Short Paper

Rapid changes in the level of Kluane Lake in Yukon Territory over the last millennium

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Abstract

The level of Kluane Lake, the largest lake in Yukon Territory, was lower than at present during most of the Holocene. The lake rose rapidly in the late seventeenth century to a level 12 m above present, drowning forest and stranding driftwood on a conspicuous high-stand beach, remnants of which are preserved at the south end of the lake. Kluane Lake fell back to near its present level by the end of the eighteenth century and has fluctuated within a range of about 3 m over the last 50 yr. The primary control on historic fluctuations in lake level is the discharge of Slims River, the largest source of water to the lake. We use tree ring and radiocarbon ages, stratigraphy and sub-bottom acoustic data to evaluate two explanations for the dramatic changes in the level of Kluane Lake. Our data support the hypothesis of Hugh Bostock, who suggested in 1969 that the maximum Little Ice Age advance of Kaskawulsh Glacier deposited large amounts of sediment in the Slims River valley and established the present course of Slims River into Kluane Lake. Bostock argued that these events caused the lake to rise and eventually overflow to the north. The overflowing waters incised the Duke River fan at the north end of Kluane Lake and lowered the lake to its present level. This study highlights the potentially dramatic impacts of climate change on regional hydrology during the Little Ice Age in glacierised mountains.
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Keywords: Little Ice Age; Kluane Lake; Dendrochronology; Drainage evolution

Introduction

Studies of lakes in regions where small changes in climate can dramatically alter lake hydrological balance provide important information on the scale and timing of Holocene climate change in western North America (e.g., Last et al., 1998; Last and Vance, 2002; Abbott et al., 2000; Barber and Finney, 2000; Campbell et al., 2000; Pienitz et al., 2000). Most studies have focused on lake sediments and what they reveal about water balance, the thermal structure of lakes, sedimentation processes, lake histories and ecosystems. As an example, high-resolution paleoenvironmental information has been extracted from lake sediment cores by studying the thickness and other properties of annually layered sediments (Gilbert, 1975; Menounos, 2002). Sequences of annually layered sediment, however, are not helpful in reconstructing past changes in lake level and volume, both of which are directly linked to changes in the water balance of a lake. A more direct and powerful proxy for this type of paleolimnological reconstruction is the direct geomorphic record of past shorelines.

In this paper, we present geomorphic and other evidence for large, late Holocene changes in the size and level of Kluane Lake, the largest lake in Yukon Territory, Canada, with an area of 420 km². We document a rise in lake level of more than 12 m in the late seventeenth century, which is exceptional for a lake of this size. We examine two hypotheses that might explain the rapid lake-level rise and conclude that base level at the former outlet rose due to aggradation caused by an advance of Kaskawulsh Glacier, a large valley glacier in the nearby St. Elias Mountains. Kaskawulsh Glacier blocked the outlet in the

mid- to late seventeenth century, forcing Kluane Lake above its present level.

Setting

Kluane Lake lies within Shakwak Trench, a Cenozoic fault-bounded basin at the east margin of the St. Elias Mountains in southwest Yukon Territory (Fig. 1). It is about 65 km long, an average of 4 km wide and up to 78 m deep (Fig. 2). Shakwak Trench was covered by glaciers at the maximum of the Late Wisconsinan Kluane Glaciation (Rampton, 1981). Kluane Lake is bordered partly by drift of the Kluane Glaciation and, on the west, by an apron of Holocene colluvial and alluvial fans issuing from the Kluane Ranges, the easternmost range of the St. Elias
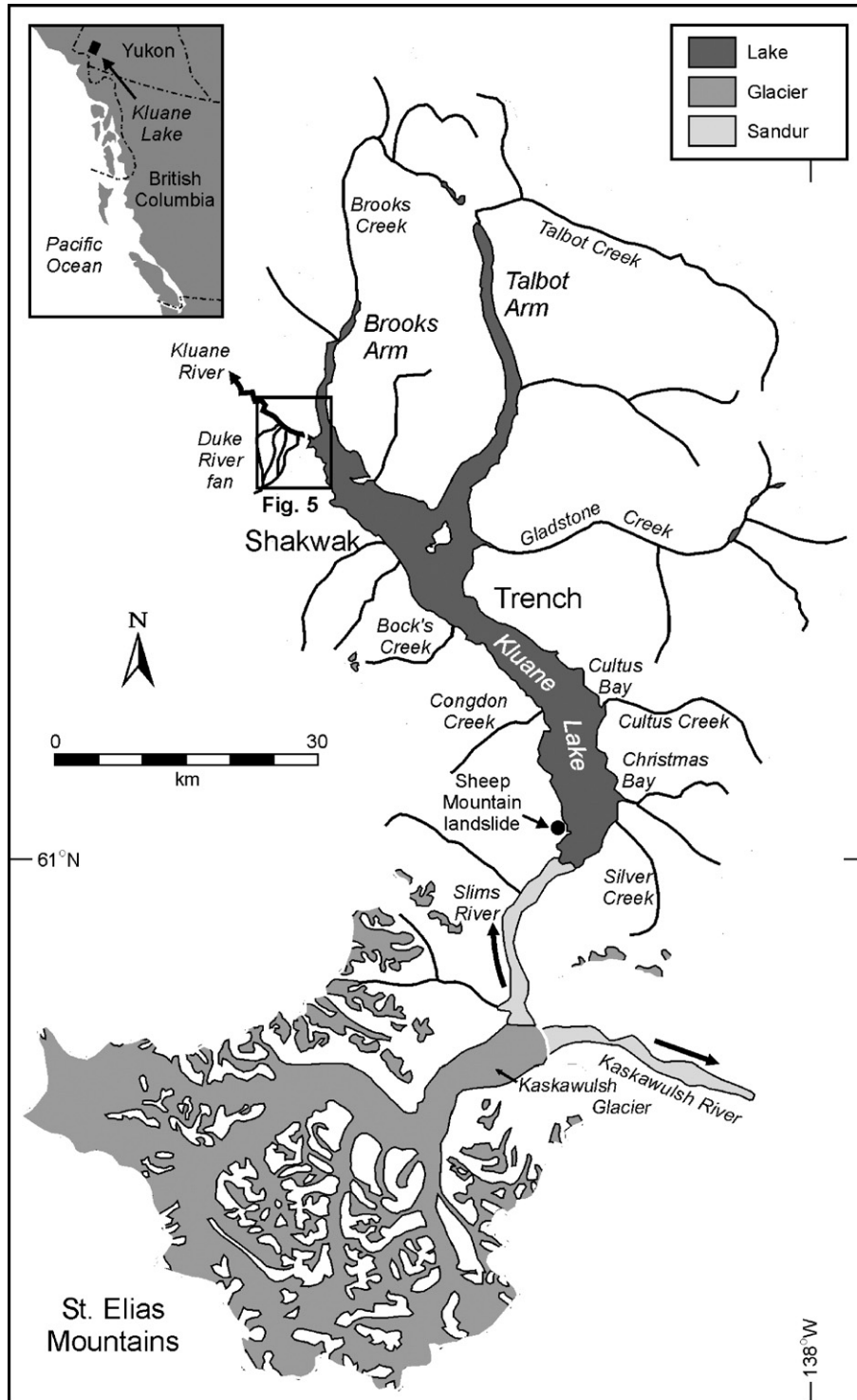

