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A huge flood in the Fraser River valley, British Columbia, near the Pleistocene Termination

John J. Clague [a,*], Nicholas J. Roberts [a,b], Brendan Miller [c], Brian Menounos [d], Brent Goehring [e]

[a] Department of Earth Sciences, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, Canada
[b] Mineral Resources Tasmania, Department of State Growth, 30 Gordons Hill Road, PO Box 56, Rosny Park, TAS 7018, Australia
[c] British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development, 5th Floor, 499 George Street, Prince George, BC V2L 1R5, Canada
[d] Geography Program and Natural Resources and Environmental Studies Institute, University of Northern British Columbia, 3333 University Way, Prince George, BC V2N 4Z9, Canada
[e] Department of Earth and Environmental Sciences, Tulane University, 210 Blessey Hall, New Orleans, LA 70118, USA

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ABSTRACT

Near the Pleistocene Termination, a glacier-dammed lake in central British Columbia suddenly drained to the south along the Fraser River valley. Floodwater travelled 330 km down the valley to Hope, British Columbia, and from there to the west into the Salish Sea near Vancouver. The flood was caused by the failure of an ice dam formed by the terminus of glaciers flowing from the central Coast Mountains across the British Columbia Interior Plateau. The ice dam impounded several hundred cubic kilometres of water to a maximum elevation of about 810 m asl (above sea level); at its maximum, the lake at the ice dam was over 250 m deep. Geomorphic and sedimentary evidence for the flood includes streamlined boulder-strewn bars, gravel dune fields, and terraces sloping up Fraser and lowermost Thompson valleys, opposite the present direction of river flow. The gravel bars and flood terraces are underlain by sheets of massive to poorly sorted gravel containing large boulders and rip-up clasts of silt and till. Shortly after the flood, a landslide near the northern margin of the former glacier dam impounded water to an elevation of about 550 m asl. This lake emptied due to overflow and incision of the landslide dam. The outburst flood from glacial Lake Fraser and the subsequent draining of the landslide-dammed lake deeply incised the older sediment fill in Fraser Valley and transported much of this sediment into the proto-Salish Sea west of Vancouver, British Columbia and Bellingham, Washington. TCN ages on flood-transported boulders at three localities along the flood path agree with radiocarbon ages on inferred flood layers in ODP cores collected from Saanich Inlet, a fiord on southern Vancouver Island, 80 km south-southwest of Vancouver.

1. Introduction

Seventeen years ago, Blais-Stevens et al. (2003) documented two anomalous, gray, silty clay beds in Ocean Drilling Program (ODP) cores collected from Saanich Inlet, a fiord on the southeast coast of Vancouver Island, British Columbia, Canada. The beds, which they dated to about 11,000 cal yr BP, contain Tertiary pollen derived from sedimentary rocks found only in the Fraser Lowland on the mainland of British Columbia and Washington east of the Salish Sea. Based on this and other evidence, Blais-Stevens et al. (2003) hypothesized that the clay beds are distal deposits of large floods that swept across the Fraser Lowland at the beginning of the Holocene. Muddy overflow plumes from these floods crossed the Salish Sea and entered Saanich Inlet, where the sediment settled from suspension and blanketed the fiord floor. Blais-Stevens et al. (2003) further speculated that the likely source of the floods was ice-dammed lakes in Fraser and Thompson valleys, which disappeared at about the time the floods occurred. Subsequently, Conway et al. (2002) identified an anomalous layer of inorganic clay above Late Glacial glaciomarine sediments and directly below organic-rich Holocene mud in cores they collected from the Salish Sea. They hypothesized that the clay layer was the distal deposit of one such large flood.

In this paper, we test Blais-Stevens et al.'s (2003) hypothesis by studying the geomorphology and latest Pleistocene and Holocene sediments in the Fraser River valley, down which any such flood must have passed. Lidar-derived elevation models, stratigraphic and sedimentological characteristics of the upper part of the valley fill, and new ^{10}Be surface exposure ages provide compelling evidence for a flood that we ascribe to the sudden draining of glacial Lake Fraser (hereafter referred to as 'Lake Fraser'), a large glacier-dammed lake in central British Columbia.

We compare the geomorphic and sedimentary record of the Lake Fraser outburst flood to well documented records of the Bonneville and Missoula megafloods in the western United States and the Altai megafloods in Siberia. The Missoula and Altai flood records are a composite of many individual outbursts (in the case of Missoula, likely >100), most of which were much larger than the Lake Fraser flood (e.g., Waitt, 1980,

* Corresponding author.
E-mail address: jclague@sfu.ca (J.J. Clague).

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1985; Atwater, 1984; Carling et al., 2002, 2009; Herget, 2005; O'Connor et al., 2020). Here we show that the landforms and sediments of the Lake Fraser flood are the product of only one, or possibly two events. Differences among these records may also reflect differences in the topography traversed by the floods (deep narrow valleys vs. broader valleys and plateaus) and, in the case of the Lake Fraser event, to widespread erosion and burial of the flood sediments due to paraglacial reworking of latest Pleistocene glacial sediments during the early Holocene. We also provide a possible explanation for peculiar sheets of flood gravel that contain large boulders and rip-up clasts of till and silt that are inconsistent with traditional fluvial hydrodynamic transport processes.

2. Geographic and geologic context

The Fraser River catchment is a major North American watershed, with an area of 220,000 km^2, nearly one-quarter of the surface area of British Columbia (Fig. 1). The river heads in the central Rocky Mountains of British Columbia. It flows northwestward in the Rocky Mountain Trench to east of Prince George. There it swing to the southwest and south to flow within a deeply incised valley for 550 km to Hope. The river flows another 145 km to the west across the broad Fraser Lowland to its mouth on the east side of the Salish Sea at Vancouver. In terms of discharge, Fraser River is the fifth largest river in Canada: its mean annual discharge near the river mouth is 3475 m^3/s; the estimated peak discharge (June 1894) is about 17,000 m^3/s (Kerr Wood Leidal, 2015).

In this paper, we focus on the 330-km-long, southerly oriented section of the deeply incised Fraser River valley, also known as 'Fraser Canyon', which extends from just north of the town of Hope on the south past Williams Lake on the north (Fig. 1). This section of the river can be, to a first order, divided into two reaches. From Hope to near Lytton, the river flows in a steep-walled bedrock canyon ranging in width from <100 m to about 500 m (Fig. 2). In places along this reach, the river is nearly as deep as it is wide (Rennie et al., 2018). This narrow bedrock canyon is nested within a broader fault-controlled bedrock valley that marks the boundary between the Coast Mountains and the Canadian Cascade Mountains, with relief as much as 1800 m from the river to the highest peaks. From south of Lytton to the north end of the study area near Williams Lake, the river flows across the Interior Plateau in a valley incised up to 300 m into Quaternary sediments

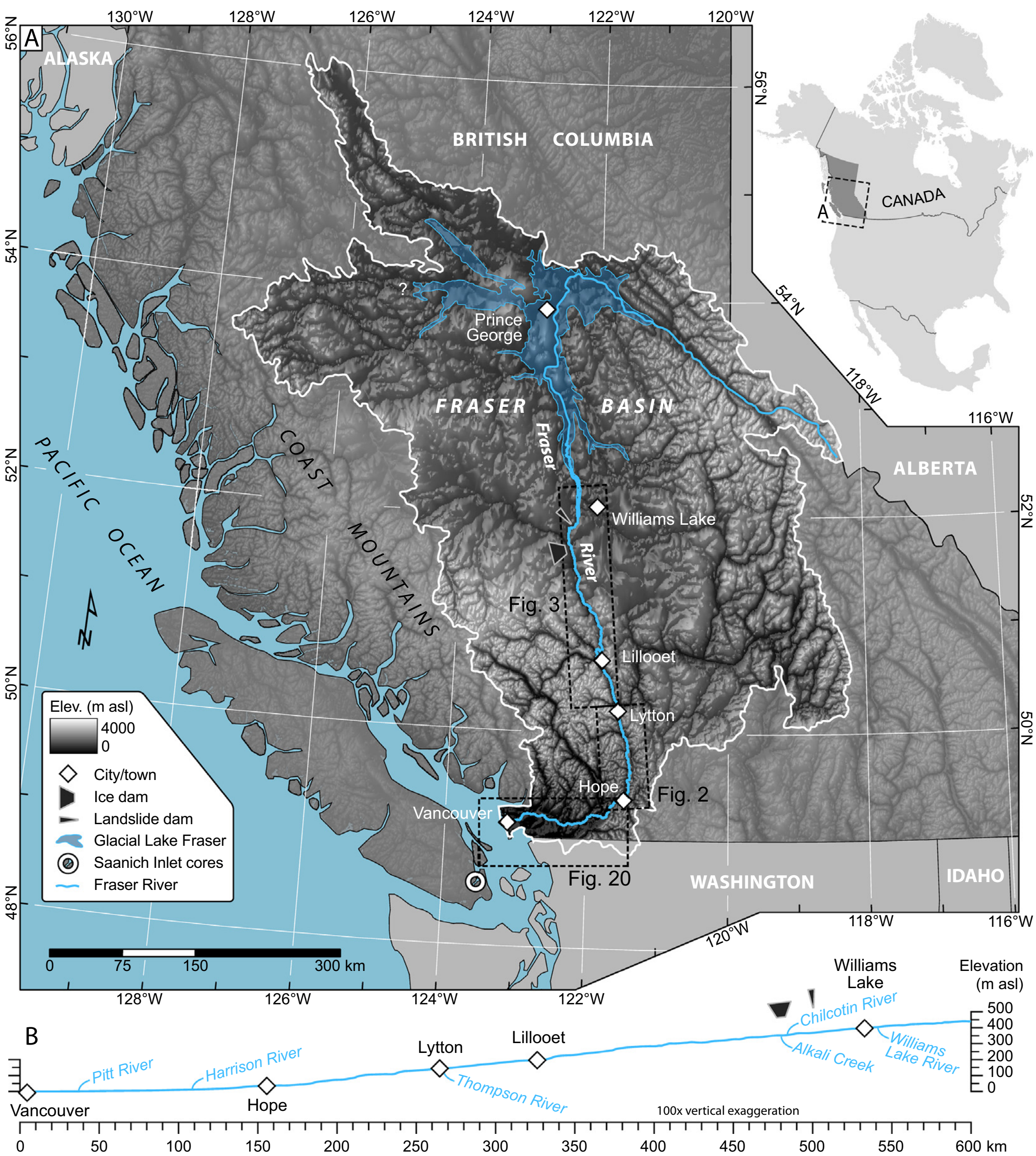

Fig. 1. A) Map of southern and central British Columbia showing places mentioned in the paper. B) Elevation profile of the modern Fraser River from the north end of the study area near Williams Lake to the river mouth near Vancouver.

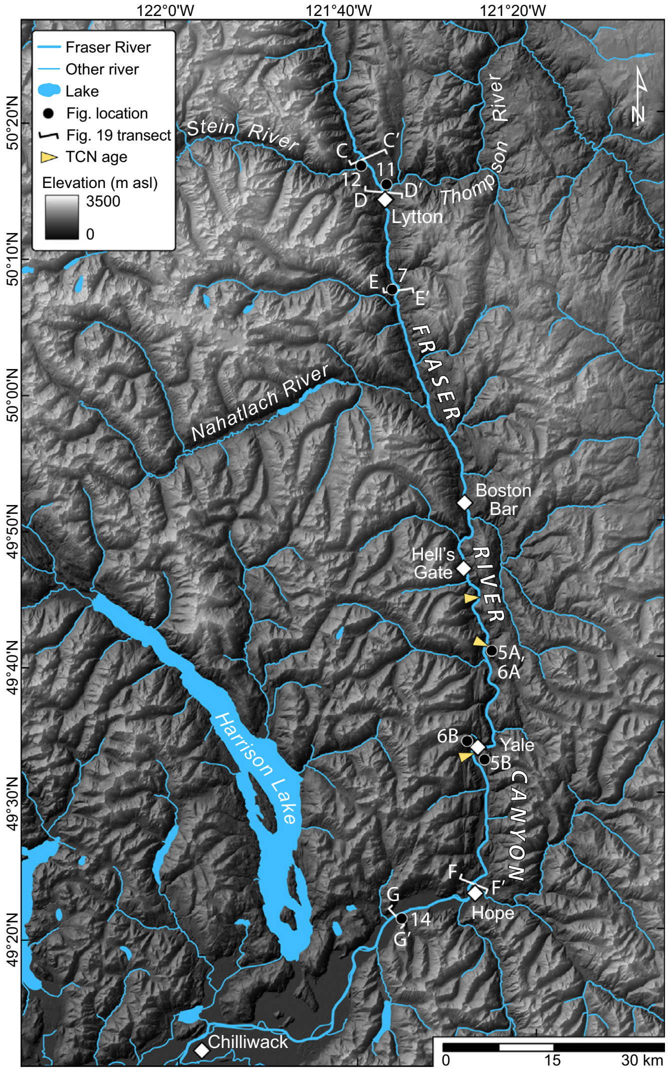

Fig. 2. Map of the southern part of the study area showing topography and place names mentioned in the text. Also shown are figure and topographic profile locations.

