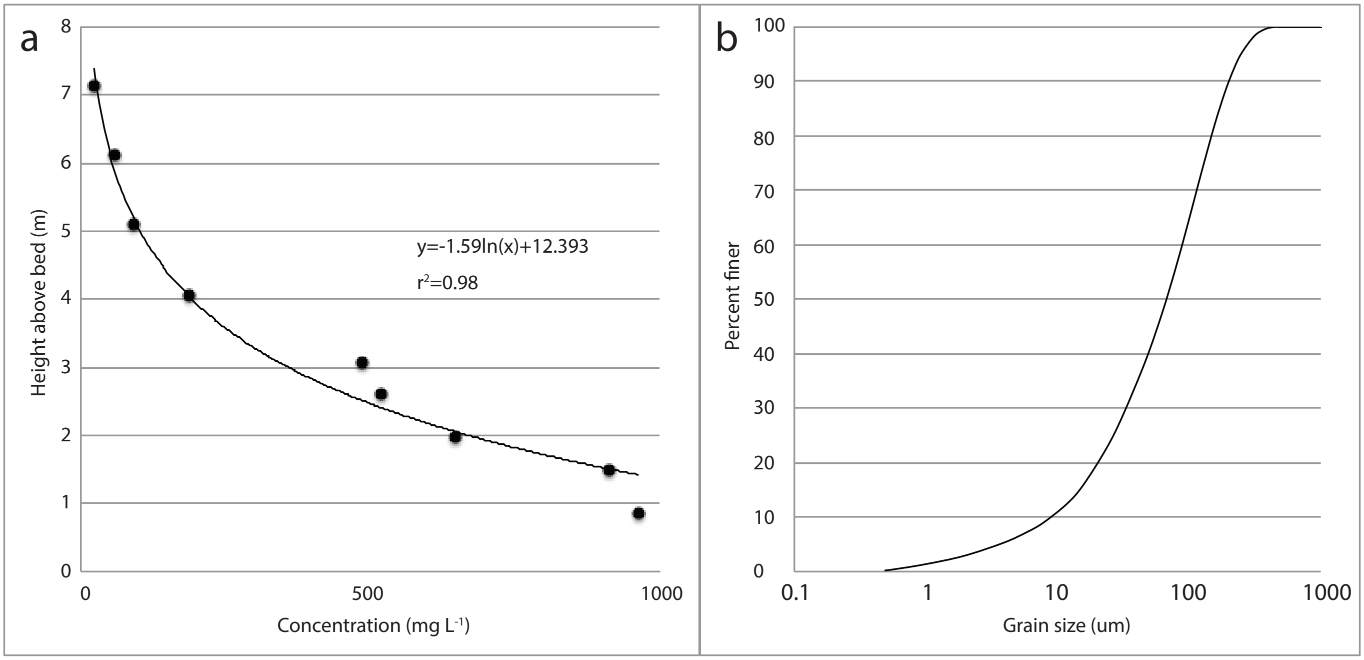

Figure 10. (a) Profile of suspended sediment concentrations near the front of the Slims River delta. (b) Grain-size distribution of a sample of bed sediment collected from the Slims River delta.

