Stratigraphic evidence for multiple Holocene advances of Lillooet Glacier, southern Coast Mountains, British Columbia

Alberto V. Reyes and John J. Clague

Abstract: Holocene lateral moraines in the Coast Mountains of British Columbia are commonly composed of multiple drift units related to several glacier advances. In this paper, we document lateral moraine stratigraphy at Lillooet Glacier in the southern Coast Mountains. Five tills, separated by laterally extensive paleosols and layers of large woody debris, were found in three cross-sectional exposures through the northeast lateral moraine and two shallow gullies incised into its steep proximal face. Eighteen new radiocarbon ages constrain the timing of five separate advances of Lillooet Glacier: (1) prior to 3000 ^{14}C years BP; (2) ~3000 ^{14}C years BP; (3) ~2500 ^{14}C years BP; (4) ~1700 to 1400 ^{14}C years BP; and (5) during the Little Ice Age (LIA), after 470 ^{14}C years BP. The Lillooet Glacier chronology is broadly synchronous with other glacier records from the Coast Mountains. These records collectively demonstrate climate variability at higher frequencies during the late Holocene than is apparent from many paleoecological reconstructions. Reconstructions of glacier fluctuations are often hampered by poor preservation of landforms that predate the extensive LIA advances of the latest Holocene. Our results highlight the potential of lateral moraine stratigraphy for reconstructing these earlier events.

Résumé : Les moraines latérales datant de l'Holocène dans la chaîne Côtière de la Colombie-Britannique sont souvent composées d'unités multiples de sédiments glaciaires reliées à plusieurs avancées glaciaires. Dans le présent article, nous documentons la stratigraphie de la moraine latérale au glacier Lillooet dans le sud de la chaîne Côtière. Cinq tills, séparés par de grandes étendues latérales de paléosols et des couches de gros débris de bois, ont été trouvés dans trois affleurements à travers la moraine latérale du nord-est et dans deux ruisseaux peu profonds coupés dans sa face proximale abrupte. Dix-huit nouveaux âges radiocarbone limitent le calcul de la durée de cinq avancées séparées du glacier Lillooet : (1) avant 3000 ^{14}C ans avant le présent; (2) ~ 3000 ans ^{14}C avant le présent; (3) ~ 2500 ans ^{14}C avant le présent; (4) ~ 1700 à 1400 ans ^{14}C avant le présent et (5) au cours du Petit Âge glaciaire après 470 ans ^{14}C avant le présent. La chronologie du glacier Lillooet est passablement synchrone avec les autres données sur les glaciers de la chaîne Côtière. Ces données démontrent collectivement une plus grande fréquence des variations du climat durant l'Holocène tardif qu'il n'est apparent à partir de plusieurs reconstructions paléo-écologiques. Les reconstructions de fluctuations glaciaires sont souvent difficiles à faire étant donné la piètre préservation des formes du terrain qui sont antérieures aux avancées extensives du Petit Âge glaciaire de l'Holocène terminal. Nos résultats soulignent le potentiel de la stratigraphie des moraines latérales pour la reconstruction de ces événements antérieurs.

[Traduit par la Rédaction]

Introduction

Climate variability during the Holocene Epoch was relatively limited compared with the high-amplitude fluctuations evident in late Pleistocene proxy paleoclimatic records. However, numerous ice core (e.g., O'Brien et al. 1995), marine (Bond et al. 2001), and terrestrial (e.g., Denton and Karlén 1973; Viau et al. 2002; Hallett et al. 2003; Hu et al. 2003) records suggest that the Holocene was characterized by marked, though less dramatic, fluctuations of climate. One manifestation of this climatic variability is the resurgence of alpine glaciers during the middle and late Holocene, commonly termed Neoglaciation (Porter and Denton 1967). Alpine glacier termini fluctuate rapidly in response to changes in mass balance, and hence to variations in temperature and precipitation, so chronologies of past glacier activity have traditionally been used as climate proxies. These records can help constrain and evaluate other paleoenvironmental reconstructions.

Our knowledge of Holocene glacier fluctuations, however, is severely limited by sparse evidence for advances prior to

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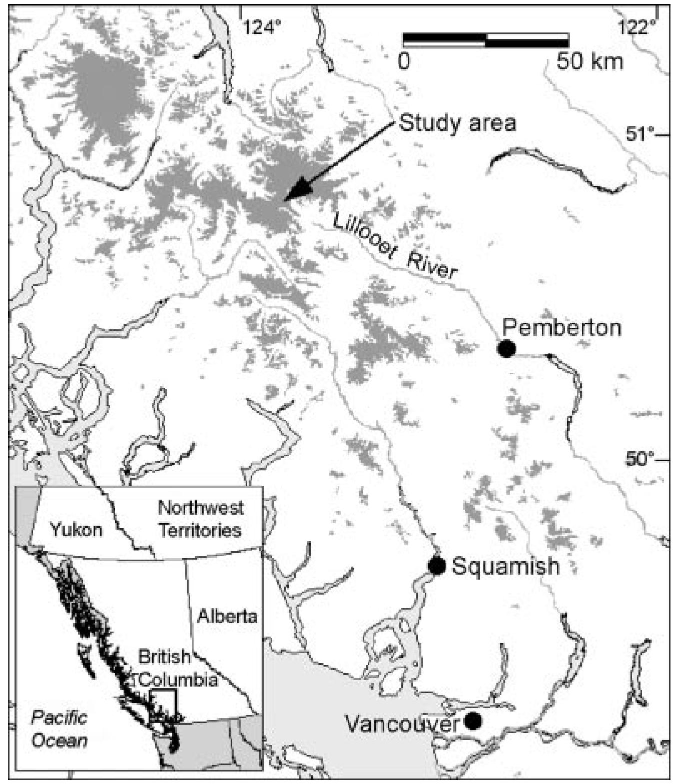
the Little Ice Age (LIA), here defined as the period between ca. A.D. 1200 and 1900 (Grove 1988). During this time, many glaciers advanced to their most extended positions of the Holocene, and surficial evidence for earlier, less extensive advances was commonly destroyed. In the Canadian Cordillera, fragmented moraines outside LIA limits have been indirectly dated using tephrochronology (e.g., Luckman and Osborn 1979), changes in lacustrine sedimentation rates and sediment organic content (e.g., Reasoner et al. 1994), and by dating beds of clastic sediment in organic sequences (e.g., Ryder and Thomson 1986). Lichenometry has been successfully used to date latest Holocene moraine sequences (e.g., Larocque and Smith 2003), but snow-kill, mass wasting, and uncertain calibration of the age–diameter relationship limit the use of the technique in investigations at longer time scales. Holocene moraines have been dated elsewhere using cosmogenic radionuclides (e.g., Finkel et al. 2003), but Walker (2003) had little success applying this technique to Holocene investigations in the Coast Mountains.

Where pre-LIA moraines are missing or cannot be dated, records of Holocene glaciation have been derived from downvalley lake sediment cores (Souch 1994; Leonard and Reasoner 1999; Menounos 2002; Menounos et al. 2004) and dated shorelines or sediments of former ice-dammed lakes (Clague and Rampton 1982; Clague and Mathews 1992). More direct dating of pre-LIA advances is possible where glacially overridden trees are exposed in situ in glacigenic sediments (e.g., Luckman et al. 1993; Wiles et al. 1999; Wood and Smith 2004) or where glacially sheared tree stumps are present on nunataks (e.g., Ryder and Thomson 1986).

Similarly, composite lateral moraines, consisting of drift related to multiple advances, can provide detailed information on the timing of glacier fluctuations. Separation and dating of tills in these moraines are facilitated by the presence of paleosols or weathered horizons, tephras, and accumulations of woody debris derived from overridden trees and shrubs. Lateral moraine stratigraphy has been used extensively in Europe and New Zealand to develop chronologies of Holocene glacial activity (e.g., Röthlisberger et al. 1980; Gellatly et al. 1988; Holzhauser and Zumbühl 1996). The only published applications of this method in the North American Cordillera, however, are in the Coast Mountains (Ryder and Thomson 1986; Desloges and Ryder 1990), at Bugaboo Glacier in the Purcell Mountains (e.g., Osborn and Karlstrom 1988) and at Stutfield Glacier (Osborn et al. 2001) and Peyto Glacier (Luckman in press) in the Rocky Mountains. Ryder and Thomson (1986), following earlier efforts by Mathews (1951) and Fulton (1971), established an important regional chronological framework for late Holocene glacier fluctuations prior to the LIA. Their pioneering study was a reconnaissance-scale investigation, and their regional glacier chronology was compiled from exposures at several sites in the southern Coast Mountains.

Here, we present the results of a detailed study of lateral moraine stratigraphy at Lillooet Glacier in the southern Coast Mountains. Buried paleosols and prominent layers of large woody debris were used to separate till units at four sites and to provide a detailed radiocarbon chronology of late Holocene glacier fluctuations. We compare our chronology to records of Holocene glacier activity elsewhere in the Coast Mountains and discuss the paleoclimatological implications of the regional glacier chronology.

Fig. 1. Map showing location of Lillooet Glacier. Darker gray areas are glaciers and icefields.



