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Early Holocene glacier advance, southern Coast Mountains, British Columbia, Canada

Brian Menounos[a,*], Johannes Koch[b], Gerald Osborn[c], John J. Clague[b], David Mazzucchi[d]

[a] Geography Program, University of Northern British Columbia, 3333 University Way, Prince George, BC, Canada V2N 4Z9
[b] Department of Earth Sciences, Simon Fraser University, 8888 University Drive, Burnaby, BC, Canada V5A 1S6
[c] Department of Geology and Geophysics, University of Calgary, 844 Campus Place Northwest, Calgary, Alta, Canada T2N 1N4
[d] School of Earth and Ocean Sciences, University of Victoria, P.O. Box 3055 STN CSC, Victoria, BC, Canada V8W 3P6

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Abstract

Terrestrial and lake sediment records from several sites in the southern Coast Mountains, British Columbia, provide evidence for an advance of alpine glaciers during the early Holocene. Silty intervals within organic sediments recovered from two proglacial lakes are bracketed by AMS ^{14}C-dated terrestrial macrofossils and Mazama tephra to 8780–6730 and 7940–6730 ^{14}C yr BP [10,150–7510 and 8990–7510 cal yr BP]. Radiocarbon ages ranging from 7720 to 7380 ^{14}C yr BP [8630–8020 cal yr BP] were obtained from detrital wood in recently deglaciated forefields of Sphinx and Sentinel glaciers. These data, together with previously published data from proglacial lakes in the Canadian Rockies, imply that glaciers in western Canada advanced during the early Holocene. The advance coincides with the well-documented 8200-yr cold event identified in climate proxy data sets in the North Atlantic region and elsewhere.

1. Introduction

Early Holocene glacier advances in western North America have been proposed and debated by many researchers (Davis, 1988; Heine, 1998; Thomas et al., 2000; Reasoner et al., 2001). The debate commonly centers on the age of moraines and other glacial landforms. Attempts to date many of these deposits are compromised because the associated radiocarbon ages can only be considered minima for the true age of the landform (Davis and Osborn, 1987). In addition, paleobotanical evidence Clague and Mathewes, 1989; Hebda, 1995; Pellatt and Mathewes, 1997) and calculated summer insolation values at this latitude (Berger, 1977, 1978, 1988) suggest that the early Holocene was warm and dry.

Nevertheless, many European sites record abrupt climate change during the early Holocene. The most significant change, which is recorded in Greenland ice cores, occurred between 8400 and 8000 cal yr BP and is known as the '8200-yr cold event' (Alley et al., 1997). This event is recognized in the North Atlantic region (Alley et al., 1997; Willemse and Törnqvist, 1999; Baldini et al., 2002) and elsewhere (Hughen et al., 1996; Alley et al., 1997; Barber et al., 1999). Recent studies suggest that the 8200-yr cold event was caused by a massive discharge of freshwater into the North Atlantic ca 8470 cal yr BP, temporarily altering ocean circulation (Barber et al., 1999; Clarke et al., 2003). Detection of this important event at sites distant from the North Atlantic region is one way of evaluating the behavior and teleconnections of the global climate system at that time. In this note, we present evidence for glacier activity in the Canadian Cordillera that is synchronous with the 8200-yr cold event. The inferred magnitude of the advance, however, is considerably smaller than the final Little Ice Age (AD 1700–1850) advances observed in western Canada.

2. Study area and methods

The southern Coast Mountains of British Columbia, Canada (Fig. 1), are a series of northwest-trending ranges with relief of 3000 m and extensive snow and ice cover (Ryder, 1981; Muhs et al., 1986). Modern

*Corresponding author. Tel.: +1-250-960-6266; fax: +1-250-960-6533.
E-mail address: menounos@unbc.ca (B. Menounos).