Figure 1. Map of the study area, showing Kluane Lake, Kaskawulsh Glacier, the Duke River fan, sample localities and other sites mentioned in the paper.
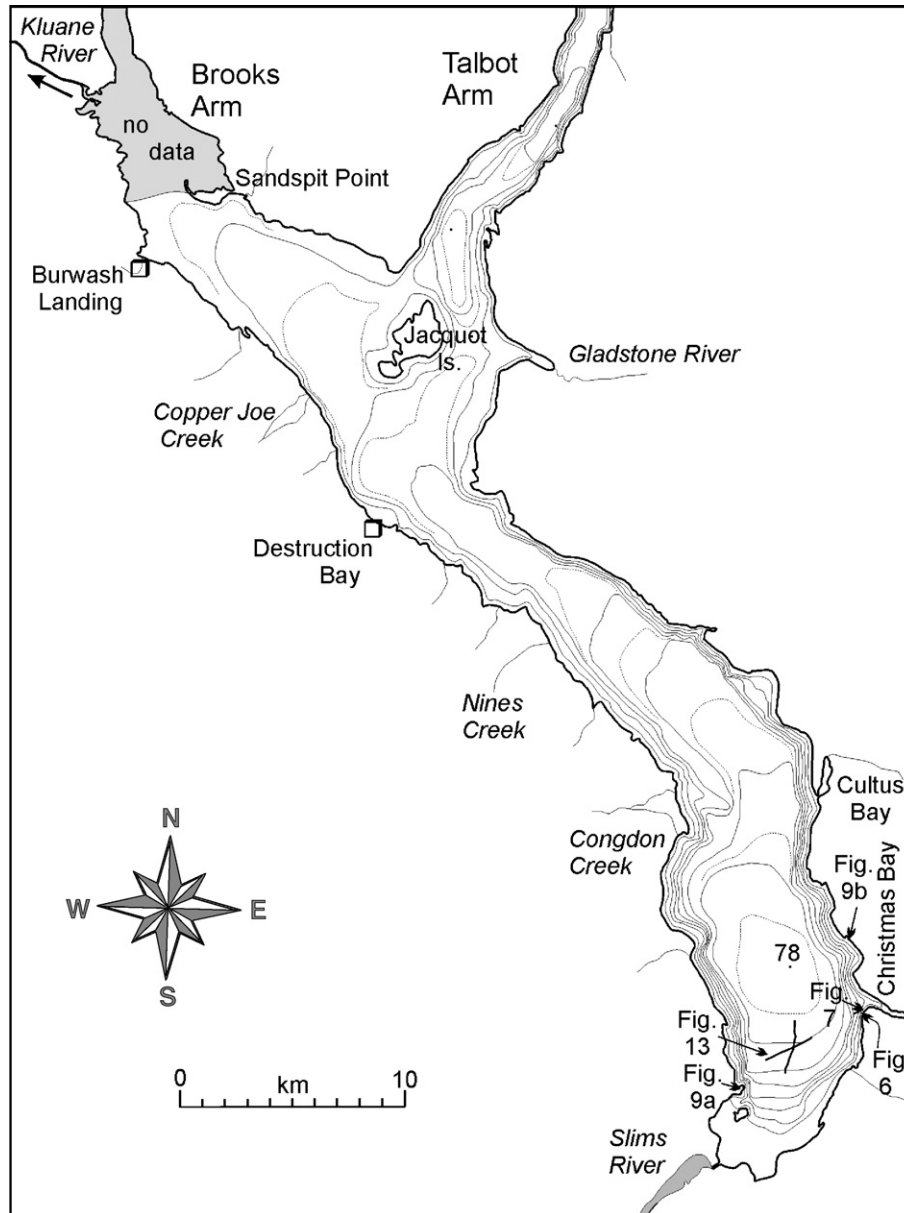
Figure 2. Bathymetry of Kluane Lake, based on a 180-km acoustic survey in August 2004. Five- and 10-m isobaths are shown by dashed and solid lines, respectively. Water depths are based on a sound velocity of 1430 m/s with reference to a water surface about 1 m below normal summer level.

Mountains. Late Pleistocene drift comprises glaciolacustrine and glaciofluvial sediments that form conspicuous benches bordering parts of the lake.

Many small streams flow into the lake, but the main source of water is Slims River (Figs. 1 and 3). Slims River heads at the terminus of Kaskawulsh Glacier and flows 19 km north to Kluane Lake where it has built a large delta of silt and sand into the southern part of the lake. Historic rates of delta growth are high (Table 1), suggesting that the lake extended several kilometres farther south up the Slims River valley as recently as the late nineteenth century. The average rate of advance of the delta front over the period 1899–1970, about 45 m/a, greatly exceeds growth of other glaciolacustrine deltas in western Canada. By way of comparison, Lillooet River, a large meltwater-fed system in the southern Coast Mountains of

British Columbia, has advanced its delta into Lillooet Lake at rates between 7 and 20 m/a since 1858 (Gilbert, 1975) and has averaged 6 m/a during the Holocene except a brief period of up to 150 m/a following the eruption of Mt. Meager volcano (Friele et al., 2005). Slims River discharge varies markedly on time scales ranging from hours to years. In addition to diurnal and seasonal discharge variations typical of glacial streams (Woo, 1993), Slims and Kaskawulsh rivers experience large fluctuations in flow due to changes in the position of meltwater discharge from the terminus of Kaskawulsh Glacier, which feeds both rivers. At times, most of the meltwater issuing from the glacier is carried by Kaskawulsh River to Alsek River, which empties into Chilkat Inlet in southeast Alaska. At these times, Slims River discharge is low and the level of Kluane Lake drops. At other times, most of the meltwater flowing from

Figure 3. Photographs of (a) Slims River and Kaskawulsh Glacier (August 2001) and (b) Slims River delta (August 1978).
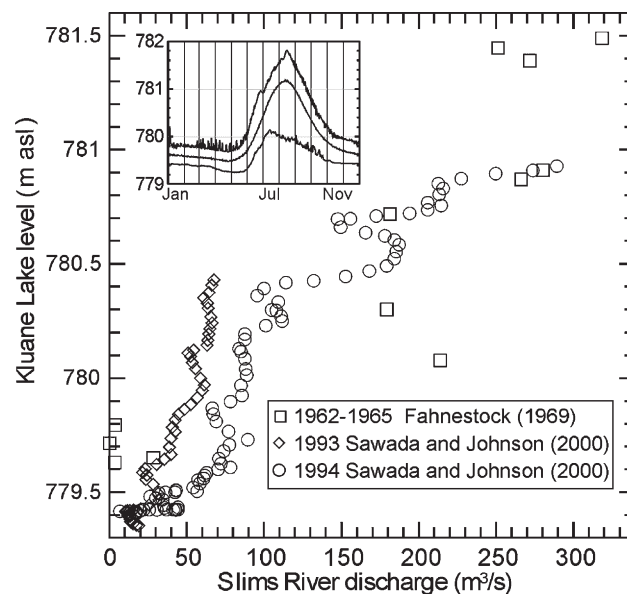

Figure 4. Relation between discharge of Slims River and the water level of Kluane Lake. Inset is the annual hydrograph of Kluane Lake showing the mean daily, maximum daily and minimum daily levels for the period 1953–2004. Slims River data are from Fahnestock (1969) and Sawada and Johnson (2001). Kluane Lake data are from the Water Survey of Canada station 09CA001.

Kaskawulsh Glacier is carried by Slims River, and peak discharges to Kluane Lake may exceed 3000 m^3 s^{-1} (Fahnestock, 1969). Kluane Lake level is several metres higher at these times than it is at times of low flow (Fig. 4). The present outlet of Kluane Lake is the head of Brooks Arm near the north end of the lake (Fig. 1). Kluane River flows out of the lake along the east edge of the Duke River fan, an alluvial and colluvial fan covering an area of about 80 km^2 (Fig. 5).