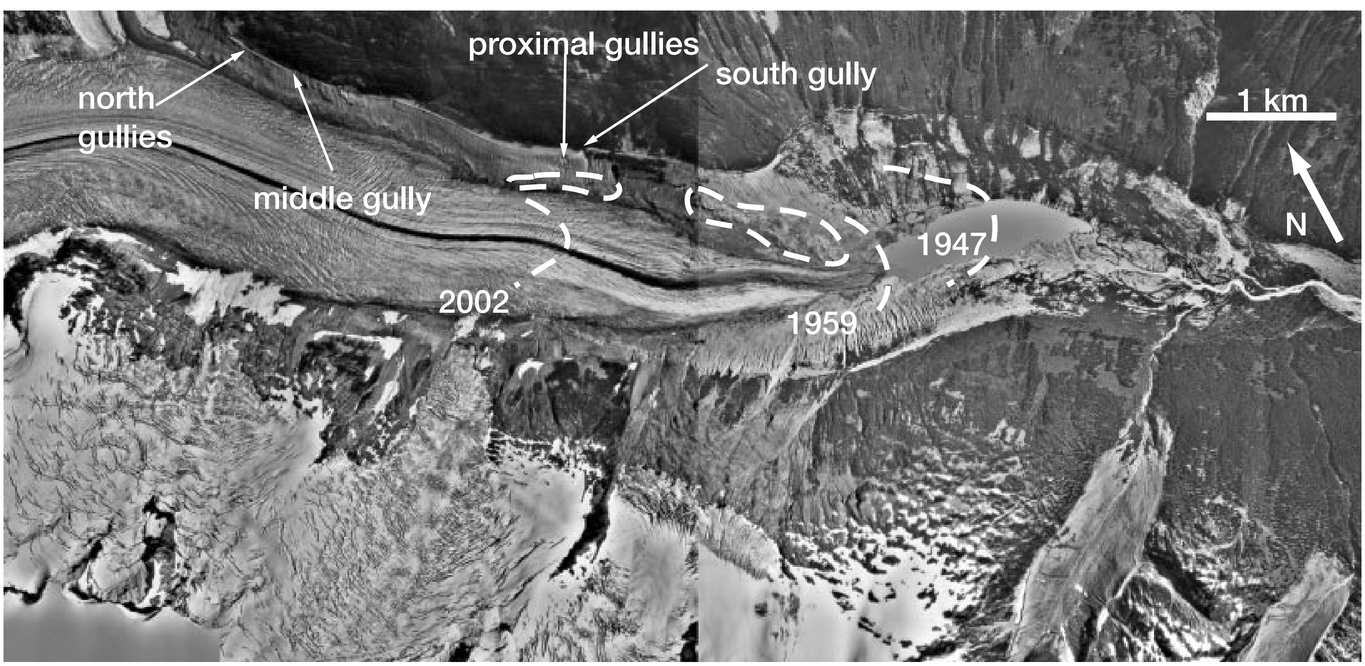
Setting

The Coast Mountains are a belt of high-relief, northwest-trending mountains that extend from southwestern British Columbia to the St. Elias Mountains of southwestern Yukon Territory and Alaska. Lillooet Glacier is located in the Pacific Ranges of the southern Coast Mountains. Bedrock in the study area is primarily late Cretaceous granodiorite and early Cretaceous volcanic and metasedimentary rocks of the Gambier Group (Monger and Journeay 1994). Presently, glaciers and icefields are common in the southern Coast Mountains, although all have thinned and retreated considerably since the end of the LIA (e.g., Mathews 1951; Ryder and Thomson 1986; Koch et al. 2003*a*; Larocque and Smith 2003; Holm et al. 2004).

Lillooet Glacier (Figs. 1, 2; 50°45′N, 123°46′W) is a large valley glacier that extends about 9.5 km southeast from extensive icefields and terminates in upper Lillooet River valley at about 1100 m above sea level (asl). The highest peaks in the area are ~2950 m asl, and relief above the glacier locally exceeds 1300 m. Lillooet Glacier has retreated ~5 km from its maximum LIA terminus, which is marked by a terminal moraine that has been severely degraded by fluvial erosion and mass wasting from steep, avalanche-prone valley slopes (Fig. 3). The glacier is fringed by large, steep, sharp-crested LIA lateral moraines. The northeast lateral moraine is up to ~100 m high, measured from the base to the crest on its

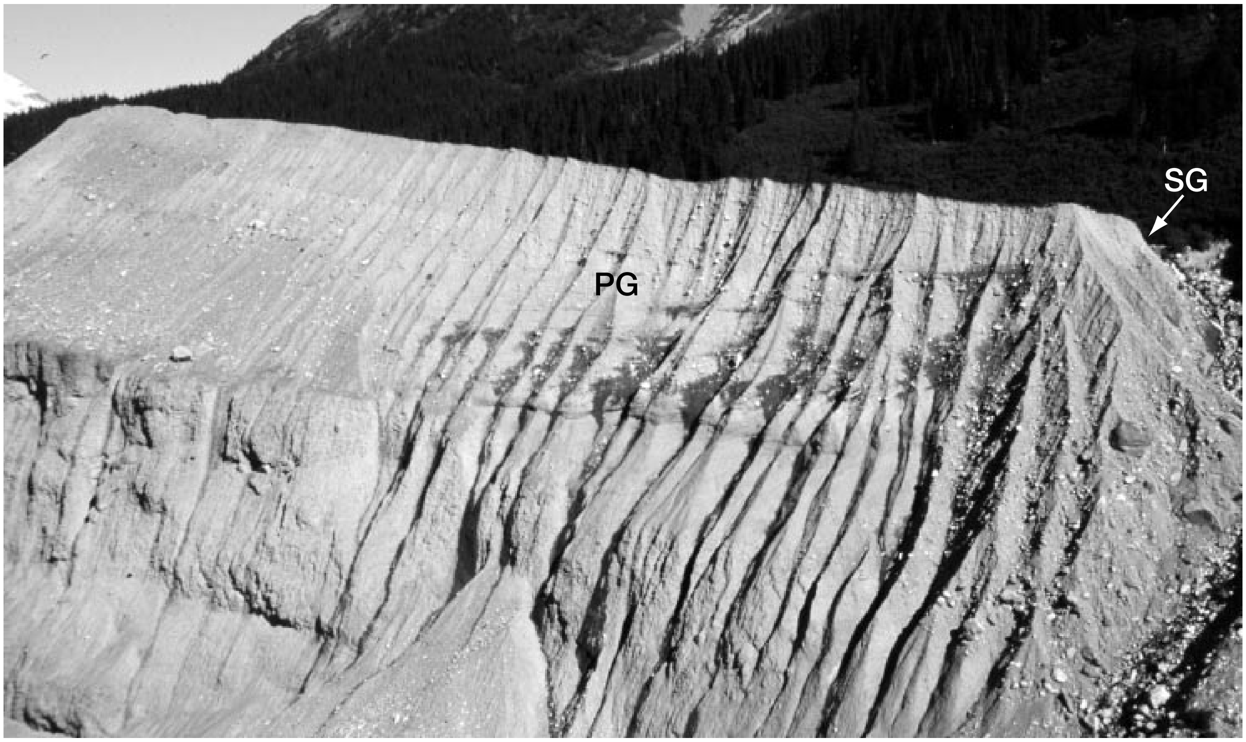
Fig. 2. Photograph looking northwest from the Mount Meager volcano massif to Lillooet Glacier, showing location of proximal gullies (Fig. 3). Photo taken in August 1932 by Mills Winram and reproduced with permission from Pat Winram, Victoria, British Columbia.

Fig. 3. Airphoto mosaic, showing Lillooet Glacier terminus and forefield in 1965 and localities mentioned in the text. Approximate ice limits in 1947, 1959, and 2002 are delineated by longer dashed lines. The 1947 and 1959 ice limits are from British Columbia airphoto BC478-17 and Hutchison (1961), respectively. Shorter dashed lines enclose extensive outcrops of jointed basalt. British Columbia airphotos BC5149-052, BC5149-053: Copyright© 2003 Province of British Columbia. All rights reserved. Reprinted with permission of the Province of British Columbia.



proximal side (Fig. 4). In contrast, the southwest lateral moraine is a small, discontinuous ridge perched on very steep granitic bedrock below icefalls (Fig. 3). The present surface of Lillooet Glacier is more than 200 m below these moraine crests, suggesting a prolonged period of negative mass balance since the culmination of local LIA activity. A subdued, forested, discontinuous moraine is locally present over a distance of about 3 km on the distal side of the prominent northeast LIA lateral moraine ridge (Walker 2003). A large cliff of jointed basalt rises ~100 m from the recently deglaciated forefield and forms a bench underlying the northeast lateral moraine (Fig. 3). Though undated, the basalt probably erupted beneath

Fig. 4. Proximal face of the northeast lateral moraine in the vicinity of south gully (SG) and proximal gullies (PG). Measured section at south gully is on the distal side of the moraine (not visible).



or against glacier ice during the late Pleistocene, based on the presence of fan-shaped jointing patterns (Mathews 1958; Hickson 2000).

The study area is located in the Engelmann Spruce – Subalpine Fir and Mountain Hemlock biogeoclimatic zones, which are characterized by long, cool, and wet winters and short, cool summers. The growing season is short due to thick, persistent winter snowpack. Arboreal vegetation at Lillooet Glacier is dominated by mixed stands of mountain hemlock (*Tsuga mertesiana*) and subalpine fir (*Abies lasiocarpa*). Disturbed sites near creeks and avalanche tracks support dense thickets of slide alder (*Alnus sinuata*).

