The genesis of an esker-like ridge at the margins of the last Cordilleran Ice Sheet

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ABSTRACT
Meltwater landforms are commonly used in the reconstructions of past ice sheets. Such reconstructions are accurate and reliable only if they are built on correct identification of meltwater landforms and sound understanding of their process implications. We investigate the morphology and sedimentary architecture of an esker-like ridge near Young Lake, British Columbia, and show how a sound understanding of landform genesis impacts deglacial reconstruction of the Cordilleran Ice Sheet. We show how exploration of digital elevation models, and use of ground penetrating radar are invaluable tools in landform classification in regions with limited geographic access and few sedimentary exposures.

RÉSUMÉ
Le modelé fluvioglaciaire est couramment utilisé dans les reconstitutions d'anciens inlandsis. Cependant, ces reconstitutions sont exactes et fiables que si elles reposent sur l'identification correcte des modelés fluvioglaciaires, ainsi que sur une bonne compréhension des processus responsables de leur formation et des implications de ces derniers sur les reconstitutions paléoenvironnementales. Cette recherche examine les éléments morphologiques et l'architecture sédimentaire d'une crête d'esker près de Young Lake, en Colombie-Britannique dans le but de démontrer l'impact d'une bonne compréhension de la genèse des éléments morphologiques sur la reconstitution de la déglaciation de l'inlandsis de la Cordillère. Nous démontrons comment un examen détaillé de modèles numériques de terrain, ainsi que des relevés au géoradar, peuvent être utilisés pour mieux classifier le modelé dans les régions où l'accès est limité et les coupes sédimentaires sont rares.

1 INTRODUCTION

Meltwater landforms have played a significant role in reconstructing the character, timing and overall dynamics of North American ice sheets (e.g., Kleman and Borgstrom, 1996; Brennand, 2000). Yet, the accuracy and reliability of such reconstructions relies on the correct identification and classification of meltwater landforms and a sound understanding of their process implications. The deglacial signature of the last Cordilleran Ice Sheet (CIS) in interior British Columbia (BC) is dominated by meltwater landforms and sediments. Currently, the classification and detailed understanding of meltwater landforms within the footprint of the CIS is inadequate for reconstructing the pattern and dynamics of ice sheet decay. In this paper we explore the morphology and sedimentary architecture of one such landform, an esker-like ridge, near Young Lake, BC (Figure 1) and show how a sound understanding of its genesis impacts deglacial reconstruction of the CIS. We demonstrate how detailed exploration of digital elevation models and the use of ground-penetrating radar (GPR) can be invaluable tools to aid interpretations in regions (such as this) with limited access and few sedimentary exposures.

2 STUDY AREA AND PREVIOUS WORK

The study area is located on the southern Fraser Plateau in interior BC, between the Coast Range to the west and the Shuswap Highlands and Columbia Range to the east (Holland, 1976). Ranging from 1200 to 1800 m asl, the relatively flat plateau surface results from underlying Eocene to Miocene basalt flows (Bevier, 1983; Andrews and Russell, 2008). The Young Lake region centres over the modern upper Bonaparte River valley (Figure 1) which has eroded roughly 200 m down into the southern end of the Fraser Plateau. Here, the flat plateau surface is mainly till covered and drumlinized (Figure 1b; Tipper 1971a, b, c; Plouffe et al., 2010). Exposed bedrock surfaces reveal one to two striae sets (Figure 1b; Plouffe et al. 2010). Initial ice advance to the west, followed by a southerly shift in ice flow direction through the last glacial cycle is inferred from the orientations of striae sets and drumlins, as well as till geochemistry (Plouffe et al., 2009, 2010). Decay of the southern sector of the CIS is generally thought to have been by a combination of backwasting from the southern ice margin, downwasting on the plateaus, and stagnation of large ice tongues within major valleys dissecting the plateaus (e.g., Fulton, 1991; Clague and James, 2002). The reported record of ice decay on the southern Fraser Plateau includes meltwater channels, eskers, outwash sediments, hummocky deposits, and glaciolacustrine sediments; notably few moraines are present (Tipper, 1971a, b, c; Plouffe, 2009). However, the detailed classification of meltwater landforms (cf. Brennand, 2000; Greenwood et al., 2007) and their associated implications for decay dynamics is inadequate for reconstructing a full picture of the pattern and dynamics of CIS decay over the plateau.

