PROVISIONAL SURFICIAL GEOLOGY, GLACIAL HISTORY AND PALEOGEOGRAPHIC RECONSTRUCTIONS OF THE TOAD RIVER (NTS 094N) AND MAXHAMISH LAKE MAP AREAS (NTS 094O), BRITISH COLUMBIA

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ABSTRACT

The Geological Survey of Canada (GSC) and British Columbia Ministry of Energy and Mines (BC MEM) are collaborating to provide new insight into surficial and applied geology of northeastern British Columbia as part of the Geo-mapping for Energy and Minerals (GEM-Energy) Program Yukon Basins Project. Remote predictive digital terrain mapping and field-based reconnaissance studies are leading to a better understanding of the regional distribution of surficial deposits, permafrost, landslides and other geomorphic processes in the Toad River (NTS 094N) and Maxhamish Lake (NTS 094O) map areas. This work is improving our knowledge of the limits of glaciation, the range of subglacial processes, the patterns of ice flow, and the history of ice retreat and glacial lake formation during a dynamic period of climate change and geomorphic adjustment in the region. From an applied perspective, our work aims to encourage new investment in northern Canada by reducing the future risks for exploration, sustainable development and management of energy and mineral resources.

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Key Words: GEM-Energy program; Yukon Basins project; Toad River map area (NTS 094N); Maxhamish Lake map area (NTS 094O); physiography; bedrock geology; surficial geology; stratigraphy; paleogeographic reconstruction

INTRODUCTION

Northeastern British Columbia (Figure 1a) has seen an increase oil and gas land sale activity in recent years as vast organic-rich shale deposits become economically viable gas reservoirs (Adams 2009; Adams and Schwabe, 2009). Exploration is targeting mainly Middle Devonian to Lower Mississippian strata, specifically the Besa River Formation in Liard Basin and Muskwa/Otter Park and Exshaw formations in the Horn River Basin and the Cordova Embayment (Ferri et al., 2011a, 2011b). As these basins are developed, drilling activity and natural gas production are expected to expand, resulting in increased demands for quality infrastructure development (e.g., roads, well pads, campsites and pipelines) to ensure access to the land base and silica sand sources to facilitate hydrofracturing in gas wells (Huntley and Hickin, 2010, Hickin and Huntley, 2011).

An understanding of the extent and iceflow patterns of the Laurentide and Cordilleran ice sheets; the distribution of glaciofluvial and glaciolacustrine deposits, meltwater features and drainage directions; the distribution of colluvial deposits, landslides and permafrost; and the extent and nature of eolian deposits is critical to reduce exploration risks, to reduce the impact of geohazards upon infrastructure and to promote sustainable long-term investment and economic development in the eastern Liard Basin and Fold Belt (Liard Plateau and Tsoo Tablelands) and the Horn River Basin (Fort Nelson Lowlands and Etsho Plateau) shale gas producing regions of northeastern British Columbia (Figure 1b).

As part of the Geo-mapping for Energy and Minerals (GEM) program Yukon Basins project, the Geological Survey of Canada (GSC) and the British Columbia Ministry of Energy and Mines (MEM) Geoscience and Natural Gas Development Branch are collaborating to provide new insight into glacial and postglacial deposits and geomorphic