The Coast Mountains are a substantial barrier to eastward penetration of maritime air masses into the British Columbia interior, and there is a strong west–east environmental gradient across the range. During winter, the Aleutian Low intensifies in the Gulf of Alaska, resulting in advection of moist air onto the coast. In summer, weakening of the Aleutian Low is accompanied by intensification of the Pacific High, which results in drier conditions in the region as storm tracks are diverted around the zone of high pressure.

Methods

Field investigations in fall 2001 and summer 2002 focussed on four sites along ~3 km of the northeast lateral moraine of Lillooet Glacier (Fig. 3). Three sites, informally named south gully (SG), middle gully (MG), and north gullies (NG), are continuous exposures through the proximal side of the lateral moraine. The gullies were eroded by streams flowing from the valley wall. The fourth site, proximal gullies (PG), is a series of shallow gullies incised into the proximal face of the lateral moraine above the basalt bench. All of these sections are steep and unstable, so investigations were necessarily brief to minimize exposure to rockfall, particularly at proximal gullies where the section could only be accessed by long rappels from the moraine crest and the rockfall hazard was acute.

At each site, moraine stratigraphy was logged using a barometric altimeter. We deviate from the standard practice of describing and numbering stratigraphic units from oldest to youngest because moraine crests were used as the datum at each measured section and because the uppermost (LIA) till was present at all sections, whereas the lowermost sediments are undated. Where organic horizons were found, we recorded their position and excavated laterally to determine their extent. These organic horizons are interpreted as remnants of soils developed on old moraine surfaces and are hereafter termed paleosols. We did not conduct detailed studies of the paleosols, but they are dark brown, organic-rich mineral horizons (Ah horizons) and (or) peat or plant litter horizons in various stages of decomposition. Sediment directly below these organic-rich layers is commonly oxidized, with colours ranging from orange to yellow and yellowish brown, and yellow (Munsell hues of 10YR and 5Y). Large wood macrofossils, including logs up to 50 cm diameter, are commonly associated with the paleosols. Paleosol bulk samples were collected and wet sieved for macroscopic wood and charcoal. Cross-sections were cut from 35 buried tree trunks and branches for radiocarbon dating and chrono-stratigraphic correlation of till units based on tree-ring cross-dating (A.V. Reyes, unpublished data, 2003). We did not date rootlets because of the potential for contamination by rootlets originating from younger surfaces. Roots are shown

Table 1. Radiocarbon ages, Lillooet Glacier.

^{14}C age (years BP)[a]	Cal. age range (cal years BP)[b]	Laboratory number[c]	Sample code[d]	Dated material[e]
South gully				
10±50	260–0	GSC-6600	CIA-01-18-1	Root from paleosol
170±60	300–0	GSC-6602	CIA-01-18-4	Root from paleosol
290±60	500–0	TO-9753	CIA-01-18-3	Root or branch from paleosol
Proximal gullies				
470±50	620–330	GSC-6769	AVR-02-43-3	Log (*Abies* sp.) in till (outer 25 rings)
1390±50	1410–1180	GSC-6760	AVR-02-43-8	Log (*Abies* sp.) on paleosol (outer 15 rings)
1527±41	1520–1330	Wk-12310	AVR-02-43-6	Twig from paleosol
2490±60	2740–2360	GSC-6756	AVR-02-51-1	Log (*Tsuga* sp.) in till (outer 10 rings)
2960±60	3320–2950	GSC-6746	AVR-02-52-2	Log (*Abies* sp.) on paleosol (outer 10–15 rings)
3034±42	3360–3080	Wk-12311	AVR-02-52-1	Wood fragment from paleosol (upper 2 cm)
Middle gully				
440±60	620–320	GSC-6604	CIA-01-21-2	Log on paleosol (outer 5 rings)
1090±50	1170– 930	GSC-6606	CIA-01-21-3	Branch on peat (outer 10 rings)
1600±70	1690–1330	TO-9754	CIA-01-21-1	Branch from top of paleosol (outer 5 rings)
1720±42	1710–1530	Wk-12306	CIA-01-21-7	Charcoal from paleosol (upper 3 cm)
2443±40	2710–2350	Wk-12307	CIA-01-21-8	Wood fragment from paleosol (lower 3 cm)
North gullies				
890±40	920–710	Beta-180885	LG-24-2	Wood fragment from paleosol (upper 3 cm)
1093±45	1170–930	Wk-12308	AVR-02-41-3	Wood fragment from paleosol (upper 3 cm)
1549±45	1530–1330	Wk-12309	AVR-02-42-2	Wood fragment from paleosol (upper 1 cm)
1700±80	1820–1420	GSC-6767	AVR-02-42-6	Log (*Abies* sp.) on paleosol (outer 20 rings)
2086±49	2300–1900	Wk-12313	LG-24-1	Charcoal from paleosol (upper 3 cm)

Note: Cal., calibrated.

[a]Error terms are 1σ for Beta, TO, and Wk ages and 2σ for GSC ages. GSC, TO, and WK ages are normalized to $\delta^{13}C$ = –25.0‰ PDB (Peedee Belemnite). Beta, TO, and Wk laboratories use the AMS technique. GSC uses a proportional gas counter.

[b]Reference datum is A.D. 1950. Determined from the decadal data of Stuiver et al. (1998) using the probability distribution method within the program CALIB 4.4 (Stuiver and Reimer 1993). Age ranges are ±2σ calculated with an error multiplier of 1.0.

[c]Beta, Beta Analytic, Miami, Florida, USA; GSC, Geological Survey of Canada, Ottawa, Canada; TO, IsoTrace Laboratory, University of Toronto, Toronto, Ontario; Wk, University of Waikato, Hamilton, New Zealand.

[d]Collector: AVR, A.V. Reyes; CIA, J.J. Clague; LG, L.A. Walker.

[e]Wood identification by R.J. Mott.

in this paper as in situ only if the rooting horizon was clearly truncated by overlying sediments.

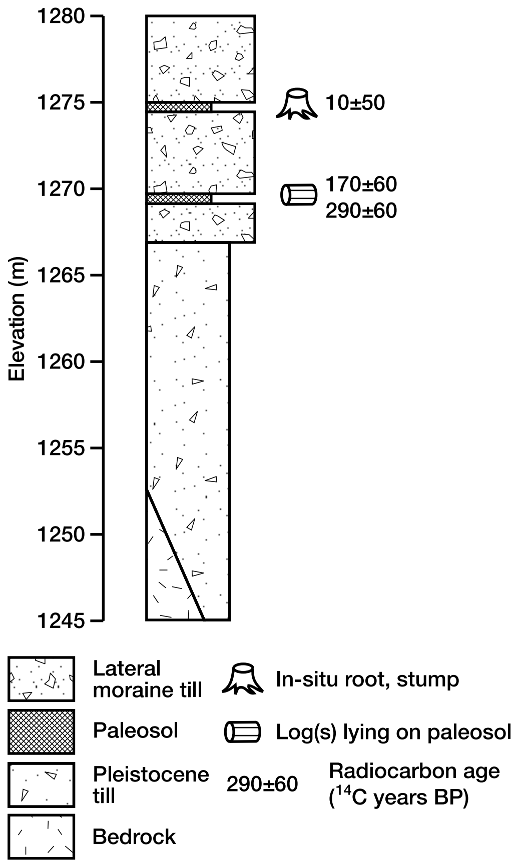
Interpretation of radiocarbon ages for moraine sediments requires consideration of the provenance and stratigraphic position of the dated material (Röthlisberger et al. 1980; Osborn 1986; Ryder and Thomson 1986). Radiocarbon analysis of bulk soil samples is problematic (e.g., Matthews 1980; Geyh et al. 1985), thus we only dated fragments of wood and charcoal from paleosols using the accelerator mass spectrometry (AMS) radiocarbon method. The resulting ages are interpreted as maximum ages for deposition of overlying tills, i.e., the overlying till is no older than the dated sample. Laterally continuous accumulations of large logs lying directly on a paleosol are interpreted as being in near-growth position, and thus radiocarbon ages of samples collected from such layers are direct dates for the glacier advance that deposited the overlying till. It is possible that wood lying on a paleosol may have been transported from upslope, for example by snow avalanches, in which case the dated sample would provide only a maximum age for the overlying till. We address this possibility and other interpretative concerns in our discussion of specific sites. Ages from logs not in contact with paleosols are regarded as maximum ages for the surrounding till, although ages from well-preserved samples, especially those with bark, may be close maxima or direct dates. Dated samples from buried tree stems were collected from the outermost 5–25 annual rings of the stems. Additional details concerning radiocarbon ages are presented in Table 1.

Lateral moraine stratigraphy and radiocarbon ages

South gully

A large creek has cut through the northeast lateral moraine about 4.5 km up-glacier from the LIA terminal moraine (Fig. 3), exposing till and two woody layers that record fluctuations of the glacier margin during LIA time (Fig. 5). About 5 m of light grey till with abundant large boulders overlie the upper layer of woody debris, which contains in situ roots. Another 5 m of similar till, of which the uppermost 1.5 m is locally oxidized and contains lenses of lami-

Fig. 5. Stratigraphy of sediments exposed at south gully. Thickness of paleosols is not to scale.



nated sand, separates the upper and lower woody layers. The lower woody layer rests on 2 m of oxidized bouldery till, which in turn overlies, perhaps unconformably, >20 m of dense, silty, dark gray, pervasively sheared diamicton draping a steeply sloping granitic bedrock surface. Clast content (~10%) and lithology (primarily basalt) distinguish the dark gray till from the overlying, more bouldery tills of the moraine. The bouldery tills contain 30%–40% stones of dominantly granitic composition.