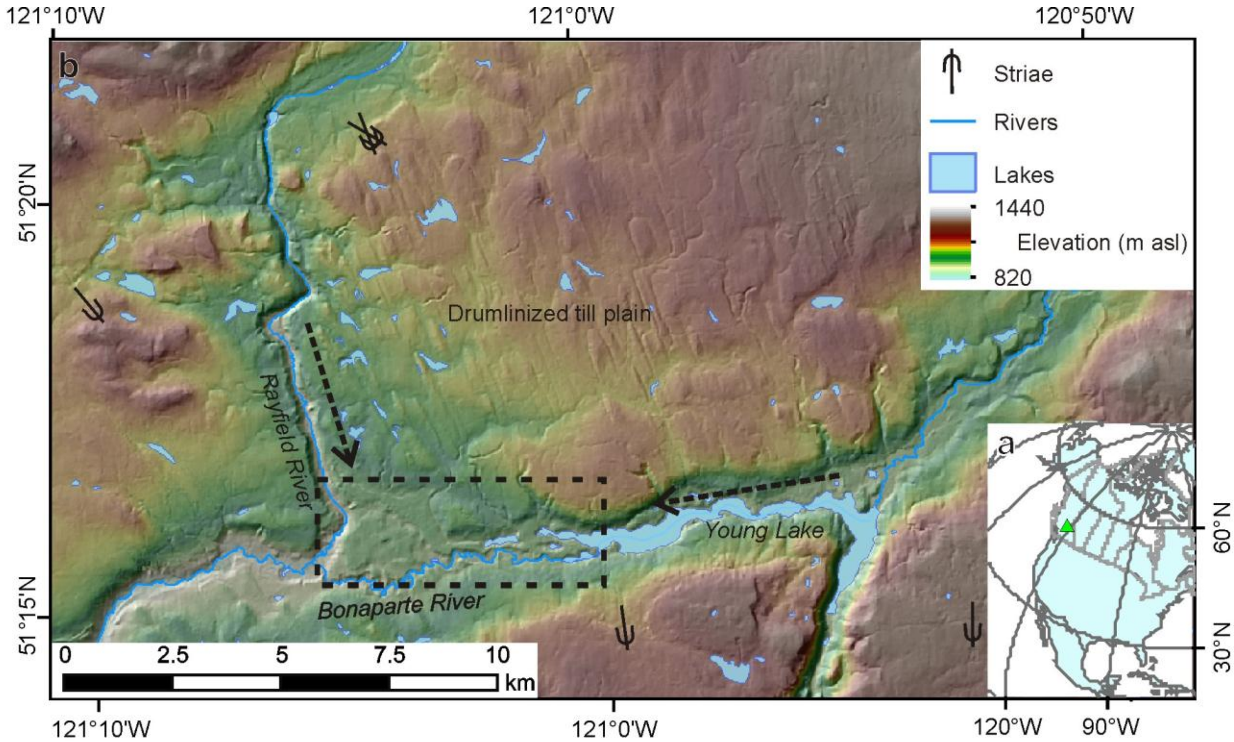

Figure 1. a) Study area (green triangle) within British Columbia, Canada. b) Elevation classed and hillshaded terrain model (Geobase®) centred on Young Lake showing striae used in ice flow reconstruction (Plouffe et al., 2009), and potential meltwater and sediment pathways (dashed arrows) that supplied sediment to Young Lake esker-like ridge. Dashed rectangle highlights the location of the Young Lake esker-like ridge.

2.1 Young Lake esker-like ridge

The Young Lake (YL) esker-like ridge (Figure 1) was first classified as an esker by Tipper (1971c) with a formative flow direction from east to west. The esker was mapped over a total distance of 5.1 km although in the report accompanying the map sheet it was noted that it may have been partially eroded by meltwater that flowed down the Young Lake valley at some later point. Owen (1997) suggests positive identification as a true esker be left to situations where geomorphology, sedimentology and regional setting are all well understood. Perhaps with this in mind, and because there were few sedimentary exposures, Plouffe (2009) had a more conservative interpretation of the landform, classifying it as an ice-contact, poorly-sorted, stratified deposit. Formative flows were inferred to be from east to west (Plouffe, 2009), based on regional meltwater interpretations and the slope of the Young Lake landform (Plouffe, pers. comm.).

3 METHODS

The geomorphology of YL esker-like ridge was mapped using stereographic aerial photographs (1:40 000) and small scale digital elevation models (DEM's; 25 m horizontal resolution, 10 m vertical resolution, Geobase®). Larger scale DEM's generated from local, real-time kinematic (RTK) differential GPS measurements (Leica system 500 dGPS, decimetre accuracy) were also used. Elevation measurements in this paper have been adjusted to local dGPS measurements in order to maintain consistency between datasets. There is an average elevation offset of ~13 m between elevation data collected directly from dGPS measurements and Geobase® DEM elevations. The ridge and associated landforms are characterized based on their surface morphology and relative relief. Interpretations of geomorphology are supplemented by ground observations of limited sedimentary exposures and surficial materials.

