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Tree-Ring Dates for the Maximum Little Ice Age Advance of Kaskawulsh Glacier, St. Elias Mountains, Canada

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ABSTRACT. A dendroglaciological study at Kaskawulsh Glacier provides the first calendar dating of a Little Ice Age glacier advance in the northeast St. Elias Mountains of Yukon Territory. Ring series from white spruce trees, *Picea glauca* (Moench) Voss, that had been sheared, tilted, and killed by deposition of till at the glacier's terminal moraine were cross-dated with a millennium-length ring-width chronology developed at a site near the south end of Kluane Lake, about 25 km north of the glacier forefield. Six cross-dated samples from two sites at Kaskawulsh Glacier suggest that the north lobe of the glacier reached its greatest Holocene extent in the mid-1750s. Additional limited data suggest that the east lobe may have reached its maximum extent somewhat earlier (ca. 1717). This chronology of Little Ice Age activity of Kaskawulsh Glacier is consistent with well-dated glacier chronologies from adjacent mountain ranges in coastal and interior Alaska. The results also demonstrate the potential to derive calendar dates from subfossil wood in the St. Elias Mountains that hitherto had been dated only with much lower precision, using radiocarbon techniques.

Key words: Kaskawulsh Glacier, St. Elias Mountains, Little Ice Age, dendrochronology, Kluane Lake

RÉSUMÉ. L'étude dendroglaciologique du glacier Kaskawulsh fournit la première datation de calendrier de l'avancée glaciaire du petit âge glaciaire, dans le nord-est des montagnes St. Elias, territoire du Yukon. Les séries de cernes d'épinettes blanches, *Picea glauca* (Moench) Voss, qui avaient été abattues, inclinées et tuées par le dépôt de till à la moraine terminale du glacier, ont été contre-datées à l'aide d'une chronologie millénaire de largeur des cernes mise au point à un emplacement situé près du côté sud du lac Kluane, à environ 25 km au nord du front du glacier. Six échantillons contre-datés provenant de deux emplacements du glacier Kaskawulsh suggèrent que le lobe nord du glacier a atteint sa plus grande étendue holocène dans le milieu des années 1750. Par ailleurs, certaines données supplémentaires suggèrent que le lobe est pourrait avoir atteint son étendue maximale un peu plus tôt (vers 1717). Cette chronologie de l'activité du petit âge glaciaire du glacier Kaskawulsh coïncide avec les chronologies bien datées des chaînes de montagnes adjacentes, sur la côte et à l'intérieur de l'Alaska. Les résultats démontrent aussi la possibilité d'établir les dates de calendrier à partir de bois subfossile dans les montagnes St. Elias qui avait été daté avec beaucoup moins de précision jusqu'ici à l'aide de techniques de datation au carbone 14.

Mots clés : glacier Kaskawulsh, montagnes St. Elias, petit âge glaciaire, dendrochronologie, lac Kluane

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INTRODUCTION

Many glaciers in the North American Cordillera advanced to their most extended Holocene positions during the Little Ice Age, a period of widespread, episodic glacier expansion between the 12th and the late 19th centuries (*sensu* Luckman, 2000). The spatial and temporal complexity of Little Ice Age glacier activity has been documented in several alpine regions in North America where tree rings have been used to date glacier advances with decadal to subdecadal resolution. These regions include the Canadian Rocky Mountains (Luckman, 2000), coastal Alaska (Calkin et al., 2001), and more recently, the southern Coast Mountains of British Columbia (Smith and Desloges, 2000; Larocque and Smith, 2003; Lewis and Smith, 2004).