Samples recovered from the woody layers yielded radiocarbon ages of 10 ± 50, 170 ± 60 and 290 ± 60 ^{14}C years BP (Fig. 5; GSC-6600, GSC-6602, and TO-9753, respectively). Calibration of the radiocarbon ages yields overlapping ages ranging from A.D. 1690 to 1950, thus the south gully exposure provides little insight into the LIA chronology of Lillooet Glacier. However, it does suggest that the lateral margin of Lillooet Glacier fluctuated enough during the LIA to allow colonization of the moraine by shrubs and perhaps small trees during periods of lesser ice extent. This inference is further supported by the multi-crested nature of the LIA lateral moraine directly downvalley of the section. We associate the basal gray, silty diamict with late Wisconsinan glaciation because it is lithologically and sedimentologically dissimilar to the Holocene morainal tills and because a probable correlative till occurs on slopes outside the Holocene glacial limit.

Proximal gullies

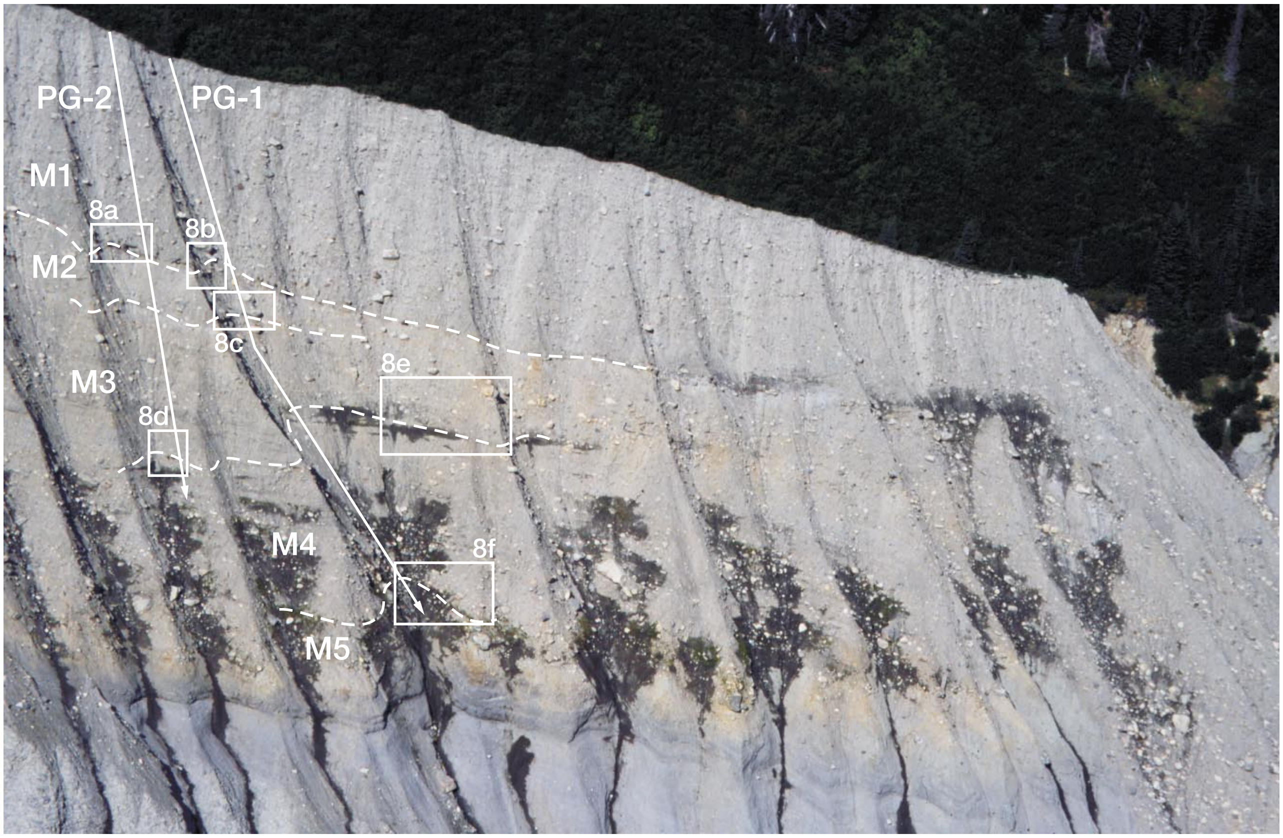
The LIA lateral moraine is steep and very sharp-crested upvalley of south gully. Slopes on the proximal and distal sides of the moraine average 50° and 35°, respectively, and gullies incised into the proximal face have an average slope of ~45°. Distal slope length from moraine crest to valley side is about 70 m, corresponding to a height difference of ~40 m, so it is unlikely that wood on paleosols exposed in the proximal moraine face was remobilized from higher on the valley slope. Near south gully, the proximal moraine face rises very steeply from the edge of the basalt cliff, and gullies extend from the moraine crest to its base (Fig. 4). In several of the gullies, contacts between till units are highlighted by laterally continuous layers of woody debris that extend across gullies onto the open face of the moraine. The upper portion of the proximal face in this area is very steep (70°–80°) and the basalt cliff at the base of the moraine prevents access from below, thus two adjacent gullies were investigated by rappelling down a rope anchored to trees at the base of the moraine's distal slope.

The two measured sections, PG-1 and PG-2 (Fig. 6), have nearly identical stratigraphy (Fig. 7). Till below the moraine crest is light gray and rich in granitic clasts (30%–40%) up to 4 m in diameter. About 30 m below the moraine crest, this till (M1) overlies a prominent paleosol and woody layer (P1; Fig. 8*a*) that is traceable across both gullies and can be traced visually downvalley for several tens of metres. The paleosol, which includes a dark brown Ah or humified organic horizon, is up to 20 cm thick and dips downvalley. Small, in situ roots are common in the paleosol, and several large tree stems up to 50 cm in diameter lie directly on, and up to 1 m above, the paleosol. One of these, a ~15 cm diameter *Abies* log with bark preserved on its lower side (Fig. 8*b*), yielded a radiocarbon age of 470 ± 50 ^{14}C years BP (GSC-6769). The stem was enclosed in till 30 cm above P1. Its excellent preservation, association with the prominent wood layer, and presence of bark suggest that its age provides a direct date for deposition of the overlying till, rather than a maximum age, which would be the case if the log had been swept onto the glacier by an avalanche and subsequently redeposited in the moraine.

Unit M1 is underlain by about 6 m of till (M2), which is similar to M1 but contains lenses of oxidized, stratified medium to coarse sand. M2, in turn, sharply overlies another laterally continuous paleosol (P2) with small, in situ roots and abundant large woody debris (Fig. 8*c*). P2 is less continuous than P1, but can nevertheless be traced across the two gullies. It has little apparent dip and was observed to intersect the more steeply dipping, upper woody horizon farther downvalley. P2 occurs mainly on till, although locally it is developed on well-sorted medium to coarse sand up to 70 cm thick. A small twig recovered from P2 gave a radiocarbon age of 1527 ± 41 ^{14}C years BP (Wk-12310), which is a maximum age for the overlying till (M2). Deposition of M2 is further constrained by an age of 1390 ± 50 ^{14}C years BP (GSC-6760) from a 30-cm-diameter *Abies* log lying directly on P2. The tree from which this log came was probably killed when it was buried by M2 or overridden by expanding ice. Two large logs lying on P2 had 80 and 100 annual rings, suggesting that the glacier was sufficiently retracted prior to deposition of M2 to allow over 100 years of tree growth on the moraine surface.

The next unit in the moraine sequence consists of about

Fig. 6. Locations of measured sections at proximal gullies. M1–M5 are lithostratigraphic units described in the text and shown in Fig. 7. Dashed lines are paleosol–wood layers shown in Fig. 7. Boxes are locations of Figs. 8*a*–8*f*.



10 m of bouldery till (M3). This till overlies a discontinuous third paleosol and an associated layer of sparse woody debris. At PG-2, three large logs, one with preserved bark, were distributed in a sub-horizontal line across the steep gully wall (Fig. 8*d*). Limited excavations failed to locate a paleosol. A third log (*Tsuga*) with < 50 annual rings, entombed in till ~1.75 m above the sand, yielded a radiocarbon age of 2490 ± 60 ^{14}C years BP (GSC-6756). It was not possible to excavate the gully interfluve separating PG-1 and PG-2 at this level, but a projection of the woody layer at PG-2 correlates with a paleosol–wood horizon at PG-1. The paleosol (P3), a dark brown Ah horizon up to 7 cm thick, was excavated laterally over 3 m and traced across the broad gully as a sparse line of woody debris (Fig. 8*e*).