To compensate for the paucity of sedimentary exposures we employed shallow geophysical methods to image the sedimentary architecture of YL esker-like ridge and determine if its interpretation as an esker is warranted based on sedimentary as well as geomorphic considerations. Although a regular grid of 100 MHz GPR data (totalling 2.02 km in length) was collected, only one ridge-parallel (X) line and two ridge-transverse (Y) lines have so far been completely processed and interpreted (Figures 2 and 3; a total of 161 m). GPR data were collected with the antennas co-polarized, perpendicular-broadside to the survey lines using a Sensors and Software Inc. pulseEKKO Pro system. During common offset (CO) data collection antennas were kept at a constant separation of 1 m, and data were collected in step mode (0.25 m). Two common mid-point (CMP) surveys provide an estimated average subsurface velocity of 0.107 ± 0.004 m/ns, which was used for data processing and to convert two way travel time (TWT) into depth. GPR data processing was carried out in REFLEXW v5.6 (Sandmeier, 2010) and included time zero corrected, low pass and bandpass filtering, migration, background removal, the application of a gain function, and topographic correction. Elevation data for topographic correction was collected with a real time kinematic (RTK) differential global positioning system (dGPS) with decimetre accuracy. Interpretations are ground truthed by observations of surface sediments and knowledge of the general regional stratigraphy from local water well logs (BCME, 2011).

4 RESULTS

4.1 Geomorphology and surface character of Young Lake esker-like ridge

The YL esker-like ridge and associated landforms extend for over 6 km in a west-east orientation, along the upper Bonaparte Valley (Figures 1 and 2). The ridge proper is composed of three segments of varying character (segments 2-4, Figure 2a). The western segment is ~2

