

Supplementary content: subglacial lake reconstruction

1. Methodological approach

The formation of the Chasm and Green Lake meltwater corridors implicate the rapid delivery of large volumes of water from a subglacial and/or supraglacial lake(s). The coincidence of lake sediments with the heads of the Chasm and Green Lake meltwater corridors (Fig. 5) suggests a subglacial lake may have been present within the Dog Creek Basin (DCB) (near the confluence of Dog Creek (DC) and Pigeon Creek (PC), Fig. S1a). Consequently, we test whether a subglacial lake could have existed within DCB using loosely constrained conditions for: 1) magnitude and azimuth of ice surface slope; 2) glacioisostatic tilt of the former ice sheet bed; 3) the proposed subglacial spillway elevations for the lake (meltwater corridors); and 4) the amount of glacial advance stage valley fill. Subglacial lake reconstruction was deemed successful (“optimal conditions”) where: 1) it stored more water (within a single lake) than the combined bankfull volume (see footnote * of the manuscript) of the Chasm and Green Lake canals; 2) the extent of the single lake allowed direct connection to the heads of the Chasm and Green Lake meltwater corridors; 3) subglacial hydraulic potential was directed toward the corridors; and 4) the input parameters are a reasonable glaciological reconstruction for the southern Fraser Plateau.

2. Calculating glaciological parameters

2.1 Subglacial lake surface slope

Subglacial lake surface slope (α_{water}), which is ~11 times that of the ice surface, may be calculated using the following equation (cf. Scambos et al., 2011):

$$\alpha_{water} = -\alpha_{ice} \frac{\rho_{ice}}{(\rho_{water} - \rho_{ice})}$$

(1)

Where α_{ice} is ice surface slope, and ρ_{water} and ρ_{ice} are the densities of ice (917 kg/m³) and water (1000 kg/m³), respectively. The subglacial lake extent is projected by pinning the lake edge to the spillway(s) and then tilting the water surface from this spillway, by the slope value calculated using equation 1, in an opposite direction to that of the ice surface slope. The underlying digital elevation model (DEM) is then subtracted from the tilted lake surface plane so that positive values represent ponded water. This lake extent can then be iteratively fit to the optimal conditions by varying: 1) glacioisostatic tilt of the underlying DEM (ice bed interface); 2) the ice surface slope; 3) valley fill elevation; and 4) the elevation and location of the lake spillway(s).

2.2 Hydraulic potential

In order to test the plausibility of water storage within DCB, hydraulic potential (φ) is calculated using the following equation (cf. Flowers and Clarke, 1999):

$$\varphi = f\rho_{ice}gh_{ice} + \rho_{water}gz_{base}$$

(2)

Where f is the flotation factor that reflects the state of the subglacial drainage system as either distributed ($f \approx 1$) or efficient ($f \approx 0$) (Flowers and Clarke, 1999), g is the acceleration due to gravity (9.81 m/s²), h_{ice} is the ice thickness (derived from the difference between the ice surface and underlying DEM elevation), and z_{base} is the ice bed elevation (derived from the DEM). We assume a distributed drainage system ($f \approx 1$) for the ice sheet prior to lake drainage because: 1) the lake could not exist if it was connected to an efficient drainage network because topography of the ice bed would have had a larger effect on hydraulic potential, preventing water storage; and 2) the geomorphic explanation for lake drainage (see manuscript) suggests that subglacial lake evolution in the region was via initial advancement of a broad floodwave

(inefficient drainage) immediately downglacier from the lake prior to connecting with efficient, antecedent ice tunnels. Ice surface elevation was defined by taking the elevation of the highest meltwater channels (1411 m asl) on the Marble Range and then back-calculating that over the area around DCB by applying the ice surface slope used to solve equation 1.

3. Parameter testing

The following subsections discuss the approach used to identifying the parameters that allow subglacial lake reconstruction within DCB. Table S1 shows selected parameter configurations (sampled from more extensive parameter testing) that correspond to the lake reconstructions in Figure S1. In Table S1 and Figure S1 only scenarios that were able to generate significant water volumes in DCB are displayed.