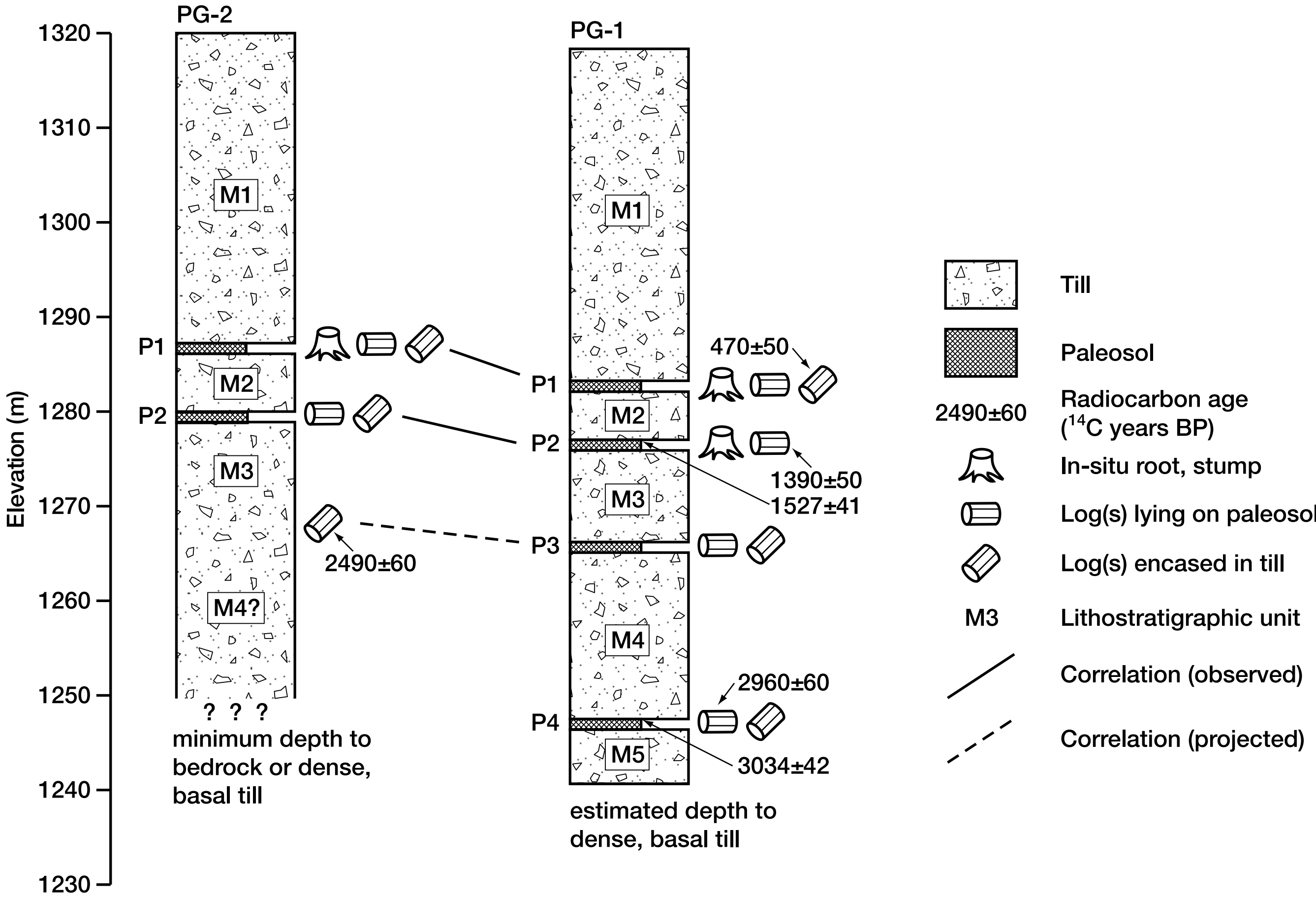
Investigations below M3 were aborted at PG-2 due to lack of rope. However, gentler slopes at PG-1 permitted access to a fourth paleosol–wood horizon over 65 m stratigraphically below the moraine crest (Fig. 8*f*). The paleosol (P4), which was traced across the entire downvalley side of the gully (>5 m horizontally), comprises a dark brown peat up to 10 cm thick. Small rip-up clasts of peaty material, likely derived from P4, are present in the overlying till, 2–3 cm above the contact. A radiocarbon age of 3034 ± 42 ^{14}C years BP (Wk-12311) on a small wood fragment recovered from P4 indicates that the overlying M4 till was deposited after about 3000 ^{14}C years BP. An age of 2960 ± 60 ^{14}C years BP (GSC-6746), obtained from an *Abies* log lying on P4, is likely a direct date for deposition of M4. A fifth gray, bouldery, granitic till (M5), < 5 m thick, separates P4 from what appears to be the same dense, gray basal till exposed at south gully. We were not able to directly inspect the dense, basal till at either PG-1 or PG-2. M5 was probably deposited during an earlier (pre ~3000 ^{14}C years BP) phase of alpine glacier expansion.

Middle gully

A large stream has incised through the lateral moraine to bedrock about 2.3 km up-glacier from south gully (Fig. 3), exposing a complete cross-section of the moraine (Fig. 9). As at south gully, the lateral moraine contains paleosols and wood that facilitate separation of till units. The upper till (M1) is light gray and contains ~30% clasts up to 2 m in diameter. About 15 m below the moraine crest, M1 overlies a discontinuous oxidized horizon (P1), which is probably a remnant of the B horizon of a paleosol. The oxidized horizon dips distally toward a swale between the distal slope of the moraine and the valley wall to the northeast and grades into a peat bed up to 40 cm thick, the lower half of which contains interbeds and laminae of silt and sand. An age of 1090 ± 50 ^{14}C years BP (GSC-6606) from a branch near the top of the peat provides a maximum age for M1. A large log buried in M1 directly above P1 gave an age of 440 ± 60 ^{14}C years BP (GSC-6604), suggesting that M1 was deposited at or after that time.

A distally thinning wedge of till similar to M1 (M2) separates P1 from a wood-bearing silty peat bed (P2) with sharp upper and lower contacts. The peat is dark brown, compact, up to 15 cm thick, and can be traced at least 10 m

Fig. 7. Stratigraphy of sediments exposed at proximal gullies. Paleosol thickness is not to scale.



laterally. Where the peat is thickest, the upper 5 cm are rich in bryophytes and the lower 10 cm have common pebbles and granules and abundant silt and sand laminae. Charcoal and a branch recovered from the uppermost 3 cm of P2 gave ages of 1720 ± 42 (Wk-12306) and 1600 ± 70 ^{14}C years BP (TO-9754), respectively. Thus, the advance that deposited M2 occurred at or after 1600 ^{14}C years BP and prior to about 1090 ^{14}C years BP, the age of the branch near the top of the upper peat sequence. A third till unit (M3), the uppermost 2 m of which are oxidized, underlies P2 and rests on steeply sloping bedrock. A wood fragment from the base of P2 yielded an age of 2443 ± 40 ^{14}C years BP (Wk-12307), suggesting that M3 was deposited before that time.

North gullies

Stream-cut gullies several hundred metres upvalley from middle gully provide excellent exposures through the moraine (Fig. 10A). Here, the crest of the LIA lateral moraine stands only 3–5 m above its distal swale. A smaller, topographically subdued moraine about 30 m outside the LIA limit ("outer moraine" of Walker 2003) impounds a small pond and bog on its distal side. Basal peat in the bog dates to ~6200 ^{14}C years BP (Walker 2003), thus the moraine is at least that old. A small stream draining the pond has cut a gully though the outer and LIA lateral moraines down to bedrock. The gully (NG-1) exposes till, stratified sand and gravel, and two paleosols in the LIA moraine (Fig. 10B). A light brown paleosol (P1) just below the moraine crest can be traced across gully interfluves into adjacent gullies. The paleosol has an apparent dip into the slope, suggesting that it developed on what was then the distal slope of the moraine. P1 defines a paleo-moraine crest near the interfluves on either side of the gully. P1 is sharply overlain by ~30 cm of crudely stratified sand and gravel that pinch out to the east. Light gray till (M1) with clasts up to 50 cm in diameter, in turn, overlies these sediments across a gradational contact and forms the crest of the LIA moraine.

A lower, wood-bearing paleosol (P2) is separated from the upper paleosol by up to ~10 m of gray till (M2) with 30%–40% clasts up to 1 m in diameter. Oxidized lenses of cobble gravel are present in the lowest 2 m of M2. This till and M3, which underlies the lower paleosol, rest on steeply sloping granitic bedrock that crops out as high as 2 m below the moraine crest. P2, which can be traced upvalley into an adjacent gully, contains abundant in situ roots. Several large logs with up to 104 annual rings lie directly on its upper contact. A wood fragment from P2 yielded an age of 1549 ± 45 ^{14}C years BP (Wk-12307), and the outer rings of an *Abies* log lying on the paleosol gave an age of 1700 ± 80 ^{14}C years BP (GSC-6767). The two ages are apparently inverted, but their calibrated ranges overlap at 2σ (Table 1). Collectively, the ages suggest that P2 was buried by M2 at or after about 1700–1550 ^{14}C years BP.

Sediments exposed in a gully directly downvalley of NG-1 (NG-2; Fig. 10C) provide additional insight into the age of the upper till at north gullies (see also Walker 2003). The

Fig. 8. Paleosols and wood horizons exposed at proximal gullies. See Fig. 6 for locations. (*a*) Uppermost paleosol (P1) at PG-2. Tree stem at far right (arrow) is ~50 cm in diameter. (*b*) Uppermost paleosol (P1) and sampled log at PG-1. (*c*) Second paleosol (P2) at PG-1 (arrows). (*d*) Lowest wood horizon at PG-2. Chainsaw (circled) is ~80 cm long. (*e*) Third paleosol (P3) at PG-1. Wood lying on paleosol is marked by arrows. (*f*) Lowest paleosol (P4) at PG-1. Arrow indicates sampled wood. Ice axe in (*b*), (*e*, circled), and (*f*, circled) is 70 cm long.

