

Geomorphological Processes Associated with an Ice-Marginal Lake at Bridge Glacier, British Columbia

Processus géomorphologiques associés à la formation d'un lac juxta-glaciaire en marge du glacier Bridge, Colombie-Britannique

Geomorphologische Prozesse in Verbindung mit einem glazialen Randsee am Bridge-Gletscher, British Columbia

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Article abstract

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GEOMORPHOLOGICAL PROCESSES ASSOCIATED WITH AN ICE-MARGINAL LAKE AT BRIDGE GLACIER, BRITISH COLUMBIA

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ABSTRACT Four well-defined strandlines mark the former extent and drawdown phases of an ice-marginal lake that was impounded by Bridge Glacier during the Little Ice Age. ^{14}C dates, tree-ring counts and historic air photographs indicate that the lake stood at the highest strandline (L1) for about 550 years, and at the lower strandlines for only a few decades in total. Estimates of rates for geomorphic processes are based on absolute chronology, ground measurements and photogrammetry: benches along L1 may have been cut into bedrock and till at rates of about 3.6 and 7.3 cm yr^{-1} respectively; a spillway channel was incised into a lateral moraine at 2.2 m yr^{-1} , and mean bedload transport to a delta from a 6.25 km^2 ice-covered sub-basin was about 945 $\text{m}^3 \text{yr}^{-1}$. Major floods from the stable, rock-cut spillway of the highest lake, that may have been caused by temporary damming of the lake outlet by snowbanks or lake ice, constructed a large fan on the main Bridge Glacier outwash apron. The lower lakes probably drained catastrophically due to failure of moraine and ice dams, but the resulting floods were rapidly attenuated downstream.

RÉSUMÉ *Processus géomorphologiques associés à la formation d'un lac juxta-glaciaire en marge du glacier Bridge, Colombie-Britannique.* Quatre lignes de rivage bien définies montrent l'étendue d'un lac juxta-glaciaire retenu par le glacier Bridge pendant le Petit Âge glaciaire. Des datations au radiocarbone, des comptages de cernes annuels et l'analyse d'anciennes photos aériennes démontrent que le lac s'est maintenu au niveau correspondant à la plus haute ligne de rivage (L1) pendant environ 550 ans, et aux niveaux inférieurs pendant tout au plus quelques décennies. Les vitesses associées aux processus géomorphologiques sont fondées sur la chronologie absolue, les levés de terrain et la photogrammétrie. Les banquettes le long du rivage L1 ont peut-être été entaillées dans la roche et le till à des taux d'environ 3,6 et 7,3 cm a^{-1} respectivement; un chenal déversoir a incisé la moraine latérale à une vitesse de 2,2 m a^{-1} et le transport de la charge de fond provenant d'un sous-bassin englacé de 6,45 km^2 vers un delta s'est fait à une vitesse moyenne d'environ 945 $\text{m}^3 \text{a}^{-1}$. Des crues majeures débouchant du chenal déversoir associé au niveau lacustre supérieur ont construit un grand cône alluvial sur la principale plaine d'épandage fluvio-glaciaire. Ces crues ont probablement été causées par les engorgements temporaires de l'exutoire par des congères ou des embâcles. Les lacs des niveaux inférieurs se sont probablement vidangés de façon brutale en raison de la rupture des barrages morainiques ou glaciaires, mais les crues qui en ont résulté ont vite été atténuées en aval.

ZUSAMMENFASSUNG *Geomorphologische Prozesse in Verbindung mit einem glazialen Randsee am Bridge-Gletscher, British Columbia.* Vier klar abgegrenzte Uferlinien markieren die ehemalige Ausdehnung und die Rückzugsphasen eines glazialen Randsees, der während der Kleinen Eiszeit durch den Bridge-Gletscher eingesperrt war. ^{14}C -Daten, dendrochronologische Zählungen und historische Luftaufnahmen zeigen, dass der See ungefähr 550 Jahre lang die höchste Uferlinie einnahm (L1) und insgesamt nur einige Jahrzehnte lang die niedrigeren Uferlinien. Die Schätzungen der Geschwindigkeit der geomorphologischen Prozesse stützen sich auf die absolute Chronologie, Bodenabmessungen und Photogrammetrie: Leisten entlang L1 sind wahrscheinlich in anstehendes Gestein und Till mit einer Rate von etwa 3,6 bzw. 7,3 cm Jahr^{-1} eingeschnitten worden; ein Ablasskanal wurde in eine seitliche Moräne mit einer Geschwindigkeit von 2,2 m Jahr^{-1} eingeschnitten, und der durchschnittliche Transport der Sedimentfracht von einem 6,25 km^2 grossen eisbedeckten Unterbecken zu einem Delta war etwa 945 $\text{m}^3 \text{Jahr}^{-1}$. Grössere Hochfluten von dem festen in den Fels geschnittenen Ablasskanal des höchstgelegenen Sees, die möglicherweise durch vorübergehende Eindämmung des See-Ausflusses durch Schneeبانke oder Seeis bewirkt wurden, formten einen breiten Alluvialfächer auf der glazialen Hauptschwemmebene des Bridge-Gletschers. Die niedriger gelegenen Seen haben sich wahrscheinlich katastrophentartig geleert aufgrund des Zusammenbruchs von Moränen- und Eisdämmen, doch wurden die entstandenen Fluten stromabwärts schnell gemildert.

INTRODUCTION

The marginal zones of receding glaciers are one of the most active geomorphic environments. Lack of vegetation, abundant runoff from both precipitation and meltwater, variable stream discharge, readily available debris and a periglacial climate all promote rapid erosion and sediment transfer. Floods that result from failure of ice or moraine dams pose hazards to human activities. This paper is a case study of an ice-marginal lake that existed for several hundred years during the Little Ice Age. A chronology of the lake is developed and used to estimate rates of associated geomorphological processes and flood magnitudes.