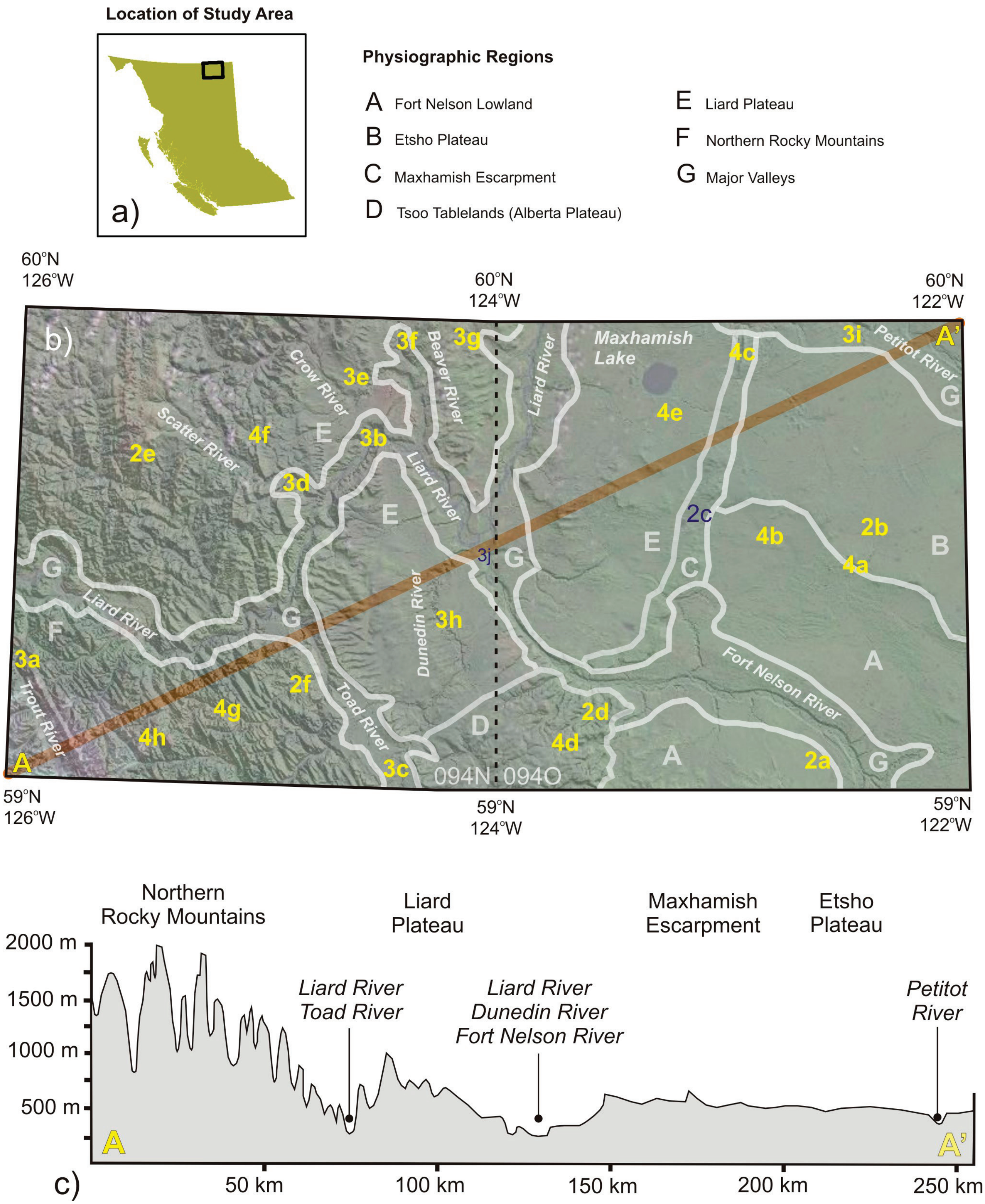


Figure 1. Toad River (NTS 094N) and Maxhamish Lake (NTS 094O) map areas are currently being investigated as part of the Geo-Mapping for Energy and Minerals (Energy) program Yukon Basins project: a) location of area of interest in northeastern British Columbia; b) major physiographic elements (after Bostock, 1970), rivers and line of section (A-A'); c) Line of section A-A' showing the range of topography, major physiographic elements and drainage features in the mapped area Location of photographs in Figures 2 to 4, shown as bold yellow numbers and letters (i.e., 2a-f, 3a-j, 4a-h).

processes in northeastern British Columbia (Figure 1a). Reconnaissance surficial geology mapping is focused on the Toad River (NTS 904N) and Maxhamish Lake (NTS 094O) map areas (Figures 1b and 1c). In this paper we present a regional overview of the bedrock and surficial geology, along with a geomorphic history interpreted from 16 sections representing the major physiographic elements and propose paleogeographic reconstructions for the map area from the last glacial maximum >18 C^{14} ka BP (21.4 calendar ka BP) to the present.

PHYSIOGRAPHY AND GEOLOGY OF THE STUDY AREA

The study area encompasses parts of a number of physiographic regions (Bostock, 1970). The northwestern limit of the Fort Nelson Lowland is generally below 530 m elevation (Figures 1b, 1c and 2a). The western Etsho Plateau lies between 600 to 740 m elevation (Figures 1b and 2b). The Maxhamish Escarpment (and Bovie Lake structure) range from 590 to 610 m elevation (Figures 1b, 1c and 2c). The Tsoo Tablelands, the northernmost part of the Alberta Plateau, reaches elevations up to 820 m (Figures 1b, 1c and 2d). The Liard Plateau rises from around 400 m west of the Maxhamish Escarpment to over 1200 m in the northwest of the map area (Figures 1b, 1c and 2e). In the Northern Rocky Mountains, southwest of the Liard and Toad rivers, some mountain peaks reach elevations over 2000 m (Figures 1b, 1c and 2f). The Liard, Toad, Scatter, Beaver, Crow, Dunedin, Petitot and Fort Nelson river valleys, with active flood plains at elevations generally below 320 m elevation, are incised into the landscape (Figures 1b, 1c and 3a to 3h).

The major landscape forms are controlled by bedrock characteristics and geological structures, and are modified by geomorphic processes over time. Lowland regions are underlain by shallowly dipping shale, siltstone and sandstone (Upper Cretaceous Kotaneelee Formation overlying Lower Cretaceous Fort St. John Group rocks) (Figures 4a, 4b). Folded and fault-bounded Lower Carboniferous (Mississippian) sandstone, natural gas-hosting sandstone (Mattson Formation) and limestone (Flett Formation), and Upper Cretaceous conglomerate, sandstone, carbonaceous shale and coal (Dunvegan and Wapiti formations) form escarpments, tablelands and plateaux (Figures 4c, 4d; Stott and Taylor 1968). West of the Bovie Lake structure, the Liard Basin is defined on the basis of thick Late Paleozoic and Cretaceous successions, and exploration targets the stratigraphically higher shale of the Exshaw Formation (Ferri et al., 2011a, 2011b). Folding and faulting, consistent with east to southeast crustal transpression, exposes Lower Mesozoic to Lower Paleozoic carbonate, shale and sandstone in the highest parts of the Liard Plateau (Figures 2e, 4e and 4f). South of the Liard River and west of Toad River, in the Northern Rocky Mountains (Figures 4e and 4f), Cretaceous and Triassic sedimentary rocks are folded and fault-bounded with Lower Paleozoic (Cambrian, Ordovician and Devonian) and Proterozoic carbonate and clastic sedimentary rocks (Ferri et al., 2011a, 2011b).

SURFICIAL GEOLOGY OF THE STUDY AREA

Surficial earth materials and landforms were interpreted and mapped using 1:60,000 scale black-and-white stereo-pair air photos (e.g., 15BCB97010 series), free online Landsat 7 Pan-sharpened imagery and a Shuttle Radar Topography Mission 3-arc-second resolution DEM accessed through Global Mapper software, and base maps generated from CanVec shape files downloaded from the NRCAN GeoGratis website (http://geogratis.cgdi.gc.ca/geogratis/ [URL 2011]; Huntley and Sidwell, 2010). Terrain polygons, landforms and other site symbols were digitized using commercially available computer software packages (Global Mapper, ArcMap and ArcGIS), edge-matched and rectified with published maps, reports and digital data (e.g., Bednarski, 2003a-c; Bednarski, 2005a, b; Clement et al., 2004).