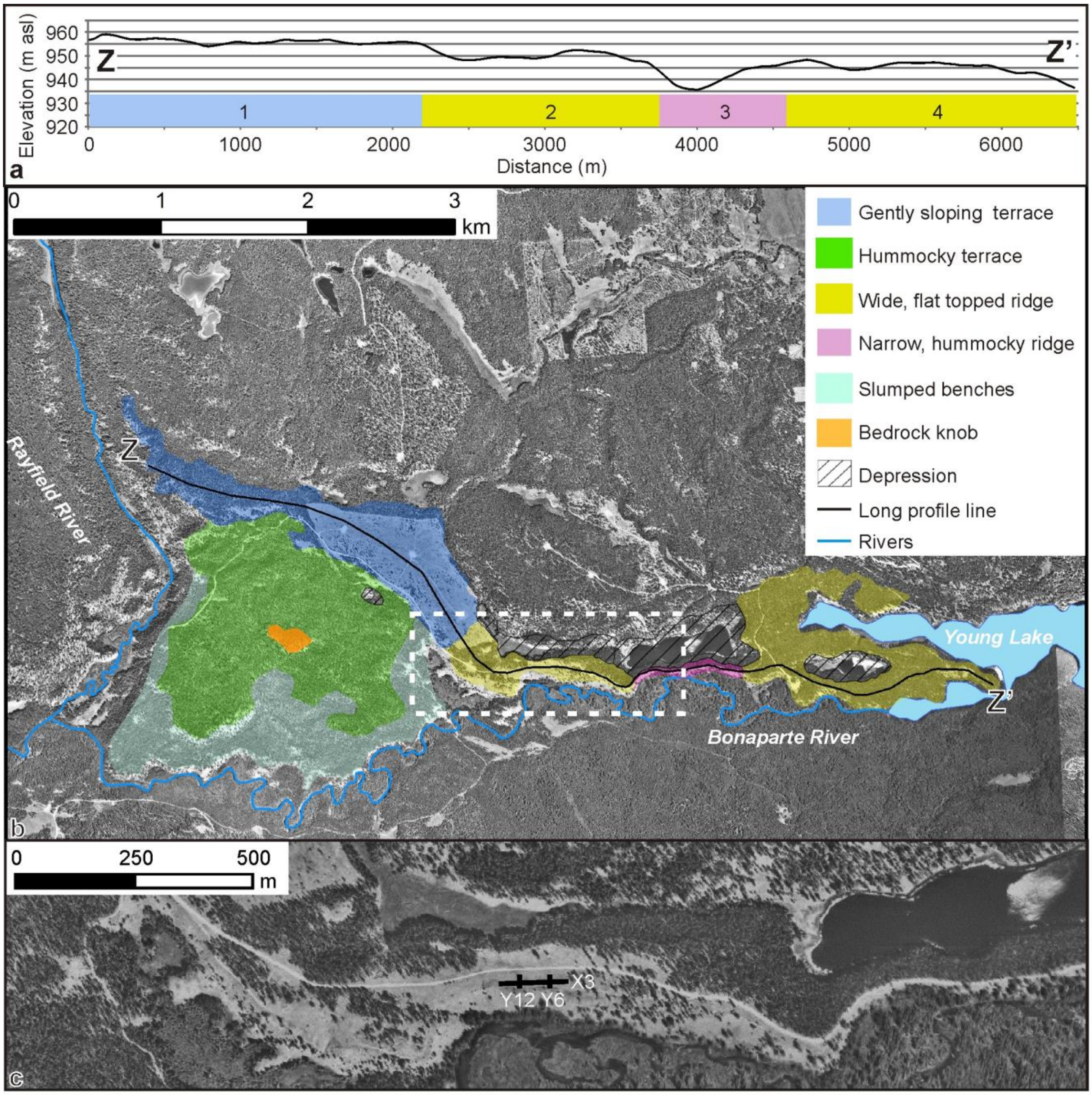

Figure 2. a) Long profile of Young Lake esker-like ridge (8x vertical exaggeration). Colours bars below profile correspond to legend in Figure 2b, and numbers refer to landform segments as discussed in text. Refer to Figure 2B for path of long profile. b) Geomorphic map of Young Lake esker-like ridge and associate landforms superimposed on an orthophotograph (clip from 1:125 000 orthophoto mosaic 092Pse, Province of British Columbia, 2010). Dashed box indicates location of Figure 2c. c) Detailed view of orthophotograph showing GPR line locations, on segment 2. Bonaparte River is visible in the bottom of the orthophotograph.

km long, 85-260 m wide, and relatively flat-topped with a maximum elevation of 952 m asl (segment 2, Figure 2a). It is bounded to the north by enclosed dry, sediment-floored depressions and to the south by the Bonaparte River (Figure 2b). Several slump depressions or scarps are evident along its surface and flanks (Figures 4 and 5a). The surface of the south side of segment 2 is composed of sand, pebbles, cobbles and occasional boulders (Figure 5c). Clasts are subrounded to rounded. The north side of segment 2 is ornamented with low amplitude (0.5 m) aeolian sand dunes (Figures 4 and 5b). At the end of segment 2 the ridge abruptly drops in elevation to 930 m asl, narrowing into an 800 m long, round-crested ridge that is, in places, less than 40 m wide and undulatory (segment 3, Figure 2a). The ridge is bounded to the north by an enclosed pond-filled depression (Figure 2b) that appears to be hydraulically connected to Young Lake as it has no surface outlets but maintains an equivalent water surface elevation. The south side of this segment 3 is rimmed by depressions and scarps formed by post-depositional slumping. The eastern segment of the ridge proper is 1.3 km long, up to 1 km wide, and relatively flat-topped (segment 4, Figure 2a). Its surface exhibits a gap filled by Young Lake (Figure 2b) and a large pond-filled enclosed depression (~500 m long) that appears to be hydraulically connected to Young Lake (they have the same water surface elevation). It is also delimited by depressions and scarps on its south side. This segment gently grades towards 939 m asl, but stops short of the elevation of modern Young Lake (which is at 923 m asl).

Segment 1 connects to the western end of the ridge proper and consists of two landform elements (Figure 2b) extending toward Rayfield River over a ridge-parallel distance of ~2.5 km. The northern landform element is a very gently sloping, relatively flat-topped (local relief of ~2 m), 400 m wide terrace that is in grade with segment 2. The terrace is in contact with bedrock on its northeast side. The southern landform element is a ~2 km wide, hummocky terrace (mounds and hollows with local relief of >8 m) ~10 m lower in elevation than the flat-topped terrace to the north (947 m asl compared to 957 m asl). A bedrock knob breaks the surface of the hummocky terrace. Considering all 4 segments together, the surface of YL esker-like ridge slopes gently (~3 m/km) down to the east (Figure 2a).

4.2 Description of radar elements

Radar reflections (labelled *R1*-*R10* in Figure 3) were used to reconstruct the bounding surfaces of radar elements (labelled A-K in Figure 3 and hereafter referred to as RE-A to RE-K). Both are described in detail below following the classification of Neal (2004). Radar reflections that constitute bounding surfaces are high in amplitude and can be traced over multiple GPR lines.

4.2.1 RE-A

RE-A is the lowermost element and can be identified throughout the grid by rapid signal attenuation. Few 'real' reflections are visible in this element, as most are veiled by noise and ringing. The upper bounding surface of RE-A is represented by *R1*, a moderately continuous, irregular reflection that truncates RE-A in places (e.g., ~46 m and ~128 m of line X3 in Figure 3). The lower bounding surface is not discernable due to signal attenuation within the element.

4.2.2 RE-B and RE-E to RE-G

RE-B is delimited by *R1* and *R4*, except where it is truncated by RE-C and RE-D. It is a tabular element and is, on average, 4 m thick. Internal reflections are onlapped onto *R1,* and are planar and subhorizontal in geometry across all lines. Several sets of offset reflections cross *R4* into RE-B. Lines connecting these offsets (dotted lines, Figure 3) trend in both east and west directions on X3, at moderately high angles (40-50°). Sets of offset reflections passing through *R4* into RE-B exist in line Y6 (Figure 3b) with an angle of offset of 45° to the north.