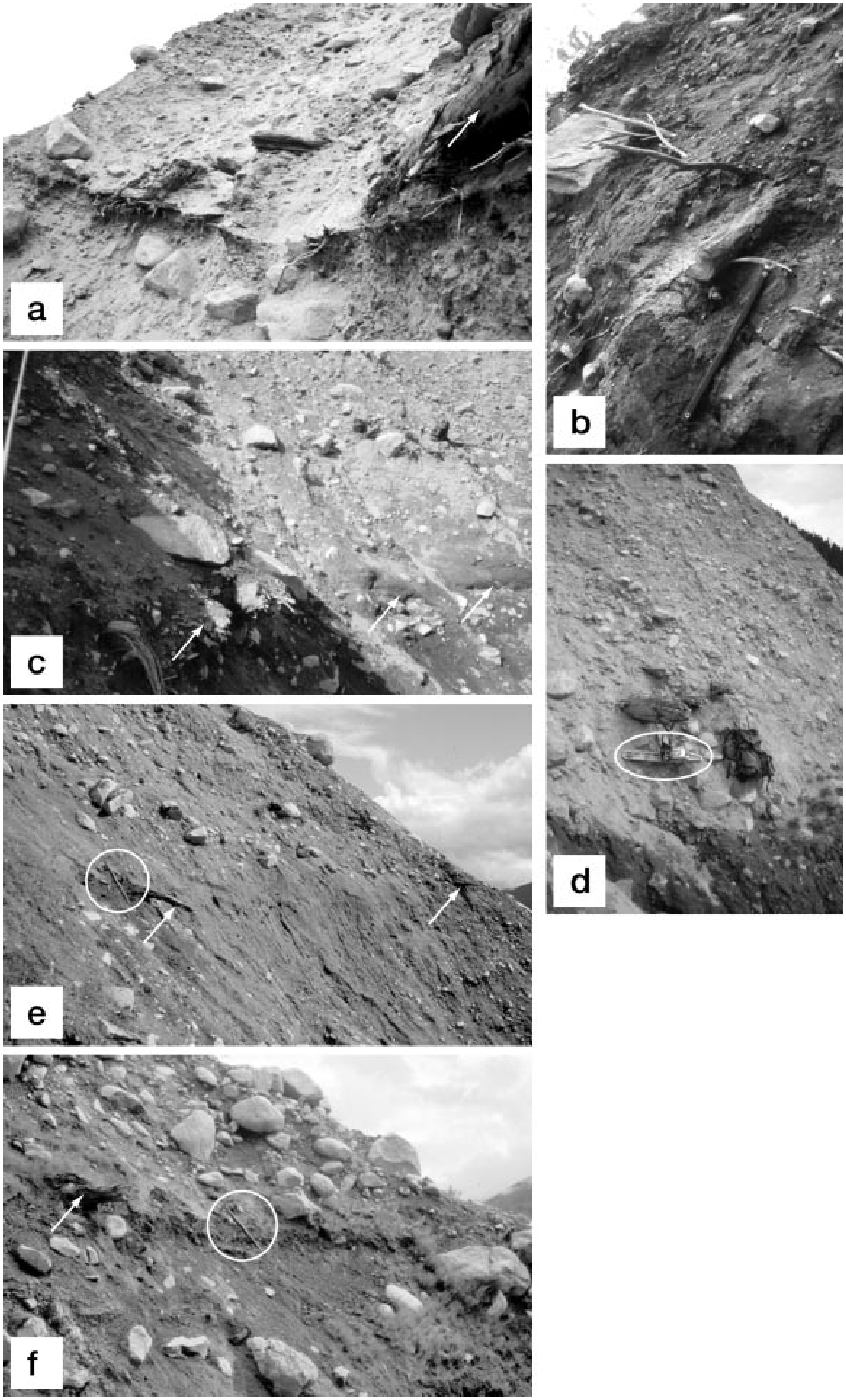
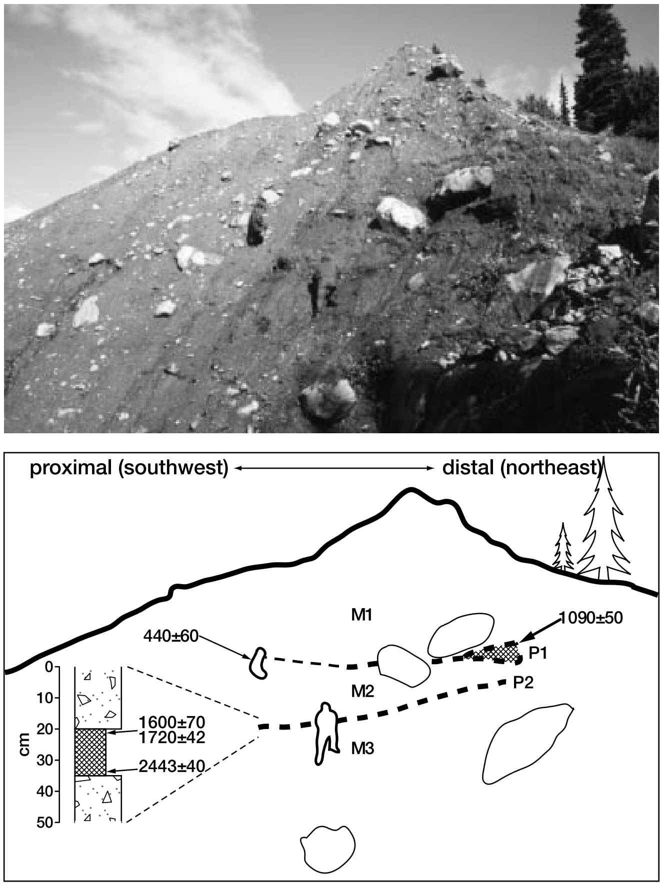


Fig. 9. (Top) Sediments exposed at middle gully; view upvalley. (Bottom) Thick dashed lines mark peat beds. The thin dashed line indicates an oxidized horizon. The upper paleosol drops about 1.5 m from the sampled log (outlined) to the distal edge of the peat. Stratigraphic symbols and units as in Fig. 7.



horseshoe-shaped gully cuts through a fragment of a very subdued, discontinuous lateral moraine (“middle moraine” of Walker 2003) that lies between the LIA and outer moraines. We excavated a 70-cm-thick peat bed (P1b) that lies beneath up to 125 cm of middle moraine till (M1b; Fig. 10C, section NG-2b) and traced it downvalley to a point ~2 m below the LIA moraine crest. A thinner (<2 cm), light brown paleosol (P1a) is developed on M1b. It defines a conspicuous paleo-moraine crest that drops to within ~40 cm of the lower paleosol, then rises to the surface near the proximal side of the middle moraine (Fig. 10C, section NG-2a). The upper, thin paleosol was tracked near the present moraine crest over several adjacent gullies and is correlative with P1 at NG-1 (Fig. 10A). At section NG-2a, the two paleosols are separated by sand and gravel that grade laterally into bouldery till (M1b). This till forms the paleo-moraine defined by P1a. A thin cap of bouldery till (M1a) forms the crest of the LIA moraine and, along with crudely stratified sand and gravel, fills the swale between the middle and LIA moraines.

Three radiocarbon ages from the peat at NG-2 constrain the age of the advance that deposited the middle moraine and hence unit M1b. A piece of charcoal from the top of the peat (P1b, section NG-2b) yielded an age of 2086 ± 49 ^{14}C years BP (Wk-12313). Two wood fragments from the same peat at section NG-2a gave ages of 890 ± 40 and 1093 ± 45 ^{14}C years BP (Beta-180885 and Wk-12308, respectively). P1b was overridden by ice that deposited M1b at or after 890 ± 40 ^{14}C years BP. We consider it unlikely that the peat accumulated over ~1100 years, as implied by the radiocarbon age on charcoal at section NG-2b (i.e., between ~2100 and 900 ^{14}C years BP), because a thick till was deposited during that time at NG-1 and at middle and proximal gullies. The old charcoal age may be due to secondary transport (Hallett et al. 2003) or the inbuilt age of wood charcoal (Gavin 2001). Unit M1a could not be dated because no suitable material was found, but it was presumably deposited during the most recent LIA advance because it forms the present crest of the lateral moraine.