The former ice-marginal lake was impounded by Bridge Glacier at 1500 m elevation in a sub-alpine valley on the eastern side of the Coast Mountains (Figs. 1 and 2). Inflow to the lake was largely glacier meltwater from a rugged, 15 km² basin. When water level was highest, the lake was about 2 km long and 0.4 km wide. In common with most other glaciers in this region, Bridge Glacier achieved its greatest Holocene extent

during Late Neoglacial time, *i.e.*, during the Little Ice Age; a general glacier expansion commenced before 900 ¹⁴C yr BP and terminal moraines date from the eighteenth and nineteenth centuries (Ryder and Thomson, 1986).

Field work at Bridge Glacier was carried out in 1977 and 1978 during regional terrain mapping. Time limitations restricted ground work to qualitative observations, sample collection, and an altimeter survey of strandline elevations. Elevations were recorded with respect to a local datum that was assigned a value of 4950 ft (1508 m) by interpolation from a 1:50 000 NTS map with a 100 ft contour interval. Surveyed altitudes are accurate to ± 1 m with respect to this datum, and are thus within ± 50 ft of their true geodetic values. Additional elevations and dimensions of the lake sub-basins were determined photogrammetrically; measurement errors are estimated at less than 10%. ¹⁴C dates were obtained from wood and peat; the calibration curve of Stuiver and Pearson (1986) was used to transform ¹⁴C dates < 700 yr BP to calendar years AD (Table II).

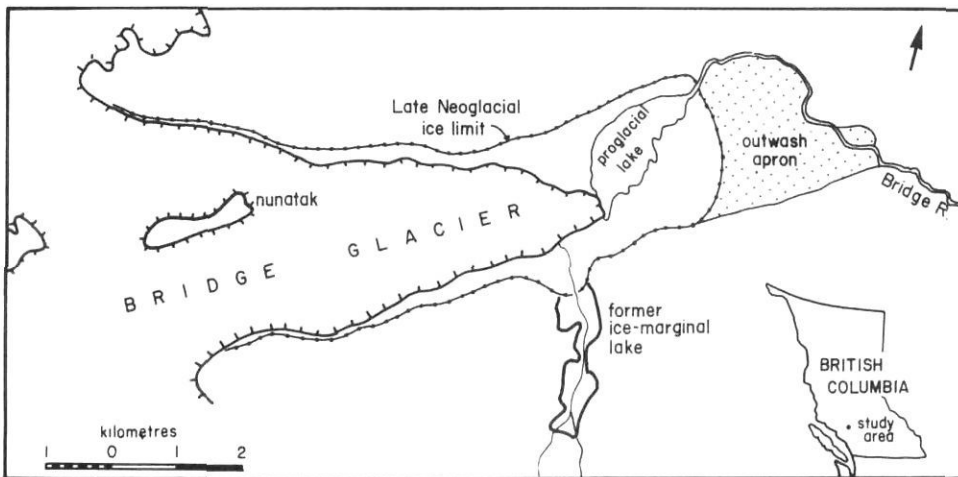


FIGURE 1. Location map for Bridge Glacier study area.

Localisation de la région à l'étude.



FIGURE 2. General view of the basin of the former ice-marginal lake (1977). BM = bevelled moraine; L1-L4 = strandlines; S = section in bevelled moraine (BL5).

Vue générale de l'ancien lac juxta-glaciaire (1977). BM = moraine tronquée; L1-L4 = lignes de rivage; S = coupe dans la moraine tronquée (BL5).

**ESTABLISHING A CHRONOLOGY FOR THE LAKE
END MORAINES AND OUTWASH**

The terminal moraine (A, Fig. 3) and recessional (B-E) moraines of Bridge Glacier are well defined ridges with first generation coniferous trees (Fig. 4a). Estimates of substrate age based on ring counts from the largest trees and adjusted for height of core and ecesis interval (Table I) suggest that Bridge Glacier had receded from the terminal moraine shortly before 1860 AD and from the first recessional moraine (B) about two decades later. Moraines C, D, and E were uncovered by ice during the early twentieth century (Table I).

A broad outwash apron that has formed since the late Neoglacial maximum extends 2.5 km beyond the terminal moraine (Figs. 3 and 5). Seven phases of outwash, distinguished by differing vegetation density, can be linked to former ice front positions by old channels. Phases 04, 05 and 06 relate to drainage from the ice-marginal lake and are discussed below. Phases 01, 02, and 03 were deposited by the main proglacial stream when the ice front stood in the vicinity of moraines B, C and D, and 07 is the modern channel zone. No parts of the extant outwash relate to moraine A, which is an erosional remnant of a formerly more extensive ridge.

THE BEVELLED MORAINE

A prominent, flat-topped lateral moraine was constructed by Bridge Glacier across the mouth of the tributary valley that contained the lake (Fig. 2). The modern stream has cut a steep-sided notch through the moraine, exposing several units of till and stratified drift (Figs. 6 and 7).

The uppermost stratigraphic unit (6), which constitutes the bulk of the ridge, is a loose, water-laid till (*cf.* Dreimanis, 1976) with plutonic clasts, deposited when Bridge Glacier impounded the late Neoglacial lake. The underlying sands and gravels (5), which dip in various directions, are delta foresets deposited during late Neoglacial ice advance. The mid-section till (4) is dis-

tinguished from the late Neoglacial till by its greater consolidation, finer texture, and a high proportion of volcanic clasts. It is capped by a truncated (no A horizons) palaeopodzol which contains abundant charcoal fragments. A similar and probably correlative palaeosol on lodgement till that underlies a single unit of lacustrine silt in middle basin (Sites BL3 and BL4, Figs. 7 and 8) contains charcoal dated at 6590 ± 135 ¹⁴C years BP (S-1464; Table II). These characteristics confirm the lack of evidence for any Holocene glacial expansion (or lake) prior to that of the Late Neoglacial, and indicate that the lower till in the bevelled moraine (unit 4) and the till in middle basin both date from Fraser (Late Wisconsinan) Glaciation.