3.1 Ice and lake surface slopes

Ice marginal meltwater channels on the slopes of the Marble Range (southwest of the Chasm meltwater corridor) have no temporal control and so cannot be spatially correlated to estimate ice surface slope. Consequently, the average slope of all ice-marginal channels (3.4°) may provide a first-order approximation of ice surface slope (cf. Syverson and Mickelson, 2009; Mannerfelt, 1949). However, this relatively high ice surface slope forced a subglacial lake surface slope (equation 1) that was higher than the topographic slope within DCB and so would not allow water storage. This inferred high ice surface slope does not fit with the inference that the ice mass was inactive during late-stage decay (cf. Fulton, 1991), which is when the meltwater corridors were most likely formed. Inferring ice surface slope from ice-marginal channel slope assumes that the ice was cold based at its margins, all channels paralleled the ice surface slope, they did not have sections that ran down hillslope and/or subglacially (cf. Syverson and Mickelson, 2009), and that there has been no post-glacial reworking. Given rapid deglaciation (Fulton, 1991) and an abundance of meltwater landforms (Tipper, 1971), these

assumptions are likely invalid. Consequently, an inverse approach was taken, whereby lake surface slope was iteratively reduced until a subglacial lake could have existed in DCB (scenarios 1-5, Table S1 and Fig. S1). This lake was then further constrained by ensuring it could access the Chasm and/or Green Lake spillways (CS and GS, respectively) and would have stored sufficient water to fill the Chasm and Green Lake canals (scenarios, 1-5, Table 1 and Fig. 5). Using equation 1, this optimal subglacial lake surface slope (0.164°) was used to calculate the maximum ice surface slope to retain this lake (0.015°).

The azimuth of ice surface tilt (and opposing lake surface tilt) was varied between 270° and 360° N (scenarios 1-5, Table S1, Fig. S1) based on a reasonable variation from regional glacioisostatic tilt (332° N over the southern interior plateau, cf. Johnsen and Brennand, 2004; $319\text{-}354^\circ$ N, cf. Fulton and Walcott, 1975), local ice flow indicators to the southeast (cf. Plouffe et al., 2011), and a local retreat pattern to the northwest (cf. Perkins et al., 2011). The optimal azimuth of ice (170.78° N) and lake surface (350.78° N) slopes (scenarios 4-5, Table 1 and Fig. S1e-f) are consistent with regional glacioisostatic tilt reconstructions (Johnsen and Brennand, 2004; Fulton and Walcott, 1975).

3.2 Glacioisostatic tilt

It is likely that DCB was depressed to some extent by the overlying CIS and that the direction of glacioisostatic tilt was toward regional ice centres (Coast Mountains). Consequently, the modern DEM was initially tilted using the regional glacioisostatic tilt derived from the deformation of glacial Lake Thompson shorelines in the Thompson basin ~ 105 km to the southeast (0.103° dip at an azimuth of 332° N; Johnsen and Brennand, 2004). This is consistent with local late stage ice flow direction indicators northwest to southeast (cf. Plouffe et al., 2011) and inferred ice retreat patterns (cf. Perkins et al. 2011). In order to attain optimal subglacial lake extent, the glacioisostatic tilt (0 to 0.103°) and azimuth (270° to 0° N) were iteratively adjusted (scenarios 1-2, Table S1 and Fig. S1). However, it was determined that the application