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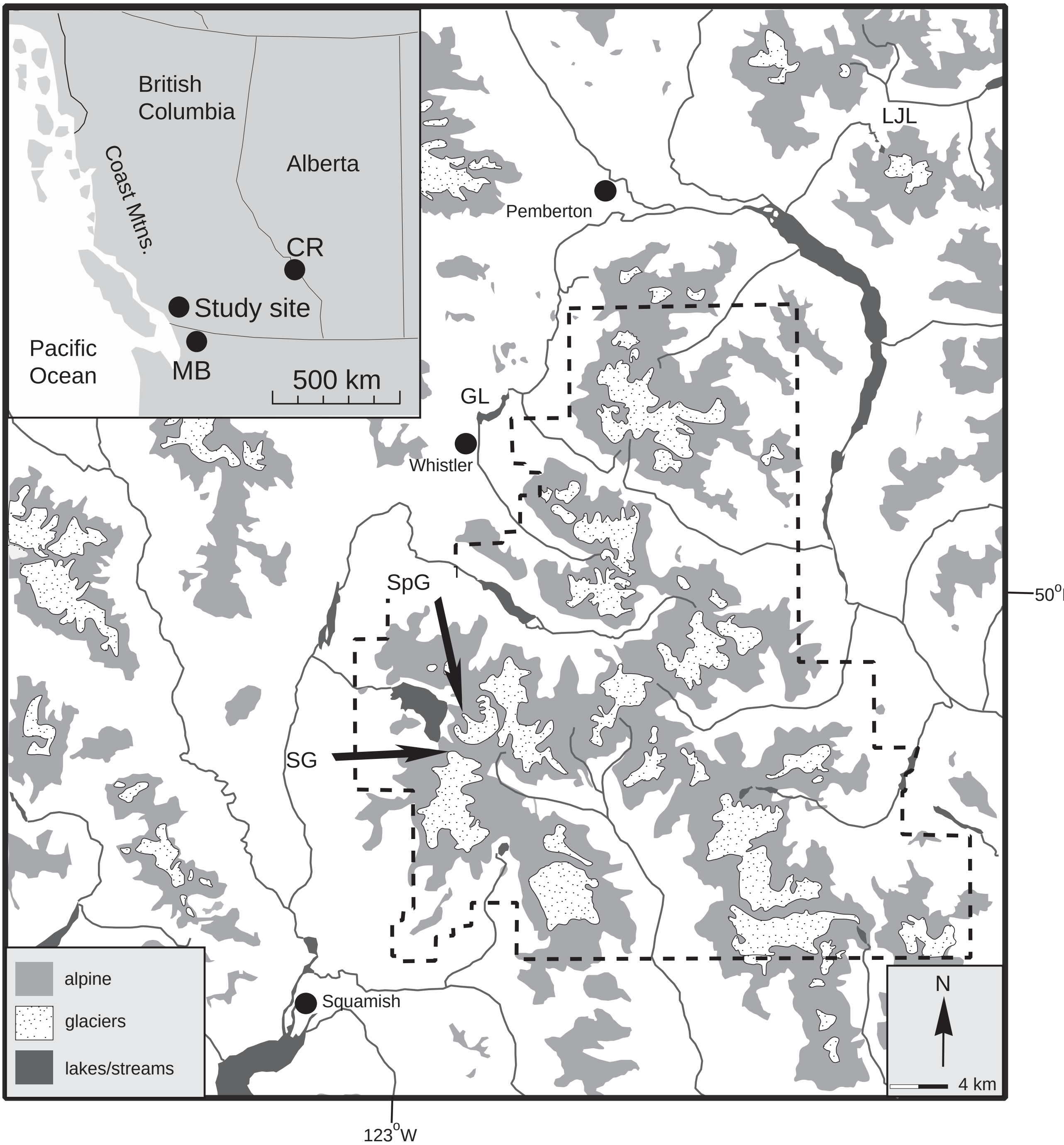

Fig. 1. Location of study area. Study sites include Sentinel Glacier (SG), Sphinx Glacier (SpG), Green Lake (GL), and Lower Joffre Lake (LJL). Dashed line indicates extent of Garibaldi Provincial Park. Inset map shows location of Mount Baker (MB) and proglacial lakes in the Canadian Rocky Mountains (CR).

equilibrium line of glaciers is 1600 m a.s.l. in the coastal watersheds of the Coast Mountains, rising to 2200 m to the east of the range, reflecting the transition from a maritime to continental climate. Most glaciers in the southern Coast Mountains have fresh, unweathered moraines 1–5 km from their margins, constructed during the later phases (AD 1700–1850) of the Little Ice Age (Mathews, 1951; Ryder and Thomson, 1986; Desloges, 1987; Smith and Laroque, 1996; Larocque and Smith, 2003). Dendrochronologic and lichenometric ages of outermost moraines in the study area (Koch et al., 2003) indicate that they too were constructed during the Little Ice Age. Moraines outside the Little Ice Age deposits are uncommon.

We collected vibracores (Smith, 1998) from proglacial Lower Joffre and Green lakes (Fig. 1). The cores were split, photographed, and sampled for bulk physical properties (water content, density, organic content, magnetic susceptibility, and particle size analysis). The loss-on-ignition (LOI) method was used to estimate organic matter content (Dean, 1974) and is used as a proxy for the clastic content of the lake sediments. In oligotrophic lakes draining glacierized terrain, changes in LOI appear to reflect changes in the fraction of clastic sedimentation (Karlén, 1981; Leonard, 1986, Souch, 1994, Leonard and Reasoner, 1999; Nesje et al., 2001). Sediment samples were dried overnight at 105°C, weighed, combusted for 2 h at 550°C, and allowed to cool in a desiccator before re-weighing. Mass lost by the LOI procedure was compared to total carbon determined with a Carlo Erba CN Analyzer (Verardo et al., 1990). The data are linearly related ($r^2 = 0.98; n = 15$) over the range of measured LOI values (0.38–30.79%). Representative samples were treated with 35% H_2O_2 and dispersed in a sodium metaphosphate solution prior to particle size analysis with a Malvern analyzer. Sediment was wet sieved on a 63 μm screen. Macrofossils were collected with tweezers, oven-dried (70°C), and placed in sealed glass vials prior to submission for radiocarbon dating.