Synthesis and regional correlation

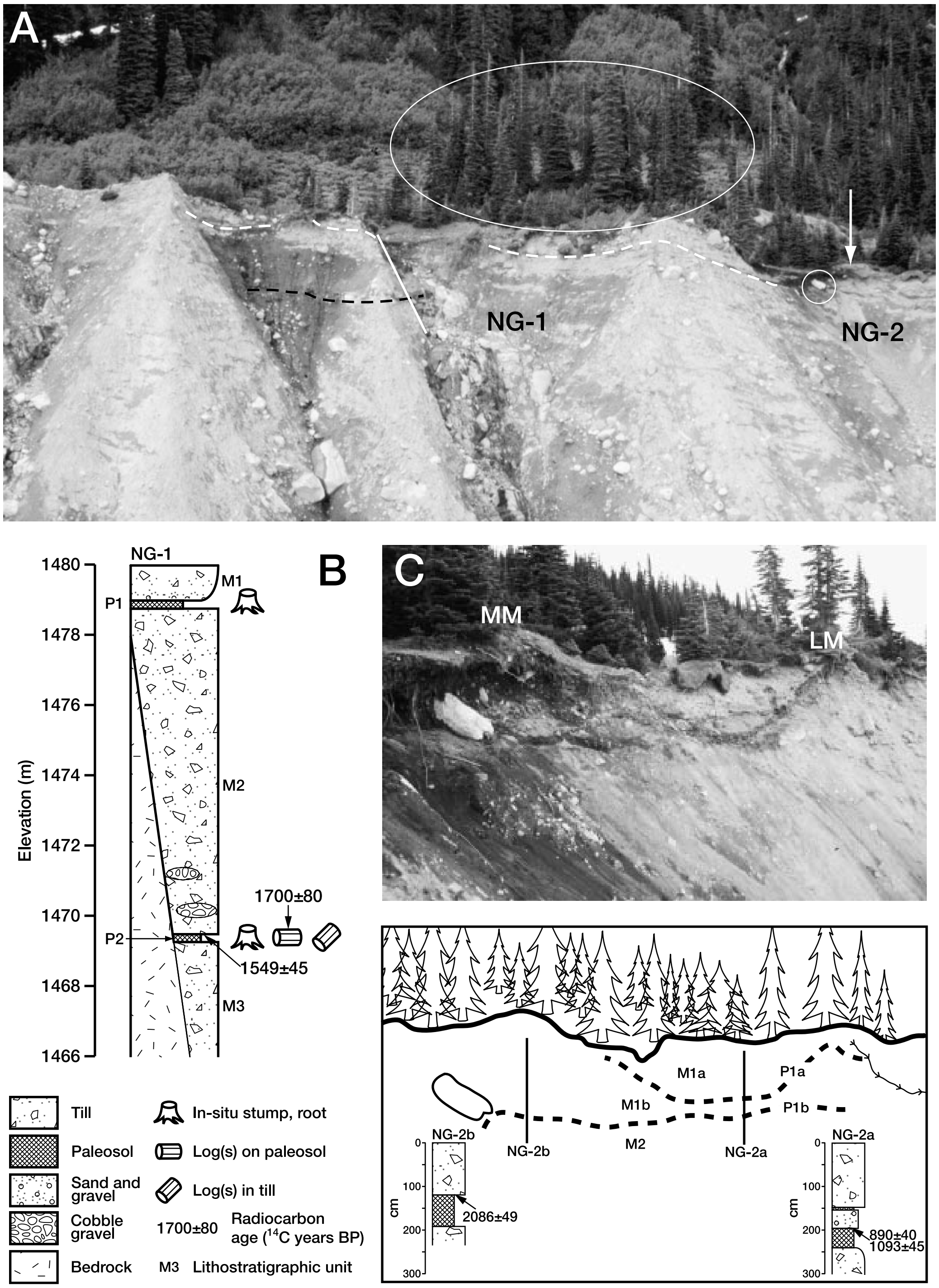
Stratigraphy and radiocarbon ages at the four study sites provide a detailed chronology of Lillooet Glacier advances during the late Holocene (Fig. 11). The oldest morainal till (M5), exposed at the base of proximal gullies, is at least 3000 ^{14}C years old. Two younger tills at proximal gullies (M4 and M3) were deposited ~3000 ^{14}C years BP and at or after ~2500 ^{14}C years BP, respectively. A pre-LIA advance deposited M2 at all sites except south gully. At north and middle gullies, M2 buried paleosols and forest vegetation ~1700–1550 ^{14}C years BP. Farther downvalley, ages from a buried paleosol and forest layer suggest that M2 was deposited slightly later, ~1400 ^{14}C years BP. Advances during the LIA are constrained by radiocarbon ages on woody material at the base of M1 at proximal and middle gullies. The earliest LIA advances were well underway by ~450 ^{14}C years BP, and there is evidence for later fluctuations at south gully.

Latest Pleistocene or early Holocene advance

The time of the advance that deposited M5, the oldest morainal till at Lillooet Glacier, is poorly constrained. It may be associated with the regional Garibaldi phase of glacier expansion, between about 6000 and 5000 ^{14}C years BP, when several glaciers in the southern Coast Mountains are known to have advanced over forested valley floors and nunataks (Ryder and Thomson 1986; Koch et al. 2003*b*; Smith 2003). One or more advances of this age are also recognized in interior and coastal Alaska (Calkin 1988). Alternatively, M5 may be associated with a glacier advance during the “8200-year cold event” (Alley et al. 1997). However, we consider this possibility unlikely because glacier termini during this period were probably severely retracted due to regional warm and dry conditions (e.g., Clague and Mathewes 1989; Hallett et al. 2003), and because the cold event is thought to have been very short-lived (Baldini et al. 2002). Menounos et al. (2004) suggest that several glaciers in the southern Coast Mountains advanced during the 8200-year cold event, but the inferred magnitude of the advance is much less than those described here for Lillooet Glacier.

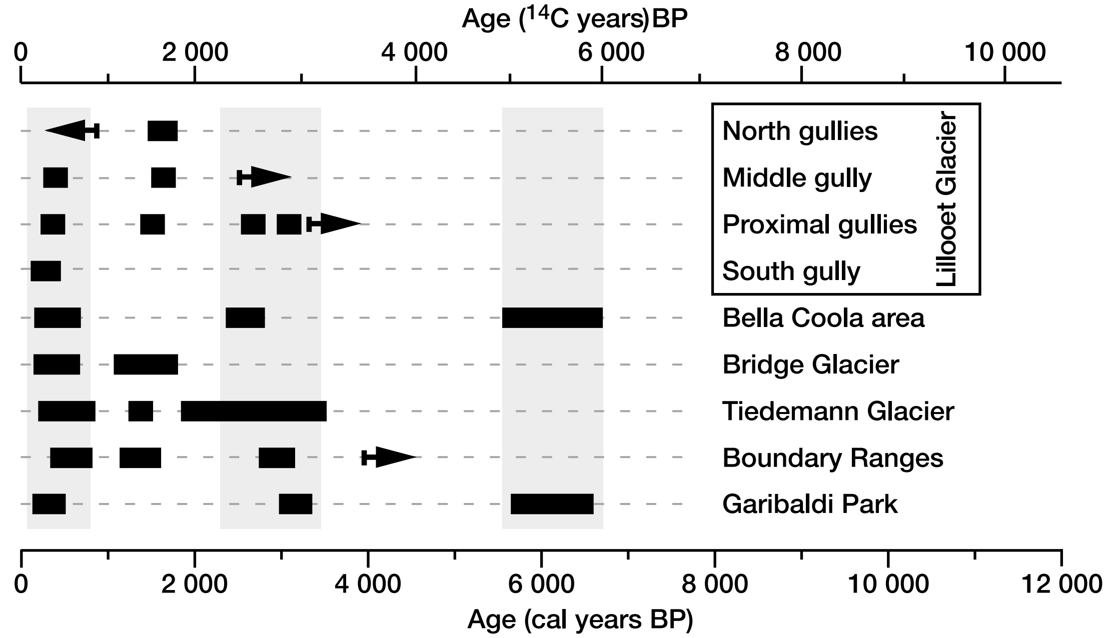
M5 could also be associated with a latest Pleistocene glacier advance, possibly during the Younger Dryas chronozone. A large valley glacier near Squamish, in the southern Coast Mountains, readvanced shortly after 10 650 ^{14}C years BP (Friele and Clague 2002). Evidence for a possibly correla-

Fig. 10. Proximal face of the lateral moraine at north gullies. (A) The outer and middle moraines are marked by a prominent stand of subalpine fir (ellipse) and a white arrow, respectively. The white line marks the location of the measured section at NG-1. The position of P2 at NG-1 and an adjacent gully is indicated by a black dashed line. Dashed white line delineates the excavated extent of the upper paleosol at north gullies. (B) Stratigraphy of sediments exposed at NG-1. Paleosol thickness is not to scale. (C) (Top) Sediments exposed at NG-2. MM, middle moraine; LM, LIA moraine. (Bottom) Dashed lines mark locations of excavated paleosols. Arrowed line at far right marks the ridge crest separating NG-2 from the adjacent downvalley gully. The white boulder at far left is circled in (A).



tive advance in the Canadian Rockies, termed the Crowfoot advance, is preserved in terminal moraines overlain by Mazama ash (Luckman and Osborn 1979), composite lateral moraines (Osborn et al. 2001), and downvalley lake sediments (Reasoner et al. 1994). We prefer the latter, latest Pleistocene interpretation for the age of M5 for several reasons. The outermost moraine at north gullies is older than ~6200 ^{14}C years BP, based on basal radiocarbon ages from a pond impounded by the moraine (Walker 2003). It is probably much older than 6200 ^{14}C years BP, because peat would not

Fig. 11. Summary chronology of dated Holocene advances at selected sites in the Coast Mountains. Horizontal bars represent dated periods of glacier advance. Left and right arrows represent, respectively, maximum and minimum ages for glacier advances. Vertical shaded bars mark established periods of glacier advance in the Coast Mountains. Sources of glacier data: Lillooet Glacier (this study); Bella Coola area (Desloges and Ryder 1990; Smith and Desloges 2000; Smith 2003; D.J. Smith, personal communication, 2003); Bridge Glacier (Ryder and Thomson 1986; Ryder 1991; Allen and Smith 2003); Tiedemann Glacier (Ryder and Thomson 1986; Larocque and Smith 2003); Boundary Ranges (Clague and Mathews 1992; Clague and Mathewes 1996; Laxton and Smith 2004); Garibaldi Park (Ryder and Thomson 1986; Koch et al. 2003*a*, 2003*b*).



likely have accumulated at the site of the pond under the warm, dry conditions of the early Holocene. The glacier advance that built the outer moraine was of comparable extent to the climactic LIA advance, so it almost certainly would have deposited till in the vicinity of proximal gullies, where M5 is exposed. Since M5 is the only bouldery till unit between the fourth paleosol (P4) and the compact, sheared, silty gray till that we associate with late Wisconsinan glaciation, it probably correlates with the outer moraine. Thus, M5 is older than ~6200 ^{14}C years BP and probably predates the early Holocene xerothermic period.