Methods

A sub-bottom acoustic survey of Kluane Lake was conducted in July 2004 using a Datasonics (Benthos) Chirp II system with four low-frequency transducers and one high-frequency transducer mounted in a streamlined platform towed

Table 1
Average rates of advance of Slims River delta

Period	Total advance (m)	Average rate (m/a)
1899–1914	1110	74
1914–1947	1590	48
1944–1970	460	18
1899–1970	3160	45

Note. Data from Terrain Analysis and Mapping Services (1978).

beside the survey vessel at a depth of 1 m. Thirty oblique cross-transects and one long profile totalling 180 km were completed. Positions were established by GPS and linked to the digital record at 10-s intervals. The estimated error in positions is ±5 m or less. We assumed a velocity of sound in water of 1430 m/s, corresponding to a water temperature of 5.5°C. We transcribed bathymetric and sub-bottom data at 1-min intervals (mean, 217 m) along the track lines and at intermediate points where depths or acoustic facies changed rapidly. The bathymetry was plotted from these data (Fig. 2).

Stems of in situ drowned trees at Cultus and Christmas bays (Fig. 1) and driftwood near the south end of the lake were dated by radiocarbon and dendrochronological methods. Conventional radiocarbon ages were obtained on the outermost rings of tree stems and branches. Disks of tree stems and driftwood were analyzed at the University of Western Ontario Dendrogeomorphology Laboratory. Annual ring widths were measured to the nearest ±0.001 mm with a Velmex measuring system. Long ring-width chronologies were developed from living *Picea glauca* and snags on the Sheep Mountain landslide at the south end of Kluane Lake (the "Landslide chronology", AD 950–2000; Luckman et al., 2002; Van Dorp, 2004) and from living trees at a site near Burwash Landing using standard techniques. Ring-width series from subfossil material were internally cross-dated and used to develop "floating" (undated) chronologies for individual deposits or sites. These were subsequently cross-dated with one of the reference "master" living tree chronologies to assign calendar dates to the ring series using the ITRDB program COFECHA (Holmes, 1994). The tentative correlations were then verified by visual cross-dating (Stokes and Smiley, 1968).

Sections of Duke River fan sediments were examined in natural exposures between the lake outlet and the confluence of
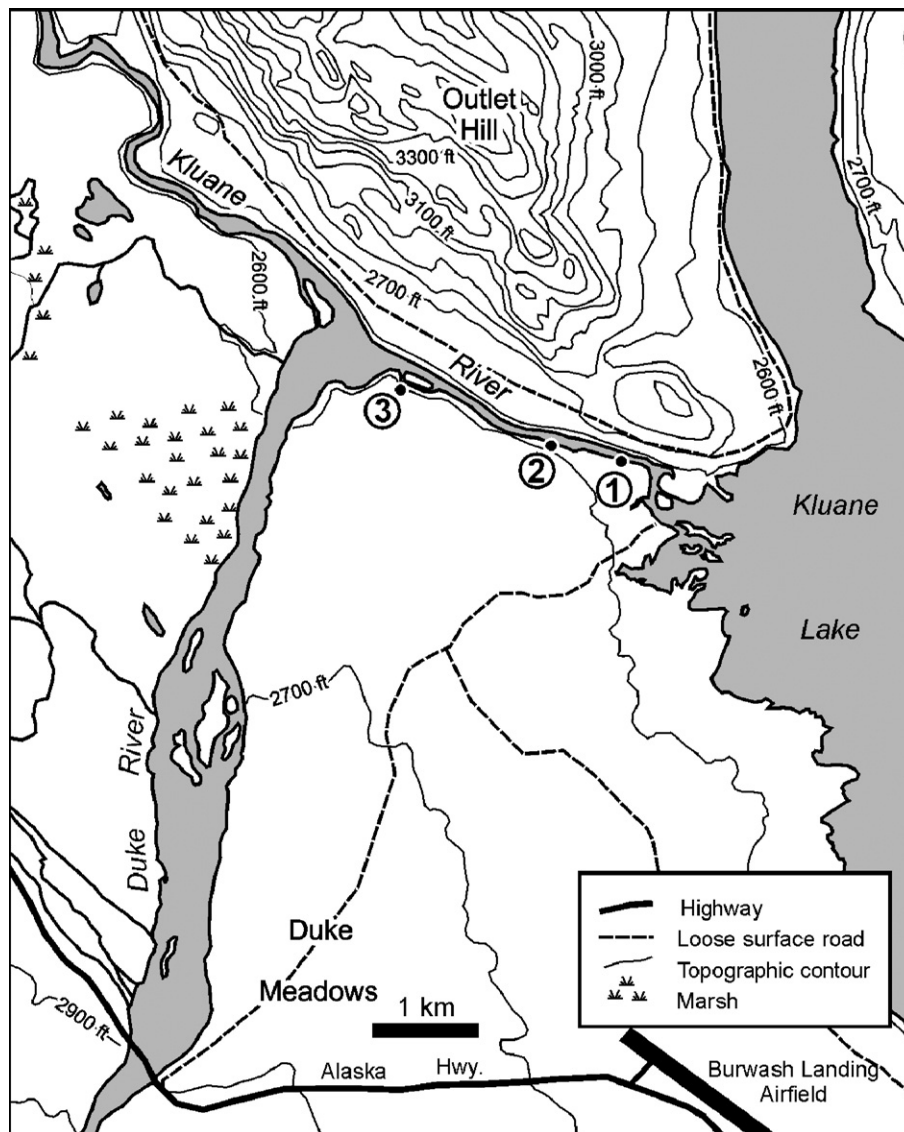
Figure 5. Map of the north end of Kluane Lake, showing the Duke River fan and locations of studied sections bordering Kluane River (see Fig. 1 for location). Reproduced from Natural Resources Canada 1:50,000 scale topographic map, NTS 115 G/6.

Duke and Kluane rivers. Vertical distances were measured with an aneroid altimeter, with measurement errors of 1 m or less. Measurements were keyed to the level of Kluane Lake in July 2004 with a surveying level. Samples of detrital wood and tree stems in growth position were collected from these deposits for radiocarbon and tree ring dating. The samples were processed in the same manner as the drowned tree stems and driftwood.

Results

Submerged shorelines and other low lake-level features

The acoustic records show a series of underwater terraces that nearly surround the main body of Kluane Lake (Fig. 6). Most of these features comprise a shoreward wave-cut terrace and an associated lakeward wave-built terrace. Some wave-built terraces exhibit foreset beds that were progressively built lakeward from sediment eroded from the adjacent wave-cut

terrace. The terraces are present at different depths up to about 42 m below present lake level. Some scatter is expected because the terraces record wave base, not former levels of the lake. Wave base in Kluane Lake today, and in the past when the lake
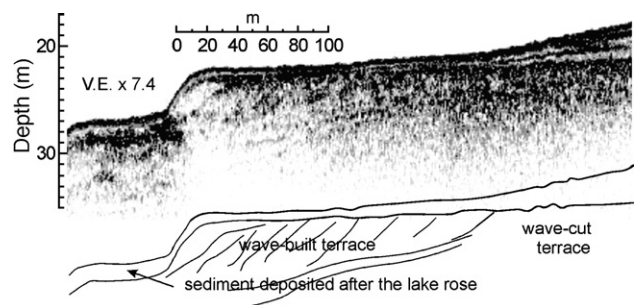

Figure 6. Representative nearshore acoustic transect in southern Kluane Lake showing a terrace formed at a lower lake level (see Fig. 2 for location).

was lower, varies because of different exposures of the lake floor to waves. To estimate former lake level, we calculated wave base from maximum effective fetch (Gilbert, 1999), which is 7.5–12 km depending on the configuration of the shoreline. Relations for significant wave heights and periods (Sinclair and Smith, 1972) produce heights of 1.75–2.2 m and periods, T, of 4.7–5.4 s for winds of 100 km/h, which is a major, but not extreme, wind event in this area. The significant wavelength, L, for deepwater waves is given by $L = 1.56 \ T^2$. This equation yields a range for L of 34.4–45.5 m. Wave base, B, is 0.25 L (Sly, 1978), or 8.6–11.3 m. Hence, we estimate the terraces to correspond to undated lake levels up to about 32 m below the present level (i.e., about 750 m asl).