STRANDLINE L1

The various water planes of the former lake are indicated by clearly-defined strandlines (L1-L4) at elevations of 1508, 1484-1482, 1474, and 1462 m respectively (Figs. 2 and 7). The highest strandline, L1, was formed when the glacier stood at or close to the bevelled moraine. It encircles the upper and middle basins and continues for about 200 m along the east side of the lower basin (Fig. 7). On till, the strandline is a gravelly bench, 5 to 40 m wide. Where Lake 1 abutted bedrock (Fig. 7), the strandline is a well-defined, rocky bench up to 20 m wide, and backed by cliffs (Fig. 4b). *In situ* bedrock is exposed over most of the bench, which has a rough, irregular surface. In places, protruding outcrops are sharp-edged and the adjacent bench is veneered by a pavement of angular rock fragments; elsewhere, the exposed rock is edge-rounded.

The flat top of the bevelled moraine is at the same elevation as the L1 strandline, indicating that bevelling was accomplished by lacustrine processes. The bevelled surface is a pavement of bouldery gravel with patches of sand. Some boulders rest upon the pavement, whereas others are partially buried (Fig. 4c). Clast roundness and sizes are similar to those of clasts elsewhere on local moraines, suggesting that frost shattering was not a significant levelling process. Probably, bevelling was accomplished by scour and shove of floating lake-ice

FIGURE 3. Outwash apron and end moraines of Bridge Glacier. Map is uncorrected from British Columbia Government air photographs BC 7788: 147-149 and 177-179 (1975).

Plaine d'épandage fluvio-glaciaire et moraines frontales du glacier Bridge. Carte non corrigée établie à partir des photos aériennes du gouvernement de la Colombie-Britannique BC 7788: 147-149 et 177-179 (1975).

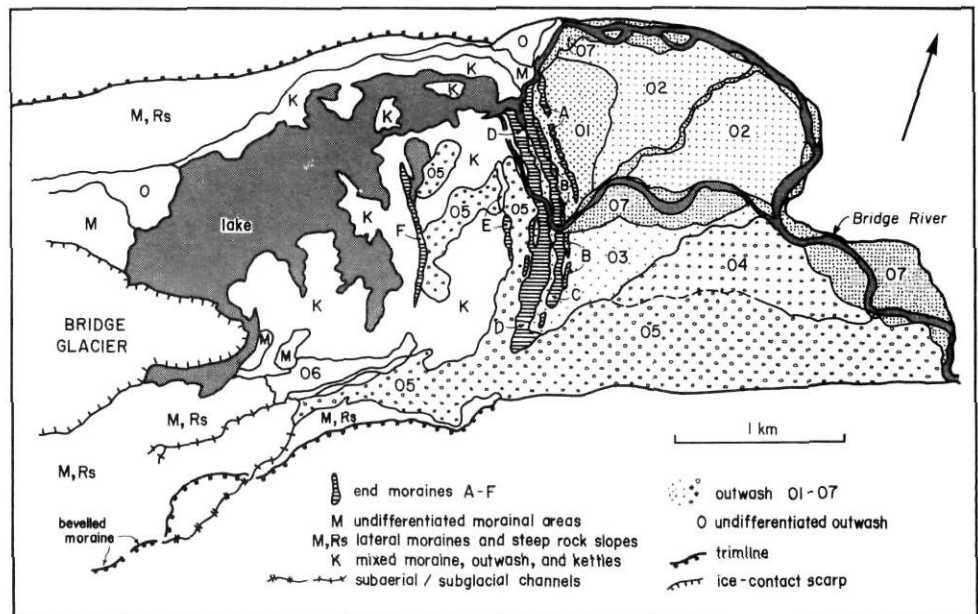




FIGURE 4a. View southeastward along moraine A: note bouldery substrate and young *Pinus albicaulis* and *Abies lasiocarpa*; outwash 01 can be seen beyond the moraine.

Vue vers le sud-est le long de la moraine A; noter le substrat blocailleux et les jeunes Pinus albicaulis et Abies lasiocarpa; on peut apercevoir l'épandage fluvio-glaciaire au-delà de la moraine.

FIGURE 4b. Strandline L1 on the west side of the middle basin; note bench cut in till in foreground, and beyond, a rock bench backed by low cliffs.

Ligne de rivage L1 sur la rive ouest du bassin lacustre moyen; noter la banquette entaillée dans le till au premier plan et, derrière, la banquette rocheuse devant les falaises basses.

and rafting of boulders, with wave action relatively unimportant. A similar "planed sub-aqueous moraine ridge" that had clearly been bevelled by lake ice was observed by Worsley (1975) in a recently lowered lake in Norway. He noted that the boulder pavement on the ridge-top was about 1 m below the original lake level.

The main inflowing streams constructed a delta in Lake 1 which prograded northward for about 1 km to fill most of the upper lake basin (Fig. 7). Deltaic sediments become finer northward, grading from topset and foreset-bedded gravel (Site BL 2, Fig. 8) to cross-bedded sand (Site BL 1). 2 to 3 m of silt accumulated over the palaeopodzol and Fraser Glaciation till in middle basin (Sites BL 3 and BL 4).



FIGURE 4c. View southeastward along the bevelled moraine to the threshold of the L1 spillway (arrow).

Vue vers le sud-est le long de la moraine tronquée jusqu'au seuil du déversoir L1 (flèche).

FIGURE 4d. Strandline L4 on the proximal side of the bevelled moraine.

Ligne de rivage L4 sur le versant proximal de la moraine tronquée (flèche).

The duration of Lake 1 can be estimated from ^{14}C dates and tree ages. At Site BL 1, deltaic sands at 1505 m a.s.l. overlie a 5 cm-thick peat bed dated at 1115 ± 40 ^{14}C years BP (S-1569; Table II and Fig. 8), which is thus a maximum date for initiation of Lake 1. However, similarity of elevations of L1 (including the bevelled moraine at 1508 m) and the Late Neoglacial trimline, indicates that Bridge Glacier must have stood close to its Late Neoglacial maximum (moraine A) before water level in the lake reached the elevation of the peat bed at 1505 m. Thus this date is considerably older than Lake 1.