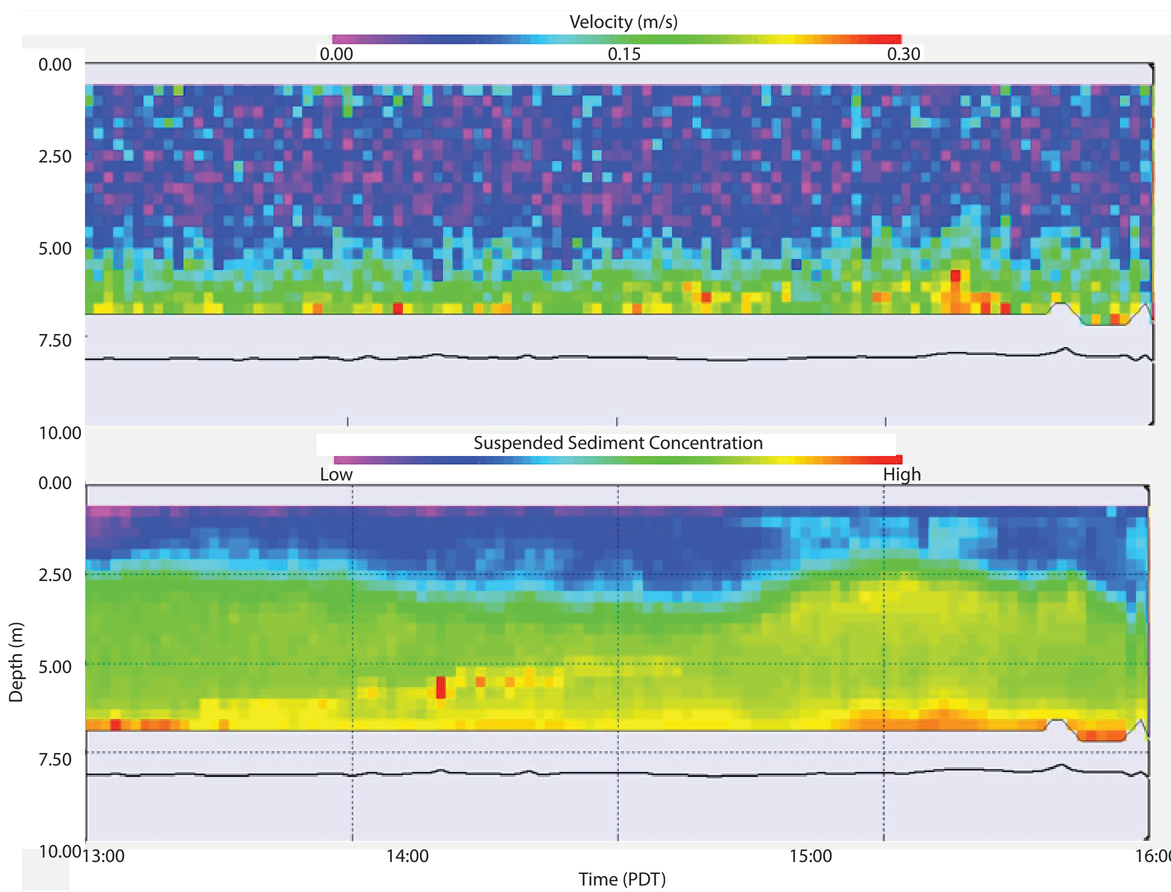

Figure 11. Velocity and (uncalibrated) suspended sediment concentration record from 3-hr time series while moored near the front of the Slims River delta.

HOLOCENE TERRACES

Drowned terraces (Fig. 12) are evident in the PES data west of Cultus and Christmas bays. The most well defined drowned terraces are approximately 25, 30, 37, and 47 m below the lake surface. The terraces range in width from approximately 50 m to more than 200 m, and are either flat or slope at a very low angle (<1°) toward deeper water. The drowned terraces appear to be eroded surfaces that are draped by younger sediments, some of which dip more steeply lakeward than the surfaces on which they lie. PES penetration in these sediments is poorer than in the fine-grained deltaic sediments, suggesting that the terrace sediments are sand and/or gravel.

Our preliminary interpretation of the terraces is that they are wave-cut benches that developed when Kluane Lake was lower than present. Clague *et al*. (2006) presented evidence that the lake was lower than at present prior to the seventeenth century, although by how much was uncertain. Brahney *et al*. (2007; 2008; 2010) interpreted late Holocene lake levels of -20 to -30 m based on sediment cores collected from the lake. If the terraces that we have mapped are wave-cut benches, Kluane Lake at some time during the Holocene was at least 47 m lower than today and the entire northern half of the lake basin at that time was subaerial.