Middle Neoglacial advances

The advances that deposited M4 (~3000 ^{14}C years BP) and M3 (at or after ~2500 ^{14}C years BP) are correlative to previously recognized periods of Neoglacial glacier expansion in the Canadian Cordillera. Ryder and Thomson (1986) defined the Tiedemann Advance in the southern Coast Mountains and placed it at 3300–1900 ^{14}C years BP on the basis of radiocarbon-dated moraine exposures at Tiedemann and Gilbert glaciers. The advance is thought to have culminated about 2300 ^{14}C years BP. Similar ages have been obtained on glacially overridden wood near Whistler, north of Vancouver (Koch et al. 2003*b*). Farther north in the Coast Mountains, alpine glaciers were advancing around this time near Bella Coola (Desloges and Ryder 1990) and in the Boundary Ranges near Stewart (Clague and Mathews 1992; Clague and Mathewes 1996; Laxton and Smith 2004). A similar phase of glacier expansion, termed the Peyto Advance (Luckman et al. 1993), is well documented in the Canadian Rocky Mountains (e.g., Osborn et al. 2001; Wood and Smith 2004; Luckman in press). Non-surging glaciers were also advancing during this interval in the St. Elias Mountains (Denton and Karlén 1977).

These regional records are broadly synchronous, but individual glacier chronologies are less so. The diachronous nature of glacial deposits and the distribution of datable material at any one site complicate inter-glacier comparison, as does the variable quality of dating control. Our results suggest that the Tiedemann Advance at Lillooet Glacier encompassed at least two periods of ice advance, separated by a short interval when the glacier was sufficiently retracted that at least part of the moraine surface was colonized by vegetation. The vegetated moraine surface was overridden during the later Tiedemann advance. Ring counts of large logs in M3 suggest that at least 145 years elapsed between deposition of M4 and subsequent burial by M3 at or after ~2500 ^{14}C years BP. This is a minimum estimate only, as it does not consider time for moraine stabilization and vegetation colonization.

Post-Tiedemann, pre-Little Ice Age advance

An advance subsequent to the Tiedemann Advance, but prior to the onset of LIA activity, is recorded by diachronous deposition of M2 at proximal, middle, and north gullies. Counts of annual rings in logs recovered from the base of M2 suggest that recession of Lillooet Glacier, following its Tiedemann-age advances, was sufficient to allow at least 100 years of tree growth on a stabilized moraine surface. The advance was underway by ~1700–1550 ^{14}C years BP and culminated at or after ~1400 ^{14}C years BP. This event is well documented in Alaska, where advances occurred about 1500 ^{14}C years BP at Tebenkof Glacier (Wiles et al. 1999), in the southern Kenai Mountains (Wiles and Calkin 1994), in the Wrangell Mountains (Wiles et al. 2002), and in coastal Alaska (Calkin 1988; Calkin et al. 2001). Some glaciers in the Canadian Rockies may have advanced at this time, based on radiocarbon-dated detrital and in situ wood at one site (Luckman in press).

Evidence for a glacier advance at this time is sparse in the Coast Mountains. Ryder and Thomson (1986) suggested that recession of Tiedemann Glacier from its maximum Neoglacial position was slow and pulsatory until at least ~1300 ^{14}C years BP, based on limited stratigraphic and morainal evidence. Lichenometric evidence suggests that moraines stabilized at the same site at about this time (Larocque and Smith 2003). Glaciers in the Duffey Lake watershed, on the leeward side of the southern Coast Mountains, are thought to have expanded ~1500 ^{14}C years BP, based on increases in mineral sediment flux recorded in lake sediment cores (Menounos 2002). In the northern Coast Mountains, Frank Mackie Glacier was advancing at 1600 ^{14}C years BP (Clague and Mathews 1992). Ongoing research at Bridge Glacier, 20 km northeast of Lillooet Glacier, suggests that a forest was overridden by the glacier ~1500 ^{14}C years BP (Allen and Smith 2003).

Little Ice Age advances

Advances during the LIA deposited M1 at all four sites. The forest bed buried by M1 is particularly well exposed at proximal gullies, and counts of annual rings from large logs indicate over 173 years of forest growth on the stabilized moraine deposited during the earlier, pre-LIA advance. Our investigations, however, provide only limited insight into LIA fluctuations of Lillooet Glacier because of substantial overlap in the calibrated (cal) age ranges of radiocarbon-dated wood samples, particularly at south gully (Table 1). Although we are unable to date the first LIA advance of Lillooet Glacier, the advance that deposited M1 at middle and proximal gullies was well underway by ~450 ^{14}C years BP (1330–1630 AD). Ryder and Thomson (1986), Ryder (1987), Desloges and Ryder (1990), and Larocque and Smith (2003) report radiocarbon ages on in situ, glacially overridden wood material at other sites in the Coast Mountains that suggest LIA expansion occurred at about the same time as, or up to several centuries earlier than, deposition of M1 at Lillooet Glacier. More precise records of regional LIA glacier activity have been obtained using lichenometry and tree-ring dating of overridden and detrital wood (Smith and Laroque 1996; Smith and Desloges 2000; Koch et al. 2003*b*; Larocque and Smith 2003; Lewis and Smith 2004).

Late Holocene climate variability

The broad similarity of our Lillooet Glacier chronology to other records of glacier advance in the Coast Mountains suggests that a common climatic forcing mechanism may have led to periods of prolonged positive glacier mass balance. However, deconvolution of the climatic controls on past glacier advances is complicated (Bradley 1999). Paleoecological investigations are sources of additional paleoclimatic insight that complement chronologies of glacier advance.

Paleoecological proxy data indicate that warm, dry conditions during the early Holocene (~9500–7000 cal years BP) were gradually replaced by a warm, moist climate regime, which, in turn, gave way to cool, moist conditions characteristic of modern climate about 4000–3000 cal years BP (e.g., Hebda 1995; Walker and Pellatt 2004). Many authors have noted the apparent link between this climatic deterioration and the regional onset of Neoglaciation, but they have been unable to resolve specific periods of glacier advance from their paleoecological data. This is probably due in part to the large ecological range of the regional flora, which would dampen the response of vegetation to high-frequency climate change (Whitlock and Grigg 1999). Site selection is likely an additional factor. Results from two recent palynological investigations of ponds directly outside Neoglacial moraines in the Coast Mountains suggest that rapid increases in *Alnus* pollen are associated with independently dated Tiedemann-aged glacier advances nearby (Walker 2003; T.A. Arsenault, personal communication, 2003).

Fire frequency reconstructions based on high-resolution charcoal data potentially offer more detailed records of climate variability. Whereas many paleoecological reconstructions provide little or no evidence for marked climatic fluctuations since ~4000–3000 cal years BP, fire frequency data from the southern Coast Mountains exhibit sub-millennial variability that is broadly synchronous with Tiedemann-age and LIA glacier advances (Hallett et al. 2003). The glacier and fire frequency records, however, are in slight disagreement between ~1900 and 1300 cal years BP. Well-dated glacier advances occurred at this time at Bridge and Lillooet glaciers, and possibly in the Boundary Ranges, but Hallett et al. (2003) suggest that this period was characterized by drought and dry fuel conditions, perhaps due to strengthening of the Pacific High. The occurrence of glacier advances during a period that was probably dominated by conditions leading to enhanced loss of glacier mass during the ablation season may reflect the importance of winter climate, in particular precipitation, for producing positive net mass balance and hence glacier advance.

Conclusions

Paleosols and layers of woody debris exposed in the northeast lateral moraine of Lillooet Glacier provide a detailed chronology of late Holocene advances of the glacier. Four periods of glacier advance are recognized in the moraine stratigraphy: (1) an advance prior to ~3000 ^{14}C years BP, and probably before 6200 ^{14}C years BP; (2) two advances at ~3000 and ~2500 ^{14}C years BP, corresponding to the regional Tiedemann Advance; (3) an advance between ~1700 and 1400 ^{14}C years BP that buried paleosols and forest vegetation at almost all of the study sites; and (5) several advances during the Little Ice Age, after 470 ^{14}C years BP. The record presented here is in broad agreement with, and improves the resolution of, existing glacier chronologies in the Coast Mountains. In particular, we present the first direct evidence for a glacier advance in the Coast Mountains after the Tiedemann Advance and before regional LIA glacier expansion. Detailed paleoclimatic interpretation of the glacier record is difficult, but comparison with paleoecological data, particularly fire frequency reconstructions, suggests that increases in winter precipitation may have played an important role in contributing to lengthy periods of positive net mass balance and thus glacier advance. Stratigraphic evidence for multiple glacier advances is exceptionally well preserved at Lillooet Glacier, and our results and earlier successes by other workers (e.g., Ryder and Thomson 1986; Osborn et al. 2001) highlight the importance of moraine stratigraphy in developing Holocene glacier chronologies. Future investigations of Holocene glaciation in the Coast Mountains, where composite moraines are relatively common, will likely benefit from detailed examination of moraine stratigraphy.

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