Dates that more closely approximate the local Late Neoglacial maximum were obtained from overridden trees on a nunatak in Bridge Glacier (Ryder and Thomson, 1986) (Table II; Figs. 1 and 5). *In situ* remains of several partly buried trees are a few metres downslope from the crest of a lateral moraine, suggesting that the site was overridden shortly before the gla-

TABLE I
Tree Ring Data and Substrate Age

Landform	Species	No. of rings*	Correction factor**	Germination yr AD	Estimated ecesis +	Stabilization date (yr AD)
Moraine A	<i>Abies lasiocarpa</i>	64	5	1908	30 yr	1856
	" "	79	12	1886		
	<i>Pinus albicaulis</i>	64	0	1913		
	" "	79	6	1892		
Moraine B	<i>Abies lasiocarpa</i>	49	4	1924		
	<i>Pinus albicaulis</i>	34	4	1939		
	" "	70	6	1901		
Moraine C	" "	44	1	1932	30 yr	1899
	" "	44	4	1929		
	" "	41	2	1934		
Moraine D	" "	36	2	1939	30 yr	1908
	" "	37	2	1938		
Moraine E	" "	19	1	1957	30 yr	1921
	" "	19	1	1957		
	" "	24	2	1951		
L1 delta	<i>Abies lasiocarpa</i>	30	1	1946	5 yr	1935
	" "	36	1	1940		

* Ring counts as of 1977

** Adjustment for height of core above ground level: seedling growth rate 5 cm yr⁻¹.

+ See discussion in Desloges and Ryder (1990)

TABLE II
Radiocarbon dates from the Bridge Glacier area

Site	Laboratory number*	Date** (¹⁴ C yr BP) (years AD) +	Latitude (N)	Longitude (W)	Altitude (m)	Material (species)	Reference/collectors +
BL1	S-1569	1115 ± 40	50°49.0'	123°29.2'	1506	peat	Ryder & Thomson (1986)
BL2	S-1466	380 ± 60	50°49.8'	123°29.8'	1506	outer wood from trunk <i>Abies</i> sp.	JMR & BT
		1475 ± 60					
BL3/4	S-1464	6590 ± 135	50°49.4'	123°29.4'	1480	charcoal	Ryder & Thomson (1986)
BL3/4	S-1468	685 ± 60	50°49.4'	123°29.4'	1482	outer wood from trunk <i>Abies</i> sp.	"
		1280 ± 60					
BL5	S-1465	530 ± 65	50°49.7'	123°29.5'	1465	branch <i>Abies</i> sp.	"
		1400 ± 65					
BL6	S-1467	655 ± 60	50°49.7'	123°29.7'	1465	branch <i>Tsuga</i> sp.	"
		1290 ± 60					
Nunatak	S-1463	680 ± 50	50°49.3'	123°34.6'	1750	outer wood from trunk <i>Pinus albicaulis</i>	"
		1285 ± 50					
Nunatak	S-1571	540 ± 45	50°49.3'	123°34.6'	1750	root <i>Abies</i> sp.	"
		1405 ± 45					

* Saskatchewan Research Council

** Error term on dates is 1σ

+ Conversion of dates and σ from ¹⁴C yr calendar years AD according to calibration curve of Stuiver and Pearson (1986); rounded to 5 yr.

++ JMR = J. M. Ryder; BT = B. Thomson.

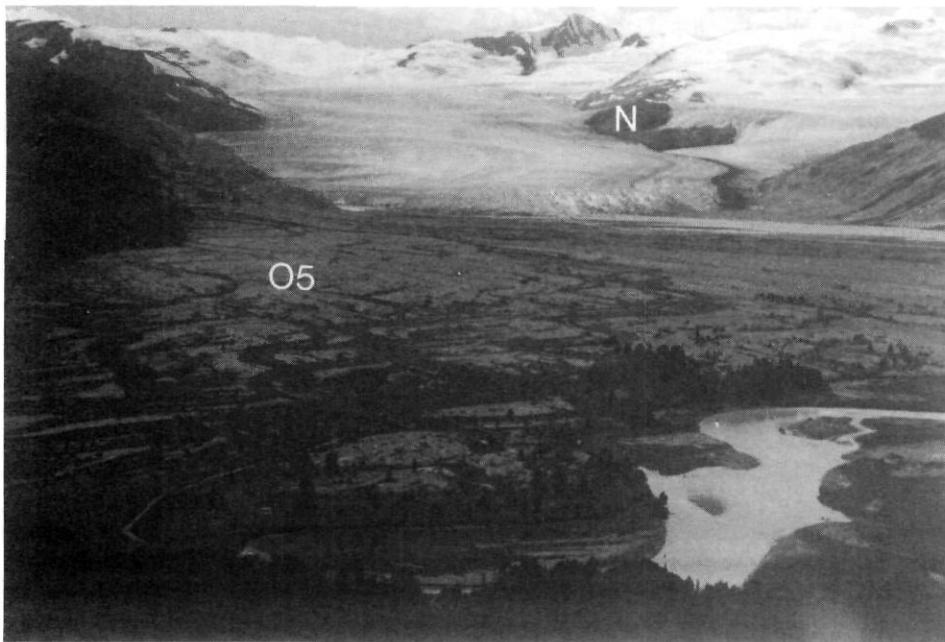


FIGURE 5. The outwash apron of Bridge Glacier: outwash O5 is the conspicuous braidplain on the left side. N = nunatak in Bridge Glacier.

La plaine d'épandage fluvio-glaciaire du glacier Bridge: l'épandage O5 est une plaine anastomosée. N = nunatak.

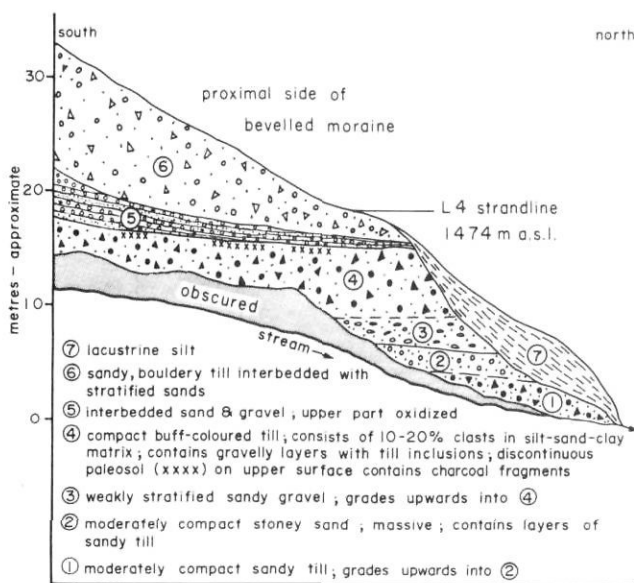


FIGURE 6. Stratigraphy of the bevelled moraine.
Stratigraphie de la moraine tronquée.

acier achieved its greatest extent. A root fragment and the outer part of a trunk gave dates of 540 ± 45 ^{14}C yr BP (S-1571) and 680 ± 50 ^{14}C yr BP (S-1463) respectively (Table II). The most recent date is interpreted as a close maximum for the approach of Bridge Glacier to moraine A and the initiation of Lake 1. The older tree appears to have died more than a century before it was overridden: Luckman (1986) has demonstrated that dead trees near timberline can be preserved for several centuries.