Surficial deposits and landforms were described from more than 300 observation stations and waypoints digitally archived in the field and edited later in the office. Sixteen lithostratigraphic sections provide a sedimentary record of processes occurring in the major physiographic regions of the study area. Logged sections were located and measured with a handheld GPS unit and an altimeter during ground observation or logged remotely with the aid of oblique aerial and ground-level photographs (Figure 5). Surficial and stratigraphic units were distinguished from surrounding terrain on the basis of landform associations, earth material genesis, environment of deposition, sedimentology, morphology, texture, sorting, colour, thickness, degree of consolidation, physical limits, geological age, stratigraphic relationships and other distinguishing characteristics (Huntley and Hickin, 2010; Huntley and Hickin, 2011).

Etsho Plateau and Petitot River Valley

In the Petitot River valley (Figure 6) up to 10 m of Laurentide till overlies glacially streamlined bedrock of the Fort St. John Group and, locally, advance-phase glaciolacustrine and glaciofluvial deposits preserved in buried paleochannels. Sub-till ice-thrust features in older glacial deposits suggest the Laurentide Ice Sheet overrode partly frozen sediments during its advance (cf. Boulton and van der Meer, J.J.M,1999; Benediktsson et al., 2009). Tills are unconformably overlain by 15 to 80 m of terraced deposits of glaciofluvial sand and gravel, colluvial diamictons and glaciolacustrine silt and clay graded to a glacial lake

Figure 2. Major physiographic regions of the study area (after Bostock, 1970): a) Fort Nelson Lowland; b) Etsho Plateau; c) Maxhamish Escarpment (Bovie Lake structure); d) Tsoo Tablelands (Alberta Plateau); e) Liard Plateau; f) Northern Rocky Mountains.

with a surface elevation of approximately 420 m. Multiple upward-fining sequences from diamicton to gravel to sand and silt are interpreted to represent changes in sediment supply and meltwater recharge related to periods of rapid lake drainage and impoundment controlled by retreating (and surging) ice lobes in the Petitot and Liard river valleys.

Fort Nelson Lowland and Fort Nelson River Valley

Laurentide till, 5-10 m thick, overlies glacially streamlined Fort St. John Group and Dunvegan Formation rocks in the Fort Nelson River valley (Figure 7). Tributaries draining the Tsoo Tablelands are infilled with more than 30 m of glaciolacustrine clay, silt, sand and diamicton, deposited when the retreating Laurentide Ice Sheet in the Fort Nelson River valley impounded a glacial lake with a surface

Figure 3. Major rivers in the study area: a) Trout River; b) Liard River; c) Toad River; d) Scatter River; e) Beaver River; f) Crow River; g) La Biche River; h) Dunedin River; i) Petitot River; and j) Fort Nelson River.