We searched glacier forefields in Garibaldi Provincial Park (Fig. 1) for wood in growth position within lateral and terminal moraines, as well as wood melting out from glacier margins. Where possible, the samples were cross-dated into living chronologies using standard methods (Smith and Laroque, 1996). In cases where samples were decayed or lacked a sufficient number of annual rings, outermost rings from the samples were submitted for radiocarbon dating. Radiocarbon ages of terrestrial and lacustrine macrofossils (Table 1) were converted to calendric age using the calibration program Calib 4.4 (Stuiver et al., 1998).

3. Results

3.1. Lake cores

Each of the vibracores recovered from Lower Joffre and Green lakes is over 10 m in length and records changes in clastic sedimentation through the Holocene (Menounos, 2002). The sediment core from Lower Joffre Lake comprises two dominant facies. Below 470 cm, the sediment is primarily grey, laminated, inorganic sandy silt. Above 470 cm, the sediment is gyttja to organic-rich silty-clay. A clastic interval of lighter-colored, denser, clayey silt with higher magnetic susceptibility and relatively low LOI occurs within the gyttja between 412 and 390 cm (Fig. 2). This interval has gradational upper and lower contacts with the gyttja. The interval is bracketed by AMS ^{14}C ages of 8780 ± 65 ^{14}C yr BP [10,150–9560 cal yr BP; 2σ] at 469 cm and by a 1-cm-thick bed of fine-grained tephra at 378 cm (Table 1, Fig. 2). A weakly graded bed of sandy silt with abundant macrofossils occurs above the tephra (Fig. 2). Conifer needles from this bed (Table 1, Fig. 2) yielded an AMS ^{14}C age of 6700 $\pm$100 ^{14}C yr BP [7730–7430 cal yr BP].

Sediments recovered from Green Lake are laminated, silty clay to clayey silt. Sediments between 1000 and 800 cm are weakly laminated and organic-rich (Fig. 2). A clastic interval with relatively low LOI between 940 and 890 cm is constrained by an AMS age of 7940 ± 45 ^{14}C yr BP [8990–8630 cal yr BP] on a twig at 962 cm and a 1-cm-thick layer of tephra at 887 cm (Table 1, Fig. 2). As in Lower Joffre Lake, contacts of this clastic interval are gradational.

The tephras have physical properties similar to those reported for Mazama tephra (Hallett et al., 1997; Zdanowicz et al., 1999, which dates to 6730 ± 40 ^{14}C yr

Table 1
Radiocarbon ages used in this study

Laboratory no[a].	Field no.	Material	^{14}C age (yr BP)	Calendar age (cal yr BP)[b]
Lake sediment macrofossils				
AA-33500	99-Jof(01), 373 cm	Conifer needles	6700 ± 100	7730–7430
AA-33502	99-Jof(01), 469 cm	Conifer needles	8780 ± 65	10,150–9560
AA-33498	99-Jof(01), 496 cm	Conifer needles	8560 ± 180	10,150–9030
AA-38707	00-Grn(B), 800 cm	Conifer needles	5040 ± 50	5900–5660
AA-38708	00-Grn(B), 962 cm	Twig	7940 ± 45	8990–8630
Glacier forefield samples				
Beta-148786	Sentinel Glacier (1650 m)	Detrital wood	7380 ± 80	8350–8020
Beta-148787	Sentinel Glacier (1650 m)	Detrital wood	7720 ± 70	8630–8390
Beta-157267	Sentinel Glacier (1650 m)	Detrital wood	7470 ± 80	8410–8060
GSC-1993[c]	Sphinx Glacier (1650 m)	Detrital wood	7640 ± 80[d]	8540–8370
GSC-6770	Sphinx Glacier (1550 m)	Detrital wood	7720 ± 80[d]	8590–8410

[a] Radiocarbon Laboratory ID: AA = University of Arizona; Beta = Beta Analytic. Inc.; GSC = Geological Survey of Canada Radiocarbon Laboratory.
[b] Calendar ages ($\pm 2\sigma$) determined using Calib 4.4 (Stuiver et al., 1998).
[c] From Lowdon and Blake (1975).
[d] 2σ uncertainty.