(Fig. 3). Locally, flights of river terraces record Holocene incision of the valley fill subsequent to deglaciation (Fig. 4).

British Columbia and southern Yukon were covered by a large ice sheet and its satellite glaciers at the peak of the last Pleistocene glaciation (Fraser Glaciation, MIS 2) (Clague, 1989; Jackson Jr. and Clague, 1991). The ice sheet extended west onto the British Columbia continental shelf and south into northern Washington, Idaho, and Montana. It was contiguous with glaciers covering southern Alaska, and at the Last Glacial Maximum it coalesced with the Laurentide ice sheet along the Rocky Mountain Foothills in Alberta and northeast British Columbia. The interior of the ice sheet had an irregular undulating surface, with several ice divides that shifted through time (Clague, 1989; Stumpf et al., 2000). These ice divides were subordinate to the main divide along the axis of the Coast Mountains. Although there may have been localized areas of cold ice at the base of the Cordilleran ice sheet, especially at high elevations where the ice was relatively thin, the ice sheet was dominantly warm-based (Lian and Hicock, 2000).

The event described in this paper happened during the final demise of the Cordilleran ice sheet. Deglaciation began about 16,500 years ago and proceeded by frontal retreat at the periphery of the ice sheet and by downwasting, complex frontal retreat, and localized stagnation in its interior areas (Clague, 1981, 1989, 2017; Fulton, 1991; Clague and Ward, 2011; Burke et al., 2012; Margold et al., 2013; Perkins and Brennand, 2015; Brennand and Perkins, 2017; Menounos et al., 2017;

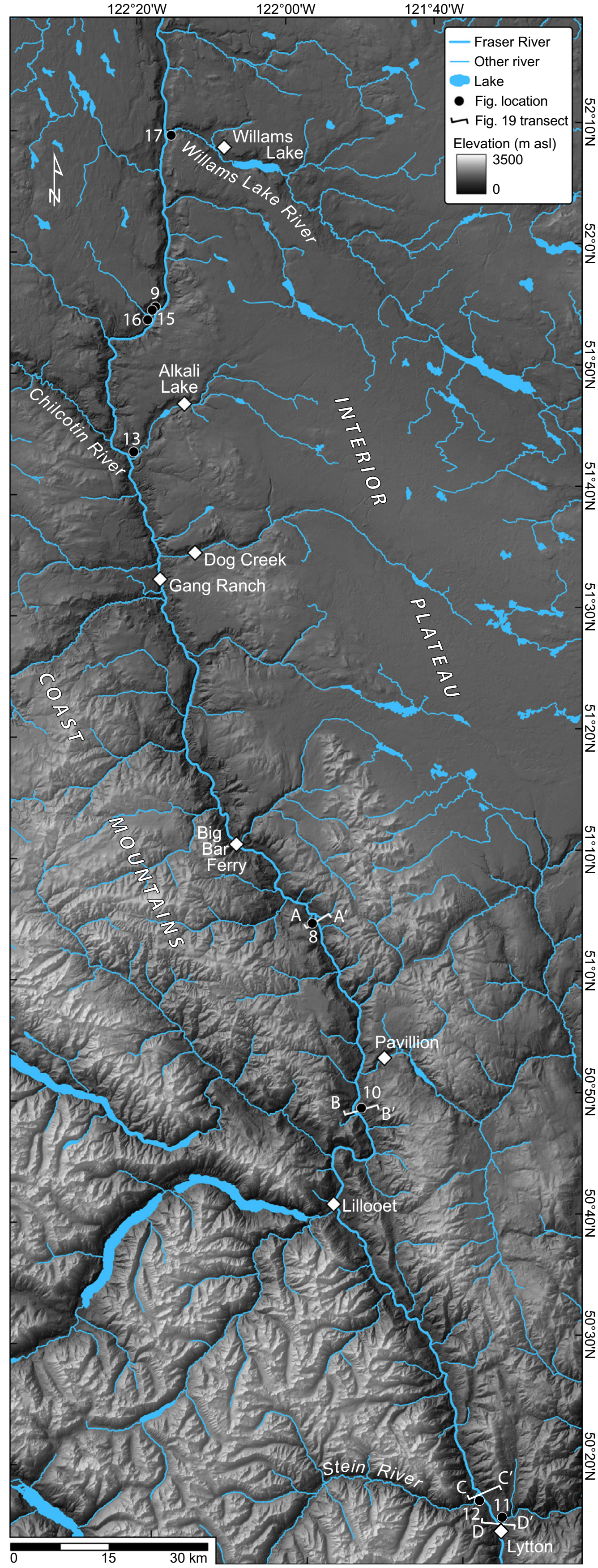

Fig. 3. Map of the northern part of the study area showing topography and place names locations of sites mentioned in the text. Also shown are figure and topographic profile locations.

Fig. 4. The Fraser River valley south of Big Bar Ferry. Fraser River flows in a deep valley incised into Quaternary sediments that fill a larger bedrock valley on the Interior Plateau. Gently sloping, post-flood colluvial aprons (arrowed) cover much of the valley walls outside the canyon in which Fraser River flows.

Darvill et al., 2018). The chronology of deglaciation is constrained by accelerator mass spectrometry (AMS) radiocarbon and ^{10}Be surface exposure ages. High-elevation sites at the western margin of the British Columbia Interior Plateau, east of the Coast Mountains, became ice-free between about 15,000 and 12,000 years ago (Margold et al., 2014). Ice cover in the southern Coast Mountains was sufficiently extensive during the Younger Dryas Chronozone (12,900–11,700 years ago) that glaciers re-advanced into low-lying areas north and east of Vancouver (Saunders et al., 1987; Clague et al., 1997; Friele and Clague, 2002a, 2002b). At the same time, however, a labyrinth of dead or dying tongues of glacier ice covered some interior valleys (Lakeman et al., 2008).

Many interior valleys were sites of ephemeral glacier-dammed lakes during this final stage of deglaciation. Clague (1987, 1988a) provided geomorphic and stratigraphic evidence for the largest of these lakes, 'Lake Fraser', located in central British Columbia (Fig. 1). Lake Fraser extended north in the Fraser River valley from at least Williams Lake to north of Prince George and from there west past Vanderhoof and east into the Rocky Mountain Trench (Armstrong and Tipper, 1948; Leaming and Armstrong, 1969; Tipper, 1971; Clague, 1988b, 1988c; Plouffe and Williams, 2001; Plouffe et al., 2004; Blais-Stevens and Clague, 2007; Margold et al., 2013). The lake was impounded by the remnant Cordilleran ice sheet as it thinned and retreated to the west, south, and southwest back toward the Coast Mountains (Margold et al., 2013). Locally, thick silt and clayey silt were deposited over large areas on the floor of the lake, and streams flowing into the lake built deltas and subaqueous outwash fans.

Initially, Lake Fraser drained northward into the Peace River watershed. The level of the lake west and south of what is today Prince George is defined by a shoreline at 810 m asl (above sea level). A flight of beaches extends from this uppermost shoreline to 736 m asl. When the level of the lake had fallen to 736 m asl, the lake had an area of about 7500 km^2. It no longer drained to the north, although it remained impounded by the remnant ice sheet south of Williams Lake. When the north margin of the ice sheet receded to a point about 20 km south of Williams Lake, the lake suddenly drained. Its level fell from 736 m asl to at least 540 m asl, with the sudden release of several hundred cubic kilometres of water through the remaining glacier dam to the south. The absence of shorelines below 736 m asl within the lake basin is consistent with a rapid fall in Lake Fraser from that level.

3. Methods

Our geomorphic descriptions and interpretations are based on analysis of airborne lidar data over parts of the Fraser Valley between Hope and Williams Lake acquired specifically for this project. We viewed bare-earth digital elevations models (DEMs) in both orthographic and three-dimensional perspective forms using the GIS software Global Mapper. We also used satellite imagery available on the Google Earth platform and field observations to support our morphologic analyses of the lidar data. Fieldwork included detailed stratigraphic and sedimentological observations at 78 sites in 2017, 2018, and 2019. We located field sites on the lidar images and on the ground using hand-held GPS units, and we measured vertical heights at sections with a laser rangefinder. Elevations of sections were determined from the lidar imagery. We described exposures, noting unit thickness, the nature of contacts between units, colour, grain size, sorting, clast support, and sedimentary structures, including flow-direction indicators. All landforms and sections were photographed on the ground. In addition, we took photographs and acquired continuous video footage during three helicopter reconnaissance flights of the valley between Williams Lake and Lillooet. Lithofacies types follow the terminology of Miall (1977, 1978) and Eyles et al. (1983), but without the lithofacies codes. The terminology applied to flood sediments is based on the jökulhlaup (glacier outburst flood) lithofacies types of Maizels (1993, 1997).

We used TCN (terrestrial cosmogenic nuclide) techniques to estimate the age of the flood. Specifically, we determined ^{10}Be concentrations in flood-transported granodiorite and metagranodiorite boulders on the surface of three large bi-convex gravel bars oriented parallel to the flow direction of the flood. At each of the three sites (Yale, Alexandria, and Black Canyon; Fig. 2), we collected samples from the upper surfaces of three boulders ranging from 1 m to 10 m in size. The sampled boulders lie on forested flat portions of the relict ridges and have not moved since they were deposited. The sample localities are near the floor of the Fraser River valley and have elevations that range from about 100 to 155 m asl. Because the sample sites are within a deep valley bounded by steeply sloping valley walls that reach up to 1900 m asl, we determined topographic cosmic ray shielding by measuring angles to the horizon in all directions. The sample sites are within an area that has a climate transitional between the humid British Columbia coast (average annual precipitation at Yale is 1484 mm water equivalent) and the semiarid interior (average annual precipitation at Lytton is 432 mm water equivalent). The average snowy period lasts 5.3 months, from late October until late March. The maximum thickness of snow on the ground rarely exceeds 20 cm. Although we cannot completely rule out minor loss of rock from the surfaces of sampled boulders, we found no evidence for exfoliation or significant loss of grains by weathering. We thus made corrections for topographic shielding, but not for snow cover or erosion.

4. Descriptions of flood landforms and sediments

Our field sites span the two sections of the Fraser River valley described above (Figs. 2 and 3). Space limits do not allow us to describe all sites in detail, thus in this section we include examples of landforms and sediments that are evidence of the passage of a flood along Fraser Valley from Williams Lake to Hope at or shortly after the end of the Pleistocene. The final paragraph of each subsection presents an interpretation of the landforms and sediments that we describe in that subsection. Metadata for observations made at all 78 study sites are included in a supplementary file accompanying the paper (Table S1; Figs. S1 and S2).

4.1. Gravel bars

The most common landforms that we attribute to a large flood are long irregular to streamlined ridges with an asymmetric longitudinal axis and steeper transverse axes (Figs. 5 and 6). We term these landforms 'gravel bars'. The longitudinal axes of most of these ridges are parallel to Fraser Valley and are steeper at the upvalley end (dipping up to 11° upvalley) than at the downvalley end (<5° downvalley). Many of the ridges are strewn with rounded to subangular boulders that are commonly >1 m across and at one site (Yale) up to 15 m long (Figs. 5 and 6). The ridges lie up to 210 m above the present channel of Fraser River, far above the highest flat postglacial fluvial terraces that are common in the study area. Gravel bars are most common just downvalley of constricted sections of Fraser Valley where the valley width increases, for example at Yale. At such locations, they resemble expansion bars documented along the paths of the Altai megafloods (Carling et al., 2002, 2009; Herget, 2005) and the megafloods from glacial Lake Missoula (Bretz et al., 1956; O'Connor et al., 2020, and references therein) and Lake Bonneville (O'Connor, 1993; O'Connor et al., 2020).