CONCLUSIONS AND FUTURE WORK

The preliminary results presented here include detailed visualization of surface and subsurface features on the Slims River delta, as well as of Holocene-era drowned terraces on the eastern margin of the lake. Buried sediment waves seen in Parametric Echo Sounding profiles (*e.g.*, Fig. 5), and bathymetric data (*e.g.*, Fig. 3) indicate that the delta has been rapidly prograding and aggrading in the past decades to centuries. Drowned lake terraces on the eastern margin of the lake (*e.g.*, Fig. 12) indicate at least four periods of relative lake-level stability lower than the present level and the +12 m level previously described by Clague *et al*. (2006).

The 2013 field data are currently being processed and a 3D model of the surface and subsurface structure of the Slims River delta is being constructed from the MBES and PES data. The focus of future work will be on obtaining a higher-density grid of the delta, extending our survey further into the lake, quantifying annual changes to lake-bed topography in the vicinity of the delta, and mapping the Denali fault where it crosses the lake. Initial results indicate that the Denali fault was imaged by PES in 2013, but these data are not yet processed. This study intends to core through the lacustrine sediment sequence at the Kluane Lake Research Station to obtain samples for radiocarbon dating and paleo-ecological analysis in an effort to further elucidate the low-stand history of the lake. It is expected that coring will occur in summer 2014, while further MBES, PES, and aDcp surveys will occur in summers 2015 and 2016, subject to funding. Findings are expected to be published in peer-reviewed journals beginning in 2014.

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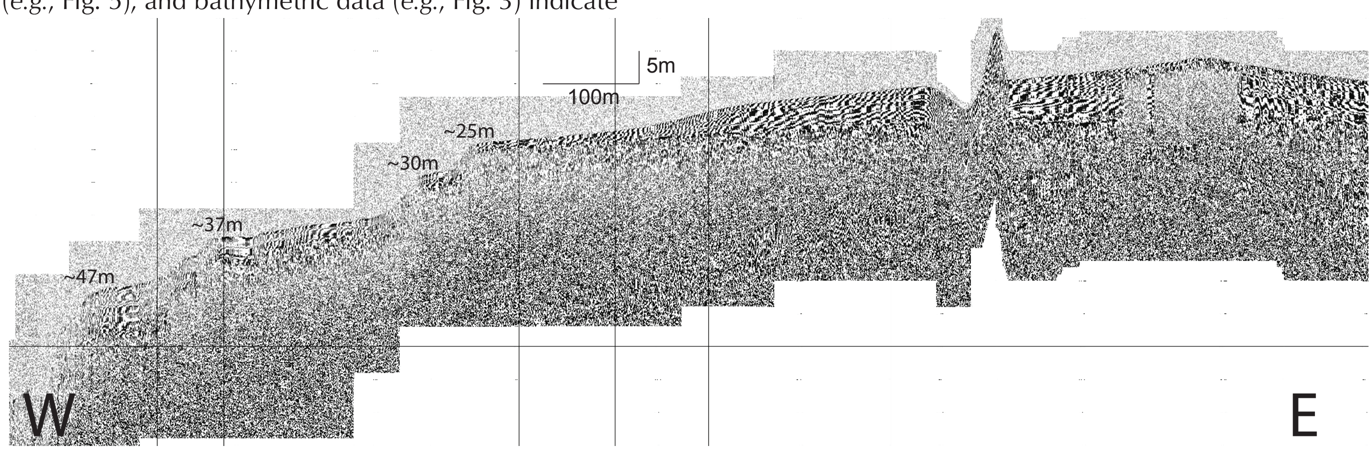

Figure 12. *Parametric echo sounder (PES) profile showing lake bottom morphology and sediment stratigraphy from Christmas Bay showing at least four drowned terraces, with depths below lake level indicated.*

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