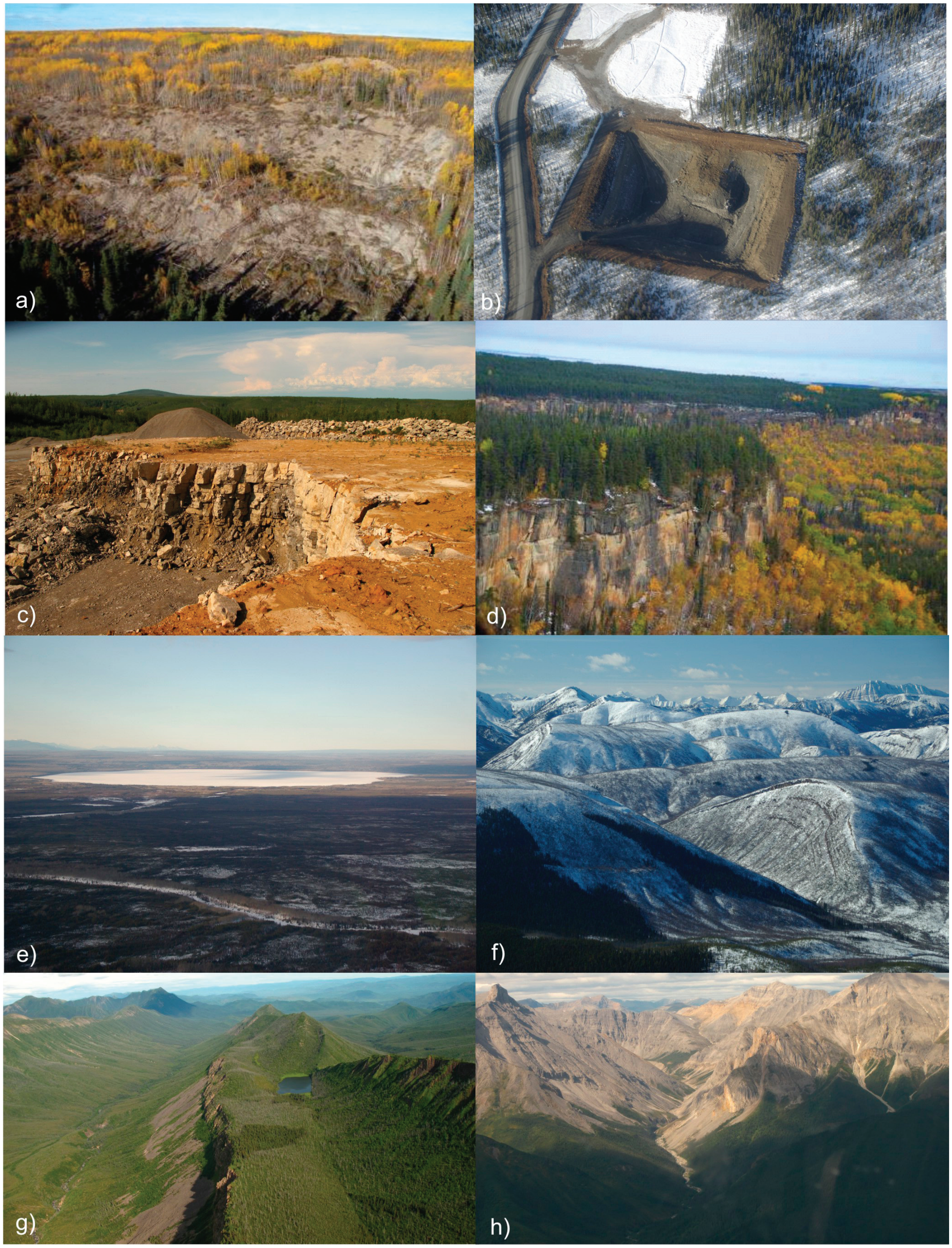
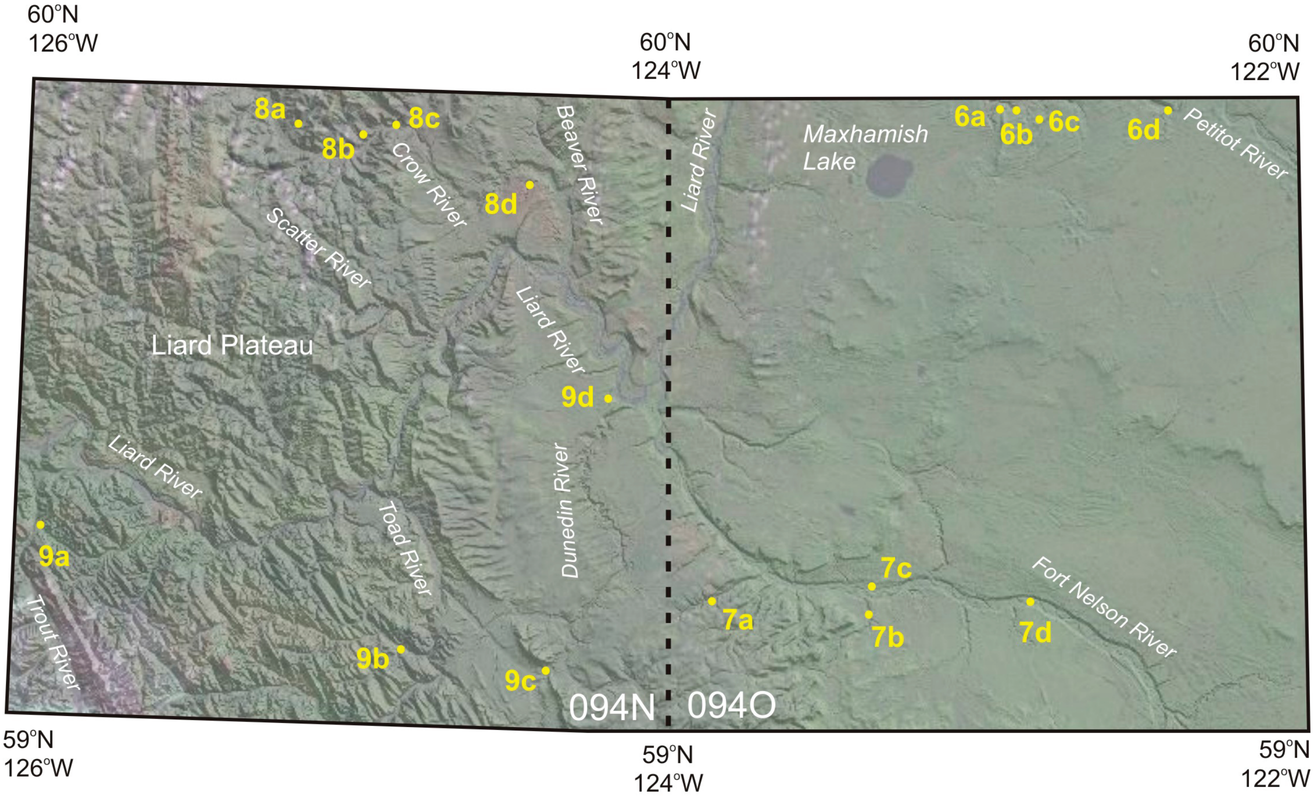


Figure 4. Geological overview of the study area: a) landslide involving till, siltstone and shale of the Fort St. John Group, Etsho Plateau; b) 3-5 m of Laurentide till overlying siltstone and shale of the Fort St. John Group, Fort Nelson Lowland; c) Carboniferous Flett Formation limestone with glacial striae indicating Laurentide iceflow towards 248°, Maxhamish Escarpment (Bovie Lake structure); d) Dunvegan sandstone and quartz-pebble conglomerate forming an escarpment of the Tsoo Tablelands; e) Till, glaciofluvial sediments and organic deposits blanket Upper Cretaceous clastic sedimentary rocks west of the Bovie Lake structure, in the vicinity of Maxhamish Lake, Liard Plateau; f) broad anticlinal-synclinal folds developed in Carboniferous to Triassic rocks, Liard Plateau; g) mid-Cretaceous and Triassic sequences, Cordilleran glaciers flowed southeast following the structural grain of the valleys, Northern Rocky Mountains; h) intensely folded and faulted Devonian, Ordovician, Cambrian and Proterozoic carbonate and clastic sedimentary rocks, Northern Rocky Mountains.