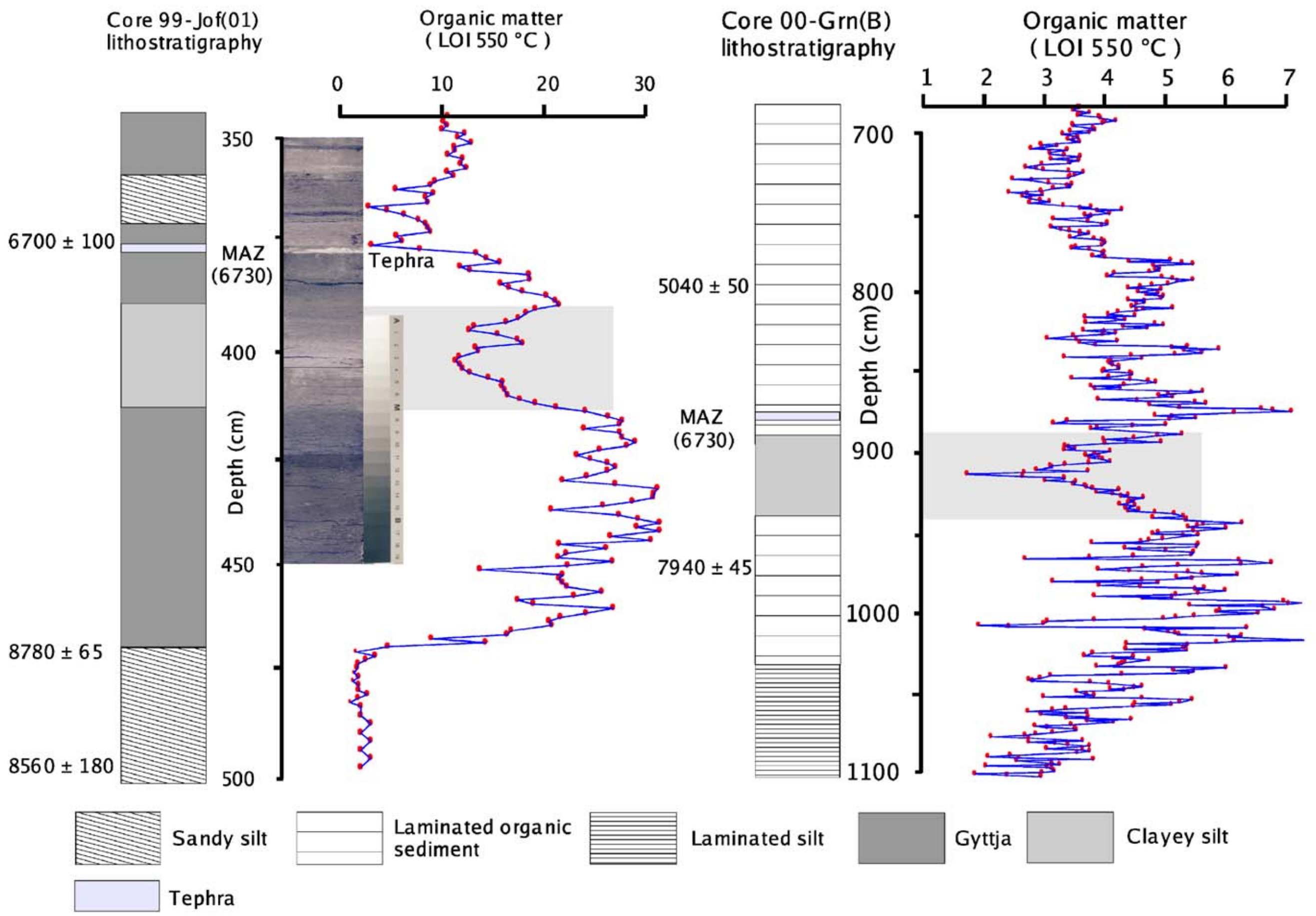

Fig. 2. Lithostratigraphy and organic matter content of early to middle Holocene sediments from Green and Lower Joffre lakes. The interval of clastic sediment (denoted by the light gray bar) is clearly visible in the sediments of Lower Joffre Lake (upper left image). Maz = Mazama tephra.

BP [7670–7510 cal yr BP]. The properties include a fine texture, absence of biotite-rich phenocrysts, and thin bubble-wall glass shards (Reasoner and Healy, 1986). The stratigraphic context of the tephras in Lower Joffre and Green lakes with respect to AMS-dated terrestrial macrofossils (Fig. 2), its thickness, and the presence of Mazama tephra at other sites within the study area (e.g. Hallett et al., 1997) confirm the correlation with Mazama tephra.

The age range of the clastic interval in both cores is considerably less than the bracketing radiocarbon and tephra ages (Fig. 2). To estimate the duration of clastic sedimentation for each core, we determined lake sedimentation rates (0.04 cm yr^{-1} for Lower Joffre Lake and 0.06 cm yr^{-1} for Green Lake) for sediments deposited between the lower AMS ^{14}C ages and the upper Mazama tephra (Fig. 2). These sedimentation rates are then used to estimate the onset and termination of the clastic interval in each sediment record. Clastic sedimentation began about 8200 cal yr BP in Lower Joffre Lake and 8400 cal yr BP in Green Lake. It ended about 7850 cal yr BP in Lower Joffre Lake and 7750 cal yr BP in Green Lake. However, given likely nonlinear rates of sedimentation, the onset and termination of the clastic event could differ from these values by up to several hundred years.