The well-dated glacier records from these regions collectively suggest broad synchroneity in the timing of Little Ice Age activity in northwestern North America (Luckman and Villalba, 2001). However, significant spatial gaps remain in our knowledge of the chronology of North

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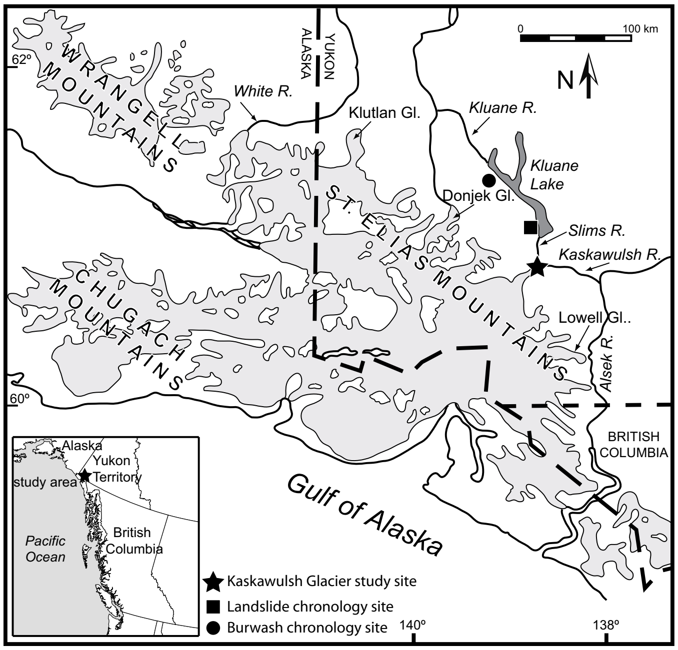

FIG. 1. Location of the study area and other sites mentioned in the text. Light grey shading denotes glaciers and icefields. Modified from Denton and Karlén (1977: Fig. 1).

American glacier response to climate change during the Little Ice Age. The St. Elias Mountains in southwest Yukon Territory contain the largest glaciers in the Canadian Cordillera, yet none of the Little Ice Age advances of these glaciers is precisely dated. The few available chronological data are mainly derived from radiocarbon dating (Denton and Stuiver, 1966; Rampton, 1970), limited dendrochronology (Sharp, 1951), lichenometry (Denton and Karlén, 1977), and indirect dating of related features such as glacial lake shorelines (Clague and Rampton, 1982).

Recent dendrochronological investigations in the eastern St. Elias Mountains (Luckman et al., 2002; Van Dorp, 2004) have produced reference tree-ring chronologies that permit calendar dating of subfossil wood up to several hundred years old. In this paper, we present the first calendar dates for the maximum Little Ice Age advance of Kaskawulsh Glacier, one of the large valley glaciers in the St. Elias Mountains, based on tree-ring dating of white spruce, *Picea glauca* (Moench) Voss, that were killed during construction of the outermost terminal moraine.

STUDY AREA

The St. Elias Mountains rise from sea level at the Gulf of Alaska to over 6000 m asl at Mt. Logan. They support extensive icefields that are drained by large valley glaciers, including Kaskawulsh Glacier, which flows generally northeast about 70 km to its present terminus at 820 m asl (Fig. 1). The terminal area of Kaskawulsh Glacier comprises an extensive zone of stagnant glacier ice (Johnson, 1992), ice-cored drift, moraine ridges, and coarse proglacial outwash. The glacier terminus is divided into two lobes by a prominent, forested bedrock hill that rises up to 150 m from the surrounding gravelly outwash plain (Fig. 2). Meltwater issuing from the glacier's east lobe drains to the Gulf of Alaska via the Kaskawulsh and Alsek rivers. Meltwater from the north lobe feeds the Slims River, which flows north into Kluane Lake and ultimately the Bering Sea via the Yukon River system.

Prominent moraine ridges fringe both glacier lobes and loop around the southern flank of the intervening bedrock hill. The ridges delineate the maximum Holocene extent of Kaskawulsh Glacier (Fig. 2). Borns and Goldthwait (1966) mapped three distinct suites of Little Ice Age moraines on the basis of morphology, vegetation cover, and the ages of trees and shrubs growing on them. Tilted white spruce snags are present at several locations along the distal edge of the outermost moraine, termed drift I by Borns and Goldthwait (1966) and Denton and Stuiver (1966). Radiocarbon ages from four trees along the outer moraine margin range from 110 to 450 ^{14}C yr BP (Borns and Goldthwait, 1966; Denton and Stuiver, 1966).