Facies codes

Fm silt and clay, massive
Fl silt and clay, laminated
Fd silt and clay, with dropstones

Sm sand, massive
Sp sand, planar-bedded
Sr sand, ripple-bedded
St sand, trough-cross-bedded

Gm gravel, massive
Gp gravel, planar bedded
Gt gravel, trough-cross-bedded
Bm boulder, massive

Dmm diamicton, matrix-supported, massive
Dms diamicton, matrix-supported, stratified
Dcm diamicton, clast-supported, massive
Dcs diamicton, clast-supported, stratified

Texture

d mixed fragments
b boulders
g gravel
s sand
z silt
c clay

Lithostratigraphic units

Organic
Alluvial
Eolian
Colluvial
Glaciolacustrine
Glaciofluvial
Laurentide till
Cordilleran till
Bedrock
Iceflow (Cordilleran)
Iceflow (Laurentide)
Paleocurrent

Figure 5. Location map and legend for facies codes, textures, lithostratigraphic units and paleoflow indicators appearing on graphic logs of sections in Figures 6 to 9. Holocene deposits include organic and alluvial units; eolian and colluvial deposits are Late Pleistocene to early Holocene in age; tills are late Pleistocene (Late Wisconsinan) deposits; bedrock in the map area ranges from Proterozoic to early Tertiary in age.

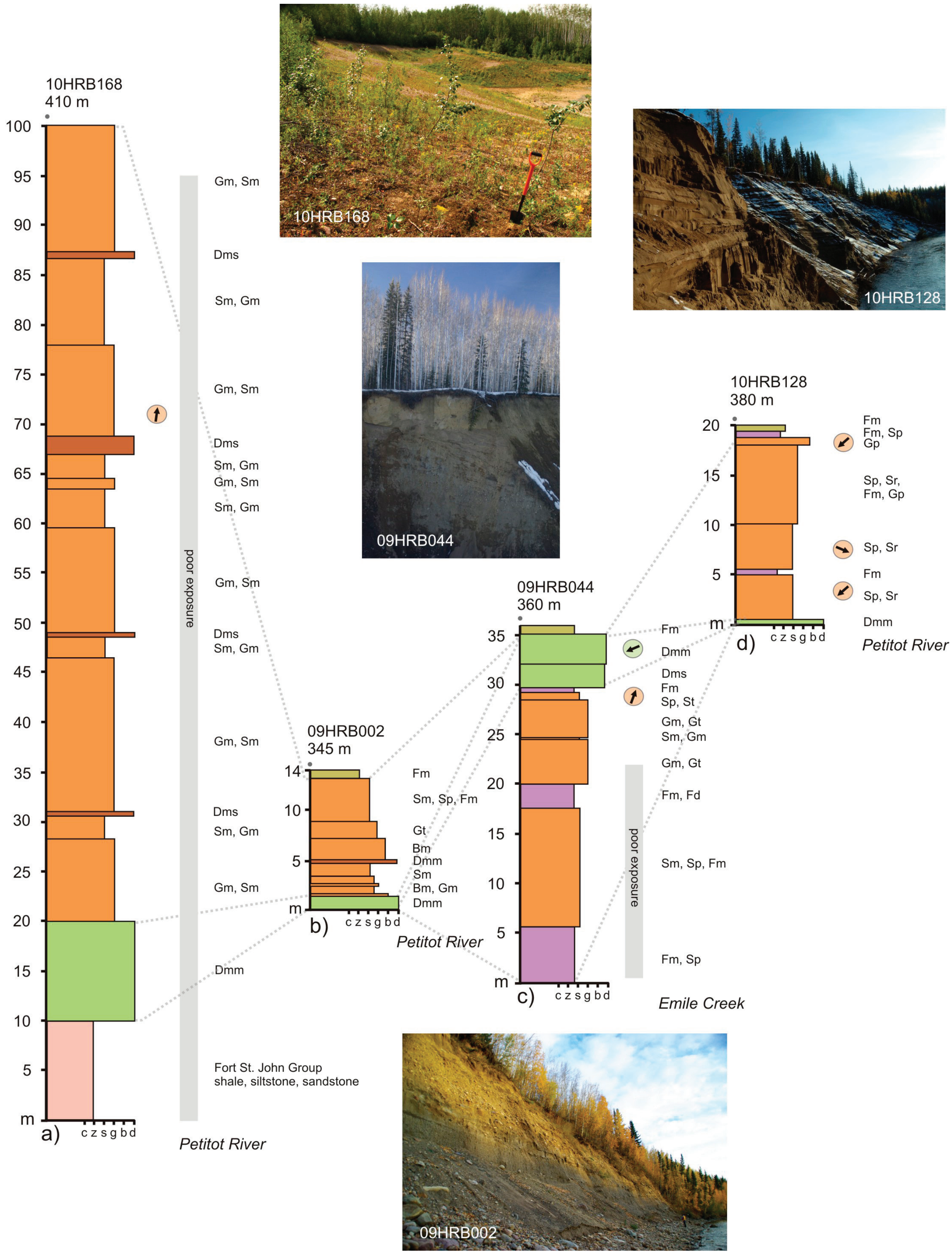


Figure 6. Graphic logs and station photographs for stratigraphic sections along the Petitot River and tributaries cutting across the Etsho Plateau. Logged profiles are measured from the top down, and each show the station identifier and surface elevation. Locations of logs a-d are shown in Figure 5.

ranging from 720 m to 540 m elevation. Multiple cycles of upward fining from diamicton to sand, silt and clay indicate that lakes periodically infilled then drained in response to retreating ice margins. Eolian-reworked glaciolacustrine sediments are deposited up to an elevation of 420 m in the Fort Nelson Lowland and parabolic dunes indicate katabatic winds flowed to the southeast. Glaciofluvial terraces graded to 300 m elevation, comprising sand and gravel 10-20 m thick, are confined to the spillway channel of the Fort Nelson River. Terrace and bedrock scarps are draped by a discontinuous veneer of colluvium resulting from debris slides, slumps and flows triggered by fluvial incision of the modern channel.