of any glacioisostatic tilt toward the northwest would not allow water storage within DCB. This is because the DC outlet to the Fraser River (FR) basin is depressed relative to the rest of the DEM, enhancing what is already a major hydraulic potential low and forcing subglacial water flow away from DCB through DC (scenarios 1 and 2, Table S1 and Fig. S1e). Although it is likely DC was partially filled by glacial advance-stage glaciofluvial sediments (§ 3.4), because the modern valley depth (~200 m) is increased by the glacioisostatic tilt, unrealistic amounts of glacial advance-stage valley fill are necessary to dam DC and prevent water drainage through it. Furthermore, if the tilted subglacial lake surface is pinned to the Chasm spillway (CS) and the underlying DEM is tilted to regionally derived glacioisostatic values (Johnson and Brennand, 2004), the lake cannot be dammed at the Green Lake spillway (GS), and lake extent is significantly greater than that indicated by its sedimentary record (scenario 1, Table 1 and Fig. S1b). In order to prevent unconstrained drainage through the Green Lake corridor, the subglacial lake surface was pinned to GS, and the azimuth of glacioisostatic tilt was adjusted to 0°N. Although this azimuth is not supported by the few local ice flow indicators available, it could reflect complicated ice flow coalescence on the interior plateau (Clague and Ward, 2011). However, the resulting subglacial lake would not have stored enough water to achieve bankfull conditions in both meltwater corridors (scenario 2, Table 1 and Fig. 1c). Consequently, glacioisostatic tilt was not applied to the optimal subglacial lake reconstruction (scenario 5, Table 1 and Fig. S1f).

3.3 Spillway elevation

The spillways for the subglacial lake are assumed to be at the head of the Chasm and Green Lake meltwater corridors. However, selection of the appropriate spillway elevation is complicated because: 1) the modern DEM does not represent the terrain prior to lake drainage as the spillways on the modern DEM have been eroded by ice-dammed lake drainage and then likely modified further by Holocene erosion; and 2) the direction of ice surface slope utilized in

subglacial lake reconstructions was not always perpendicular to a straight line connecting both corridor heads. In an attempt to realistically simulate spillway elevation prior to meltwater corridor formation, spillway elevations were taken as a linearly-interpolated elevation between the surrounding walls of the meltwater corridors. Depending upon the direction of ice surface slope (section 3.1), the lake was pinned to either the CS alone (1135 m asl), GS alone (1130 m asl), or both the CS and GS (1135 m asl) when the azimuth of ice surface slope was perpendicular to a line connecting both spillways (Table S1 and Fig. S1b-f). Pinning the lake surface to either spillway would only allow drainage down that spillway (e.g., scenario 1 and 2, Table S1 and Fig. S1b, c), whereas pinning the lake surface to both spillways means the subglacial lake could have drained through either, or both spillways (e.g., scenarios 3-5, Table S1 and Fig. S1d-f). Consequently, in the optimal subglacial lake reconstruction (scenario 5, Table S1 and Fig. S1f) the ice surface tilt azimuth (170.78°N) is perpendicular to a line connecting the heads of both meltwater corridors and so is pinned to both spillways.

3.4 Glacial advance-stage valley fill

The modern Canoe Creek (CC) and lower DC valleys (Fig. S1a) form significant low points in the landscape that would have drained water away from the DCB (assuming relatively low ice surface slopes, section 3.1), preventing subglacial lake formation here (scenarios 1-4, Fig. S1b-e). However, it is probable that at the time of subglacial lake formation the DC, PC, and CC valleys were partially filled with proglacial outwash sediments delivered from the margin of the CIS as it advanced westward from the Caribou Mountains (Huntley and Broster, 1996; Heginbottom, 1972). Indeed, faulted and sheared fluvial sequences can be seen in the DC valley fill, which are probably glaciofluvial outwash that was tectonized by the overriding, cold based ice during glacial advance. As this ice approached the FR basin, meltwater would have carried sediment into the pre-existing DC and PC valleys, aggrading them up to a base-level elevation, perhaps consistent with glacial Lake Camelsfoot (an advance stage glacial lake in the