The bathymetry shows a broad, shallow, submerged plain in Brooks Arm gently sloping to a break of slope southwest of Jacquot Island (Fig. 2). Acoustic data indicate that this surface is cut by many small channels that are overlain by up to 2 m of modern lake sediment. We interpret this surface to be a braided sandur built southward into a low-level Kluane Lake from Brooks Creek (Fig. 1) and possibly Duke River.

Drowned trees

Stumps and tree stems rooted below present lake level are common along much of the shoreline of Kluane Lake (Fig. 7). They extend from the normal high water mark to an unknown distance offshore.

Radiocarbon ages of three drowned trees, reported previously by Lowdon and Blake (1970) and Clague (1981), range from 250 ± 50 to 490 ± 50 ^{14}C yr BP (Table 2). The tree that yielded the youngest radiocarbon age died sometime after AD 1480 (Table 2). Thirty-two drowned trees at Cultus and Christmas bays and the Landslide site were cross-dated to the Landslide chronology (Van Dorp, 2004). The outermost ring of most of these trees dates to AD 1640–1650 (Fig. 8). The innermost ring of the oldest drowned tree dates to AD 1398 (Fig. 8). Driftwood thought to have been derived from trees that were killed by lake-level rise and lying on high-level beaches

Figure 7. Stems of in situ drowned trees at the shore of Kluane Lake near its southern end (see Fig. 2 for location).

(see below) have pith dates as old as AD 1041. We infer from the tree ring and radiocarbon ages that Kluane Lake rose through its present level in the middle of the seventeenth century and that, before this, it was below this level for at least 250 yr and probably more than 600 yr.

High-level beaches and driftwood

A piece of driftwood collected from the highest (+12 m) beach near Sheep Mountain (Figs. 1 and 9) yielded a radiocarbon age of 120 ± 130 ^{14}C yr BP (younger than AD 1515). Cross-dating of 26 logs from this beach produced outer ring ages that are no younger than those of the drowned tree stems just below the present shoreline (Fig. 8). The 12-m shoreline is older than AD 1693, which is the estimated germination year (based on earliest ring date) for a living tree rooted 2 m below that shoreline. Living trees 5 m and 2 m above present lake level germinated ca. AD 1753 and AD 1792, respectively (Van Dorp, 2004). These dates indicate that the lake rose rapidly to the 12-m level and only occupied it a short time before dropping close to present levels about 200 yr ago. The living tree dates have not been corrected for ecesis (the time between surface exposure and plant germination), which in this area may be 10 yr or more (B.H. Luckman, unpublished data). An ecesis correction would further reduce the time separating the mid-seventeenth century transgression and subsequent regression.

Kluane River sections

Sections through the upper part of the Duke River fan along Kluane River are a palimpsest of deposits of two ages (Fig. 10). The older deposits comprise stratified sand, silt, and peat that are older than the eastern lobe of the White River tephra (ca. 1150 cal yr old; Clague et al., 1995), which is present as a discontinuous layer in the deposits. Radiocarbon ages from wood within these older deposits confirm that they predate the glacier advances of the Little Ice Age (Table 2; Fig. 10).

The younger deposits are inset into the older deposits and comprise two main lithofacies: stratified pebble-cobble gravel, and laminated to massive silt and sand. The lower, coarser facies is interpreted to be Duke River fan deposits. Clast imbrication shows that the gravel was deposited by a stream flowing to the southeast across Kluane River toward Kluane Lake. Gravel beds dip gently in this direction, parallel to the surface of the fan. Rafts of branches and small logs are locally present within the gravel. Radiocarbon and tree ring dating indicate that the fan gravel is between about 600 and 2000 yr old (Fig. 11, Table 2). The finer facies dominates the upper part of younger sequence. It includes laminated to bedded silt and rippled fine to very fine sand interpreted to be Duke River overbank sediments that may have been deposited when Kluane Lake was higher than today. Ripple orientations suggest that the flow was to the southeast. Most sections along Kluane River are capped by 1–2 m of massive to weakly bedded silt, interpreted to be aeolian in origin.

Table 2
Radiocarbon ages

Radiocarbon age (^{14}C yrs BP) [a]	Calibrated age range (AD) [b]	Laboratory number [c]	Location		Elevation (m)	Material	Reference
			Lat. (N)	Long. (W)			
Drowned trees							
250±50	1480–1950	GSC-2575	61° 15′	138° 40.5′	782	In situ stump [d]	Clague (1981)
340±130	1300–1950	GSC-867	61° 03.5′	138° 21′	782	In situ stump [e]	Lowdon and Blake (1970)
490±50	1300–1500	GSC-2860	61° 07.9′	138° 29.6′	782	In situ stump [f]	Clague (1981)
Driftwood							
120±130	1515–1950	GSC-1569	61° 02′	138° 29′	794	Driftwood [g]	Lowdon and Blake (1973)
Kluane River sections							
400±40	1410–1650	Beta-200711	61° 25.7′	139° 04′	784	Conifer needles	This paper
810±50	1040–1300	Beta-100712	61° 25.7′	139° 04.2′	785	In situ stump	This paper
840±50	1040–1290	Beta-200714	61° 26.1′	139° 05.9′	788	Branch	This paper
890±70	1020–1270	Beta-187088	61° 25.7′	139° 04.2′	784	Log [h]	Van Dorp (2004)
910±80	990–1280	Beta-180881	61° 25.6′	139° 03.1′	781	Branch	This paper
930±60	990–1230	Beta-187089	61° 26.1′	139° 05.8′	787	Log [i]	Van Dorp (2004)
1070±50	860–1040	Beta-200713	61° 26.1′	139° 05.8′	786	Branch	This paper
1150±50	770–1000	Beta-189151	61° 25.7′	139° 04′	789	Log	Van Dorp (2004)
1750±60	130–420	Beta-187087	61° 25.7′	139° 04′	783	Log [j]	Van Dorp (2004)
1870±60	0–330	Beta-180882	61° 25.7′	139° 04′	781	In situ stump [k]	This paper
2210±70	400 BC–90 BC	Beta-180883	61° 26.1′	139° 05.8′	783	Branch [l]	This paper
2240±40	400 BC–200 BC	Beta-180884	61° 26.1′	139° 05.8′	782	Twig [m]	This paper
Kaskawulsh Glacier							
110±80	1660–1950	Y-1489	60° 59′	138° 33′	c. 915	Log [n]	Denton and Stuiver (1966)
270±60	1460–1950	Y-1480	60° 49′	138° 36′	c. 915	In situ stump [o]	Denton and Stuiver (1966)
390±80	1400–1660	Y-1490	60° 59′	138° 33′	c. 915	Log [n,f]	Denton and Stuiver (1966)
450±100	1300–1650	Y-1354	60° 59′	138° 33′	c. 915	Log [o]	Denton and Stuiver (1966)

[a] Laboratory-reported uncertainties are 1σ for Beta and I ages and 2σ for GSC ages. Ages are normalized to $\delta^{13}C=-25.0\%$ PDB. Datum is AD 1950.

[b] Determined from the calibration data set IntCal98 (Stuiver et al., 1998) using the program OxCal 3.9 (Bronk Ramsey, 2001). Age ranges are ±2σ calculated with an error multiplier of 1.

[c] Beta—Beta analytic; GSC—Geological Survey of Canada; Y—Yale University.

[d] Outer rings of an in situ stump just below present Kluane Lake level.

[e] Outer rings of an in situ *Picea* stump buried in modern Kluane Lake beach gravel.

[f] Innermost 30–50 rings of an in situ *Picea* stump with 210 annual rings. Sample collected just below present Kluane Lake level.

[g] *Populus* branch from driftwood mat 12 m above present Kluane Lake level.

[h] Thirteen rings (113–126 yr in from outermost ring) of log.

[i] Sixty-three rings (149–212 yr in from outermost ring) of log.

[j] Two hundred and ninety rings (130–420 yr in from outermost ring) of log.

[k] Outer rings of in situ *Picea* stump.