Liard Plateau and Crow River Valley

Sections along the Crow River valley record the transition from Cordilleran to Laurentide deposition and erosion (Figure 8). Cordilleran tills rest on glacially streamlined Paleozoic and Mesozoic bedrock: roches moutonnées and drumlins indicate a lobe of the Cordilleran Ice Sheet flowed southeast into the Crow River valley from the Liard River valley in southeast Yukon. Laurentide tills rest on the streamlined Toad Formation and were deposited by continental ice flowing northwest. Glaciofluvial outwash terraces contain clasts of predominantly Cordilleran provenance; although rare granitic erratics indicate some reworking of Laurentide tills and outwash at the terminal limit of continental ice. Multiple upward-fining cycles of boulder-rich gravel fining to sand, silt and clay indicate changes in sediment supply and meltwater discharge, and periodic drainage and refilling of a proglacial lake confined by retreating ice margins in the valleys of the Liard, Crow and Beaver rivers. Outwash and glacial lake deposits are graded to elevations from 620 m to 420 m. Loess and parabolic dunes mantle glaciolacustrine deposits, tills and bedrock, and indicate southeast katabatic wind flow from the remnants of Cordilleran Ice Sheet on the Liard Plateau.

Northern Rocky Mountains, Toad, Dunedin and Liard River valleys

Cordilleran and Laurentide conditions and the formation of an extensive retreat-phase glacial lake system in the major valleys are also recorded in logged sections of valleys draining the Northern Rocky Mountains and the southern Liard Plateau (Figure 9). Cirque basins are confined to the southwest of the map area and record the presence of a local accumulation centre in the Trout River watershed (cf. Mathews, 1980). Valley glaciers from this accumulation centre were confluent with the Liard lobe of the Cordilleran Ice Sheet. An upper limit to montane glaciation of 1800-2000 m elevation is inferred from the distribution of Cordilleran tills and features in valleys south of the Liard Plateau. Glacial striae and streamlined bedrock on glaciated mountain summits below this limit indicate that Cordilleran ice flowed southeast, parallel to the structural grain of the Northern Rocky Mountains, and obliquely to west-flowing Laurentide ice. The zone of confluence between the two ice sheets is interpreted to lie along the axis of the Toad River valley. West of Toad River, basal surficial units in valleys contain clasts with Cordilleran provenances. On the Liard Plateau to the east, Laurentide tills were deposited over glacially streamlined clastic sedimentary rocks of the Kotaneelee Formation. Cordilleran and Laurentide tills are conformably overlain by outwash, colluvial and glaciolacustrine deposits that are a record of retreating ice sheet margins and inundation of valleys by proglacial lakes in the Liard River basin with stable surfaces at elevations of approximately 720 m, 640 m, 540 m and 420 m.

PALEOGEOGRAPHIC RECONSTRUCTIONS OF THE STUDY AREA

Paleogeographic reconstructions presented here are based on a preliminary interpretation of earth surface materials, landforms and geomorphic processes observed in the Toad River and Maxhamish Lake map areas. The distinctive landscape of this area is largely a product of underlying bedrock and geological structures, with ornamentation by Late Wisconsinan ice sheets, ice fields and valley glaciers (equivalent to the Fraser Glaciation in British Columbia and the McConnell Glaciation in the Yukon). The landscape evolution model spans the period from the end of the last glacial maximum >18 C14 ka (>21.4 calendar ka) to the Present. The chronology presented is relative, but is constrained by radiocarbon dates on organic material and cosmogenic ages of glacial erratics in adjacent areas (e.g., Mathews, 1980; Rampton, 1987; Rutter et al., 1993; Lemmen et al., 1994; Duk-Rodkin and Lemmen, 2000; Smith, 2000, 2002; Bednarski and Smith, 2007; Bednarski, 2008; Hartman and Clague, 2008; Trommelen and Levson, 2008, Demchuk, 2010a, b).

Glacial Maximum (>18 C^{14} ka [>21.4 calendar ka])

As continental ice advanced into the region, the Tsoo Tablelands and the Maxhamish Escarpment formed barriers to westward meltwater drainage. Glacial lakes became impounded in paleovalleys east of the escarpment and were infilled with sand and gravel outwash (Figure 6c). The Laurentide and Cordilleran ice sheets subsequently overrode and deformed local ice sources, glacial lakes and advance-phase deposits. At the glacial maximum (>18 ka), the two ice sheets were confluent, and the Cordilleran Ice Sheet was