Sediments underlying the gravel bars are exposed locally in cutbanks of Fraser River and in a few gravel quarries. One of the best exposures is on the west side of Fraser River 13 km south of Lytton (Fig. 7). At this site, up to 60 m of gently inclined, planar-bedded, clast-supported sandy gravel is exposed over a valley-parallel distance of 500 m beneath a southwest-trending ridge that is anchored against two bedrock ridges at its upvalley end. Gravel beds dip up to 9° to the southwest. The dips of beds decrease gradually upward; the uppermost beds dip only 1° and conform to the downvalley slope of the ridge. The lowest sediment within this downvalley-dipping sequence is

Fig. 5. Examples of large boulders sampled for ^{10}Be dating on ridges A) near Alexandria and B) east of Yale (see Fig. 2 for the site locations and Fig. 6 for lidar DEMS of the two sites). We sampled the boulders at the crests of biconvex ridges aligned more-or-less parallel to the valley and downstream of bedrock obstructions. The boulder in B) is about 3 m high.

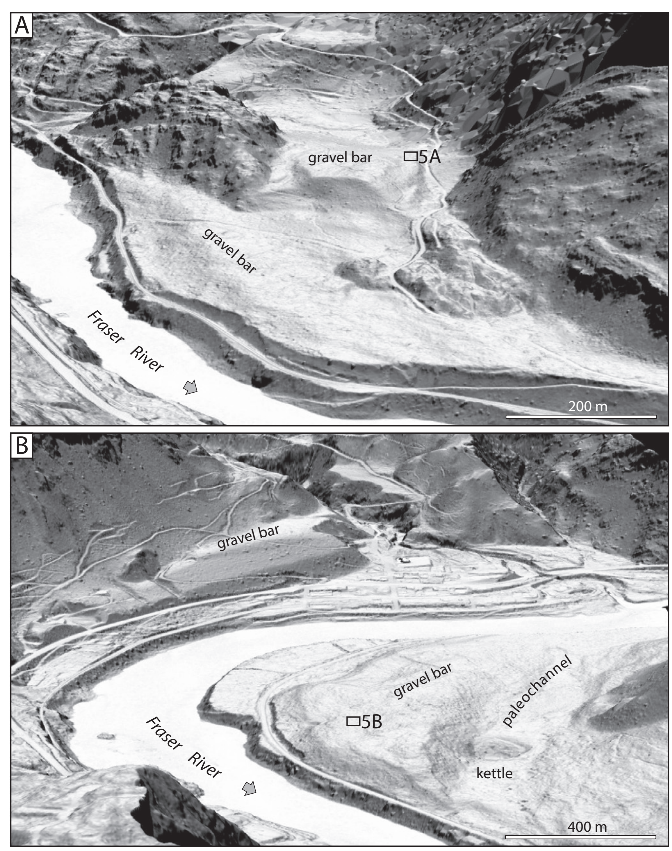

Fig. 6. Oblique slope-shaded lidar DEMs of large gravel bars A) south of Alexandria and B) east of Yale (both up-river views). Note paleochannel and kettle in B). The paleochannel probably was eroded, and a large ice block stranded at the site of the kettle, either during the waning stage of the Lake Fraser outburst flood or during a second flood. Gravel bars are present on both the east and west sides of Fraser River at Yale.

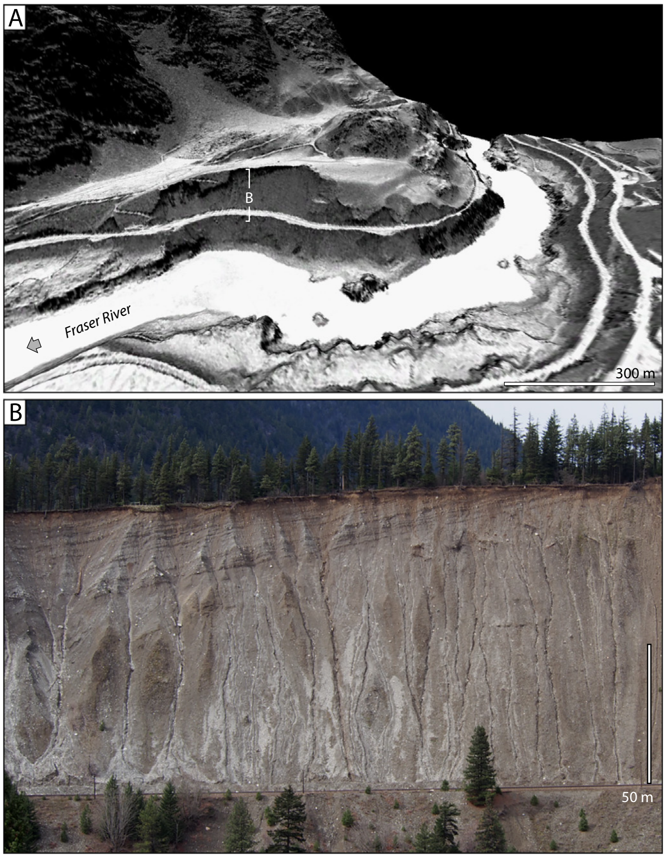

Fig. 7. A) Oblique slope-shaded lidar DEM and B) photograph of a flood bar and the gravel coring it on the west side of Fraser River, 13 km south of Lytton. Note the dipping planar beds of gravel that thicken in a downvalley direction away from an anchoring bedrock ridge. Sediments underlying the dipping beds, although poorly exposed, are weakly stratified and may also have been deposited by the flood. The height of the section above the railroad track (near bottom of photograph B) is about 100 m.

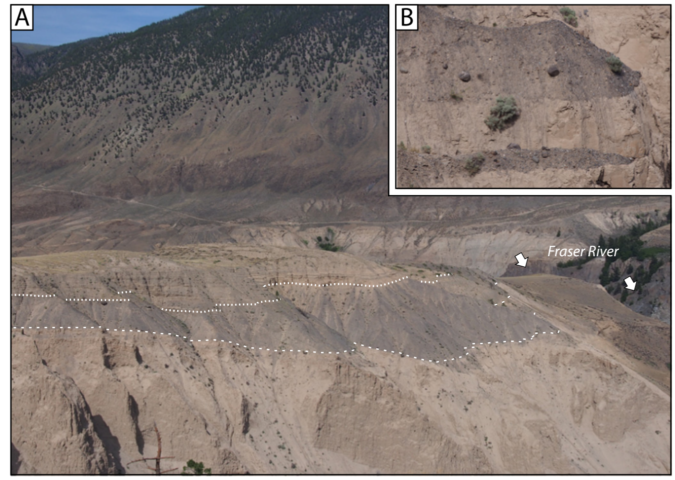

Fig. 8. Exposure of sediments underlying a gravel bar with a whaleback form on the west side of Fraser River, 16 km south-southeast of Big Bar Ferry. The exposure is located along a tributary stream that has incised through outburst flood sediments in an oblique direction to the longitudinal axis of the bar, which is parallel to Fraser River. The gray flood unit comprises up to 25 m of very poorly sorted, weakly stratified gravel with stones up to 2 m across (inset photo). It truncates a lacustrine silt unit (dashed line) >70 m thick and is overlain (dotted line) by weakly bedded, Holocene, paraglacial fan sediments. The sheet of flood gravel slopes downward toward Fraser River.

cobble-boulder gravel with rounded clasts up to 0.5 m in size. This downvalley-dipping gravel sequence appears to conformably overlie a poorly exposed body of pebble gravel, pebble-cobble gravel, and gravelly sand. Boulders up to 1.8 m across are scattered through this lower unit. The sediment is more poorly sorted than the overlying downvalley dipping gravels, but the clasts are also well rounded.

Another good exposure of sediments coring a gravel bar is on the west side of Fraser River 16 km south-southeast of Big Bar Ferry (Fig. 8). The crest of this bar is parallel to Fraser River and slopes gently downvalley; the transverse axis of the bar slopes toward the centre of the valley. A small stream has incised the bar, exposing up to 25 m of very poorly sorted, weakly stratified gravel with rounded to subrounded clasts up to 2 m across and rare large silt intraclasts. The gravel unit truncates a Pleistocene lacustrine silt unit that is >70 m thick. The erosional unconformity separating these two bodies of sediment drops about 50 m toward the centre of the valley over the 450 m length of the exposure to an elevation of 398 m asl, which is about 120 m above Fraser River.

A third example of sediments coring a gravel bar is located on the west side of Fraser River about 26 km south-southwest of Williams Lake (7 km south of the Highway 20 crossing of Fraser River). The site is near the northern edge of what we interpret to be the ice dam that impounded Lake Fraser. The bar extends downvalley from an anchoring bedrock ridge that extends part way across the valley. The crest of the bar dips downvalley from about 595 m asl to 535 m asl (~160–200 m above Fraser River). Its west flank dips gently toward the steep wall of the valley, and its east flank dips toward Fraser River, which has truncated the bar, providing a long exposure of the sediments that underlie it (Fig. 9). The bar is underlain by up to 70 m of very poorly sorted, pebble-cobble-boulder gravel containing intraclasts of till, silt, and sand, and rounded to subangular boulders up to 10 m across (Fig. 9). The lower, downvalley portion of the gravel bar is covered by up to 11 m of horizontally bedded and laminated silt and very fine sand, which extend up to an elevation of about 545 m asl, 170 m above the level of Fraser River.

Other gently inclined ridges and swaley benches cored by sediments that we attribute to a large flood are common throughout the study area. Notable examples are gently downvalley-sloping surfaces that are partly covered by postglacial paraglacial fan sediments about 20 km north-northwest of Lillooet and 5 km southwest of Pavilion (Fig. 10). Exposures of sediments underlying these streamlined surfaces are continuous over a distance of several kilometres at the edge of ~200-m-high escarpment dropping down to Fraser River. The sediments comprise up to 30 m of massive to weakly stratified, clast-supported gravel,[1] with rounded to subrounded stones up to 10 m across, as well as multi-metre intraclasts of a distinctive reddish brown till derived from the Marble Range to the north (Fig. 10A and B). The gravel unconformably overlies thick glaciogenic sediments that predate the Fraser Glaciation. The thickness and the caliber of the gravel decrease to the south (downvalley). Near the northern limit of the exposures, the uppermost streamlined surface steps down about 15 m to a lower surface on which an 8-m-long basalt block and many other metre-size boulders rest (Fig. 10C). The large basalt clast probably was derived from bedrock outcrops about 0.3 km to the north. Near the outer margin of the highest of the streamlined benches at ~491 m asl (265 m above Fraser River), we found several metres of foreset-bedded, granule gravel, sand, and sandy silt dipping up to 20° to the southeast. These capping sediments fine upward and likely were deposited near the local upper limit of the flood.

We interpret the ridged gravel bars to have formed during a large flood on the basis of: 1) their form; 2) position in the landscape; and 3) their constituent sediments. Specifically, many of the bars have a streamlined 'whaleback' form with a convex longitudinal axis that is oriented more-or-less parallel to the valley axis. The transverse axis of

[1] Because the gravel is very poorly sorted and contains outsized clasts, it might be termed 'diamicton'. We prefer to use the term 'gravel' because the sediment is clast-supported, the clasts are rounded to well rounded, and some of the sediment is crudely stratified.