METHODS

We recovered cross sections from 11 tilted and sheared white spruce snags (Figs. 2, 3) on the distal side of the outermost terminal moraine. All 11 stems were oriented approximately perpendicular to the moraine crest. The cross sections were sanded and polished to a high finish, and ring widths (two radii per sample) were measured to the nearest 0.005 mm using a Velmex-type stage and binocular microscope at the University of Victoria Tree-Ring Laboratory. In some cases, the outermost few rings were difficult to measure and were only counted.

Living white spruce trees near the glacier's terminus in the Slims valley are less than about 290 years old (Allen, 1982) and thus of limited value for cross-dating. Consequently, we dated the Kaskawulsh Glacier samples using a millennium-length white spruce ring-width chronology developed from trees that grew at the Landslide site near the southwest end of Kluane Lake (Fig. 1). The chronology comprises 161 ring-width series from living trees (up to 300 years old) and snags (oldest tree was more than 668 years old) and spans the period AD 913 – 2001 (Van Dorp, 2004). Sample depth is more than 18 ring-width series after AD 1200.

Tree-ring and lichen ages in this paper are reported as years AD. Radiocarbon ages are reported as uncalibrated radiocarbon years before the present (^{14}C yr BP). Ranges of calibrated years AD (cal yr AD) were determined at the 2σ level from the decadal data set of Stuiver et al. (1998), using the program CALIB 4.4 (Stuiver and Reimer, 1993).