FR basin, cf. Huntley and Broster, 1994). The elevation of lake bottom sediments within former glacial Lake Camelsfoot are ~670 m asl, though it is likely lake surface elevation was much higher if a relatively deep lake and some erosion of the lake sediment record, by overriding ice, can be presumed. Thus, local valleys were probably aggrading to a relatively high base-level during glacial advance. The maximum elevation of glaciotectionized glaciofluvial sediments in DCB was ~825 m asl, although these may have been truncated by later erosion. Therefore, valley fill was modelled by iteratively filling the modern DEM within the DCB to increasingly higher elevations (ranging from 750 m asl (modern elevation of DC outlet at FR) to 1090 m asl) and then testing whether this fill dammed a subglacial lake within DCB using equation 2 (section 3.5, Fig. S1e-f). To prevent drainage out of lower DC valley, when the lake was pinned to CS and GS, and the lake surface dipped 0.164° towards an azimuth of 350.78° N, the DC and PC valleys would need to be filled to an elevation of at least 1076 m asl (scenario 5, Table 1 and Fig. S1f). The CC valley drains into FR, via Indian Meadows Creek (IM) from a higher elevation than the DC valley (Fig. S1a) and so proglacial outwash sediment here probably aggraded to a higher elevation. Consequently, CC valley was iteratively filled independent of DC (ranging from 990 m asl (modern elevation of CC at its confluence with IM) to 1126 m asl). The optimal fill (damming) elevation for CC (1126 m asl), if it had a horizontal surface, would have infilled both CC and PC (reducing water storage in the putative subglacial lake) and so was sloped from the centre of CC to toward PC (scenario 5, Table 1 and Fig. S1f).

3.5 Hydraulic potential

In order to confirm that water would flow up and out of the optimal subglacial basin (scenario 5, Table S1 and Fig. S1f) through the Chasm and Green Lake meltwater corridors, hydraulic potential was calculated for the area surrounding the DCB (using equation 2). Using the optimal ice surface slope (0.015°), and the elevation of the highest ice-marginal channels on the Marble Range (1411 m asl), we infer that the ice dipped toward the southeast (azimuth of

170.78°), consistent with local ice flow indicators (Plouffe et al., 2011). We used a DEM that was filled to an elevation representing damming thickness of glacial advance-stage sediments (section 3.4) as the ice bed elevation term of equation 2, and to calculate ice surface thickness (by subtracting the DEM from ice surface elevation). The resulting map of hydraulic potential shows that regional drainage would have been directed towards the southeast, matching the proposed route of meltwater through the Chasm and Green Lake meltwater corridors (scenario 5, Table 1 and Fig. S1f).

4. Summary of optimal subglacial lake reconstruction (scenario 5)

We tested the plausibility of a subglacial lake within DCB at the head of the Chasm and Green Lake meltwater corridors. We have demonstrated a subglacial lake could have existed in this location. However, this subglacial lake could only exist given a very low ice surface slope (0.015° dipping towards an azimuth of 170.78°), with no glacioisostatic depression through DCB, and with a relatively large amount of preserved glacial-advance stage valley fill in the DC, PC and CC valleys (scenario 5, Table 1 and Fig. S1f). This subglacial lake would have been $\sim 132 \text{ km}^2$ in area, stored 1.46 km^3 of water, and would have connected to both the CS and GS. The hydraulic potential in the area surrounding the subglacial lake would have driven water up and out towards the southeast, probably through the Chasm and Green Lake meltwater corridors. Given the strict antecedent conditions required to form the subglacial lake, its existence seems unlikely. Conversely, had the CIS had a frozen margin at this time, this may have facilitated subglacial water storage and catastrophic drainage (cf. Cutler et al., 2002). However, there is no evidence for a frozen margin on the Fraser Plateau (e.g., ice wedge casts) and the CIS is thought to have been temperate following glacial maximum (cf. Lian and Hickock, 2000), so a frozen margin seems unlikely.

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Table S1. Selected input parameters associated with five subglacial lake reconstructions (scenarios 1-5).

Scenario Number ^a	Ice surface slope (°)	Ice surface slope azimuth (°N)	Lake surface slope (°)	Lake surface slope azimuth (°N)	Glacioisostatic tilt magnitude (°)	Glacioisostatic tilt azimuth (°N)	Active spillway(s) elevation (m asl)	Dog and Pigeon creek fill (m asl)	Canoe Creek fill (m asl)
1	0.036	152	0.4	332	0.103	332	Chasm (1135)	None	None
2	0.0136	180	0.15	0	0.103	0	Green Lake (1130)	None	None
3	0.02	180	0.218	0	0	0	Chasm & Green Lake (1135)	None	None
4	0.015	170.78	0.164	350.78	0	0	Chasm & Green Lake (1135)	None	None
5 ^b	0.015	170.78	0.164	350.78	0	0	Chasm & Green Lake (1135)	1076	1126

^a Scenarios 1-5 correspond to those presented in Figure 1.