3.2. Detrital wood in glacier forefields

Radiocarbon ages on detrital wood samples from glacier forefields in Garibaldi Park range from about 9000 ^{14}C yr BP to modern. Several peaks are evident in the calibrated probability distribution of these ages, including one centered at 8500 cal yr BP. To facilitate comparisons with the lake sediment record, we limit our discussion to samples with calibrated ages between 8600 and 7600 cal yr BP. A small, poorly preserved piece of wood was found 100 m from the present terminus of Sphinx Glacier at an elevation of 1550 m (Figs. 1 and 3). The sample was partially buried in till, 200 m above and 2 km upvalley from Little Ice Age end moraines (Fig. 3). The wood yielded a radiocarbon age of 7720 ± 80 ^{14}C yr BP [8630–8390 cal yr BP] (Table 1). Another piece of detrital wood was collected during a previous study (Table 1) and gave an age of 7640 ± 80 ^{14}C yr BP [8540–8370 cal yr BP]. The sample was 2 m long and 40 cm

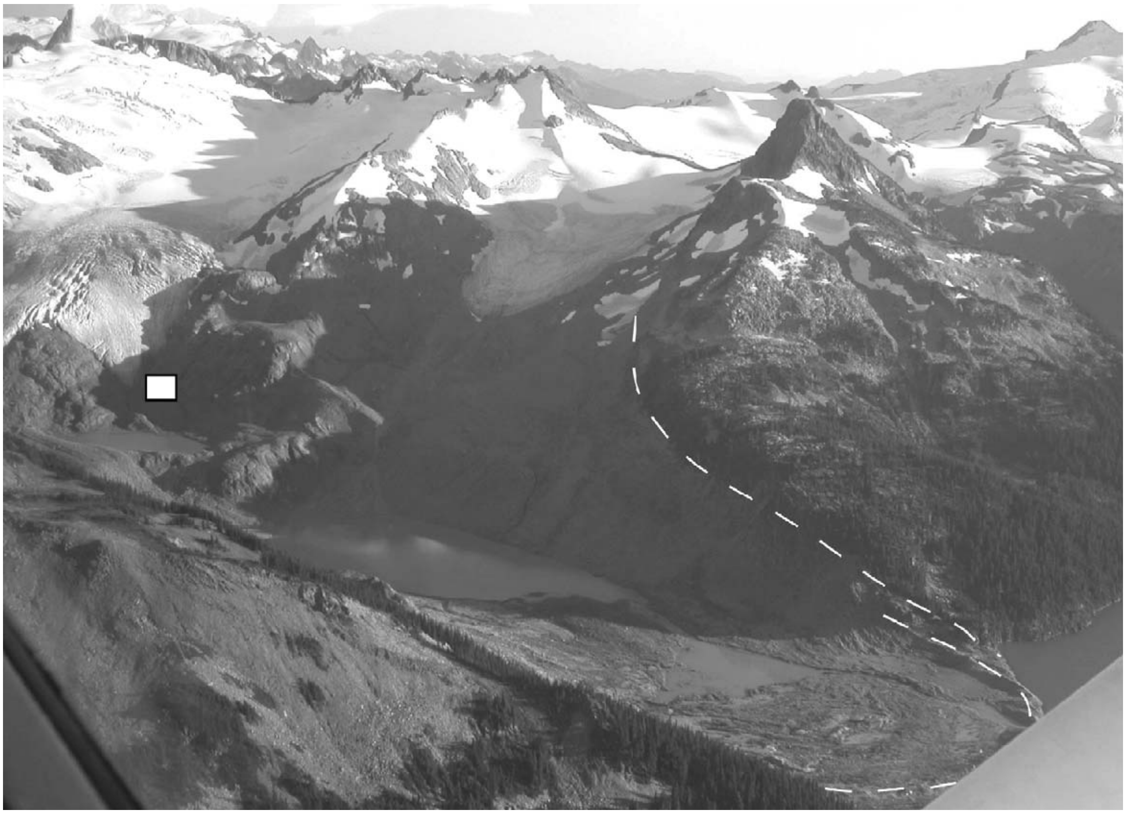

Fig. 3. Forefield of Sphinx Glacier, showing Little Ice Age moraines (white dashed lines) and location of dated detrital wood (open box).

wide and was found 170 m above and 3.5 km upvalley from Little Ice Age end moraines (Lowdon and Blake, 1975). Three small pieces of detrital wood were collected at 1650 m elevation, 50 and 400 m from the terminus of Sentinel Glacier and 2 km upvalley from Little Ice Age moraines (Fig. 1). Radiocarbon ages on these samples (Table 1) range from 7720 to 7380 ^{14}C yr BP [8630–8020 cal yr BP]. The five detrital wood samples have a combined calibrated age range ($\pm 2\sigma$) of 8630–8020 cal yr BP. As all but one of the five samples appear to be from small-diameter boles, the loss of outermost rings due to abrasion or weathering is likely minimal. Nevertheless, such effects could produce radiocarbon ages that predate the death of the tree by perhaps several decades.