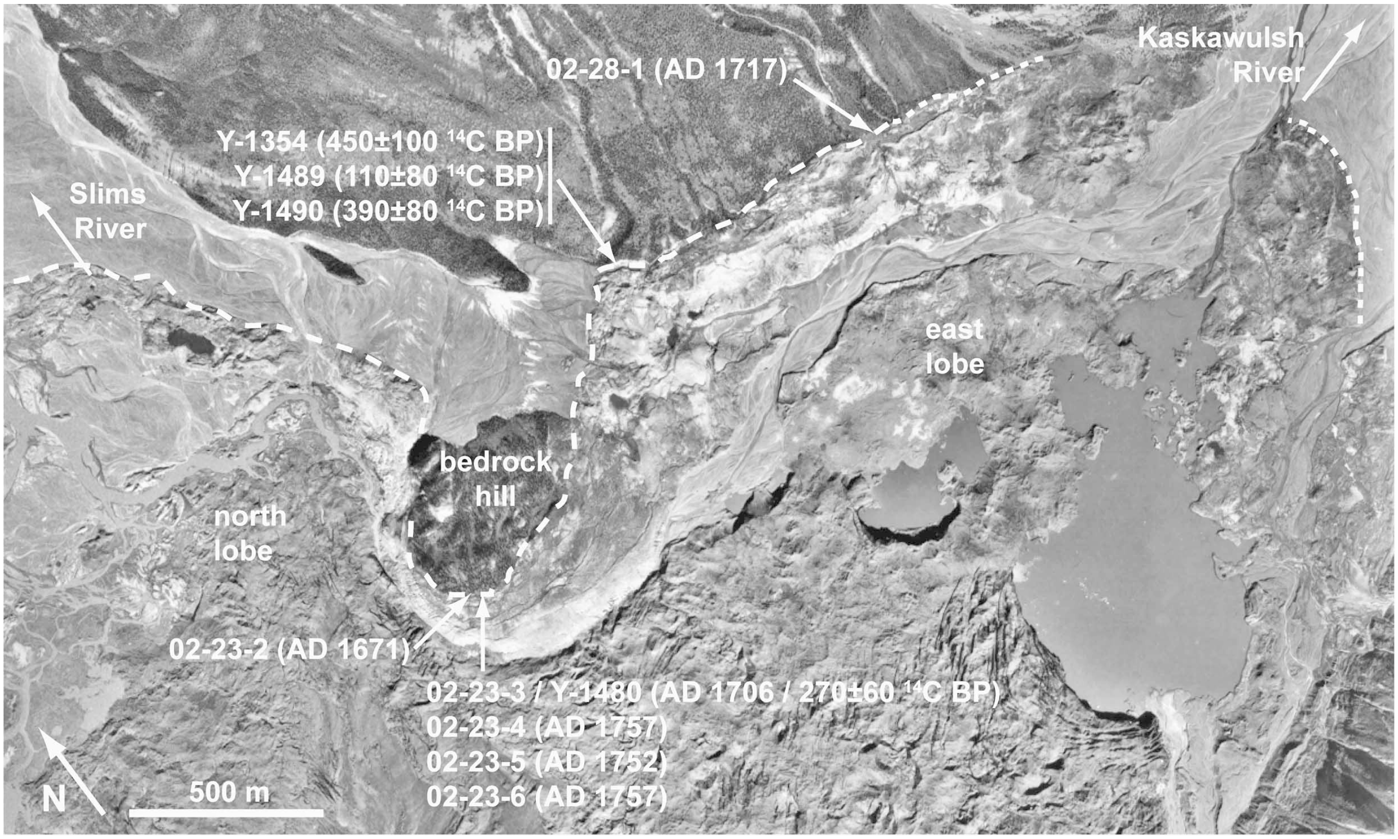

FIG. 2. Vertical aerial photograph showing the debris-covered terminus and forefield of Kaskawulsh Glacier in 1974, locations of sampled trees, and tree-ring and radiocarbon ages. The outermost moraine is marked by a dashed line. Long dashes denote the portion of the moraine that we investigated for glacially tilted and sheared trees. Samples designated Y are the white spruce snags radiocarbon-dated by Borns and Goldthwait (1966) and Denton and Stuiver (1966). Government of Canada airphoto A23894-200: Copyright © 2003 Her Majesty the Queen in Right of Canada, Centre for Topographic Information (Ottawa), Natural Resources Canada.

RESULTS AND DISCUSSION

Tree-Ring Cross-Dating

Two radii from each snag were first cross-dated to verify measurement and internal dating consistency. Subsequent cross-dating trials between trees led to the development of a 252-year "floating" (undated) chronology comprising radii from 6 of the 11 trees. The floating chronology was calendar-dated to AD 1504 – 1755 using the Landslide chronology, and calendar ages were assigned to the outermost rings in each tree (Table 1). The calendar dates were independently verified against a living white spruce chronology (AD 1480–1999) from a site near Burwash Landing (Luckman et al., 2002), about 50 km north-northwest of the study site (Fig. 1). Outer-ring dates for the tilted trees, which take into account faint outer rings that could be counted but not measured, are between AD 1671 and AD 1757 (Table 1, Fig. 4). Only one cross-dated sample (02-23-4) retained bark, but the excellent preservation of the perimeters of the sampled snags suggests that, at most, only a small number of rings were missing from samples without bark. Therefore, the outer ring dates are assumed to be close to the times the trees died. The tilted trees are assumed to have died at the time of tilting, or shortly after they were tilted, because their outer rings do not contain compression wood, which is normally produced on the downslope side of living tree stems soon after they are tilted.

The three tilted spruce snags with the youngest kill dates (02-23-4, -5 and -6; Fig. 3A) are from a section of moraine about 10 m in length and have outer rings that date to between AD 1752 and AD 1757. Bark is present on one of the trees killed in AD 1757. Excavation of these snags prior to sampling confirmed that their stems were deeply buried in diamicton forming the moraine, but we were unable to determine whether the stems had attached roots. A prominent set of tangential resin ducts in sample 02-23-5 suggests that the tree experienced physical trauma (Schweingruber, 1996) around AD 1718 that could be related to mass movement off the distal moraine slope. However, none of the nearby, cross-dated samples show any evidence of trauma at this time.