RE-E to RE-G are trough shaped elements that contain planar, subhorizontal reflections. Their extent passes beyond the boundaries of the GPR survey but they are at least 2-3x longer in flow-parallel section as the trough shaped RE-C and RE-D, resulting in a length to depth ratio of about double that of RE-C and RE-D. They are separated from RE-B by the lower bounding surface *R4* that is continuous across all lines. The lower bounding surface of RE-F at its eastern end (*R5*) is steeply dipping (22° to the west), truncates the planar reflections of RE-E and is onlapped by subhorizontal reflections within the element. RE-E is separated from RE-G by *R6*, an irregular, but continuous reflection that truncates the reflections within RE-E and is onlapped by reflections within the element. RE-E and RE-F average 4 m thick whereas the average thickness of RE-G is 1 m. Sets of aligned offset reflections within RE-E and RE-F continue through *R4*. These reflections have a low offset angle in both east and west directions. Angles of offset for offset reflections fully contained within RE-E to RE-G are steeper (close to 90° in some cases) and dip in both east and west directions as well as north and south in the Y lines.

4.2.3 RE-C and RE-D

RE-C is a trough-shaped element that is bounded by *R2* and *R4*. *R2* truncates the reflections within RE-B, and the reflections within RE-C are downlapped onto this bounding reflection. RE-C is up to 3 m thick, 25 m long (line X3, Figure 30), and over 20 m wide (line Y6, Figure 3). Within RE-C reflections dip ~26° to the east in X3 and have a low angle dip of 2-3° to the south in Y6, suggesting a true dip of 28° to 97° east of north. RE-C is truncated by *R3,* and dipping reflections within RE-D onlap *R3*. RE-D is trough-shaped and bounded by *R3* and *R4*. Sets of offset reflections (dashed lines, Figure 3) cut through the lower bounding surface of RE-C (*R2*) into RE-B in both X and Y profiles, with offset angles dipping at 75° to the east and 45° to the west, respectively.