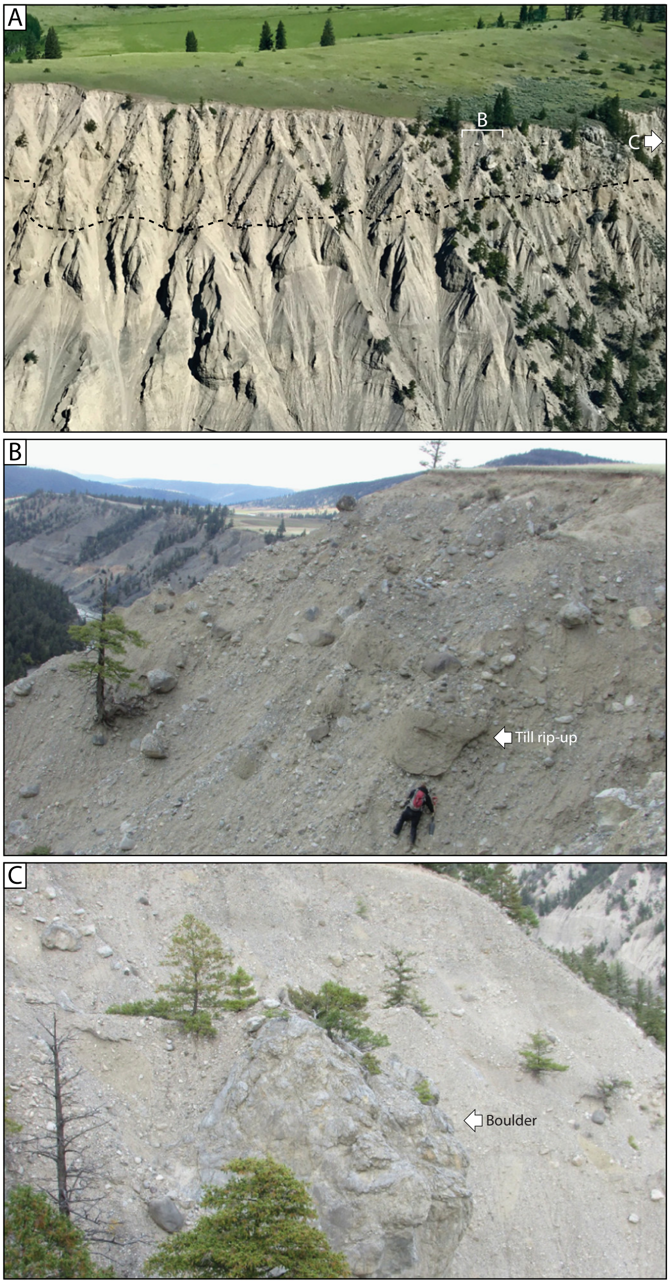

Fig. 9. Chaotic pebble-cobble-boulder gravel containing intraclasts of till and sand, and rounded to subangular boulders up to 20 m across in an exposure 7 km south of the Highway 20 bridge over Fraser River. A) Oblique view of bi-convex flood bar and underlying gravel unit. The base of the gravel is marked by a dashed line. B) Photograph of typical chaotic gravel with large boulders and till intraclasts; person at bottom for scale. The location of the photograph is shown in panel A. C) 10-m-high boulder within gravel. The approximate location of the photograph is shown in panel A.

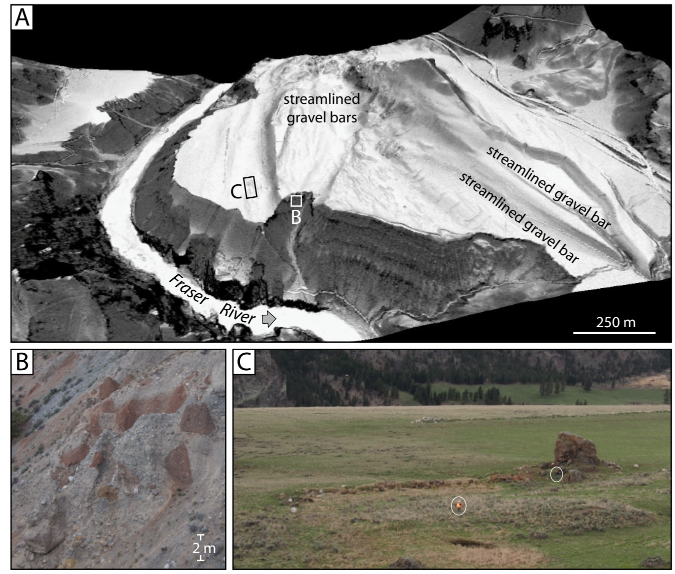

Fig. 10. A) Oblique slope-shaded lidar DEM of stepped flood-sculpted terrain on the east side of Fraser River, 5 km southwest of Pavilion. The flood deposits underlie a series of down-stepping streamlined gravel benches. B) Photograph of very poorly sorted, clast-supported gravel/diamicton with rounded to subrounded stones up to 10 m across and multi-metre intraclasts of a distinctive reddish brown till with a northern provenance. This sediment underlies the benched surface seen in panel A. C) A 15-m-long basalt block possibly transported by the flood and stranded on the lowest bench seen in panel A. One-metre-size boulders are common on this bench. Note circled people for scale. Locations of photos B and C are shown in panel A.

many of the bars is also convex. Their gradients are commonly much steeper than the modern Fraser River channel. As mentioned above, some of the bars are just downvalley of bedrock spurs or constrictions in the valley and in this sense are similar to expansion bars that are common within the flood track of the great Missoula floods (e.g., Bretz et al., 1956). The gravel bars lie above, and have a different morphology from, Holocene fluvial terraces that are common within Fraser Valley at and upriver of Hope. Unlike the gravel bars, fluvial terraces are planar and dip gently downriver, with a surface gradient nearly the same as that of the modern river channel. Sediments underlying the bars are also dissimilar to those underlying the Holocene fluvial terraces. The former are typically poorly sorted and contain boulders and sediment rip-up clasts, which in some instances are multi-metre in size. Most of these sediments are weakly stratified (a notable exception is the bar 13 km south of Lytton, illustrated in Fig. 7). In contrast, gravel underlying Holocene fluvial terraces is well sorted, horizontally bedded, and in many cases imbricated. The bar gravels overlie older sediments across an erosional unconformity. We infer that these older sediments were eroded by the floodwaters.

4.2. Upvalley-sloping terraces

We identified several planar terraces that dip gently (<5°) upvalley, opposite the present direction of river flow in the Fraser and lowermost Thompson valleys. A notable example is a 250-m-long terrace that slopes 1–2° north-northeast up Thompson River valley. The terrace is located about 1 km north of the Fraser-Thompson river confluence and 85 m above the level of modern Thompson River (Fig. 11). We could find no exposures beneath this terrace, but rounded clasts up to 0.9 m across are present on its surface.

Another possible example of upvalley-sloping surfaces exists on the south side of Fraser River, 5 km north of Lillooet. Two surfaces are located along a west-trending reach of the river between two wider, south-trending reaches. The upper surface is about 350 m long, slopes 3–4° upriver (northeast), and lies 160–180 m above Fraser River. The lower surface is also about 350 m long; it slopes 4–5° east-northeast and lies 111–145 m above Fraser River.

It is implausible that these upvalley-sloping terraces formed by normal fluvial deposition. Holocene fluvial terraces below these surfaces consistently slope downvalley with gradients approximately equal to that of the Fraser River (~0.1–0.2°). At the above-mentioned sites, there are no tributary alluvial or colluvial fans that might explain upvalley slopes. Accordingly, we attribute these surfaces to a large flood with water depths perhaps 100–200 m above present-day Fraser River. We hypothesize that the Thompson River terrace formed as the flood wave backed into lowermost Thompson Valley from Fraser Valley. Floodwaters coursing through the narrow, west-trending section of

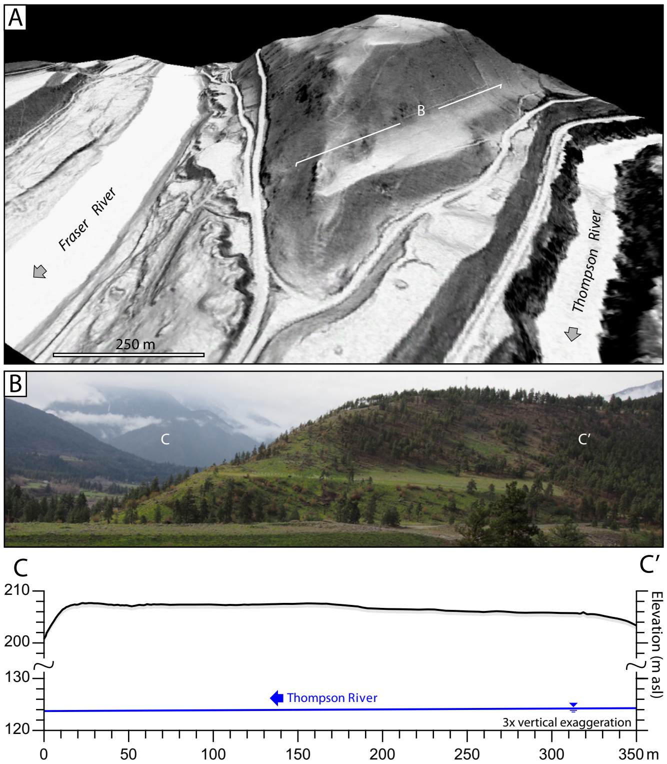

Fig. 11. A) Oblique slope-shaded lidar DEM, B) photograph, and C) topographic profile of a terrace in lowermost Thompson Valley. The terrace dips gently northeastward (toward the right), up the valley and is ~85 m above present-day Thompson River. We interpret the terrace to have formed by reverse flow of floodwaters from Fraser Valley into lowermost Thompson Valley.

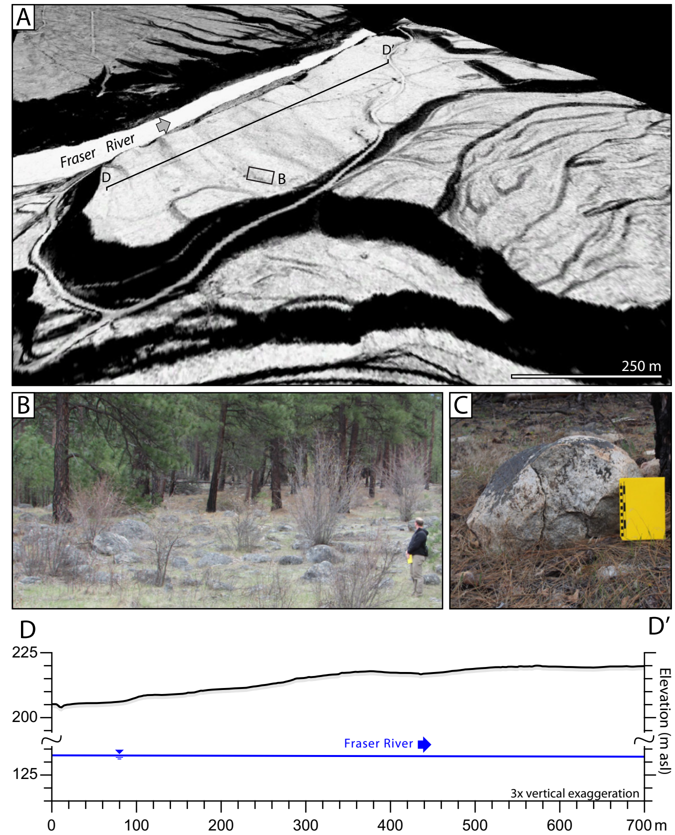

Fig. 12. A) Oblique slope-shaded lidar DEM of a Fraser River terrace ornamented with gravel dunes; view approximately to the east. The site is southeast of the mouth of Stein River (bottom of image) and 6 km north-northwest of Lytton. The average spacing of the ridges is 40 m, and relief from ridge crests to adjacent trough floors ranges from 0.5 to 2 m. B) and C) Photographs of boulders on the surface of the terrace; scale on the notebook in photograph C is 15 cm. Some boulders exceed 1 m in size. D) Topographic profile of the terrace. Profile and photograph locations are shown in panel A.

Fraser Valley 5 km north of Lillooet briefly ponded to unusually high levels, with localized upvalley transport of gravel.

4.3. Gravel dunes

We found fields of sinuous gravel ridges, which we interpret to be gravel dunes (or giant ripple marks) at three localities. One of the localities is a postglacial terrace on the west side of Fraser River southeast of the mouth of Stein River and 6–7 km north-northwest of Lytton. The terrace is about 80 m above the level of Fraser River and has an area of approximately 30 ha (Fig. 12). It is ornamented with subdued sinuous ridges and intervening troughs (Fig. 12A). Sediment underlying the sinuous ridges and troughs is rounded gravel; many of the stones on the surfaces of the terraces are >1 m across (Fig. 12B and C). The ridges are spaced about 40 m on average, and relief from ridge crests to adjacent trough floors ranges from 0.5 to 2 m. The axes of the ridges trend east-northeast, orthogonal to the local direction of Fraser Valley.

A second small field of sinuous gravel dunes is located 19 km southeast of Big Bar Ferry on the east side of the Fraser River valley. The ridges lie on the gently sloping flank of a small hill that is about 250 m above benched remnants of the Quaternary valley fill in this area and 450 m above the present level of Fraser River. The ridges are underlain by pebble-cobble gravel.

The third set of gravel dunes ornaments a gently westward-sloping bench on the west side of Fraser River north its confluence with Williams Lake River. They lie at elevations of 600–620 m asl, 200–220 m above Fraser River. These dunes, unlike the other two sets described above, are upvalley of the glacier dam that impounded Lake Fraser.