Sample 02-23-3 (Fig. 3B) is a tilted spruce that died in AD 1706 or shortly thereafter. It was found 10 – 15 m from samples 02-23-4, -5, and -6. The lower portion of the snag was buried in diamicton, but we were unable to excavate down to roots. The upper portion had an old saw cut and notch, indicating that a small wedge of wood had been removed before June 2002. We suspect, from the location

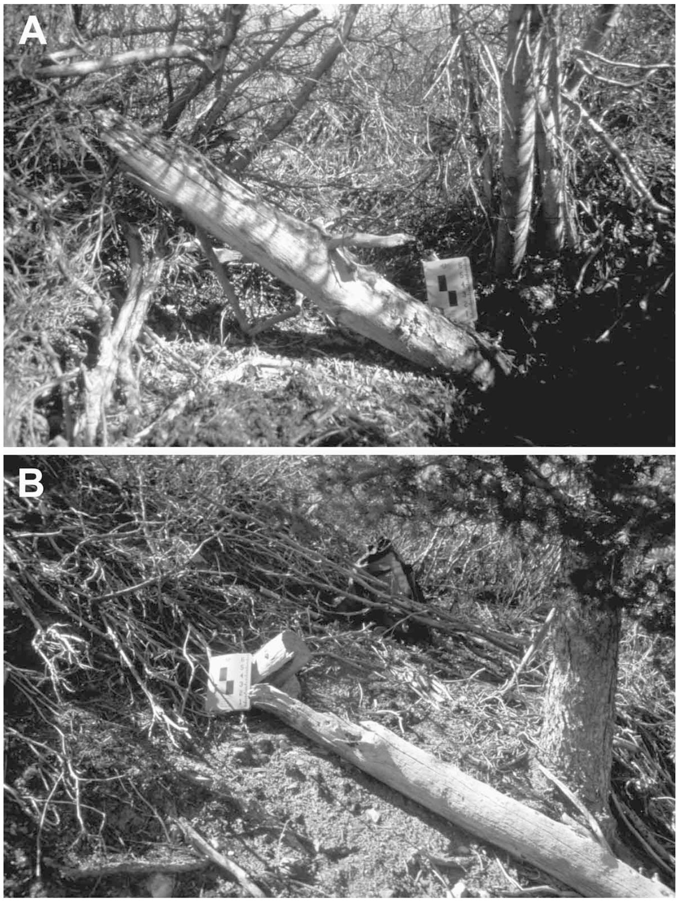

FIG. 3. Tilted white spruce samples. (a) 02-23-6, moraine to right. Notebook is 20 cm high. (b) 02-23-3, moraine to left.

of the snag and the recollection of George Denton (pers. comm., 2004), that the wedge was collected by Denton and Stuiver (1966: Fig. 3, site 2) and dated to 270 ± 60 ^{14}C yr BP (Y-1480). The calibrated age range (AD 1470 to 1950) is consistent with our tree-ring dating (Fig. 4). There is no obvious explanation why this sample died several decades before three other trees (samples 02-23-4, -5, and -6) that are only 10–15 m away. The most plausible scenario is that the tree had been dead for some time before it was tilted.

The oldest kill date (AD 1671) came from sample 02-23-2, a spruce stem protruding from the moraine and lying on the forest floor about 30 m west of the four tilted spruce snags discussed above. The sheared end of the stem was exposed after shallow excavation into the moraine, and we could not locate the other half of the buried stem. The earlier date suggests that the tree died before glacier advance, or that it died and was transported earlier during the advance. Trees killed, transported, and deposited by Little Ice Age advances of glaciers in the Canadian Rockies show a wide range of outer ring ages that predate the LIA maximum (Luckman, 1996; Robinson, 1998).