4. Discussion

The most conclusive evidence for glacier fluctuations prior to the period of photographic records and other documentary sources is tree stumps in growth position in glacier forefields (Luckman, 1995). The stumps can be radiocarbon dated or, in some instances, cross-dated into living tree ring chronologies to provide the year of death of the tree. It is more tenuous to infer glacier fluctuations from either detrital wood in glacier forefields or from changes in the clastic content of proglacial lake sediments (Karlén, 1981; Leonard, 1986; Souch, 1994). Detrital wood can be delivered to glaciers by snow avalanching and, unlike wood derived from glacially overridden trees, may not relate to glacier fluctuations in any meaningful way (Ryder and Thomson, 1986). Intervals of clastic sedimentation in proglacial lakes may record advances of cirque or valley glaciers (Leonard, 1986, 1997), but they may also stem from large floods or hillslope processes (Menounos, 2000). Although the relationship between clastic lake sedimentation and glacier dynamics is complex (Leonard, 1997), clastic sedimentation commonly increases during and immediately following a glacier advance (Karlén, 1981; Souch, 1994; Leonard, 1997; Leonard and Reasoner, 1999; Nesje et al., 2001).

An advance of local glaciers is the most logical explanation for detrital wood from different glacier forefields being the same age as clastic intervals from two separate lake basins in the study area. We therefore interpret the lake and terrestrial data presented in this paper as evidence for a glacier advance between 8630 and 8020 cal yr BP, and we correlate it with the 8200-yr cold event in the North Atlantic region.

The proximity of the detrital wood to contemporary ice margins (Fig. 3) and its location upvalley from Little Ice Age moraines imply that this advance was considerably smaller than the Little Ice Age advances of the last several hundred years in the southern Coast Mountains. The magnitude of the advance can also be inferred from the relative difference in the amount of organic matter in the early Holocene and Little Ice Age clastic intervals (Karlén, 1981; Souch, 1994; Leonard and Reasoner, 1999). The clastic interval correlative with the 8200-yr cold event contains two to three times as much organic matter as sediments deposited during the Little Ice Age.

Proglacial lake sediment records from the Canadian Rocky Mountains (Fig. 1) indicate that the glacier advance may have been regional in scope. Three lakes (Hector, Crowfoot, and Bow) contain clastic-rich sediments immediately below Mazama tephra (Leonard and Reasoner, 1999). In one sediment core (H93-III; Hector Lake), the interval is bracketed by the tephra and an AMS ^{14}C yr age of 7230 ± 80 ^{14}C yr BP [8190–7870 cal yr BP](OS-6682) on a small twig. The calendar age range of this clastic interval is thus 8190–7510 cal yr BP. This interval, like the corresponding intervals in Lower Joffre and Green lakes, contains several times more organic matter than late Holocene sediments. In both the Candian Rocky Mountains and the southern Coast Mountains, the interval of clastic sedimentation appears to end after the 2σ age range [8630–8020 cal yr BP] of the detrital wood and the termination [8000 cal yr BP] of the 8200-yr cold event (Alley et al., 1997; Barber et al., 1999; Baldini et al., 2002). Such effects are to be expected if clastic sedimentation remains high for one to two centuries after glaciers achieve their maximum extent. Lags of this magnitude are relatively common in proglacial environments (Ballantyne, 2002).

Based on the lack of data for higher than present treeline in western North America between 7500 and 6600 ^{14}C yr BP [8360–7430 cal yr BP], Reasoner et al. (2001) hypothesized that if alpine glaciers advanced ca 8200 cal yr BP, the advance was minor and short lived. Their conclusions are not at odds with the lacustrine and terrestrial evidence presented here. In contrast, paleobotanical records from southern British Columbia and the moraine record from Mount Baker, Washington, 100 km to the south (Thomas et al., 2000), appear to be in conflict with the results of this study. Pollen (Hebda, 1995) and chironomid (Palmer et al., 2002) reconstructions of summer air temperature in southern British Columbia indicate that the early Holocene was 2–4°C warmer than today. Considering the short duration of the 8200-yr cold event (Baldini et al., 2002), it is likely that the low resolution of the paleobotanical records hindered detection of the event. A recent study has also suggested difficulties in detecting short duration, climatic episodes such as the 8200-yr cold event using paleobotanical methods (Kurek et al., in press). The lack of evidence of the 8200-yr event at Mount Baker may imply that Little Ice Age advances overrode the older moraines or that the ages ascribed to the early Holocene moraine system there (8400–7700 ^{14}C yr BP; [9450–8400 cal yr BP]) are incorrect. Given the apparently minor extent of glaciers in the Canadian Cordillera during the 8200-yr cold event, any moraines correlative to the 8200-yr cold event at Mount Baker are likely to have been destroyed by late Holocene advances.