The gravel dunes resemble features found along the paths of the Lake Missoula and Lake Bonneville floods (Bretz et al., 1956; O'Connor et al., 2020), although they are smaller in both height and crest-to-crest spacing. Traction transport of boulders >1 m across, which is required to explain the duned surfaces at the mouth of Stein River, requires rapidly moving, valley-wide flow that, at least briefly, reached >80 m above present-river level. We attribute these dunes to the outburst flood from Lake Fraser. The extraordinary height of the third set of dunes, 19 km southeast of Big Bar Ferry, may be due a change in the orientation and narrowing (to <1.5 km) of Fraser Valley 6 km to the south. We hypothesize that this bottleneck induced short-lived, upvalley hydraulic ponding of floodwaters. Finally, the gravel dunes upvalley of the glacier dam, within the Lake Fraser basin, are similar to, although smaller than dunes that ornament the floor of the glacier-dammed lake that occupied the Kuray and Chuja basins in the Altai Mountains of Siberia in the Late Pleistocene (Baker et al., 1993; Carling et al., 2002; Agatova et al., 2020). This lake drained rapidly in a manner to similar to Lake Fraser, mobilizing sediment on the floor of the lake into dunes. Similar gravel dunes also occur on the former floor of glacial Lake Alsek in Alsek River valley above Lowell Glacier in the Yukon (Clague and Rampton, 1982, their Fig. 7). They formed in water depths approaching 100 m when Lake Alsek rapidly emptied following the failure of the glacier dam in the mid-1800s.

4.4. Sheet of very poorly sorted gravel at the mouth of Alkali Creek

A sheet of weakly stratified, very poorly sorted gravel underlies a bench at about 650 m asl on the northwest side of Alkali Creek near its confluence with Fraser River (Fig. 13A and B). The sheet is up to 15 m thick and comprises sandy pebble-cobble gravel with rounded to subangular stones up to 6 m across and brown diamicton intraclasts

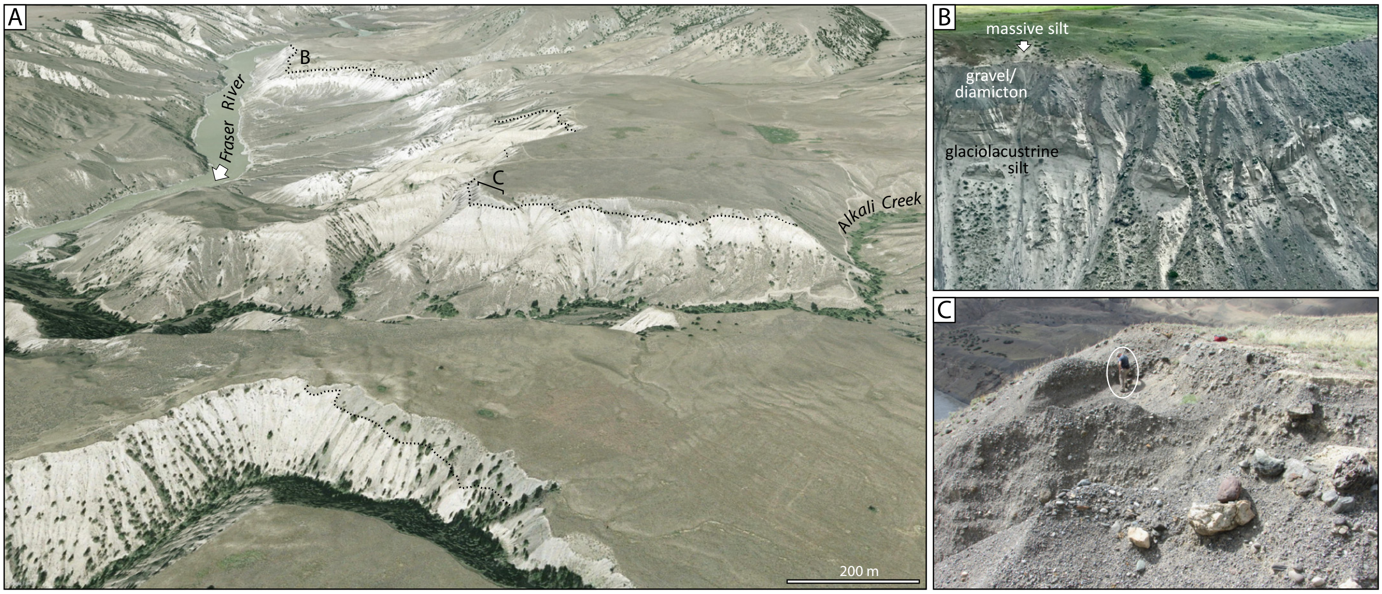

Fig. 13. A) Google Earth image of the sheet of very poorly sorted gravel on the northwest side of Alkali Creek near its mouth. The base of the unit is delineated by a dotted line. B) Photograph of gravel sheet, here up to about 15 m thick. The gravel unconformably overlies thick glaciolacustrine silt and is capped by to 5 m of massive clayey silt with discontinuous thin lenses of fine to very fine sand near its base. C) Photograph of typical gravel underlying the Alkali Creek bench; note circled person for scale. Rounded to subangular stones up to 6 m across and brown diamicton intraclasts up to 1 m across are surrounded by a 'matrix' of clast-supported sandy pebble-cobble gravel. Note downvalley-dipping gravel beds at this site. Photograph locations are shown in panel A.

up to 1 m across. Parts of the deposit are massive, but layers of better structured, clast-supported pebble-cobble gravel are common (Fig. 13C). At one site, the uppermost 2–3 m of the deposit contain striated and faceted clasts; no striated stones were found lower in the unit. The gravel sheet is thickest in exposures nearest Fraser River and thins and pinches out to the northeast away from the river (a distance of about 1 km). It has an undulatory surface with relief of up to 10 m.

In places, the gravel sheet is capped by up to 5 m of massive clayey silt. Discontinuous thin lenses of fine to very fine sand occur near the base of this silt unit. The gravel unconformably overlies a thick (>140 m) sequence of weakly bedded, glaciolacustrine silt that probably was deposited during the early stage of the Fraser Glaciation (Eyles and Clague, 1991; Huntley and Broster, 1994).

We traced the gravel sheet continuously over a distance of about 5 km along the east side of Fraser River from the Chilcotin-Fraser river confluence to south of the mouth of Alkali Creek. About 1.4 km northwest of Alkali Creek, the gravel sheet rises downriver, to the south, from an elevation of 490 m asl to the undulating bench at the mouth of Alkali Creek (650 m asl) (Fig. 13A). This 160-m rise is achieved over a horizontal distance of only 500 m.

The Alkali Creek gravel sheet is located within the footprint of the glacier lobe that impounded Lake Fraser. The presence of huge boulders, blocks, and diamicton intraclasts indicates transport by, and deposition from, a high-energy flow. The deposit blankets the steep slope 1.4 km north of the mouth of Alkali Creek, which we consider evidence that the flow was hydraulically confined. We hypothesize that the flow was confined to a large broad channel at the base of the glacier dam. The presence of striated and faceted clasts in the upper part of the gravel sheet may indicate that debris lodged at the base of the glacier was released from the roof of the subglacial channel. The flow ran up lowermost Alkali Creek valley and deposited the northeast-thinning gravel sheet on the benches on the northwest and southeast sides of the valley. As mentioned above, the gravel sheet has an undulating surface form; overall, however, the surface rises about 10 m, from 650 to 660 m asl, in an northeast direction up Alkali Creek valley (i.e., away from Fraser River). House-size blocks litter the ground at the far northeast end of the Alkali Creek bench and may mark the local margin of the glacier dam when Lake Fraser drained. Small closed-depressions on the Alkali Creek bench on both sides of the creek (Fig. 14A) may be kettles left when collapsed blocks of glacier ice melted.

4.5. Sand deposits

An 8-m-thick sequence of postglacial sand grades down into sandy pebble-cobble gravel beneath a bench on the north side of Fraser River, 2 km northwest of Hope. The bench surface is 55 m above the level of the river and 35–50 m above a flight of Holocene fluvial terraces on which the town of Hope is located. The bench lies below the projected upper limit of the flood where the Fraser River valley widens at Hope. No correlative surface is present west of Hope; in fact, the highest alluvial surface directly west of Hope is 50 m lower than the bench.

A second unusual deposit of sand was exposed in an aggregate quarry just south of the Trans-Canada Highway 11 km west-southwest of Hope (Fig. 14). The sand underlies a terrace, which, at about 58 m asl, is 27 m above Fraser River and is nested against the steep rising wall of the northern Cascade Range to the southeast. When the quarry was active, sediments were well exposed over a vertical range of 7 m from the quarry floor (40 m asl) to a level about 11 m below the terrace surface. They consist of beds of sand and pebbly sand with rare isolated stones up to cobble size (Fig. 14C). The lowest 2.5 m of sediment in the exposure is horizontally bedded. The upper 5 m consist of foreset beds dipping up to 15° to the southwest.

We link the two sand deposits described above to the Lake Fraser outburst flood. Both are surface deposits, located well above Fraser River (55 m and 27 m); they also postdate local deglaciation, although probably not by much given that Fraser River was flowing at its present level and building its delta out into Salish Sea in earliest Holocene time (Clague et al., 1983). The foreset-bedded sediments underlying the terrace south-southwest of Hope resemble megaflood sediments described elsewhere (e.g., Carling et al., 2009; Agatova et al., 2020). No correlative terraces are present in this section of Fraser Valley; instead, the gravelly floodplain of Fraser River extends from the rising southern margin of the Coast Mountains to the northern edge of the Cascade Range. The terrace is located just southwest of a bedrock slope that projects northward into the valley, which protected the sediments from erosion by the laterally migrating river.

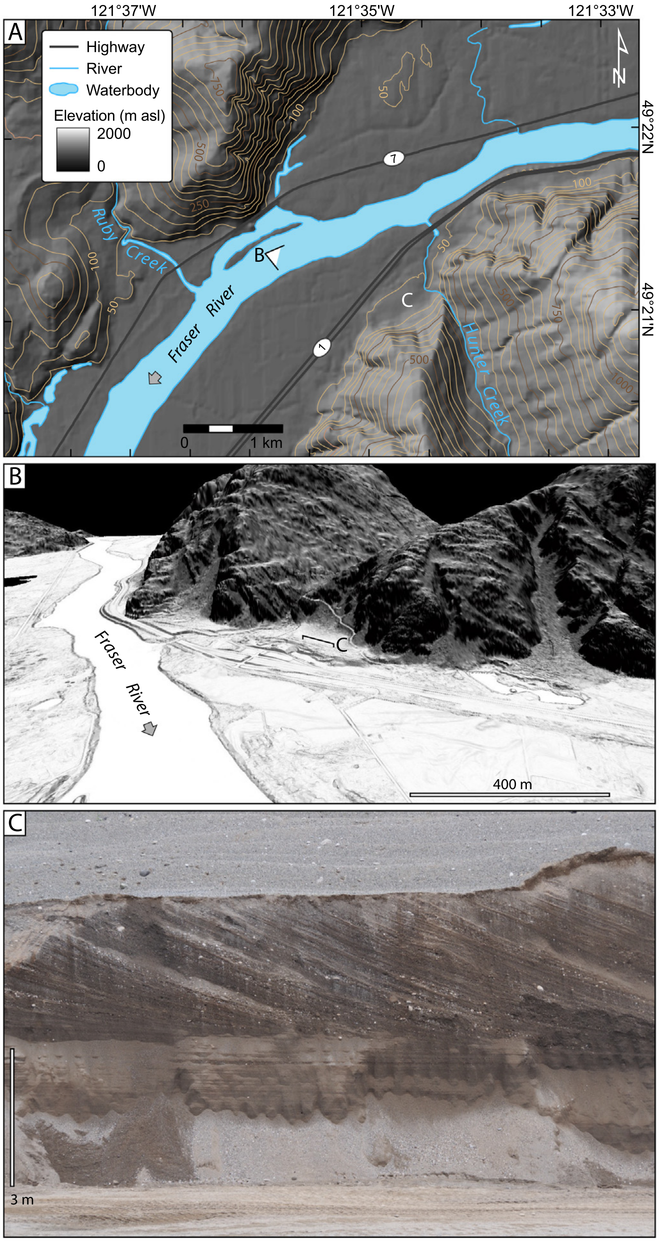

Fig. 14. Planar-bedded sand underlying a terrace just south of the Trans-Canada Highway, 11 km west-southwest of Hope. The terrace surface is 27 m above the level of Fraser River. A) Location of terrace (labeled 'C'). B) Oblique lidar hillshade image of the terrace and its environs. Direction of view is indicated in panel A. C) Planar cross-beds inclined up to 15° to the southwest, overlying horizontally stratified sand. The vertical bar at the left side of the photograph provides scale.