We obtained a tree-ring kill date of AD 1717 on a tilted spruce snag (02-28-1) east of the bedrock hill, on the distal side of the outermost terminal moraine bordering the east lobe of Kaskawulsh Glacier (Fig. 2). Three detrital spruce logs buried in the outer moraine of the east lobe (Fig. 2) had previously yielded radiocarbon ages of 110 ± 80 ^{14}C yr BP (Y-1489; cal AD 1670–1950), 390 ± 80 ^{14}C yr BP (Y-1490; cal AD 1410–1660), and 450 ± 100 ^{14}C yr BP (Y-1354; cal AD 1300–1650) (Borns and Goldthwait, 1966; Denton and Stuiver, 1966: Fig. 4). Two of these ages are on outer rings from intact stems (Y-1489 and Y-1490), and the third (Y-1354) is on wood fragments (Stuiver, 1969). Our tree-ring date of AD 1717 provides a direct date for moraine emplacement that is consistent with the maximum age of the east lobe moraine derived from the radiocarbon ages of Borns and Goldthwait (1966) and Denton and Stuiver (1966).

In summary, our tree-ring cross-dates suggest that Kaskawulsh Glacier was close to its Little Ice Age maximum position in the 1670s and reached its maximum extent along the bedrock hill separating the glacier's north and east lobes by the 1750s. This conclusion is based on the similarity of ages derived from the three youngest, closely spaced trees (02-23-4, -5, and -6; Table 1). The older dates from samples in the same area are interpreted as trees that either were killed earlier during the advance and re-transported, or died before being incorporated into the moraine. The east lobe may have reached its maximum position several decades earlier than 1750, although this conclusion is based on only a single cross-dated, tilted tree. These dates are consistent with the radiocarbon chronology developed by Denton and Stuiver (1966). Our data do not indicate how long Kaskawulsh Glacier remained at its maximum Little Ice Age position. However, Borns and Goldthwait (1966) suggested, on the basis of ages of living trees on the outermost moraine and estimates of ecesis, that ice retreat and moraine stabilization did not occur until the early or middle 19th century.

Comparison with Other Little Ice Age Glacier Chronologies

The tree-ring dates provided in this paper have greater temporal precision than most previous estimates of timing of Little Ice Age glacier activity in the St. Elias Mountains. Radiocarbon dates on wood in moraines at nearby Donjek and Klutlan glaciers (Denton and Stuiver, 1966; Rampton, 1970) suggest that the maximum Little Ice Age advances may have occurred there at about the same time as at Kaskawulsh Glacier, but the large calibrated radiocarbon age ranges (as much as 500 years) preclude detailed correlation of the events. Living trees on the outermost Little Ice Age moraine of Klutlan Glacier indicate that ice retreated from the moraine before AD 1730 (Rampton, 1970). Lowell Glacier probably reached its maximum Little Ice Age position in the 17th or early 18th century, as indicated by limited radiocarbon and tree-ring dating of driftwood strandlines of Neoglacial Lake Alsek, which was dammed by the glacier during the Little Ice Age (Clague and Rampton, 1982). Earlier Little Ice Age maxima (ca. AD 1500), dated by lichenometry, have been reported