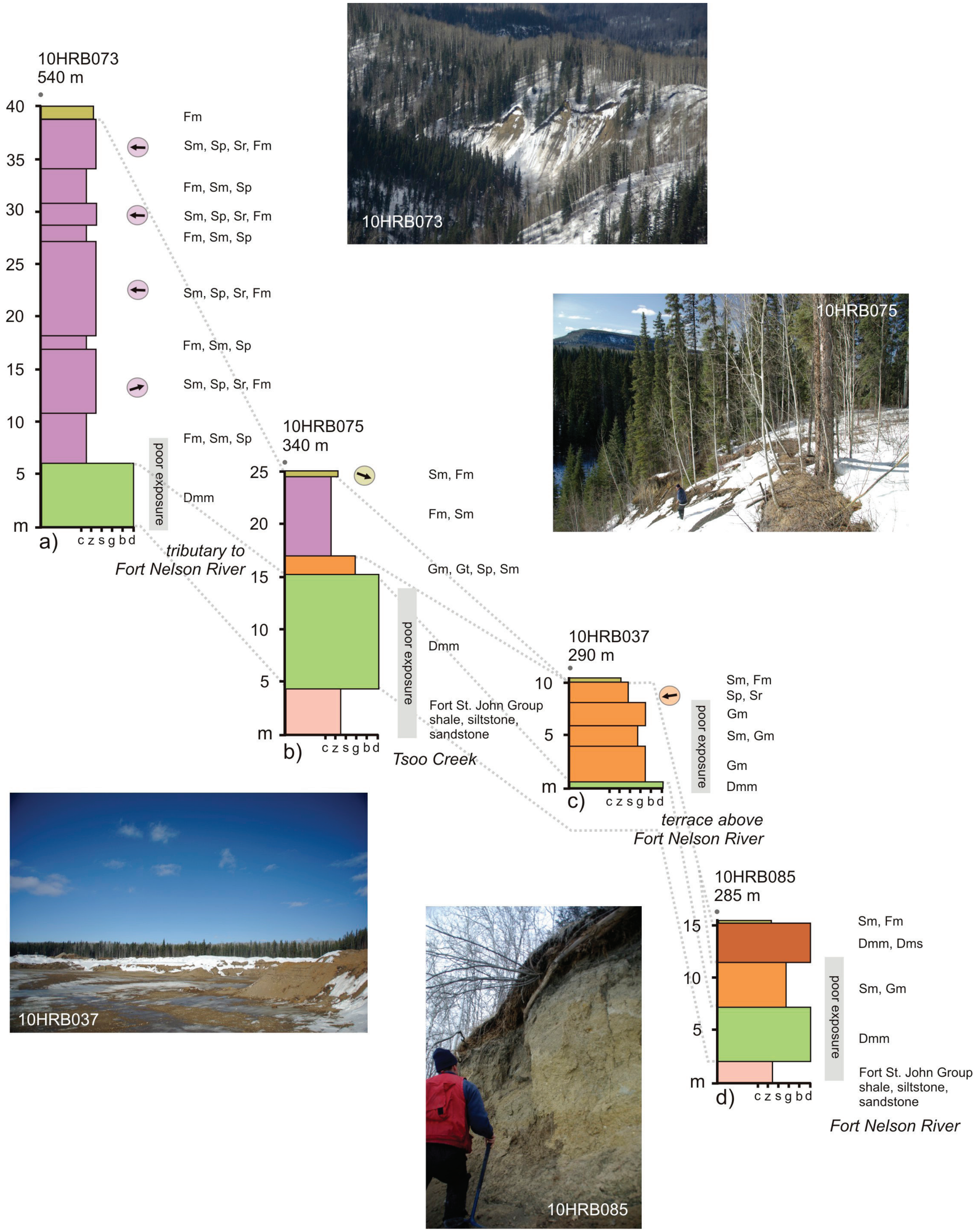


Figure 7. Graphic logs and station photographs for stratigraphic sections along the Fort Nelson River cutting across the Fort Nelson Lowland. Logged profiles are measured from the top down, and each show the station identifier and surface elevation. Locations of logs a-d are shown in Figure 5.