5. Stratigraphic evidence for a second lake phase

We also present evidence that the level of Lake Fraser fell suddenly from about 736 m asl to least 550 m asl near Williams Lake. Afterwards, a much smaller lake either persisted or formed anew in Fraser Valley due to a landslide that formed a barrier across the valley about 30 km south-southwest of Williams Lake. A key section to support of this assertion is the previously mentioned expansion bar 7 km south of the Highway 20 bridge over Fraser River and 2 km northeast of the landslide barrier (Fig. 9). At this site, up to 11 m of horizontally bedded, lacustrine silt and sand thin and pinch out to the north at an elevation of 550 m asl against flood gravel that forms the core of the bar (Fig. 15). The lacustrine sediments extend down Fraser Valley to the landslide barrier, onto which they lap (Fig. 16B). We could not find them farther downvalley, beyond the landslide barrier.

Debris of the landslide barrier is well exposed in a steep bluff on the west side of Fraser River over a distance of about 1.5 km (Fig. 16). It comprises up to 20 m of basalt blocks derived from Miocene basalts that underlie the plateau surface directly to the west up to about 980 m asl. The volcanic rocks below the plateau escarpment repeatedly failed during the Holocene, leaving a large hummocky deposit of colluvium on the slope below (Fig. 16A). Silt, sand, and rounded polylithic pebbles form the matrix of the landslide deposit in the exposures along the river. In exposures near the north end of the deposit, however, basalt blocks float within silt; the deposit there is matrix-supported. In places, the landslide deposit supports a veneer of stony silt containing rounded to subrounded polylithic stones, some of which are striated.

The landslide deposit overlies flood sediments left by the draining of Lake Fraser (Fig. 16B), thus the landslide postdates that event. The landslide may have occurred in a fully subaerial setting, although the debris appears to be isolated from the hummocky basaltic debris that mantles the slope to the west. Alternatively, it may have entered standing water or crossed the recently exposed lake floor. Finally, it is also possible that the landslide fell onto thin dead ice that was not completely removed by the Lake Fraser flood. In this scenario, the debris streamed toward the centre of the Fraser Valley, where it accumulated at the glacier margin or perhaps fell into crevasses in the thin ice and melted out. Support for this scenario is provided by the veneer of till-like stony silt that covers part of the landslide deposit.

The existence of a second lake phase is supported by landforms and valley-wall exposures near the confluence of Williams Lake River and Fraser River, 8 km west of Williams Lake. Remnants of a Gilbert delta are preserved on both the north and south sides of Williams Lake River at this locality. The delta is graded to a water plane with an elevation of 550 m asl and comprises gravelly topset and angular and tangential foreset beds; the foreset beds dip up to about 15° west, toward Fraser River (Fig. 17). The delta sequence overlies up to 2 m of horizontally laminated and thin bedded lacustrine sand that, in turn, overlie up to 4 m of very poorly sorted, planar-bedded pebble-cobble gravel dipping up to 20° to the east, up the Williams Lake River valley. We interpret this last unit to be gravel deposited during the draining of Lake Fraser, prior to the construction of the Gilbert delta at ~550 m asl. The thin lacustrine sand unit is interpreted to have been deposited in the re-formed lake in which the Gilbert delta was built. A remnant of another gravelly Gilbert delta similar to that at the mouth of Williams Lake River, and at the same elevation, is present at the mouth of Chimney Creek, 11.5 km to the south.

6. Age of the flood

^{10}Be ages for nine boulders at the three sample sites range from 9.4 to 13.1 ka (Fig. 18, Table 1). Taking into account the uncertainty ranges of the individual ages, seven of the nine boulders have statistically equivalent ages, suggesting that the flood probably happened sometime between about 10.5 and 12.5 ka (Fig. 18). The median of all nine ages is 11.1 ± 0.6 ka BP.

A radiocarbon age on wood just below the lower of the two flood layers in one of the Saanich Inlet ODP cores provides a maximum calendric age of 11.4–12.0 ka for the first of the two floods documented by Blais-Stevens et al. (2003) (Fig. 18). The age of the first flood in the ODP cores is further constrained by a calibrated, reservoir-corrected age on shell fragments in sediment between the two flood layers of 10.6–11.8 ka (Fig. 18). Finally, the oldest reservoir-corrected shell ages just above the upper flood layer have calibrated age ranges of 10.8–12.3 ka (Fig. 18).

Given that our TCN ages for the flood are in agreement with the age constraints provided by the Saanich Inlet cores, we conclude that the flood from Lake Fraser left at least one of the anomalous flood beds in Saanich Inlet and that this flood happened at the end of the last glaciation.

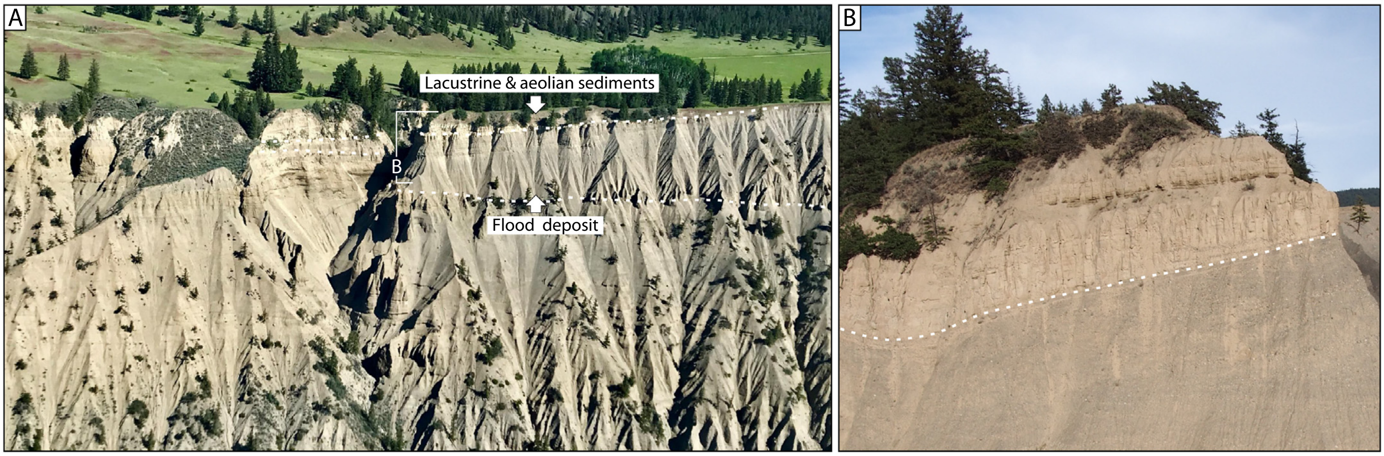

Fig. 15. A) Photograph of horizontally bedded, lacustrine silt and sand overlying outburst flood gravel on the west side of Fraser River, 7 km south of the Highway 20 bridge; view to the north-northwest. B) Close-up photograph of the lacustrine sediments, which are up to 11 m thick in this exposure. The location of photograph B is shown in A. The lacustrine sediments indicate that a lake with a surface elevation of about 550 m asl persisted or, alternatively, re-formed after the outburst flood.

7. Discussion

7.1. Style and pattern of deglaciation leading to the flood

Near the end of the Pleistocene, the Cordilleran ice sheet separated from the Laurentide ice sheet and retreated along all its margins. It thinned over the British Columbia interior, resulting in initial top-down wasting with increasing topographic control on ice flow (Fulton, 1967, 1991; Clague, 2017). Ice was mainly sourced in the Coast Mountains to the west. With continued thinning, ice sourced in the Rocky, Cariboo, Selkirk, and Purcell mountains separated from ice flowing from the Coast Mountains, and the Interior Plateau between these mountain systems became increasingly free of ice. As glaciers issuing from the central Coast Mountains retreated to the west and southwest, Lake Fraser expanded to the south along the Fraser River valley, eventually to the area near Williams Lake. At that time, lower Fraser Valley north as far as Big Bar Ferry was also ice-free. The tongue of glacier ice that extended across Fraser Valley from about Big Bar Ferry on the south to near Williams Lake on the north impounded Lake Fraser. This ice lobe further thinned, and eventually Lake Fraser emptied or nearly emptied, probably through one or more subglacial channels. Evidence for subglacial flow includes the aforementioned 160 m vertical rise of the flood gravel near the mouth of Alkali Creek and its deposition as a gently undulating sheet on the benches north and south of the creek. The restriction of striated and faceted clasts to the upper part of this gravel sheet supports this interpretation, as they can be explained by release of debris from the roof of the subglacial channel.

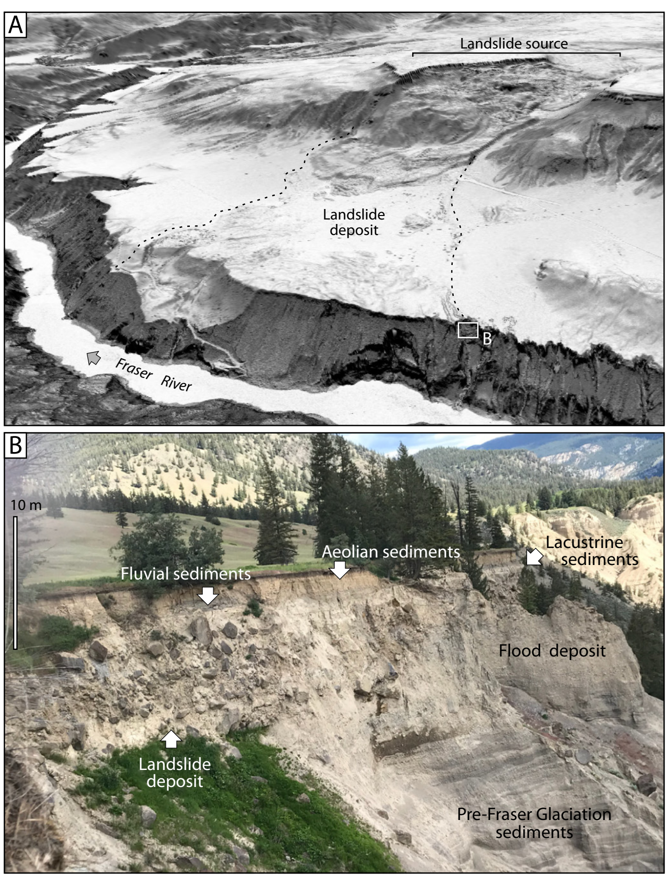

Fig. 16. A) Oblique slope-shaded lidar DEM and B) photograph of the landslide deposit about 9 km south of the Highway 20 bridge (ca. 2 km south of Fig. 15). The margin of the landslide is delineated by a dashed line. The blocky landslide debris overlies flood deposits and is successively overlain by lacustrine silt, fluvial gravel, and aeolian silt and sand. The flood deposits unconformably overlie a thick body of pre-Fraser Glaciation stratified sand and gravel (lower right portion of panel B).

After this flood, a remnant of Lake Fraser, or perhaps a new lake, stabilized at an elevation of about 550 m asl north of the landslide barrier south of the Highway 20 bridge (Figs. 15 and 16). A lake at this elevation would reach northward past the present town of Quesnel. This lake emptied due to incision of the landslide dam and the underlying sediment fill below the Highway 20 bridge. Unlike the first draining, it is unclear whether the second draining was sudden or gradual. We note, however, that flood-scoured surfaces at several sites are nested inset into higher flooded surfaces. It is possible that they record a slightly younger and smaller flood than the first one, although we cannot rule out the possibility that the lower surfaces are products of the waning stage of a single flood.