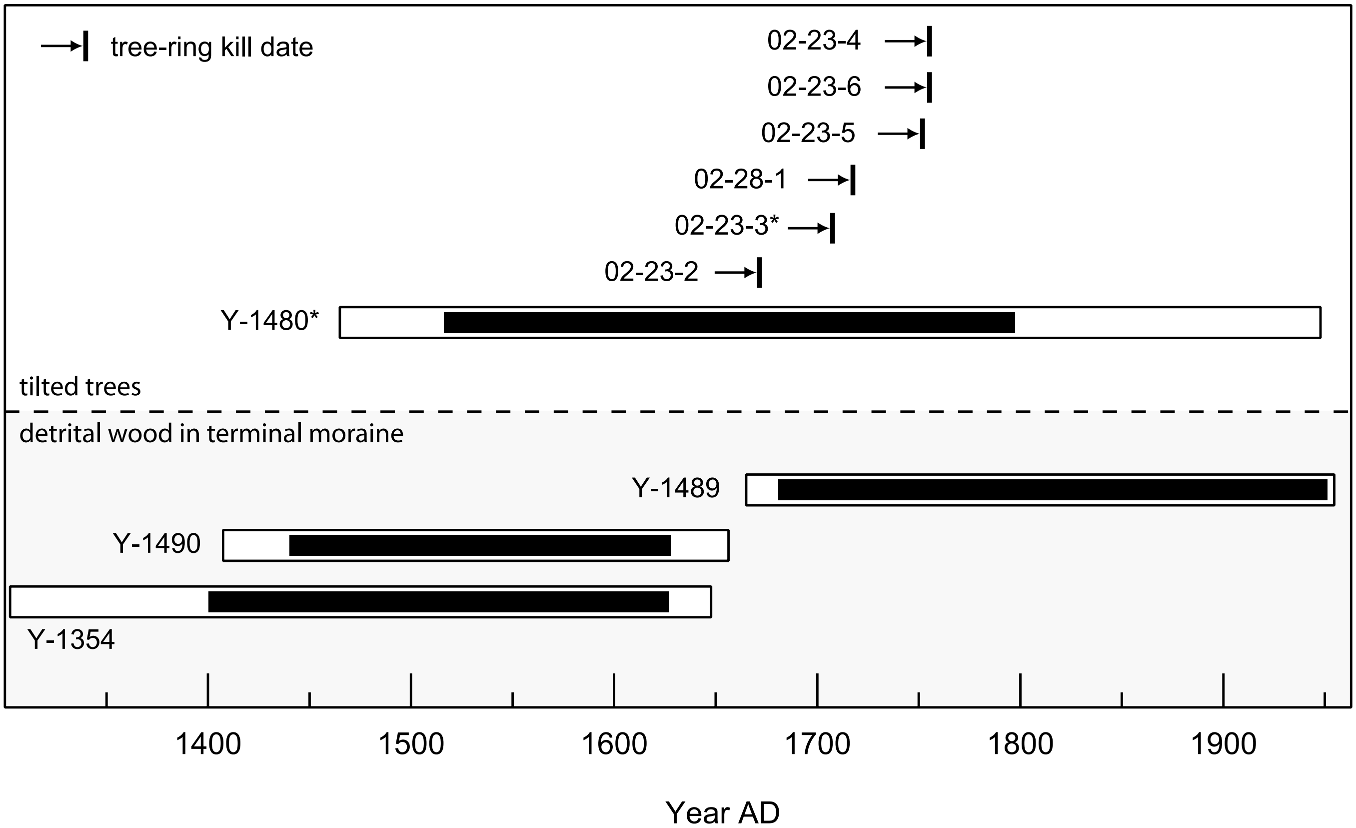

FIG. 4. Calibrated radiocarbon age ranges and tree-ring dates. Black bars represent the 1σ calibrated age ranges and white bars the 2σ calibrated age ranges for wood dated by Borns and Goldthwait (1966) and Denton and Stuiver (1966). The asterisk indicates that Y-1480 and 02-23-3 are from the same tilted tree.

for several glaciers in the White River valley and Skolai Pass area, on the Alaskan side of the International Boundary (Denton and Karlén, 1977).

Comparisons of Little Ice Age glacier chronologies in the St. Elias Mountains are also complicated by the surging nature (e.g., Donjek and Lowell glaciers) and extensive debris mantles (e.g., Klutlan Glacier) of many glaciers in the region (Clarke and Holdsworth, 2002). These local conditions make it more difficult to interpret the relation between glacier fluctuations and climate.