^b Scenario 5 produced a subglacial lake that could have supplied water to the Chasm and Green Lake meltwater corridors and would not have drained through Dog Creek or Canoe Creek.

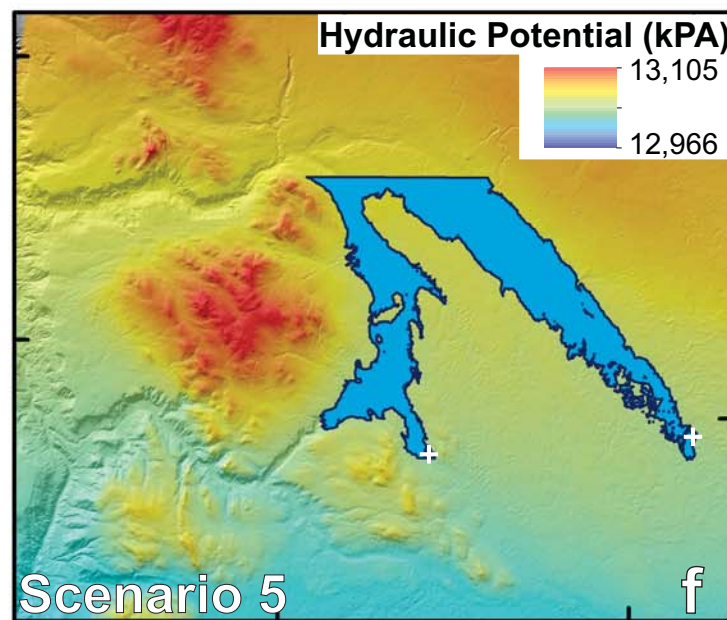