7.2. Morphology of Fraser Valley immediately before the flood

We have few constraints on the immediate pre-flood river level in Fraser Valley below Williams Lake. Flights of postglacial fluvial terraces are present in places along Fraser River. Because they postdate the flood, the highest terraces presumably provide constraints on the level of the valley floor at the time of the flood. We have not yet exploited this indirect body of pre-flood river level evidence, but we note that post-flood Fraser River fluvial gravels extend to elevations of 530 m asl, 165 m above modern river level downstream of the landslide barrier south of the Highway 20 bridge. Furthermore, remnants of sediments that predate the Last Glacial Maximum and that are covered by flood deposits

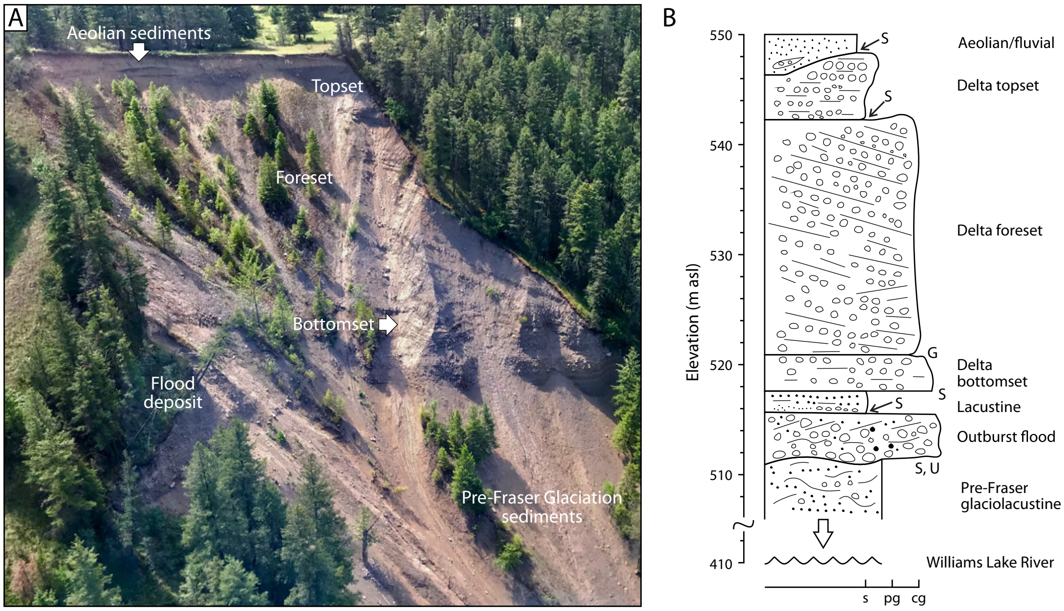

Fig. 17. A) Photograph and B) stratigraphic log of an exposure through a Gilbert delta at the mouth of Williams Lake River. Deltaic sediments are underlain, successively, by a thin lacustrine silt/sand unit, a poorly sorted gravel unit that dips up the valley of Williams Lake River, and thick glaciogenic sediments that predate the Fraser Glaciation. We attribute the gravel unit to draining of Lake Fraser. Symbols in B: s = sand, pg = pebble gravel, cg = cobble gravel; G = gradational contact, S = sharp contact, U = erosional unconformity.

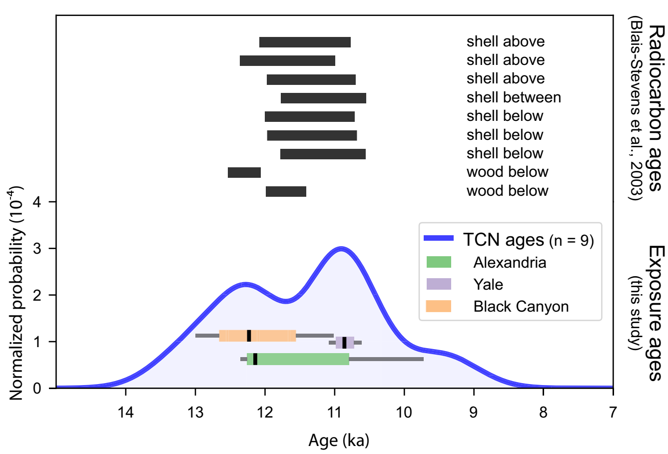

Fig. 18. Comparison of numerical ages that constrain the time of the Lake Fraser outburst flood. The plot shows calibrated radiocarbon ages that closely delimit the age of the flood beds in Saanich Inlet and ^{10}Be ages on flood boulders at three locations in Fraser Valley. Radiocarbon ages are reported in Blais-Stevens et al. (2003) and were calibrated using CALIB 7.1 (Stuiver et al., 2020). We assume a marine reservoir correction of 400–500 years based on comparison of the younger wood age and an age on shell from the same stratigraphic level. ^{10}Be ages are represented with boxplots that show median (black, vertical bar), interquartile ranges (25–75%), and whiskers (5–95%) (see Table 1 for details on these ages).

extend well above present river level. Nevertheless, the base of the flood deposit is an unconformity, and the flood likely deeply eroded the pre-existing valley fill. Based on limited evidence, we hypothesize that the Fraser Valley floor just before the flood was higher than it is today (Fig. 19), and that over the 11,000 years since the flood, Fraser River has greatly deepened its valley.

We are unable to calculate a reliable peak discharge of the Lake Fraser flood anywhere along the flood path because of uncertainties in the pre-flood Fraser River level, the exact southern limit of the glacier dam, and likely hydraulic ponding above constrictions along the flood path. However, minimum heights of the upper limit of the flood above the river, based on the landforms described in this paper, provide a sense of the size of the flood (Fig. 19, Table 2).

7.3. Passage of the flood wave

The flood was confined within Fraser Valley, although differences in the width and direction of the valley had a marked effect on the passage of the flood wave, with implications for erosion and deposition. Notably, the narrowest valley reaches, where the floodwaters were most erosive, are largely devoid of sediments. In contrast, some of the most spectacular gravel ridges are located just downvalley of these narrow reaches, where the valley broadens and flow velocity and depth decreased (e.g., at Yale). Upstream of valley constrictions, floodwaters achieved their maximum depths due to hydraulic ponding. Localized hydraulic

Table 1
^{10}Be surface exposure metadata and ages.

Sample locality	Latitude (°N)	Longitude (°W)	Elevation (m asl)	Shielding	Carrier (mg Be)	Quartz (g)	^{10}Be/^{9}Be	±	Be-10 (atoms g^{-1})	±	Age	±[a]
Yale	49.5544	121.4333	98	0.9947	0.2415	20.0955	5.59E−14	2.28E−15	4.43E+04	1.90E+03	10,592	456
	49.5547	121.4333	97	0.9715	0.2389	19.8479	5.58E−14	2.44E−15	4.43E+04	2.03E+03	10,855	499
	49.5544	121.4335	97	0.9941	0.2415	20.0356	5.83E−14	2.11E−15	4.64E+04	1.78E+03	11,106	427
Alexandria	49.6833	121.4047	175	0.9833	0.2404	20.1462	6.90E−14	3.47E−15	5.45E+04	2.83E+03	12,375	645
	49.6831	121.4051	175	0.9822	0.2398	14.9413	5.07E−14	2.12E−15	5.36E+04	2.36E+03	12,141	536
	49.6842	121.4044	175	0.9822	0.2417	15.0048	3.98E−14	2.02E−15	4.21E+04	2.24E+03	9446	504
Black Canyon	49.7448	121.4205	134	0.9373	0.2381	20.1364	6.35E−14	2.14E−15	4.96E+04	1.77E+03	12,232	438
	49.7448	121.4205	134	0.9373	0.2415	20.2568	5.66E−14	2.11E−15	4.45E+04	1.75E+03	10,883	429
	49.7447	121.4205	134	0.9373	0.2415	19.8724	6.55E−14	2.45E−15	5.26E+04	2.08E+03	13,090	519

[a] Approximately 2σ uncertainty.

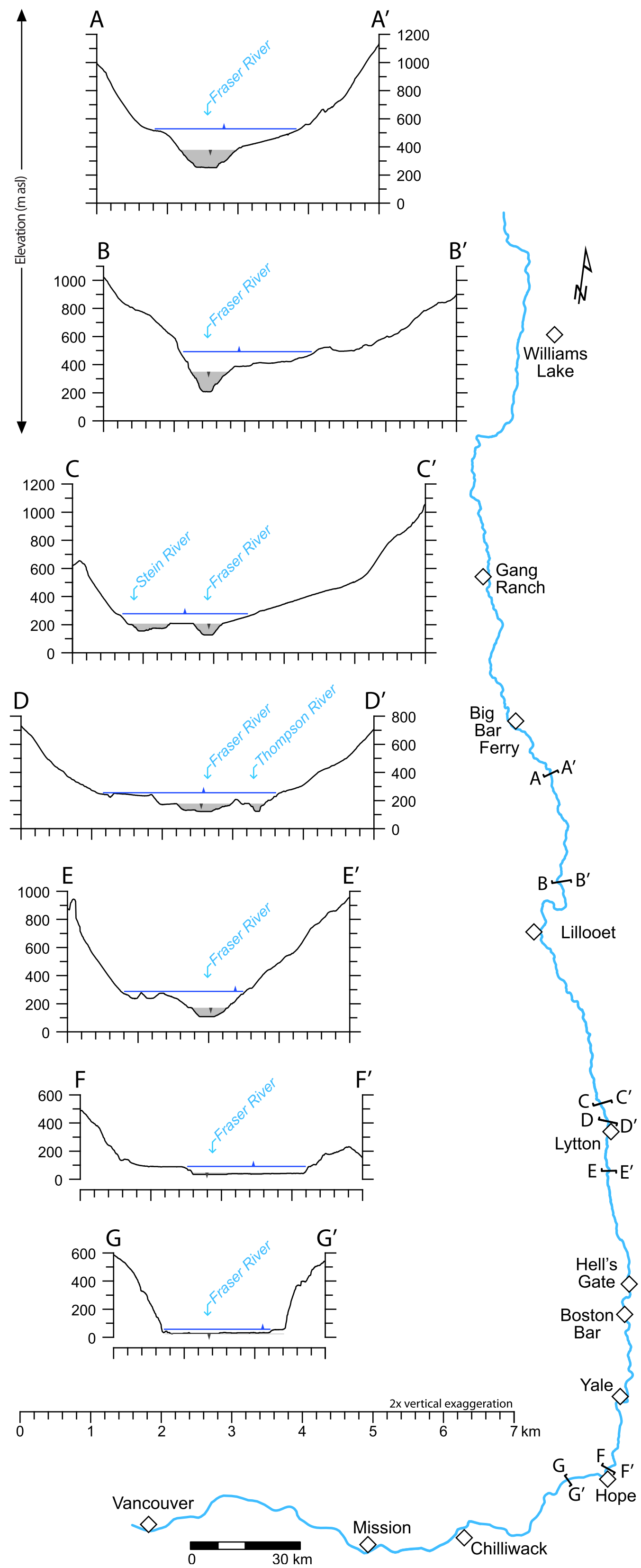

Fig. 19. Selected cross-valley transects along the flood path showing present topography and minimum inferred upper limits of the flood based on the data in Table 2. Arrowheads indicate that flood elevations and paleo-valley floor elevations at the time of the flood are minimum values. Locations of profiles are shown in Figs. 2 and 3.

ponding would have extended the duration of the flood wave, although by an unknown amount. The sand deposits west of Hope (Fig. 14) and flood-scoured surfaces in the Fraser Lowland near Lynden, Washington, and Fort Langley, British Columbia (Fig. 20), are located in areas where the floodwaters traversed a broad lowland and were much less constrained than in the canyon north of Hope. They imply that the floodwaters impacted a large area of the Fraser Lowland from Hope to Vancouver (see Section 7.6).

7.4. Formation of flood bars

Some of the best evidence for the large flood in Fraser Valley are the numerous large gravel bars, many of which are armored with large boulders and are underlain by chaotic gravel with huge outsized stones and rip-up clasts of till and glaciolacustrine sediment (Figs. 8, 9, and 10). Preservation of large soft-sediment intraclasts in gravel with stones many metres in diameter has implications for the nature of the flow that deposited the sediment. The intraclasts could not survive even short transport distances as individual particles in traction at the base of a flood flow. Isolated multi-metre boulders within clast-supported pebble-cobble gravel are also inconsistent with typical traction transport.

We hypothesize that the intraclasts and large stones were carried in a hyperconcentrated flow (a mobile traction carpet) at or near the base of a tall, rapidly flowing water column. Fisher (1983) and Pierson (2005) argued that coarse particles in the lower part of a hyperconcentrated flow move together, *en masse*, rather than individually through rolling and bouncing as they do during a water flood. The existence of traction carpets in some high-energy flows has been supported by experimental, observational, and sedimentological studies (Postma, 1986; Sohn, 1997; Lowe and Guy, 2000; Calhoun and Clague, 2017). As particle concentrations increase, the fluid dynamics of the flow change from Newtonian to non-Newtonian (Pierson, 2005), and the increase in particle concentration dampens turbulence (Bagnold, 1966; Sohn, 1997). Based on laboratory experiments, Sohn (1997) argued that the lowest part of some hyperconcentrated flows has the rheology of a debris flow.

We further hypothesize that the gravel bars are a product of both deposition and erosion. Deposition of chaotic gravel with large rip-up clasts and boulders was followed by erosion that sculpted streamlined bars over a brief period following the flood peak.