The tree-ring dates for Kaskawulsh Glacier are more readily compared to well-dated Little Ice Age glacier chronologies in the coastal ranges and Wrangell Mountains in Alaska. At least three glaciers in the Wrangell Mountains advanced into forests in the late 17th and early 18th centuries (Wiles et al., 2002), as did numerous glaciers in the Kenai Mountains and Prince William Sound region of coastal Alaska (Calkin et al., 2001). Davi et al. (2003) noted that this period of glacier activity coincides with low growing-season temperatures inferred from trends in tree-ring width and latewood density. The early 1700s are also the coldest period in a tree ring–based reconstruction of June-July temperatures in southwest Yukon Territory (Luckman et al., 2002; D. Youngblut, pers. comm., 2004). Wiles et al. (2004), building on the work of Denton and Karlén (1973), associated periods of heightened glacier activity in Alaska during the Little Ice Age with pronounced decreases in solar irradiance, including the Maunder Minimum of the late 17th century.

TABLE 1. Tree-ring dates of tilted trees at Kaskawulsh Glacier.

Sample number	Measured radii (year AD)	Minimum outer ring year (AD)[1]
02-23-2	1570–1669	1671
02-23-3	1504–1701	1706
02-23-4	1538–1755	1757[2]
02-23-5	1572–1749	1752
02-23-6	1618–1753	1757
02-28-1	1559–1710	1717

[1] Faint rings on sample perimeters were counted but not measured.
[2] Measured radius to bark.

Implications for the Drainage History of Kluane Lake

Our tree-ring dates at Kaskawulsh Glacier provide insight into rapid, late Holocene, water-level fluctuations of Kluane Lake, the largest lake in Yukon Territory. Evidence for lake-level change, including submerged forests below the present lake level and raised driftwood strandlines, led Bostock (1969) to propose that Kluane Lake drained southward via the Slims, Kaskawulsh, and Alsek rivers during the early and middle Holocene, when Kaskawulsh Glacier terminated many kilometres upvalley of its present position (Denton and Stuiver, 1966). Bostock suggested that the Little Ice Age advance of Kaskawulsh Glacier and the attendant flux of outwash into the Slims River valley caused the base level to rise at the lake's southern outlet, resulting in rapid lake-level rise and, eventually, overflow to the north via the Kluane River. The large calibrated age ranges on radiocarbon-dated drowned trees, stranded driftwood, and logs in Kaskawulsh Glacier moraines hampered efforts to determine the temporal relations between these events. Our tree-ring dates for the Little Ice Age advance of Kaskawulsh Glacier, potentially a key event in the history of Kluane Lake, dramatically reduce the dating uncertainty associated with blockage of possible southward drainage via the Slims River and base-level rise south of Kluane Lake. Ongoing dendrochronological studies of Kluane Lake stumps and driftwood (Van Dorp, 2004) will allow a more detailed evaluation of the timing of these events and of Bostock's hypothesis.

SUMMARY AND CONCLUSIONS

Outer tree-ring kill dates between AD 1671 and AD 1757 from white spruce killed at the outermost terminal moraine of Kaskawulsh Glacier suggest that the glacier was near its Little Ice Age limit in the late 17th century and reached its most extensive Little Ice Age position in the early to middle 18th century, no later than ~ AD 1757. Kaskawulsh Glacier may not have retreated from this position until the early to middle 19th century (Borns and Goldthwait, 1966). Our chronology is consistent with well-dated Little Ice Age glacial records from nearby coastal Alaska and the Wrangell Mountains (Calkin et al., 2001; Wiles et al., 2002), which collectively indicate widespread glacier advance in the late 17th and early 18th centuries. The present study provides the first calendar dating of a Little Ice Age advance in the northern St. Elias Mountains. Similar future applications of tree-ring dating in southwest Yukon, using new reference chronologies, should provide improved understanding of the nature and timing of landscape response to the latest Holocene climate change in the region.

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