5. Conclusion

An inferred early Holocene glacier advance in the southern Coast Mountains of British Columbia is correlative, within the resolution permitted by radiocarbon dating, to the 8200-yr cold event recorded in the Greenland ice cores and to climate proxies from the North Atlantic region and elsewhere. This apparent coincidence implies that the glacier advance in the Coast Mountains had the same cause as the 8200-yr cold event in the North Atlantic region. Its presence in western North America is important because it suggests a synchronous response to climate forcing between the North Pacific and North Atlantic oceans, albeit on a much smaller scale in the North Pacific region. Several studies have alluded to probable mechanisms that could explain synchronous behavior between the North Pacific and Atlantic basins (Zic et al., 2002; Hu et al., 2003), but remain equivocal. The lack of paleobotanical evidence for the event in western Canada is likely an artifact of the low temporal resolution of alpine lake sediments from non-glacierized catchments and suggests that such records are less than ideal for detecting abrupt, short-lived climate events.

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References

Alley, R., Mayewski, P., Sowers, T., Stuiver, M., Taylor, K., Clark, P., 1997. Holocene climate instability: a prominent, widespread event 8200 yr ago. Geology 25, 483–486.

Baldini, J., McDermott, F., Fairchild, I., 2002. Structure of the 8200-year cold event revealed by a speleothem trace element record. Science 296, 2203–2206.

Ballantyne, C., 2002. Paraglacial geomorphology. Quaternary Science Reviews 21, 1935–2017.

Barber, D., Dyke, A., Hillaire-Marcel, C., Jennings, A., Kerwin, M., Bilodeau, G., McNeely, R., Southon, J., Morehead, M., Gagnon, J., 1999. Forcing of the cold event of 8200 years ago by catastrophic drainage of Laurentide lakes. Nature 200, 344–348.

Berger, A., 1977. Support for the astronomical theory of climatic change. Nature 269, 44–45.

Berger, A., 1978. Long-term variations of caloric insolation resulting from the Earth's orbital elements. Quaternary Research 9, 139–167.

Berger, A., 1988. Milankovitch theory and climate. Reviews of Geophysics 26, 624–657.

Clague, J., Mathewes, R., 1989. Early Holocene thermal maximum in western North America: new evidence from Castle Peak, British Columbia. Geology 17, 277–280.

Clarke, G., Leverington, D., Teller, J., Dyke, A., 2003. Superlakes, megafloods, and abrupt climate change. Science 301, 922–923.

Davis, P., 1988. Holocene glacier fluctuations in the American Cordillera. Quaternary Science Reviews 7, 129–157.

Davis, P., Osborn, G., 1987. Age of pre-Neoglacial moraines in the central North American Cordillera. Géographie Physique et Quaternaire 41, 365–375.

Dean, W., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. Journal of Sedimentary Petrology 44, 242–248.

Desloges, J., 1987. Paleohydrology of the Bella Coola river basin: an assessment of environmental reconstruction. Ph.D. Thesis, University of British Columbia, Vancouver.

Hallett, D., Hills, L., Clague, J., 1997. New accelerator mass spectrometry radiocarbon ages for the Mazama tephra layer from Kootenay National Park, British Columbia, Canada. Canadian Journal of Earth Sciences 34, 1202–1209.

Hebda, R., 1995. British Columbia vegetation and climate history with focus on 6 KA BP. Géographie physique et Quaternaire 49, 55–79.

Heine, J., 1998. Extent, timing and climatic implications of glacier advances Mount Rainier, Washington, USA, at the Pleistocene/Holocene transition. Quaternary Science Reviews 17, 1139–1148.

Hu, F., Kaufman, D., Yoneji, S., Nelson, D., Shemesh, A., Huang, Y., Tian, J., Bond, G., Clegg, B., Brown, T., 2003. Cyclic variation and solar forcing of Holocene climate in the Alaska subarctic. Science 301, 1890–1893.

Hughen, K., Overpeck, J., Peterson, L., Trumboro, S., 1996. Rapid climate changes in the tropical Atlantic region during the last deglaciation. Nature 380, 51–54.

Karlén, W., 1981. Lacustrine sediment studies. Geografiska Annaler 63A, 273–281.

Koch, J., Clague, J., Smith, D., Osborn, G., 2003. Ice cover changes in Garibaldi Provincial Park, southern Coast Mountains, British Columbia, since the Little Ice Age. Geological Association of Canada, Program with Abstracts 28, 78.

Kurek, J., Cwynar, L., Spear, R., The 8200 cal yr BP cooling event in eastern North America and the utility of midge analysis for Holocene temperature reconstructions, Quaternary Science Reviews 23, 627–639 (doi: 10.1016/S0277-3791(03) 00211–7).

Larocque, S., Smith, D., 2003. Little Ice Age glacial activity in the Mt. Waddington area, Coast Mountains, Canada. Canadian Journal of Earth Sciences 40, 1413–1436.

Leonard, E., 1986. Use of sedimentary sequences as indicators of Holocene glacial history, Banff National Park, Alberta. Quaternary Research 26, 218–231.