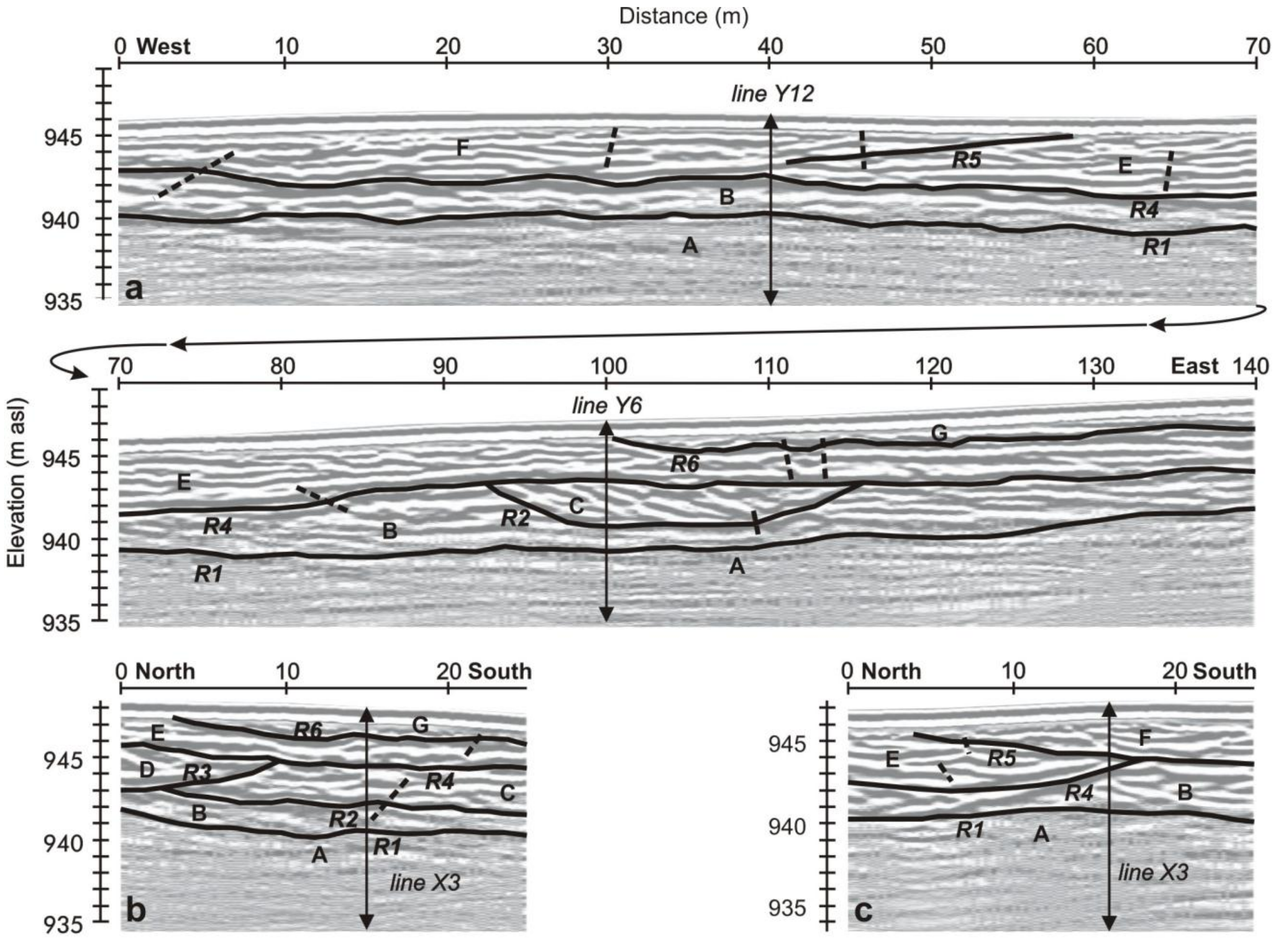

Figure 3. Processed GPR profiles of a) line X3, b) line Y6, and c) line Y12. See Figure 2c for locations of GPR lines. Radar bounding surfaces are highlighted by bold lines and are labelled *R1-R6*. These bounding surfaces delineate seven radar elements (RE) labeled A-G. The locations where GPR lines intersect are shown by labelled double arrows. Dotted lines connect sets of aligned offset reflections. There is no vertical exaggeration.

4.3 Interpretation of radar elements

4.3.1 Lacustrine sediments (RE-A)

The rapid signal attenuation associated with the lowest observable reflections in the profile (RE-A below *R1,* Figure 3) suggests a boundary between a highly transmissive medium (above), such as gravel and sand, and a low transmissive medium (below), such as silt, clay, till, or bedrock (Neal, 2004).

The top of RE-A is ~7 m (940 m asl) below the land surface of segment 2 (Figure 3). This is ~20 m higher than the current level of the Bonaparte River (920 m asl) on the south side of the ridge that has incised through unconsolidated valley-fill. Water well records (BCME, 2011) within Bonaparte Valley, east of segment 2, record up to 40 m of unconsolidated sediment overlying bedrock or till. Unconsolidated sediments include sand and gravel near surface, and silts at depth. Because no bedrock is observed at shallow depths within local water wells within Bonaparte Valley, RE-A is unlikely to record bedrock (the bedrock knob exposed in segment 1 (Figure 2b) is likely a remnant interfluve between Rayfield and Bonaparte valleys). RE-A could record till, but tills are not recorded in local water wells at this depth (BCME, 2011). Given that silt is recorded at this depth in local water wells (BCME, 2011), RE-A is inferred to record relatively fine-grained sediments such as silt and sand that were most likely waterlain in a ponded environment. Groundwater flow through this unit may explain the hydraulic connection between the ponds within the enclosed depressions north of segment 3 and within segment 4 and Young Lake.

4.3.2 Braided stream sediments (RE-B to RE-G)

Strong radar signal return from RE-B through RE-G (Figure 3) and surface observations (Figure 5c) suggest that all remaining radar elements are composed of sand and gravel. The continuity (in both X and Y lines) and subparallel, planar nature of reflections within RE-B and RE-E to RE-G suggest these are planar beds (Burke et al., 2008, 2010; Rice et al. 2009) deposited in gravel sheets (Rice et al., 2009). Bounding surfaces *R1* and *R4-6* truncate lower reflections and are therefore reactivation surfaces that suggest there were distinct erosional events between deposition of gravel sheet elements. These events may record adjustments in accommodation space