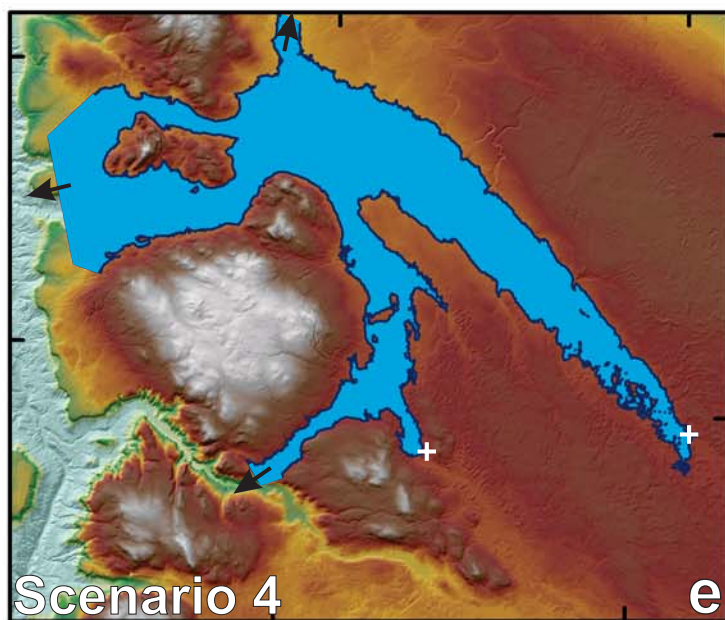
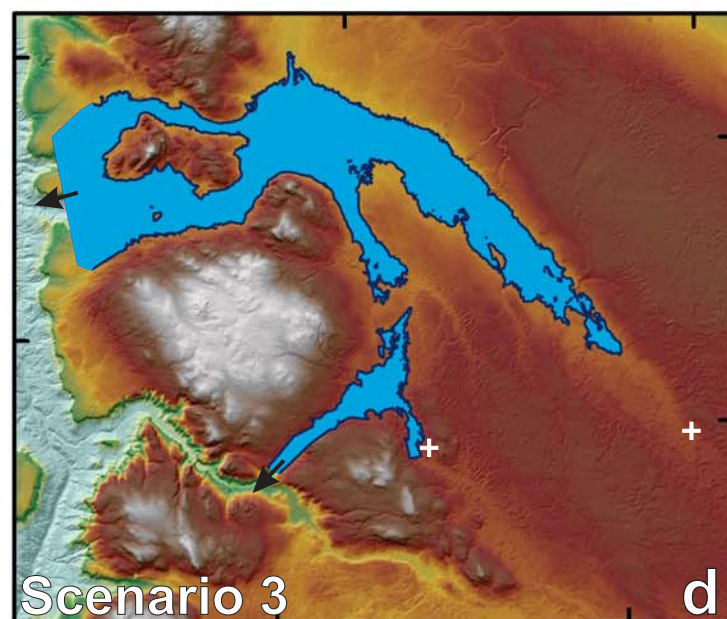
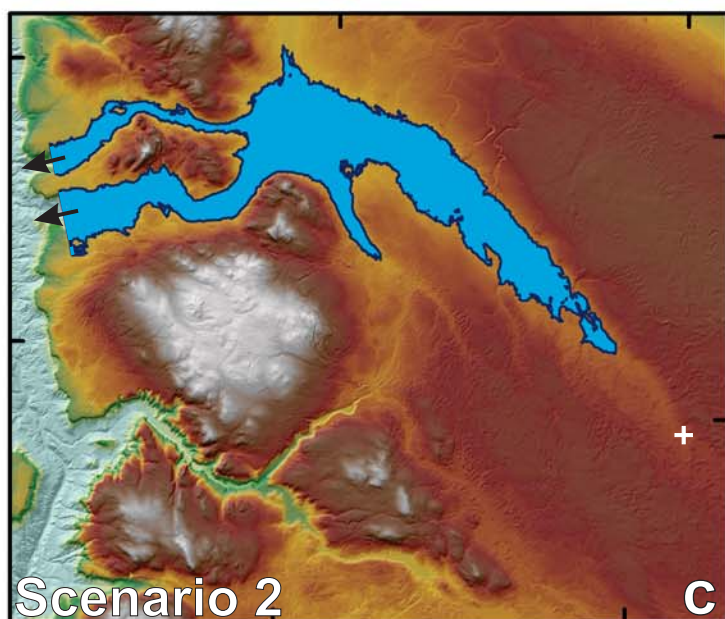
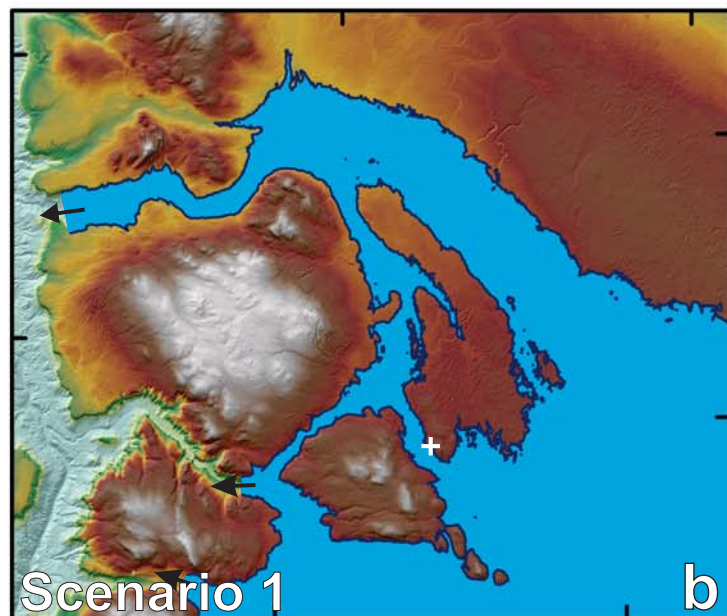
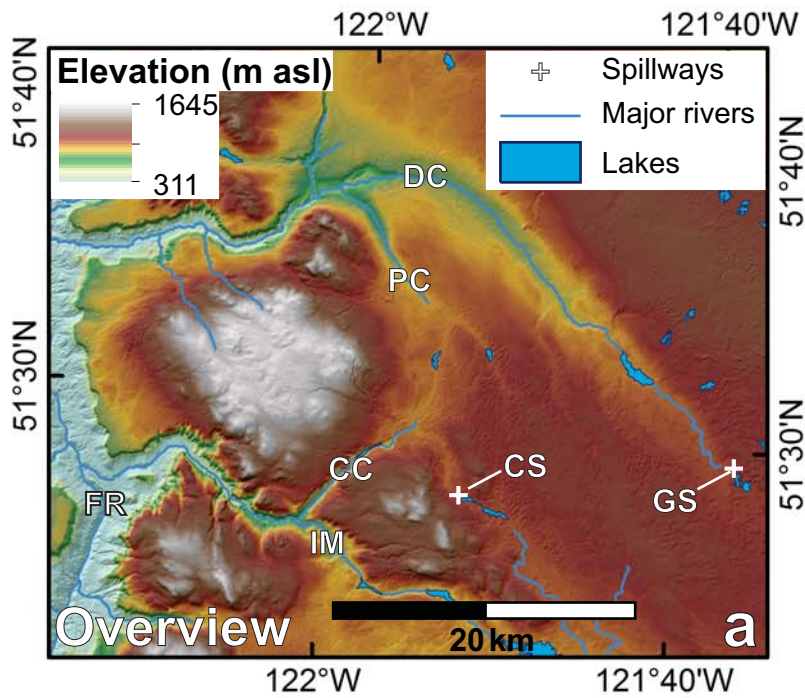