[l] Branch in peat.

[m] Twig in detrital plant layer.

[n] Outer rings of *Picea* log in till.

[o] Outer rings of a partially buried and tilted in situ *Picea* snag on the distal side of the outermost Kaskawulsh Glacier moraine.

Kluane River is locally bordered on the north by a terrace, up to several tens of metres wide and about 2.5 m above present river level. Pebble-cobble gravel underlying the terrace is inset into, and thus younger than, the gravelly fan sediments described above. The terrace gravel resembles Duke River fan gravel exposed in adjacent river bluffs, but imbrication shows that it was deposited by flow to the north. The terrace can be traced discontinuously downstream from Kluane Lake past the mouth of Duke River. The oldest trees sampled on this terrace surface are approximately 200 yr old.

Kaskawulsh Glacier

Little Ice Age moraines loop across the Slims-Kaskawulsh valley floor east and north of the toe of Kaskawulsh Glacier (Fig. 12). Denton and Stuiver (1966) obtained a radiocarbon age of 270±60 ^{14}C yr BP (younger than AD 1460; Table 2) on a rooted, tilted tree stem they interpreted to have been killed by Kaskawulsh Glacier during its advance to the outermost of the moraines. Other radiocarbon ages on the outer rings of detrital logs entombed in outermost moraine range from 110±80 to 450±100 ^{14}C yr BP
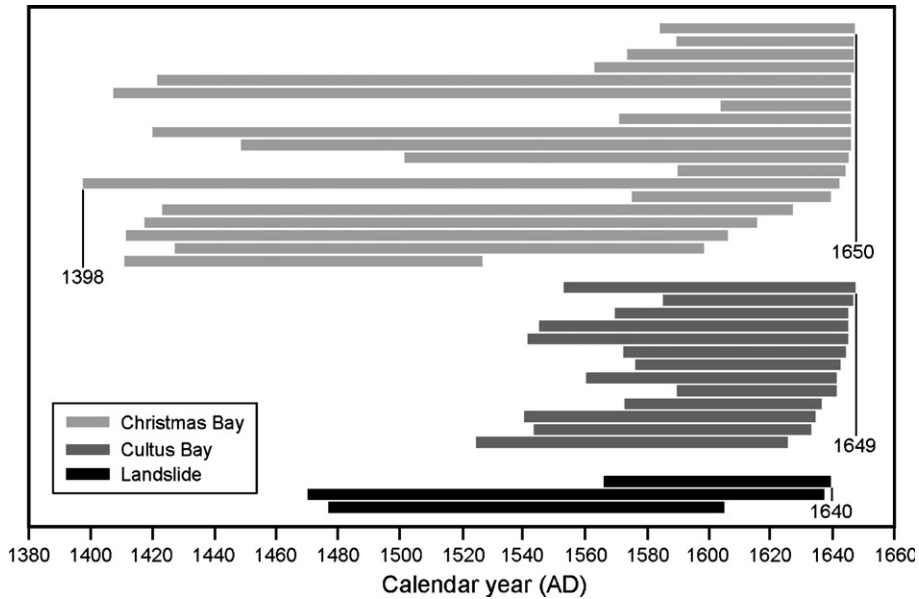
Figure 8. Age spans of analyzed, in situ drowned trees at Christmas and Cultus bays and on the Sheep Mountain landslide (see Fig. 1 for locations of sampled stumps).

Figure 9. (a) Driftwood stranded on a shoreline 12 m above Kluane Lake on the Sheep Mountain landslide. (b) Section underlying high-level beach on east shore of Kluane Lake between Christmas and Cultus bays, showing paleosol (white arrow) developed on late Pleistocene sediments and overlain by beach gravel deposited when the level of Kluane Lake was about 12 m higher than today. The soil contains a thin layer of White River tephra (see Fig. 2 for locations of photographs).

(younger than AD 1300; Table 2). Reyes et al. (2006) relocated the rooted, tilted tree dated by Denton and Stuiver (1966) and found several other similar stumps and stems that were killed during the most extensive advance of the Little Ice Age. Tree ring cross-dating places death of the trees to between AD 1671 and 1757 (Fig. 12). Kaskawulsh Glacier was thus at or near its Little Ice Age limit from the late seventeenth to middle eighteenth centuries.

Kaskawulsh Glacier constructed a gravel fan in the Slims-Kaskawulsh valley as it advanced during the Little Ice Age. The extent of the valley floor aggradation at this time is unknown, as there are no exposures of the fan sediments or geophysical or drill-hole data in the valley.

Sedimentary record of Kaskawulsh Glacier in Kluane Lake

Three sediment units are evident in the acoustic records from the southern part of Kluane Lake: a lower unit (no. 1 in Fig. 13) incompletely penetrated by the Chirp profiler and consisting of diffusely layered lacustrine sediment overlying an irregular bedrock or glacial sediment surface; a middle unit (no. 2) of well-layered sediment; and an upper unit (no. 3) consisting of acoustically transparent, faintly layered sediment. Unit 1 is up to 60 m thick where it can be resolved, and unit 2 is up to 29.5 m thick. The thicknesses of these two units do not change significantly along the length of the lake. In contrast, unit 3 is only found in the vicinity of the Slims River delta where it ranges from more than 50 m thick at the edge of the present delta to less than 1 m thick about 7 km north (Fig. 14).

Slims River is presently by far the largest source of sediment to Kluane Lake. The relatively constant thickness of units 1 and 2 along the length of the main basin of the lake suggests that either (1) the sediment was not delivered by Slims River, but rather by other streams; or (2) Kluane Lake extended southward up Slims River valley and the point of inflow of Slims River was a considerable distance from the present southern part of
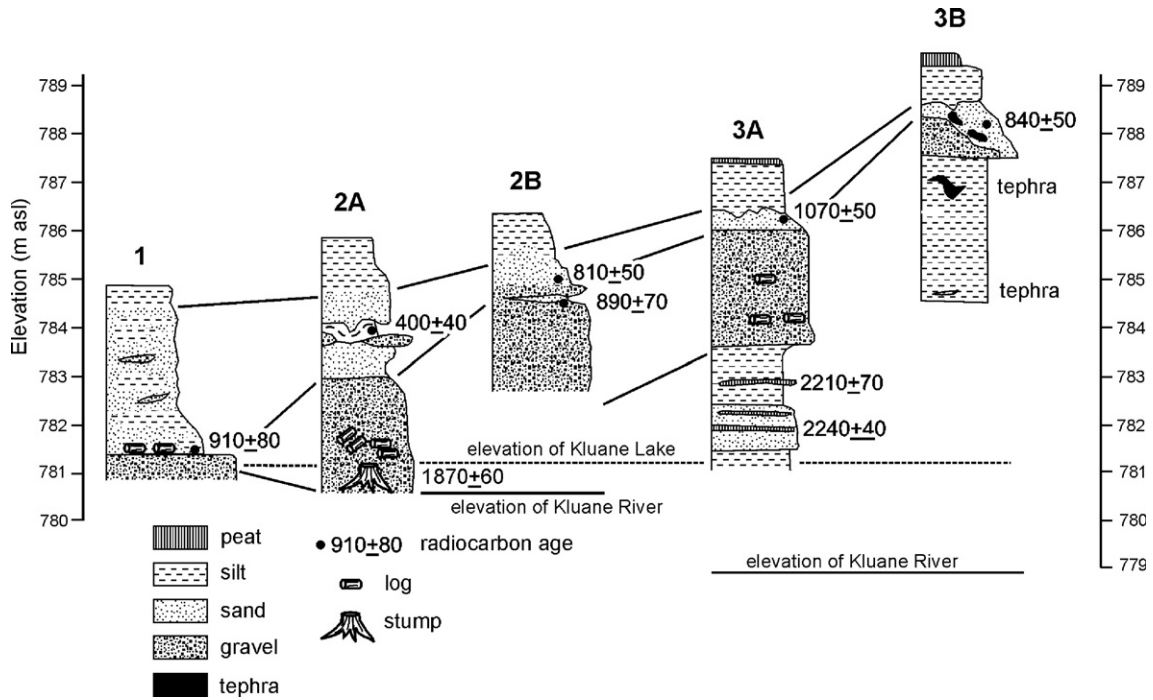
Figure 10. Lithostratigraphy of Kluane River sections between Kluane Lake and the mouth of Duke River (site numbers in Figs. 5 and 11 for additional chronological information and Table 2 for details on radiocarbon ages). Sections 2A and 2B are about 30 m apart in the same river bluff (2A is upstream from 2B). Sections 3A and 3B are about 50 m apart in a river bluff near the mouth of Duke River.