7.5. Differences between the Lake Fraser flood and other well documented large floods

Several differences between the Lake Fraser flood and well documented Late Pleistocene megafloods (Missoula, Altai, and Bonneville) may account for differences in their preserved landform and sediments. First, the Lake Fraser flood was confined over most of its length to a deep and narrow valley. In contrast, the Missoula floods travelled mainly over a plateau surface (Columbia River Plateau). The sections of the Missoula flood path that are valleys (Columbia River valley and Columbia Gorge) are much wider than Fraser Valley. Differences in flow depth and width could produce differences in the preserved sediment and landform records of these floods. Nevertheless, gravel dunes similar to those documented near the mouth of Stein River are present within Columbia Valley at West Bar, Washington (Bretz et al., 1956). Second, cataracts and scablands, which are not present along the Lake Fraser flood path, are common along the path of the Missoula and Bonneville floods, where they are a product of the geology traversed by those floods – a thick stack of layered, columnar-jointed, Miocene basalts susceptible to plucking by floodwaters. In contrast, Lake Fraser floodwaters flowed mainly over unconsolidated Quaternary sediments; bedrock reaches are resistant granitic, metasedimentary, and metavolcanic rocks. Third, the Missoula flood tract is the product of >100 outburst floods (Waitt, 1980, 1985; Atwater, 1984, 1986), and multiple floods shaped the Kuray flood tract in Siberia (Agatova et al., 2020). The glacial Lake Fraser

Table 2
Estimates of flood depths at selected cross-sections.

Cross-section[a]		Distance from Fraser River mouth (km)	Minimum upper level of flood (m asl)[b]	Present level of Fraser River (m asl)	Inferred pre-flood level of valley floor (m asl)[c]	Estimated minimum flood depth (m)[d]
A–A′	South of Big Bar Ferry (Fig. 8)	383.7	540	252	<381	>159
B–B′	West of Pavilion (Fig. 10)	350.8	492	208	<350	>142
C–C′	Stein River (Fig. 12)	271	278	127	<200	>78
D–D′	Mouth of Thompson River (Fig. 11)	265.7	256	122	<178	>78
E–E′	South of Lytton (Fig. 7)	251.4	288	108	<171	>117
F–F′	Hope	157.4	91	35	<40	>51
G–G′	West of Hope (Fig. 14)	144.5	57	27	<20	>30

[a] Locations shown in Figs. 2 or 3.
[b] Assumes minimum 10 m water column above crest of flood bar or dune.
[c] Column 6 minus column 3.
[d] Column 5 minus column 3.

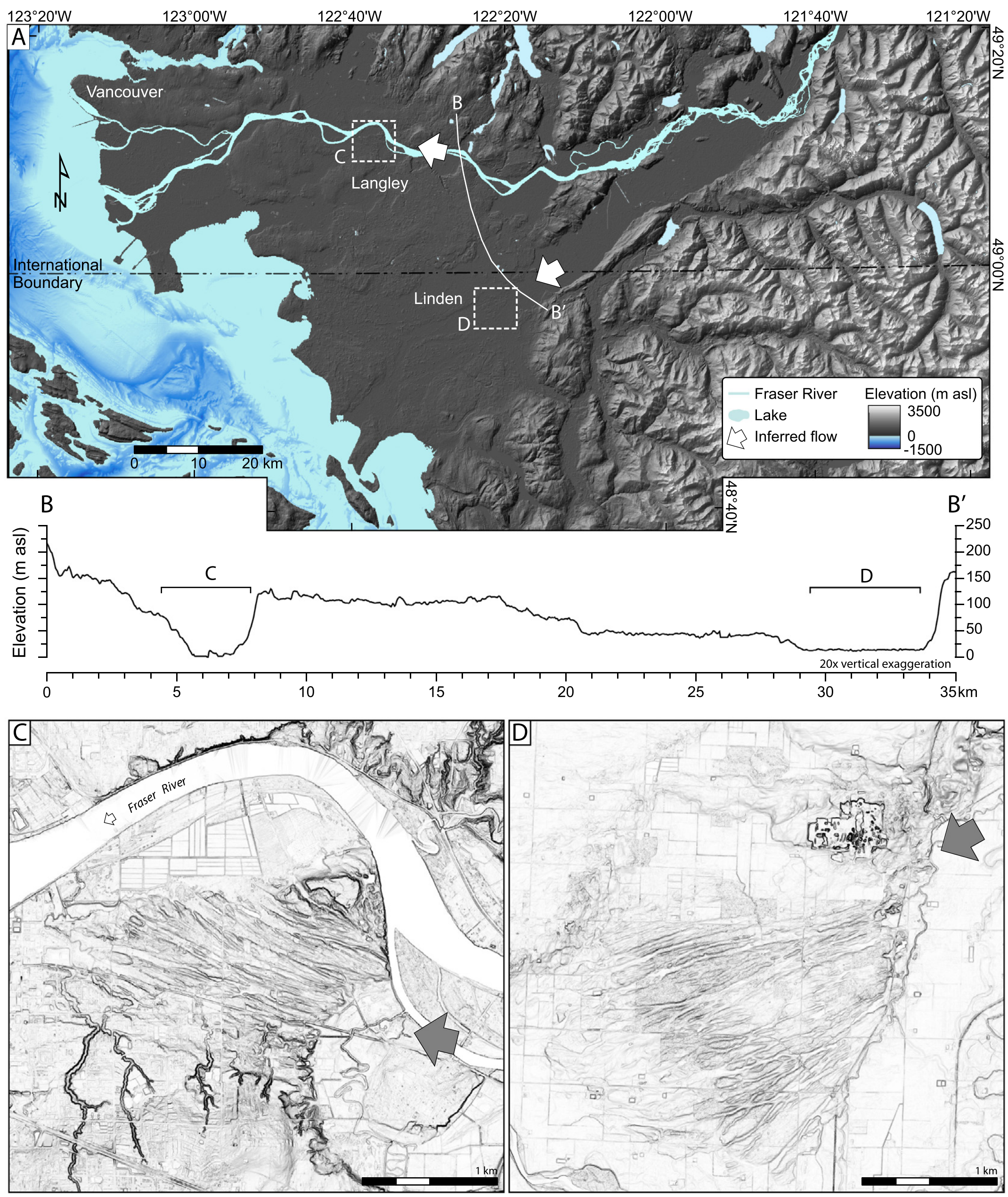

Fig. 20. A) Hillshade DEM of the Fraser Lowland derived from a 1-arcsecond SRTM DEM, showing the locations of two tracts of flood-scoured terrain (C and D). B) Topographic profile across the Fraser Lowland showing the locations of the two flood-scoured tracts within low areas in the landscape. The location of the profile is shown in panel A). C) Flood-scoured tract near Fort Langley, British Columbia. D) Flood-scoured tract just south of the International Boundary near Lynden, Washington (see Kovanen et al., 2020, p. 37). Late Glacial glaciomarine sediments (Easterbrook, 1976; Armstrong and Hicock, 1980; Lapen, 2000) underlie the two flood tracts. Note that the ridges and troughs within the two tracts fan out to the west (panel C) and southwest (panel D), consistent with the floodwaters travelling in those directions.

flood was a singular event. The numbers of floods affects the scale of the flood-eroded landscapes in the three areas. Fourth, the Missoula, Altai, and Bonneville floods travelled across unglaciated landscapes, whereas the Lake Fraser flood flowed across land that had been covered by an ice sheet until that flood happened. Slopes along the Lake Fraser flood path were blanketed by freshly deposited glacial sediments. After the flood, these sediments were mobilized and redeposited as large paraglacial colluvial fans and aprons (Ryder, 1971a, 1971b) that buried much of the evidence of the flood (Fig. 4). Fifth, with the exception of the surface at the mouth of Thompson Valley, we found no remnants of upvalley-sloping flood sediment fills in Fraser Valley tributaries. Such fills are present along the paths of the Missoula, Altai, and Bonneville floods and might be expected at the mouths of Fraser Valley tributaries. However, most of the Fraser Valley tributary valleys below the inferred ice dam (e.g., Nahatlach and Stein rivers valleys, Fig. 2) are narrow, steep-sided, and drained by energetic streams that may have removed such evidence over the course of the Holocene. The well documented tributary sediment fills left by the Missoula floods are confined to three very large (3–20 km wide) tributary valleys (Walla Walla, Yakima, and Willamette valleys), which are located upvalley of constrictions in the flood path (Wallula Gap in the first two cases and a right-angle bend in the flood path in the third case). There are no such large, strategically located valleys to capture and retain flood sediments in the case of the Lake Fraser flood, with the exception of Seton River west of the town of Lillooet. It is possible that this valley was occupied by a valley glacier at the time of the flood, but further study is warranted. In the Missoula case, there is a giant bar across Moses Coulee, but Columbia Valley at this site is wide and the bar itself is the product of many floods, not one.

Perhaps the best analog of the Lake Fraser flood is the Late Pleistocene Bonneville flood sourced from pluvial Lake Bonneville in Utah (O'Connor, 1993; O'Connor et al., 2020). It too was a single event, and it discharged through a canyon, although the Bonneville flood traversed unglaciated terrain unlike the Fraser flood. The total amount of water discharged during the Bonneville flood was much larger than the volume discharged from Lake Fraser (Lake Bonneville held about 10,000 km^3 of water (O'Connor et al., 2020), whereas Lake Fraser had a volume of ~500 km^3). Lake Bonneville, however, did not completely empty during its outburst. Differences in the size and type (sediment vs. glacier) of the dams indicate that the peak discharge of the Bonneville flood was much higher than that of the Fraser flood.

7.6. Possible effects of the flood on the Fraser Lowland and Salish Sea

The flood from Lake Fraser entrained large amounts of sediment as it moved southward down the Fraser River valley from the glacier dam. Based on exposures existing today, we infer that the Fraser River valley contained thick Late and Middle Pleistocene glacial deposits (Clague, 1987; Eyles et al., 1987), as well as sediments deposited during and shortly after local deglaciation but prior to the flood. The floodwaters eroded some of these sediments and carried the sand-, silt-, and clay-size fraction and much of the gravel into the Fraser Lowland west of Hope. We are unable to provide a reliable estimate the volume of sediment transferred from the Fraser River valley into the Fraser Lowland because the configuration of the valley above Hope immediately before the flood is uncertain.

At the time of the flood, most or all of the Fraser Lowland was ice-free (Clague, 1981, 2017). Glacio-isostatic rebound of the land surface, newly freed from the load of ice, was nearing completion – sea level in the Vancouver area was near its present level when the flood happened (Mathews et al., 1970; Clague et al., 1982; Hutchinson et al., 2004). The Fraser River delta had not yet begun to build seaward past a constriction in the Pleistocene uplands at New Westminster, and an arm of the sea perhaps extended upvalley from this point into what is now Pitt Lake (Clague et al., 1983). The flood may have filled this seaway with sediment, allowing Fraser River to begin to build its delta out into Salish Sea by 10,000 years ago (Clague et al., 1983). Much of the finest sediment carried by the floodwaters was deposited in Salish Sea (Conway et al., 2002). We surmise that the flood is recorded by an abrupt boundary in acoustic profiles collected in Salish Sea during marine geophysical surveys conducted in the 1970s and 1980s (Clague, 1976, 1977; Tiffin and Clague, 1976).

8. Conclusion

A large flood travelled down the Fraser River valley, across the Fraser Lowland, and into Salish Sea in southwest British Columbia near the Pleistocene Termination. The flood resulted from the sudden draining of glacial Lake Fraser, which was impounded by a glacier dam that blocked Fraser Valley over a distance of about 100 km north of Big Bar Ferry in central British Columbia. Lake Fraser had an area of ~7500 km^2 and was roughly 200 m deep at the dam when the flood happened. Landforms that we attribute to the flood include boulder-strewn gravel bars and dunes, as well as terraces sloping up the Fraser and lowermost Thompson valleys. Gravel bars are underlain by sheets of massive to weakly bedded gravel containing rip-up clasts of silt and till as well as boulders up to 15 m across.

Immediately after the flood, a bedrock rockslide blocked Fraser Valley near the northern limit of the glacier dam and impounded a lake to about 550 m asl, >250 m below the maximum level of Lake Fraser. This lake soon emptied due to overtopping and incision of the landslide dam.

The large flood from Lake Fraser trenched the older sediment fill in Fraser Valley and transported much of this sediment out of Fraser Canyon and west of Hope. Much of this sediment was deposited in Salish Sea and likely played an important role in the postglacial progradation of the Fraser River delta. Two tracts of flood-scoured Late Glacial glaciomarine sediments in the Fraser Lowland one near Fort Langley and a second near Lynden, Washington - likely record passage of the flood.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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