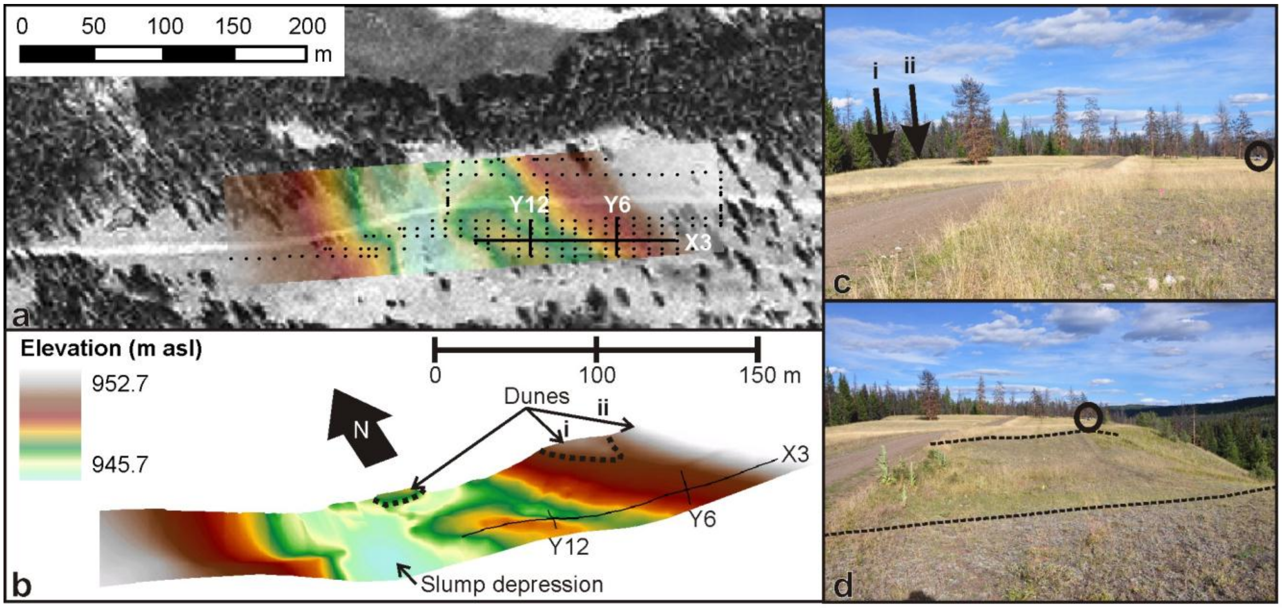

Figure 4. Geomorphololgy of segment 2 of the Young Lake esker-like ridge in the vicinity of the GPR lines. Large-scale, elevation classed DEM based on RTK dGPS elevation values obtained at decimetre accuracy along GPR lines shown a) in plan view superimposed on an orthophotograph (clip from 1:125 000 orthophoto mosaic 92Pse, Province of British Columbia, 2010) and b) in perspective view. Black points in 'a' are locations of individual elevation values used in DEM construction; they highlight the areas of greatest interpolation accuracy. The depression records a localized slump towards Bonaparte River, and aeolian dunes ornament the surface. c, d) Surface relief looking east. Arrows point to two aeolian dunes on the north side of the ridge (i, ii in Figure 4b), and dashed lines delineate the extent of the slump depression (Figure 4b). Truck for scale (circled).

in the gently sloping YL esker-like ridge (Wooldridge and Hickin, 2005).

The steeply-dipping reflections within RE-C and RE-D (Figure 3) are interpreted as avalanche surfaces, recording progradational slip-face deposition (Wooldridge and Hickin, 2005) at the edge of a scour in RE-B (recorded by *R2* and *R3*, Figure 3). The dip direction of slip-faces in RE-C suggest progradation, and hence formative flows to the east, consistent with the overall grade of the YL esker-like ridge (segments 1-4, Figure 2a).

Tabular gravel sheets and scour fills are characteristic of subaerial braided stream floodplains (Heinz and Aigner, 2003; Sambrook Smith et al., 2006) rather than subglacial esker fills. Subglacial esker fills deposited by flow under hydrostatic pressure are typically characterized by deposition in large convex-up bedforms and macroforms (e.g., Brennand, 1994; Burke et al., 2008). The relatively flat surface of segment 2 (Figure 2) is consistent with subaerial deposition. The stacked offset reflections record penecontemporaneous faults within the braided river sediments, perhaps related to differential compaction of the underlying lacustrine unit (RE-A).

5 DISCUSSION

5.1 The genesis of Young Lake esker-like ridge

Two hypotheses have been proposed for the genesis of YL esker-like ridge: 1) it is an esker formed in an ice-walled channel with meltwater flows to the west (Tipper 1971c), and 2) it is an ice-contact, poorly-sorted, stratified deposit laid down by meltwater flowing to the west (Plouffe, 2009; Plouffe pers. comm). New mapping (Figures 2 and 4) and GPR data (Figure 3) shows the landform has a general slope to the east with varied morphology, and is composed of relatively fine-grained lacustrine sediments (RE-A) overlain by gravelly sediments (RE-B to RE-G) deposited by a subaerial braided stream flowing to the east. It is not a classic subglacial esker (e.g., Brennand, 2000). Given the absence of till between, or above, the ponded and riverlain sediments the simplest interpretation is that both were deposited during CIS decay. The flat-topped character of segment 2, the presence of slump scarps along its flanks (Figures 2 and 5a), and the fact that faults do not extend though stratigraphic units (Figure 3) suggest that deposition in segment 2 was on top of land rather than ice; yet its flanks must have been ice-supported (at least on the north side). The presence of distinct fault scarps on the north side of segment 2 hints at the possibility that ridge sediments may have been deposited supraglacially there and subsequently let down as buried ice melted. By extension, we attribute the undulatory to hummocky character and pond-filled depressions of segments 3 and 4 and the southern hummocky landform element of segment 1 to ice-walled and supraglacial sedimentation. The low-relief, gently-sloping character of the terrace that forms the northern landform element of segment 1 is attributed to deposition by an outwash stream directly on land.