Leonard, E., 1997. The relationship between glacial activity and sediment production: evidence from a 4450-year varve record of neoglacial sedimentation in Hector Lake, Alberta, Canada. Journal of Paleolimnology 17, 319–330.

Leonard, E., Reasoner, M., 1999. A continuous Holocene glacial record inferred from proglacial lake sediments in Banff National Park, Alberta, Canada. Quaternary Research 51, 1–13.

Lowdon, J., Blake, W., 1975. Radiocarbon dates. Geological Survey of Canada Paper 75-7, 1–32.

Luckman, B., 1995. Calendar-dated, early 'Little Ice Age' glacier advance at Robson Glacier, British Columbia, Canada. The Holocene 5, 149–159.

Mathews, W.H., 1951. Historic and prehistoric fluctuations of alpine glaciers in Mt. Garibaldi map-area, southwestern British Columbia. Journal of Geology 59, 357–381.

Menounos, B., 2000. A Holocene debris-flow chronology for an alpine catchment, Colorado Front Range. In: Slaymaker, O. (Ed.), Geomorphology, Human Activity, and Global Environmental Change. Wiley, Chichester, UK, pp. 117–149.

Menounos, B., 2002. Climate, fine-sediment transport linkages, Coast Mountains, British Columbia, Canada. Ph.D. Thesis, University of British Columbia, Vancouver.

Muhs, D., Thorson, R., Clague, J., Mathews, W., McDowell, P., Kelsey, H., 1986. Pacific Coast and mountain system. In: Graf, W. (Ed.), Geomorphic Systems of North America, Vol. 2. Geological Society of America Centennial Special, pp. 517–581. Boulder, CO.

Nesje, A., Matthews, J., Dahl, S., Berrisford, M., Andersson, C., 2001. Holocene glacier fluctuations of Flatebreen and winter-precipitation changes in the Jostedalsbreen region, western Norway, based on glaciolacustrine sediment records. The Holocene 11, 267–280.

Palmer, S., Walker, I., Heinrichs, M., Hebda, R., Scudder, G., 2002. Postglacial midge community change and Holocene palaeotemperature reconstructions near treeline, southern British Columbia (Canada). Journal of Paleolimnology 28, 469–490.

Pellatt, M., Mathewes, R., 1997. Holocene tree line and climate change on the Queen Charlotte Islands, Canada. Quaternary Research 48, 88–99.

Reasoner, M., Healy, R., 1986. Identification and significance of tephras encountered in a core from Mary Lake, Yoho National Park, British Columbia. Canadian Journal of Earth Sciences 23, 1991–1999.

Reasoner, M., Davis, P., Osborn, G., 2001. Evaluation of proposed early-Holocene advances of alpine glaciers in the north Cascade Range, Washington state, USA: constraints provided by paleoenvironmental reconstructions. The Holocene 11, 607–611.

Ryder, J., 1981. Geomorphology of the southern part of the Coast Mountains of British Columbia. Zeitscrift für Geomorphologie 37, 120–147.

Ryder, J., Thomson, B., 1986. Neoglaciation in the southern Coast Mountains of British Columbia: chronology prior to the late Neoglacial maximum. Canadian Journal of Earth Sciences 23, 273–287.

Smith, D., 1998. Vibracoring: a new method for coring deep lakes. Palaeogeography, Palaeoclimatology, Palaeoecology 140, 433–440.

Smith, D., Laroque, C., 1996. Dendroglaciological dating of a Little Ice Age glacial advance at Moving Glacier, Vancouver Island, British Columbia. Géographie Physique et Quaternaire 50, 47–55.

Souch, C., 1994. A methodology to interpret downvalley lake sediments as records of neoglacial activity, Coast Mountains, British Columbia, Canada. Geografiska Annaler 76A, 169–185.

Stuiver, M., Reimer, P., Beck, J., Burr, G., Hughen, K., Kromer, B., McCormac, F., v. d. Plicht, J., Spurk, M., 1998. INTCAL98 radiocarbon age calibration 24,000-0 cal BP. Radiocarbon 40, 1041–1083.

Thomas, P., Easterbrook, D., Clark, P., 2000. Early Holocene glaciation on Mount Baker, Washington State, USA. Quaternary Science Reviews 19, 1043–1046.

Verardo, D., Froelich, P., McIntyre, A., 1990. Determination of organic carbon and nitrogen in marine sediments using the Carlo Erba NA-1500 analyzer. Deep-Sea Research 37, 157–165.

Willemse, N., Törnqvist, T., 1999. Holocene century-scale temperature variability from West Greenland lake records. Geology 27, 580–584.

Zdanowicz, C., Zielinski, G., Germani, M., 1999. Mount Mazama eruption: calendric age verified and atmospheric impact assessed. Geology 27, 621–624.

Zic, M., Negrini, R.M., Widgand, P.E., 2002. Evidence of synchronous climate change across the Northern Hemispherere between the North Atlantic and the northwestern Great Great Basin, United States. Geology 30, 635–639.