the lake. We speculate that unit 1 represents the late glacial or early postglacial history of Kluane Lake, and unit 2 represents the later low-level phases of the lake inferred from the submerged terraces described above. Unit 1 has not been dated, but its stratigraphic position and great thickness support a late glacial or early postglacial age. Likewise, unit 2 has not been directly dated, but it is older than an acoustically distinct wedge of sediment in the southern part of Kluane Lake (unit 3), which records a more recent, major input of water and sediment

from Slims River. We argue below that this event coincides with the rise of Kluane Lake to its highest level and with the northward advance of the Slims River delta into the lake.

Hypotheses to explain lake-level fluctuations

Bostock (1969) offered the first explanation for the late Holocene changes in the level of Kluane Lake. He suggested that the lake discharged at a lower level to the south through the
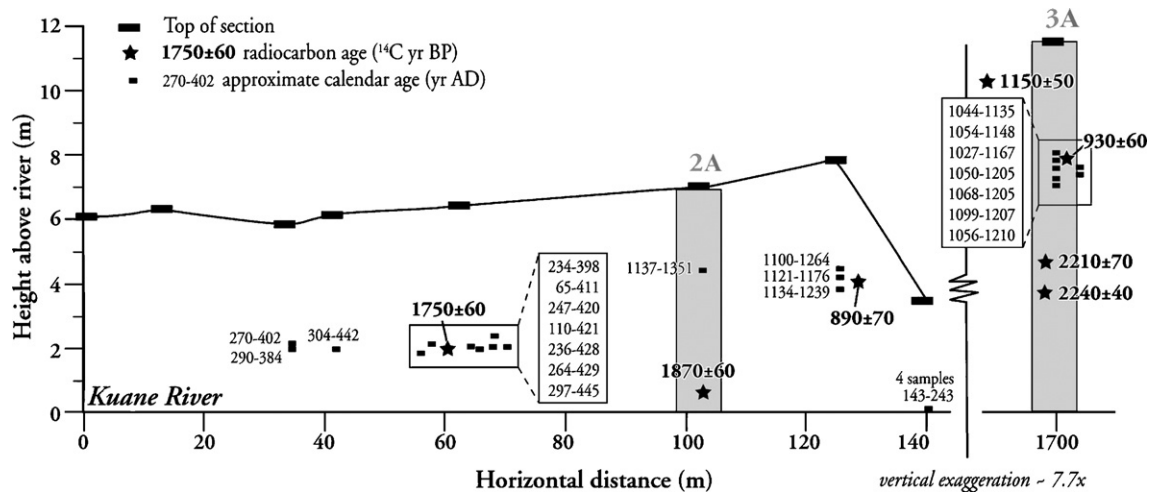

Figure 11. Position and approximate calendar age life spans of logs and a stump collected from sections along Kluane River (sites 2 and 3; Fig. 5). Calendar dates younger than AD 1000 were determined by cross-dating logs into the "Landslide chronology" from the Sheep Mountain landslide. Calendar dates older than AD 1000 were derived from a floating tree ring chronology of 381 yr anchored by a radiocarbon age of 1750 ± 60 ^{14}C yr BP on one of the logs (Table 2). Some additional radiocarbon ages and the approximate locations of sections 2A and 3A (Fig. 10) are also shown. Note that the vertical axis is the height of the section above Kluane River, whereas in Figure 10 it is elevation.
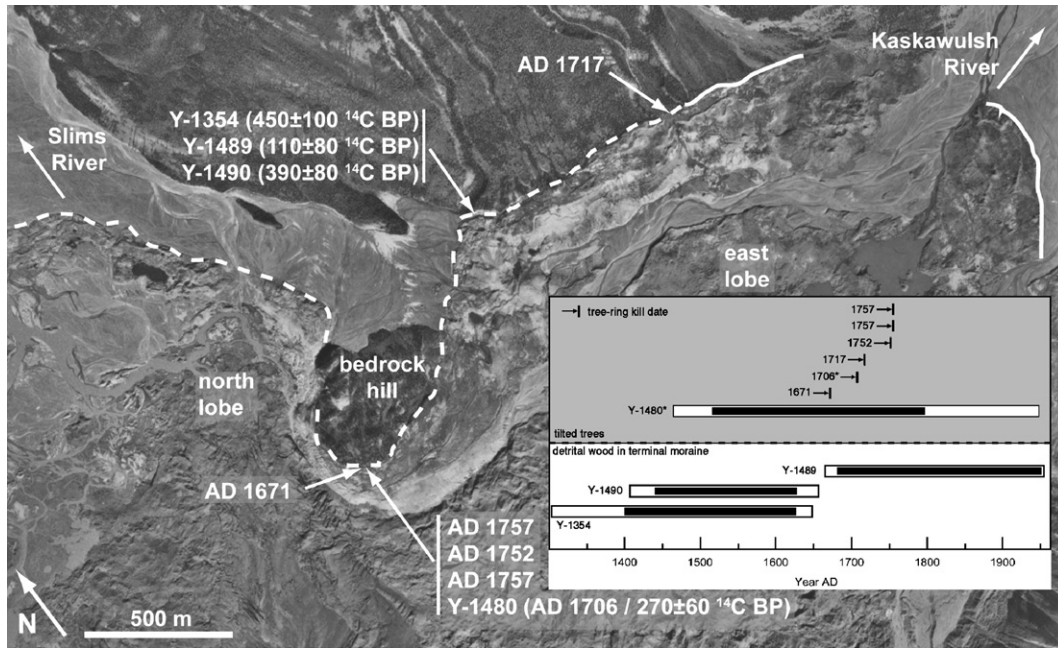
Figure 12. Vertical aerial photograph of the Kaskawulsh Glacier terminus in 1974, showing the divide between Kaskawulsh and Slims rivers, locations of dated in situ trees and detrital logs, outer tree ring dates (years AD) and radiocarbon ages (Table 2). [Government of Canada aerial photograph A23894-200: Copyright© 2003 Her Majesty the Queen in Right of Canada, Centre for Topographic Information (Ottawa), Natural Resources Canada]. The outermost Little Ice Age moraine is delineated by a dashed line. Inset shows calibrated radiocarbon age ranges (Table 2) and tree ring kill dates. The 1σ and 2σ calibrated age ranges are marked by black and white bars, respectively. The asterisk for samples Y-1480 and 02-23-3 indicates that they are from the same tilted tree. Modified from Reyes et al. (2006).

Slims-Kaskawulsh valley during the early Holocene (Fig. 15a). The climate of southwest Yukon at that time was warmer than today and the toe of Kaskawulsh Glacier was many kilometres upvalley of its present location (Borns and Goldthwait, 1966). Neoglacial advances of Kaskawulsh Glacier from its retracted early Holocene position greatly increased the amount of sediment delivered to the Slims-Kaskawulsh valley.