At Site BL 2, a log from foreset gravels was dated at 380 ± 60 ^{14}C years BP or 1475 ± 60 AD (S-1466; Table II) (Figs. 7 and 8), which is a maximum age for progradation of

the first one-third (approximately, by area) of the delta — a relation that is compatible with the estimated age of the lake.

Since drawdown of Lake 1, parts of the delta top have been colonized by conifers: the oldest tree that was sampled germinated in 1940 (Table I). Seedlings probably germinated successfully within a few years of the beginning of lake drawdown because the young trees are only a few tens of metres from mature forest and the delta would have provided a relatively favourable substrate for colonization. Accordingly, drawdown is estimated to have started about 1935. Thus Lake 1 probably existed from slightly after 540 ± 45 ^{14}C yr BP (or 1405 ± 90 AD) to about 1935 AD, a maximum duration of 530 ± 45 years. The lake remained impounded by the bevelled moraine for several decades after glacier recession commenced about 1860.

During this time, the outlet of Lake 1 was at the east end of the bevelled moraine at the head of a well defined rock-cut channel (Fig. 7). Diversion of outlet drainage to a lower sub-glacial channel caused the fall in lake level about 1935 AD. This resulted in emergence of the bevelled moraine and initiated Lakes 2 and 3 (Fig. 7). In the middle basin, there are several beaches between L1 and L2. This indicates that lake level fell episodically due to an irregular rate of downcutting into the moraine by the outlet stream. Lake level eventually restabilized at L2 after drawdown of 24 m (Fig. 7). In the lower basin on the proximal side of the moraine, water level fell abruptly (there are no intermediate strandlines) for 34 m before it stabilized at L3 (Fig. 7).

STRANDLINE L2

Middle basin is encircled by two strandlines at 1484 and 1482 m. The lower, better defined feature (L2) consists of a bench, up to 5 m wide, eroded into till and lacustrine silt. Lake 2 was initiated when water level in the middle basin ceased to fall due to stabilization of the spillway across the bevelled

FIGURE 7. Landforms associated with the ice-marginal lake. Top: longitudinal cross-section through the lake basin. Bottom: morphological map, uncorrected from British Columbia Government air photographs BC 7788: 13-15.

Reliefs associés au lac juxta-glaciaire. En haut: coupe longitudinale à travers le bassin lacustre. En bas: carte morphologique non corrigée établie à partir des photos aériennes du gouvernement de la Colombie-Britannique BC 7788: 13-15.