Fig. S1. Subglacial lake modelling scenarios (refer to Table S1 for input parameters). The putative subglacial lake is shown as a solid blue fill. We have artificially ended the lake where there is no outline so that the topographic expression of deep valleys is preserved (making drainage routes visually clearer). Only putative spillways to which the lake level has been pinned are shown in the scenario panels (b-f). a) Overview of the putative subglacial lake basin with associated valleys and spillways. CC: Canoe Creek; CS: Chasm spillway; DC: Dog Creek; FR: Fraser River; GS: Green Lake spillway; PC: Pigeon Creek; IM: Indian Meadow Creek. b) Scenario 1 is characterized by relatively high ice surface slope, glacioisostatic tilt corresponding to regional glacioisostatic tilt vectors and connection to CS. The lake is not dammed at GS, water would have drained out of lower DC and CC (arrowed), and lake extent does not correspond to its sedimentary signature (Fig. 7). c) Scenario 2 is characterized by a very low ice surface slope to the south, regional glacioisostatic tilt vectors, and connection to the GS. The subglacial lake does not connect to CS and water would likely drain out of DC to the west (arrowed) because lake surface elevation here is higher than can be dammed by fill of DC with glacial advance-stage sediment. d) Scenario 3 is characterized by a relatively moderate ice surface slope to the south, no glacioisostatic adjustment, and connection to both CS and GS. The volume of water within the lake is smaller than that required to fill both corridors and would likely have drained out of lower DC and CC (arrowed) because lake surface elevation is higher than can be reasonably dammed by fill of DC with glacial advance-stage sediment. e) Scenario 4 is optimized to form a subglacial lake that connects to both the GS and the CS. However, because DC and CC are not filled with glacial advance-stage sediment water would not be dammed there (arrows indicate drainage routes) and a lake could not form. f) Scenario 5 is optimized to form a subglacial lake that connects to both GS and CS, has sufficient volume to fill (bankfull) the Chasm and Green Lake meltwater corridors with water, and would have drained through GS and/or CS based on hydraulic potential. Drainage through DC and CC is prevented by inclusion of glacial advance-stage sediment in DC and CC.