Sediment supplied by the advancing Kaskawulsh Glacier built a low-angle fan that would have progressively impeded the flow of a southward-draining river from Kluane Lake. Bostock (1969) argued that the thickening wedge of sediment forced a rise in the level of the lake from an unspecified low-stand position (Fig. 15b). Sedimentation in the Slims-Kaskawulsh valley accelerated during the Little Ice Age as Kaskawulsh
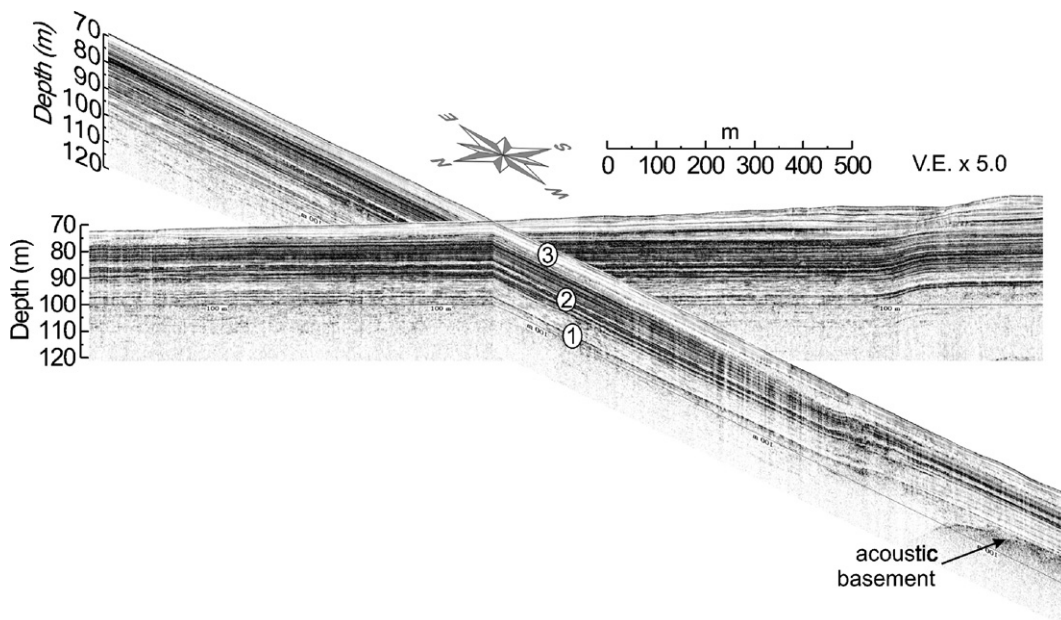

Figure 13. Two acoustic transects (see Figs. 2 and 14 for location), showing the three acoustic facies described in the text.
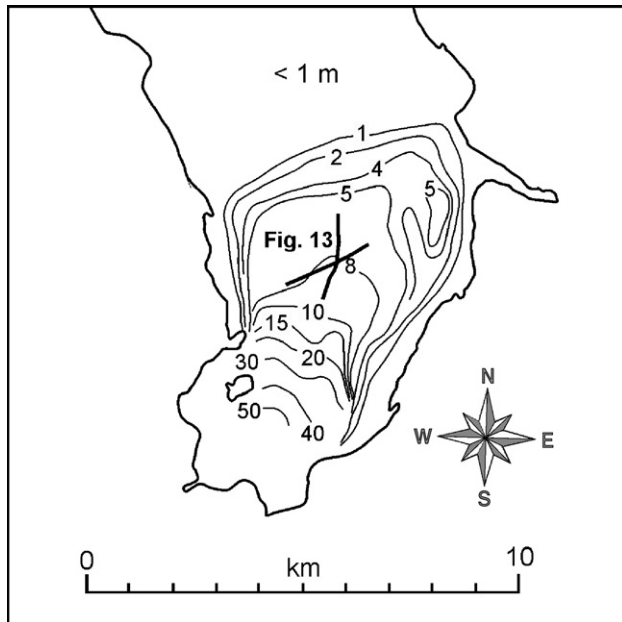
Figure 14. Isopach map of the thickness (m) of acoustic unit 3 based on a sound velocity in the sediment of 1430 m/s.

Glacier advanced closer to its maximum Little Ice Age position. When Kaskawulsh Glacier was at or near this position in the mid- to late seventeenth century, it completely blocked southerly drainage from Kluane Lake and raised the lake about 12 m above its present level, forcing it to spill over the low point on the Duke River fan (Fig. 15c). Shortly thereafter, Kluane Lake overflow (now Kluane River) incised the Duke River fan and the lake dropped to its present level (Fig. 15d). Downcutting may have taken years or decades, but was not catastrophic. The high-level outlet channel has a low gradient and extends for several kilometres across the toe of the fan. A discontinuous terrace 2.5 m above Kluane River records a short-lived cessation in downcutting of the outlet channel and lowering of the lake.

A second possible explanation for the lake-level changes requires that the Duke River fan be an active, rather than passive, player in the drainage history of the lake. Specifically, it requires that the Duke River fan aggraded during the Little Ice Age, raising base level at the northern outlet and, consequently, the level of Kluane Lake. It further implies that Kluane Lake discharged to the north prior to the Little Ice Age, but at a lower level than today. Northerly drainage, in turn, requires that Slims River flowed into Kluane Lake and that a drainage divide existed in the Slims-Kaskawulsh valley east of Kaskawulsh Glacier, just as it does today. This divide would have been higher than the highest shoreline of the lake but would not necessarily have been controlled by Kaskawulsh Glacier or the sediments deposited in its forefield. Rapid aggradation of the Duke River fan in the middle seventeenth century would be necessary to raise the lake level by at least 10 m in a few decades. Kluane Lake would have continued to discharge to the north during this time, although at a progressively higher level. According to this hypothesis, a reduction in sediment supply to the Duke River fan in the nineteenth century allowed Kluane

River to incise the fan and lower the level of the lake. The conspicuous terrace 2.5 m above present river level records a brief interval of stability during incision.

Discussion

The radiocarbon and tree ring ages and the acoustic data support Bostock's hypothesis that Kluane Lake drained south along the Slims–Kaskawulsh valley prior to the maximum Little Ice Age advance of Kaskawulsh Glacier. Prior to the seventeenth century, Kaskwaulsh Glacier was smaller than today and probably discharged to the Pacific Ocean via Kaskawulsh and Alsek rivers. Outwash deposition in the present Slims–Kaskawulsh divide area constrained the outlet of the lake, in much the same way as the Duke River fan defines the present, northern outlet. Part or all of the area occupied today by the Slims River sandur was part of Kluane Lake at this time. When Kaskawulsh Glacier advanced and blocked this outlet, it sent significant flow into Kluane Lake, developing Slims River and its sandur. The largest and most rapid increase in the level of the lake occurred when Kaskawulsh Glacier reached and blocked the outlet.

Our data rule out the second hypothesis advanced to explain changes in Kluane Lake level. The gravelly Duke River fan sediments are more than 700 yr old; some are nearly 2000 yr old (Fig. 11; Van Dorp, 2004). Thus, the last major phase of fan aggradation in the critical northern outlet area considerably predates the rise of Kluane Lake to its high-stand level. The Duke River fan thus was a passive player in this rise, providing a "backstop" at the north end of the lake for the rising waters.

We also considered the possibility that Kluane Lake drained neither to the north nor the south prior to the Little Ice Age, but rather was a closed basin. In this scenario, Kluane Lake level was lower than today because the lake did not receive Slims River discharge and because inflow from other streams and groundwater was insufficient to raise the lake high enough to overtop the drainage divide in the Slims-Kaskawulsh valley and drain to the south. When Kaskawulsh Glacier meltwater began to flow into Kluane Lake during the Little Ice Age, Kluane Lake rapidly rose and overtopped the Duke River fan, establishing its northern drainage. We consider this scenario unlikely because sources of inflow other than Slims River probably would have equalled evaporative losses and any net negative groundwater flux and thus maintained Kluane Lake at or near its present level.