In summary, the picture that emerges is of deposition of both ponded sediments and braided outwash sediments on top of decaying ice and/or within an ice-walled canyon in decaying ice. The hummocky and undulatory character of segments 1 (south) and 3, the irregularities in the long profile, and the enclosed

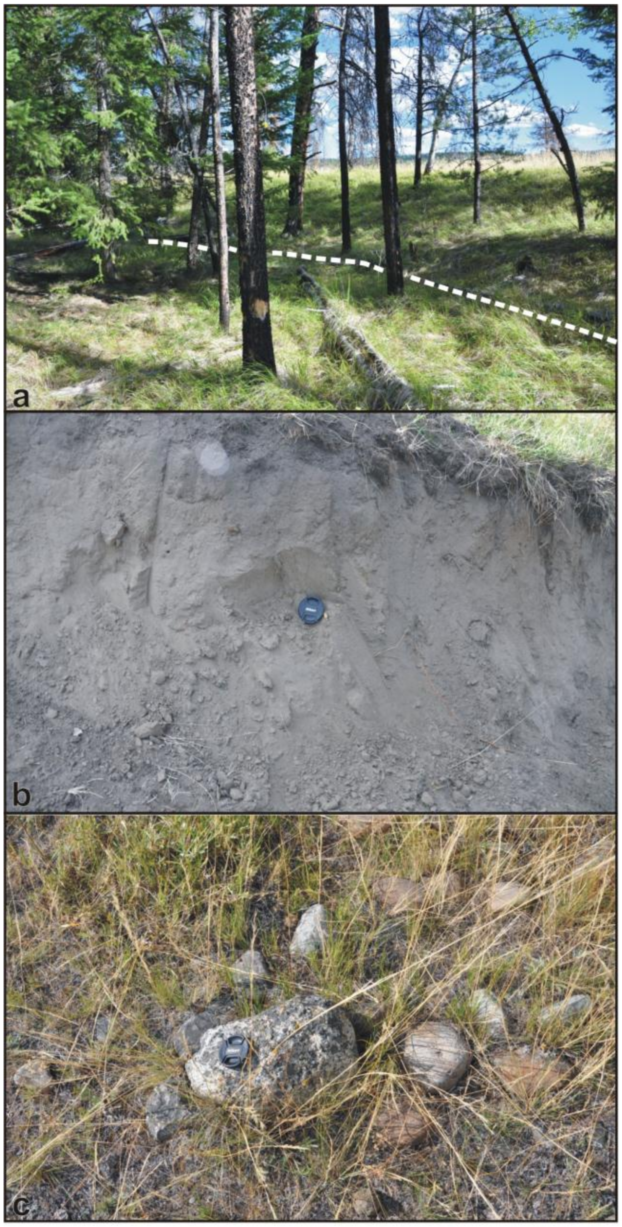

Figure 5. Characteristics of segment 2 of Young Lake esker-like ridge in the vicinity of the GPR lines (Figures 2 and 4). a) A slump block on the north side. Dashed line delineates the shear plane. The head scarp is 3 m high. b) 1 m high exposure within a dune on the north side. The dune is composed of massive, well-sorted sands. c) Dunes are absent on the south side of segment 2 (Figure 4b) and boulders, cobbles, pebbles and sand are exposed at the land surface (camera lens cap has a 6 cm diameter).

depressions and slump scarps of segments 2-4 (Figures 2, 4 and 5a) resulted from further ice decay and the removal of ice support. Consequently, the Young lake landform is certainly an ice-contact deposit (Plouffe, 2009) that is best classified as a composite landform composed of a kame terrace (northern landform element of segment 1), kames that include elements of supraglacial deposition (segment 4 and southern landform element of segment 1), and an esker deposited in a subaerial ice-walled canyon (segments 2 and 3). However, the braided outwash gravels were deposited by a stream flowing east from Rayfield River valley (Figures 1 and 2) not west through Young Lake. Aeolian sand dunes ornament some parts of the ridge surface (Figures 4 and 5b). Holocene incision by the Bonaparte River has resulted in further slumping of the south flank of YL esker-like ridge which obscures any evidence of possible ice support along the south side of the landform.

5.2 Inferences on local ice sheet behaviour

The genesis of the YL esker-like ridge gives some insight into the late stages of ice sheet decay and dynamics on the southern Fraser Plateau. First, it confirms that the ice margin decayed by downwasting (Fulton, 1967; 1991) leaving thin, dead ice patches or zones, over and through which meltwater sediments were deposited. Second, the eastward flow of the outwash stream from Rayfield River valley suggests that the ice sheet was likely more intact and perhaps thicker towards the west, damming modern drainage routes and forcing drainage east. Thicker and more intact ice to the northwest is consistent with glacioisostatic rebound inferences from the tilted shorelines of glacial Lake Thompson to the south (Johnsen and Brennand, 2004). Both suggest CIS decay on the southern Fraser Plateau likely included a component of marginal retreat to the north and west.

6 CONCLUSION

It is clear that the accuracy and reliability of our interpretations of ice sheet decay rely heavily on the correct identification and classification of meltwater landforms (e.g., Kleman and Borgstrom, 1996; Brennand, 2000) and a sound understanding of their process implications. Through exploring the morphology and sedimentary architecture of an esker-like ridge near Young Lake, BC (Figure 1) we have shown how a revised understanding of its genesis impacts overall deglacial reconstruction of the CIS on the southern Fraser Plateau. We have shown how detailed exploration using a combination of tools such as aerial photographs, DEM's, and GPR can be invaluable in confident interpretation of landforms in regions such as this, where there is limited access and few sedimentary exposures.

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