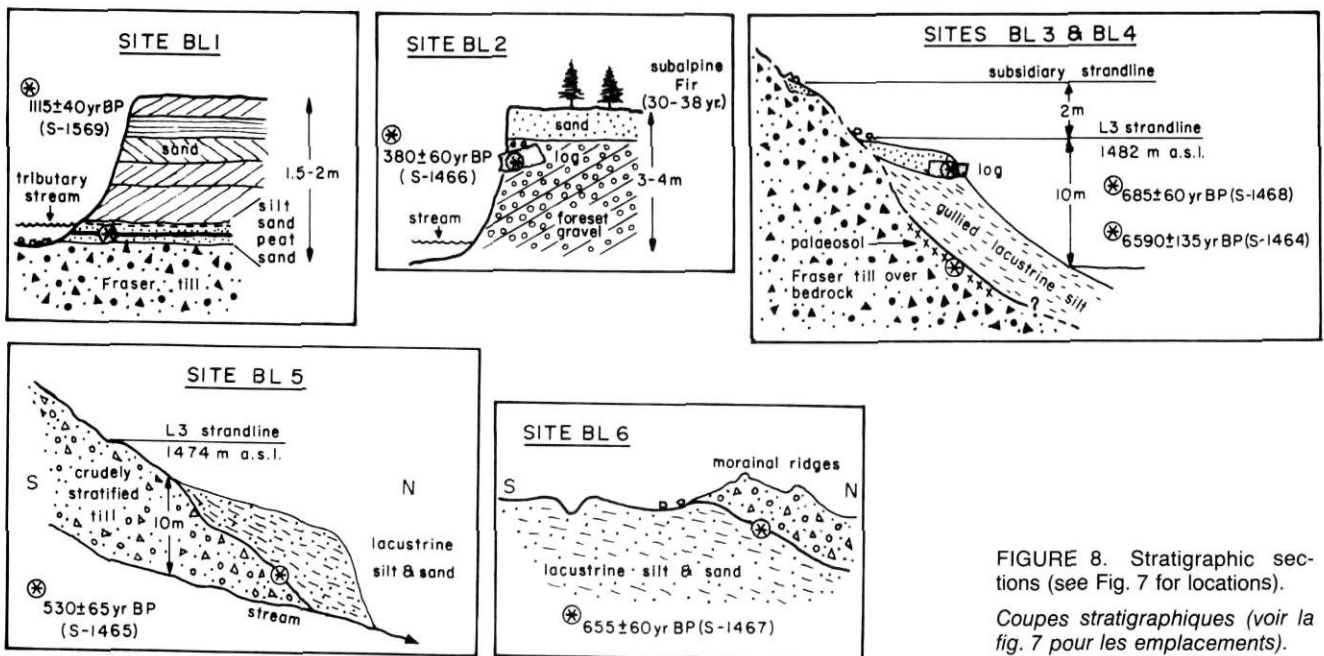
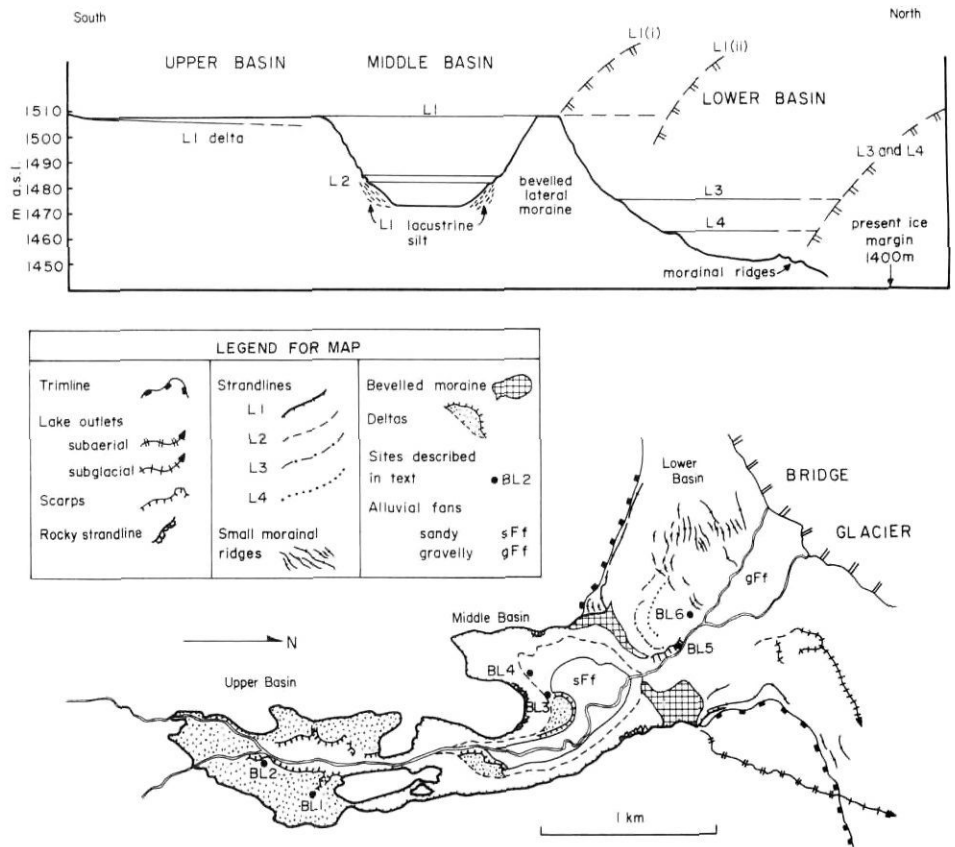


FIGURE 8. Stratigraphic sections (see Fig. 7 for locations). Coupes stratigraphiques (voir la fig. 7 pour les emplacements).

moraine. The date when this occurred is not known precisely, although the earliest air photographs (BC 477: 89-90) show that Lake 2 existed before 1947. Lake 2 was still full in July 1964 (BC 4245: 034), but had drained completely before the summer of 1970 (A 21996: 119-121). Thus the lake existed for at least 17 years, and possibly, for almost twice as long.

STRANDLINES L3 AND L4

After drainage of Lake 1, Lake 3 and then Lake 4 were ponded in the lower basin between Bridge Glacier and the bevelled moraine (Fig. 7). The L3 strandline is a clearly defined, narrow bench, although it is the least well developed strandline.

The L4 strandline is a broader gravelly terrace up to 20 m wide on one promontory (Fig. 4d). Laminated silt and sand that accumulated in Lakes 1, 3 and 4 are several metres thick on the basin floor.

Dated wood fragments (530 ± 65 ^{14}C years BP, S-1465; 655 ± 60 ^{14}C years BP, S-1467; Table II) from the upper and lower contacts of these lacustrine sediments (Sites BL5 and BL6, Fig. 8) are clearly reworked from older drift, although they may well have originated from trees that were killed by the Late Neoglacial advance of Bridge Glacier.

Lakes 3 and 4 were dammed directly by Bridge Glacier. Outflow appears to have been via a subglacial channel (Fig. 7), although englacial routes could also have been followed. Drawdown from L3 to L4 and the ultimate emptying of Lake 4 were due to failure of the ice dam. Drainage was complete before air photography in 1947, thus the duration of these lakes, from after 1935 to before 1947, was relatively short.

RATES OF EROSION AND DEPOSITION

The chronology developed above enables estimates of rates of shoreline development and stream erosion and deposition. Widths of strandline benches were determined photographically and checked against photographs taken during field work. Measurement errors are estimated at less than 20%.

Rock-cut benches along the L1 strandline vary in width up to about 20 m. If these benches developed during the slightly less than 530 ± 45 year duration of the lake, then the mean rate of formation of the broadest bench was at least 3.8 ± 0.3 cm yr^{-1} . This rate, which is a maximum, is relatively rapid, but it is comparable with maximum rates of 4.24 to 7.07 cm yr^{-1} that were determined by Matthews *et al.* (1986) for rock-cut benches along the shore of a former ice dammed lake — Böverbrevatnet — in Norway. This lake was similar to the lake at Bridge Glacier because both lakes existed under periglacial conditions and both strandlines were etched into relatively resistant rocks — gabbros at Böverbrevatnet and quartz diorite at Bridge Glacier.

Matthews *et al.* (1986), Dawson *et al.* (1987), and Shakesby and Matthews (1987) proposed that rock platforms along the shores of periglacial lakes develop rapidly due to the effectiveness of frost shattering at the interface between winter lake ice and bedrock. At Bridge Glacier, angular rocks on the L1 strandline provide evidence of frost shattering, but the presence of edge rounded rocks indicates that some additional mechanism has been effective here. Rounding could have resulted from scour by lake ice or from granular disintegration. (The latter process was observed to be occurring at present on parts of the L1 strandline.) It is also possible that glacially-abraded rock outcrops from Fraser Glaciation are aligned fortuitously with the L1 strandline, in which case, the 20 m-wide bench may be a composite feature, not formed entirely by recent lake-shore processes, and the rate of shoreline erosion may have been overestimated.