Our levelling survey of the surface of the Duke River fan showed that the lowest point at the toe of the fan, over which the lake must have drained when it first overflowed to the north, is 8 m above present lake level. Yet, shorelines at the south end of the lake are 4 m higher than this. An explanation for the apparent elevation discrepancy lies in the relation between lake level and the shorelines and between lake level and water depth at the lake outlet. The shorelines are best developed at the south end of the lake, which is exposed to strong northerly winds with long fetch. Littoral gravel and driftwood have been stranded more than 1 m above the lake during recent historic storms, and the 12-m beaches and driftwood likely have a similar relation with former lake levels. In addition, the depth of waters flowing
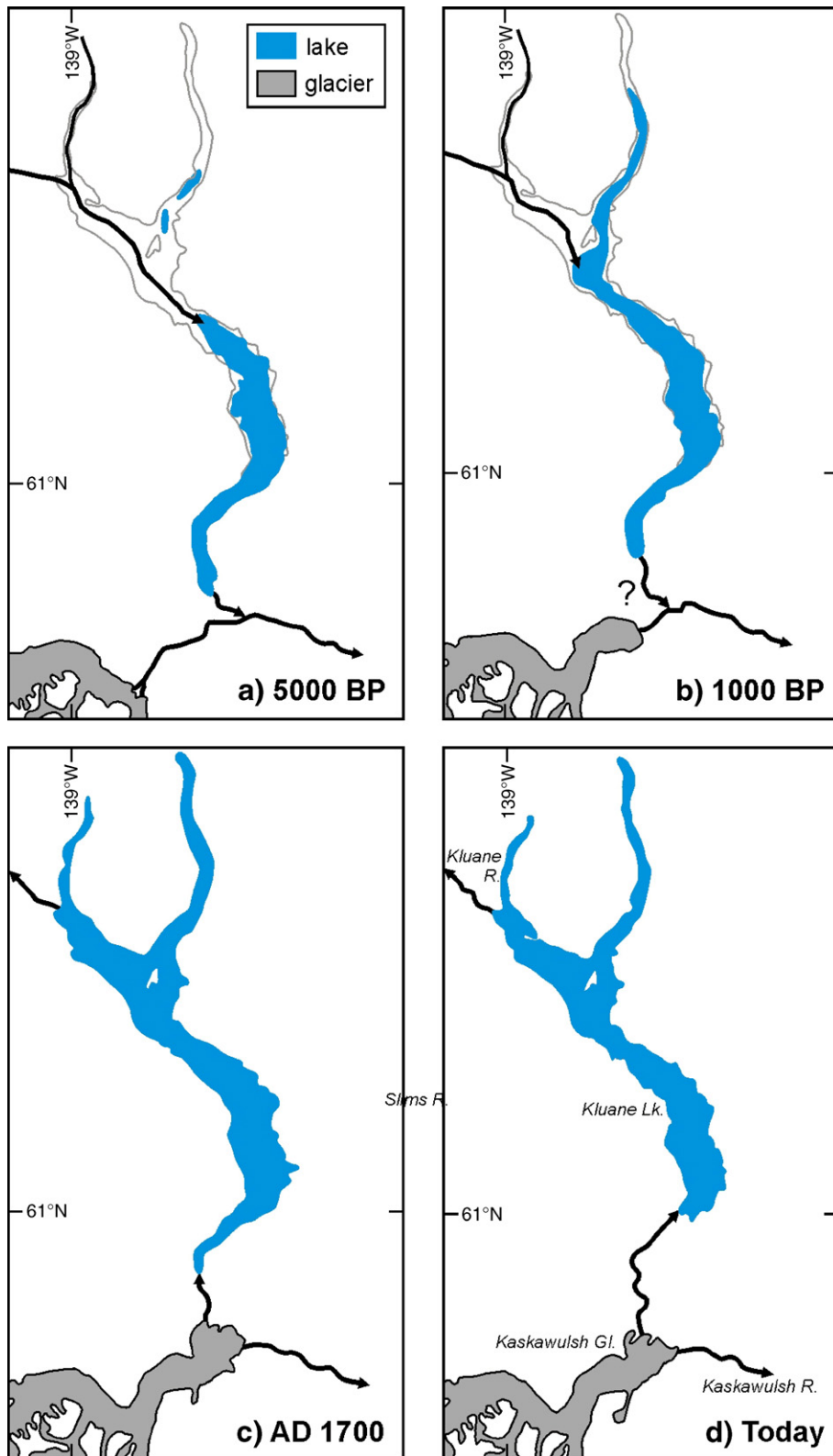
Figure 15. Favoured scenario for the late Holocene evolution of Kluane Lake. (a) Kluane Lake was lower than today and drained to the North Pacific during the middle Holocene. The reconstruction shown here is based on a lake 35 m lower than today. (b) As Kaskawulsh Glacier advanced early during the Little Ice Age, aggradation of the Slims-Kaskawulsh valley bottom caused the lake to expand and rise. (c) Kaskawulsh Glacier blocked the Slims-Kaskawulsh valley during the late seventeenth century, at which time Kluane Lake rose above its present level and overflowed north into the Yukon River drainage system. (d) The lake continues to drain to the north today, although its outlet is about 10 m lower than it was in the late seventeenth century.

out of Kluane Lake when the northerly outlet first became established may have been substantial, perhaps 2 m or more. During times of high flow today, Kluane River is more than 1 m deep. Outflow was probably greater during the late seventeenth century when Slims River discharged larger amounts of meltwater into Kluane Lake. We considered the possibility that the difference in elevation between the highest shoreline and the overflow channel on the Duke River fan results from seismic or aseismic uplift of the southern part of the lake. This possibility was rejected because high-level shorelines are not tilted or displaced by faults. Furthermore, any such deformation would have to be less than about 300 yr old. No historical, geomorphic or other evidence exists for such recent, large-scale tectonic deformation at Kluane Lake.

This study illustrates the sensitivity of Kluane Lake to modest fluctuations in the position of Kaskawulsh Glacier and its drainage either into Kluane Lake or Kaskawulsh River. Retreat of Kaskawulsh Glacier since the end of the Little Ice Age is leading to a situation in which drainage is likely to be captured into the steeper Kaskawulsh River in the future. If this occurs, the level of Kluane Lake will fall at least two metres, greatly reducing overflow into Kluane River. Establishing a new lower outlet south of Slims River, as likely existed through much of the Holocene, will take considerable time because the eastward-sloping Slims River floodplain precludes establishment of a south-draining outlet. Establishing southerly drainage at a lower base level would require headwater erosion of Kaskawulsh River, which we anticipate would take hundreds, if not thousands of years.

Rapid drainage change on the scale described in this paper is unique in Canada in the past millennium. Similar changes, however, were common in northern North America at the end of the Pleistocene. Continental-scale drainage changed rapidly and repeatedly as streams adjusted to the decay of the Cordilleran and Laurentide ice sheets and their satellite alpine glaciers. The Kluane Lake story provides a glimpse into the real complexity of the changing landscape and drainage during terminal Pleistocene deglaciation.

Conclusions

Kluane Lake was more than 30 m lower than at present during much of the Holocene and drained southward through the Slims, Kaskawulsh and Alsek valleys to the Pacific. It rose at in the seventeenth century in response to the maximum Little Ice Age advance of Kaskawulsh Glacier. A fan of outwash accumulated near the former southern outlet of the lake, and meltwater from Kaskawulsh Glacier began to flow into Kluane Lake. The meltwater built a sandur across which Slims River flowed, depositing a distinctive wedge of sediment in the lake. The lake rapidly rose to 12 m above present lake level and overflowed northward across the toe of the Duke River fan. Kluane River incised the new outlet in the eighteenth century when Kaskawulsh Glacier was blocking the southern outlet. The lake fell to near its present level before AD 1800 and has not varied more than a few metres over the last 200 yr. Continued retreat of Kaskawulsh Glacier may result in piracy of

Slims River meltwater by Kaskawulsh River due to the much steeper gradient of the latter.

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