Rates of maximum erosion of drift-cut strandlines were determined for benches of typical maximum width; exceptionally wide strandlines at promontories were excluded. Rates range from 8 to about 60 cm yr^{-1} (Table III). Processes of ero-

TABLE III
Rates of Maximum Shoreline Erosion

Strandline	Width (m) (max)		Duration of lake (yr)	Rates of Erosion (cm yr^{-1})	
	till	rock		till	bedrock
L1	40	20	530 ± 45	7.6 ± 0.7	3.8 ± 0.3
L2	5		17-30	23 ± 6	
L3	2	}	12	60	
L4	5				

sion probably included shove and drag by lake ice, slumping and flowage of saturated silt and till, and removal of fine sediment by waves. These would have been most effective immediately after drawdown from a higher lake level, when the drift was saturated.

The rate of lowering of the channel across the bevelled moraine during the episodic drawdown from L1 can be calculated from data given above. Drawdown from L1 began about 1935 and L2 was established before 1947. Thus the lake outlet was lowered by 26 m in less than 12 years, giving a mean erosion rate of >2.2 m yr^{-1} . The presence of the weakly developed beaches between L1 and L2 indicates that Lake 1 did not drain catastrophically, although it may have lowered by several metres each year. Erosion of the lake outlet most likely occurred when high stream discharge resulted in the dislodgement of boulder jams. Large instantaneous discharges could have been generated by temporary damming of the channel due to snowbanks or to collapse of steep morainal slopes. In addition, rapid lowering of the spillway could have been aided by piping, which would have been favoured by the morainal core of permeable gravels (unit 5 on Fig. 4), stratigraphic contacts between materials of differing permeabilities, and a steep hydraulic gradient through the moraine resulting from its position on the lip of a hanging valley.

Drawdown from L2 began after 1964 and middle basin was dry (basin floor elevation = 1471 m) before 1971. Thus lake level fell 11 m in less than 6 years. Since there are no subsidiary strandlines below L2, and since slopes below L2 are underlain by easily erodible silts which would readily take the imprint of a shoreline, it is likely that Lake 2 drained completely during a single phase of outlet erosion.

Rates of below sediment transport and related denudation during the Little Ice Age can be assessed for the two streams that flowed into the southern end of Lake 1 because the volume of the L1 delta can be estimated. The rates are minimum values because the volume estimate is conservative (see below) and the 530-year time interval used is a maximum value.

Deltaic gravels and sands had filled most of the upper basin by 1935 (Fig. 7). Since drawdown from L1, the delta has been dissected by stream erosion, and the height of the resulting scarps provides a minimum estimate of the delta thickness. Scarp heights in the central part of the basin range from 4 to

6 m. Sands and gravels are more than 4 m thick at site BL 2 near the centre of the basin, and 2 m thick at BL 1 closer to the basin margin. Allowing for lateral thinning and a wedge-like thickening of the delta downstream, a reasonably conservative minimum estimate of mean thickness is half of the average scarp height in the centre of the basin — about 2.5 m. The area of the delta, which is clearly demarcated by the L1 strandline is $21 \times 10^4 \text{ m}^2$, giving a minimum estimate for delta volume of $52 \times 10^4 \text{ m}^3$.

Assuming that this volume of sediment was moved during less than 530 years, the bedload sediment flux was more than $980 \text{ m}^3 \text{ yr}^{-1}$ (gravel volume), which is equivalent to about 1570 tonnes yr^{-1} . If this sediment was derived from the entire basin that drains to the delta (11.75 km^2), then the denudation rate was 0.05 mm yr^{-1} . If, as is more likely, most sediment was derived from the part of the basin that was ice-covered during Late Neoglacial time (6.25 km^2), bedload flux was 251 tonnes $\text{km}^{-2} \text{ yr}^{-1}$, with a denudation rate of 0.09 mm yr^{-1} .

These long-term mean values fall well within the range of results from short-term bedload measurements on modern proglacial streams, which show considerable variation from year to year and from basin to basin. It is worth noting, however, that mean bedload flux at Bridge Glacier was very similar to that at the two Norwegian glaciers with the longest series of data, Nigardsbreen (15 yr) and Engabreen (13 yr), where recent rates average 235 and 268 tonnes $\text{km}^{-2} \text{ yr}^{-1}$ respectively (Roland and Haakensen, 1985).

DOWNSTREAM FLOODS

The magnitude and impact of stream floods that were initiated by the release of water from the ice-marginal lake can be assessed from the available geomorphic evidence. Outflow from Lake 1, via a deeply incised, partly subaerial and partly subglacial channel resulted in the formation of a large, low-gradient outwash fan (04 and 05, Figs. 3 and 5). That this fan was formed solely by Lake 1 outflow is indicated by the radiating channels on the fan, and the presence of an ice-contact scarp and a moraine between the apical part of the fan and adjacent outwash to the north (Fig. 3). A relatively high degree of former fluvial activity on the fan associated with major floods is suggested by the large size of the fan relative to the main Bridge River outwash plain, the relatively fresh and unvegetated appearance of all of a major sector of the fan (05), and the presence of abundant boulders along high-relief channels and bars near the fan apex. Air photographs from several dates indicate that the morphology of the channels on 05 has not changed since 1947, and regular stream flow has been limited to a single, fixed channel.

It thus appears that substantial floods and large volumes of sediment originated from the Lake 1 spillway, despite the presence of a stable lake outlet and the relatively short length (1.1 km) of the channel downstream from the lake. Potential causes include temporary blockage of the lake outlet by snowbanks or by lake ice grounded in the shallows over the bevelled moraine (Fig. 4c), and temporary damming of the spillway by icefalls, snowbanks, or by landslides from its precipitous sides. No avalanche chutes feed into the channel.

The effectiveness of temporary snowbank dams at lake outlets is demonstrated by conditions at Flitaway Lake, at the Lewis Glacier (Barnes Icecap), Baffin Island. This is a modern ice-marginal lake that is similar in many respects to the former lake at Bridge Glacier. The Flitaway outlet stream also follows upper subaerial and lower subglacial reaches before it emerges onto the main proglacial outwash. Each year, the outlet stream is blocked by snowbanks and/or icefalls along the glacier margin, so that the lake surface is maintained at a high level until the dam collapses (Church, 1972). This results in rapid drawdown of about 3 m (Church, pers. comm.) and a surge of water sufficient to generate an extraordinary (*i.e.*, unrelated to weather) flood on both the lake outlet stream and the main proglacial river.

At Bridge Glacier, the L1 strandline encloses an area of 0.65 km^2 . Thus each 1 m rise in lake level would have resulted in storage of $0.65 \times 10^6 \text{ m}^3$. This is equivalent to 45 mm of water over the 15 km^2 drainage basin. In this environment, however, even two or three times this amount of runoff can be expected during a day of extreme weather conditions, such as rain on melting snow and autumn rainstorms (Church, 1988). For example, a storm in October 1984 gave rise to 130 mm of runoff from the Bridge Glacier basin; (based on discharge measured at gauging station 08ME023, 2.5 km downstream from the present snout of Bridge Glacier). The most distinctive aspect of damming by snow banks, however, is that this mechanism can cause a major flood each year, hence the active nature of the outwash fan. The instantaneous peak discharge resulting from the failure of a snow dam could also be somewhat greater than that from an event related to runoff from the entire drainage basin where flows would be attenuated due to transit time down slopes and through the lake.

The Lake 1 outlet stream probably derived most of its sediment from drift and melting ice along its subglacial reach. This too is analogous with the Flitaway stream, which has transformed a drift-covered hillside into chutes of stripped bedrock (Church, 1972). The volume of bedrock material removed during excavation of the Bridge Glacier channel was, very approximately, $12 \times 10^4 \text{ m}^3$, which is equivalent to a gravel thickness of only 10 cm over the outwash fan (04 and 05) (assuming 1.6 g cc^{-1} and 2.7 g cc^{-1} for the bulk densities of gravel and bedrock respectively). Clearly, at least several times this volume of material must have been derived from the ice and related drift.

Major floods have probably occurred on several occasions during various phases of lake drawdown since the abandonment of the Lake 1 spillway. Even the sporadic 2-3 m drawdowns during the L1 to L2 transition could each have resulted in the release of between 10^5 and 10^6 m^3 of water. A small area of bouldery outwash at the lower end of the subglacial channel is the only evidence of these floods because drainage from the lower lakes became confluent with the main proglacial stream before emerging onto the outwash plain.

Discharge records for Bridge River are available for a gauge (station 08ME004) at Lajoie Falls, 50 km downstream from Bridge Glacier from 1924 to 1948, and at the station near the glacier since 1978. The older set of records was examined for floods attributable to lake drainage during 1935-47, but all nota-

ble floods coincided with either rainstorms or warm weather, as well as with high discharge of adjacent glacier-fed rivers. It is probable that the lakes drained during periods of high discharge controlled by the weather, since this is when ice- or moraine-dam failure and outlet erosion would be most likely, but the unusual nature of the floods was masked by downstream attenuation.

The flood that may have been the largest of those initiated at the ice-marginal lake was the one that resulted from the emptying of Lake 2 between 1964 and 1970 (during the period when no discharge records were maintained). An estimate of the peak discharge that resulted from failure of the moraine dam, derived from an empirical relationship developed by Costa and Schuster (1988)

$$Q_{\max} = 0.00013 (PE)^{0.6},$$

gives a Q_{\max} of about $600 \text{ m}^3 \text{ sec}^{-1}$, where Q_{\max} is peak discharge at the dam breach and PE is the potential energy of the lake behind the dam, computed as the product of dam height (m), lake volume (m^3) and the specific weight of water ($9800 \text{ newtons m}^{-3}$). Since this value is an order of magnitude greater than all but one of the yearly maximum instantaneous discharges that have been recorded for Bridge River at the gauging site close to the glacier (the extreme record is $180 \text{ m}^3 \text{ sec}^{-1}$), it likely generated a substantial flood wave on the river for 25 km downstream to Downton Lake reservoir. That this went unreported is not surprising due to the remoteness of the upper Bridge River.

SUMMARY AND CONCLUSIONS

The highest ice-marginal lake (L1) was initiated about 1405 AD when an ice-free tributary became dammed by Bridge Glacier. Glacier recession commenced shortly before 1860, but the lake remained at its original level until about 1935. Subsequent lake history was marked by stable and unstable phases of drawdown, and floods of various magnitudes. Final drainage (Lake 2) occurred shortly before 1970. Thus lake history spans more than a century after the commencement of glacier recession.

Rates of erosion and deposition in the vicinity of the ice-marginal lake were relatively rapid. The best developed rock-cut strandline may have widened by $>3.8 \pm 0.3 \text{ cm yr}^{-1}$, a rate which may not be atypical for such lakes. Benches in drift were formed at 8 to about 60 cm yr^{-1} . Downcutting of a lake outlet channel into a moraine dam occurred at an average rate of $>2.2 \text{ m yr}^{-1}$. During the Little Ice Age, the mean denudation rate was at least $50 \text{ to } 90 \text{ mm ka}^{-1}$, with the latter figure representing glacier-covered terrain.

Major floods probably originated from the ice-marginal lake on several occasions. Discharges higher than those controlled by weather conditions may have been generated due to temporary blockage of the lake outlet by snowbanks or lake ice, and due to failure of moraine- and ice-dams. Failure of the last moraine dam could have resulted in a peak outflow of about $600 \text{ m}^3 \text{ sec}^{-1}$, and this would probably have generated an unusual flood on Bridge River. Such floods may not be recognizable in discharge records, however, due to attenuation of

the flood wave by subglacial channels and lakes, and due to coeval weather-induced high discharges.

The moraine dam is a composite feature, including at least seven distinct stratigraphic units. Piping and eventual failure of the dam would have been favoured by permeable gravels in the core of the moraine, morainal materials of markedly differing hydraulic conductivities, and a steep hydraulic gradient.

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