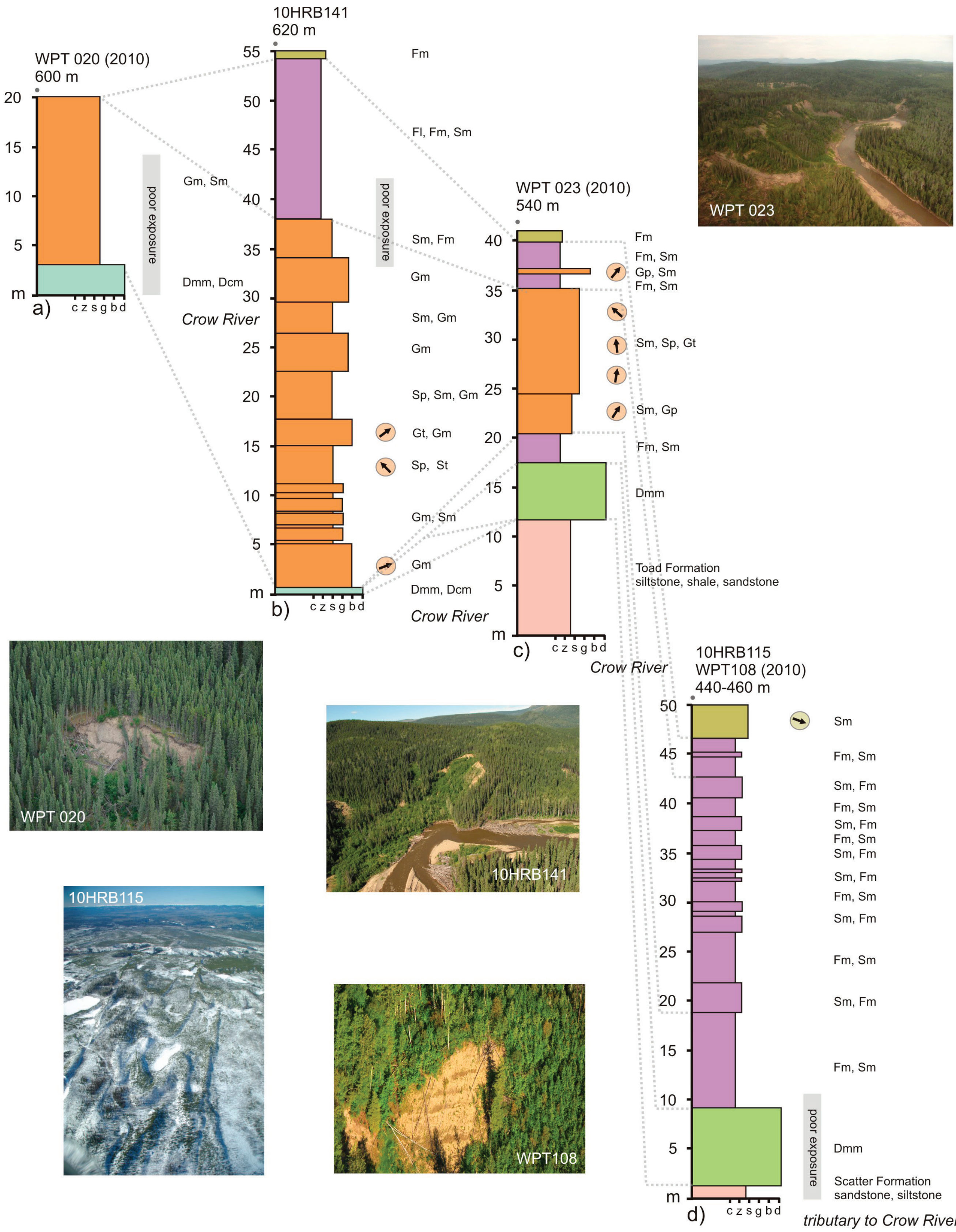


Figure 8. Graphic logs and station photographs for stratigraphic sections along the Crow River cutting across the northern Liard Plateau. Logged profiles are measured from the top down, and each show the station identifier and surface elevation. Locations of logs a-d are shown in Figure 5.

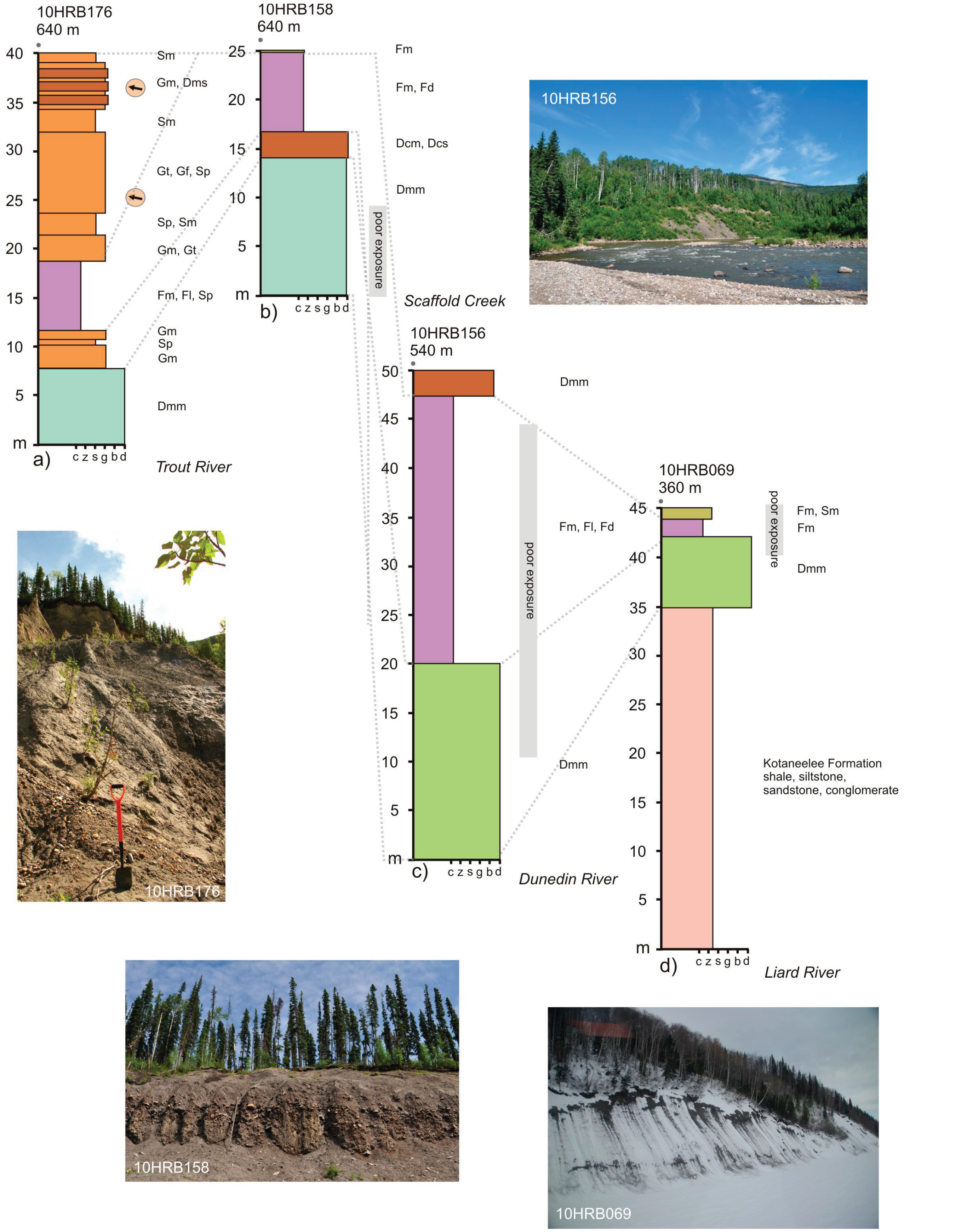


Figure 9. Graphic logs and station photographs for stratigraphic sections in tributaries to the Liard River in the Northern Rocky Mountains and southern Liard Plateau. Logged profiles are measured from the top down and each show the station identifier and surface elevation. Locations of logs a-d are shown in Figure 5.

deflected to the southeast by southwest flowing Laurentide ice (Figure 10). Topography and drainage patterns were greatly modified during the phase of maximum ice cover. Drift thicknesses in excess of 2-5 m are observed in major valleys and it is suspected that similar drift thicknesses blanket bedrock across the area (Figures 6 to 9). Laurentide tills have low clast contents (<20%) of proximally derived Cretaceous siliciclastic sedimentary rocks and distal exotic igneous and metamorphic clasts from the Canadian Shield exposed hundreds of kilometres to the northeast. Cordilleran tills have higher clast contents (>30%), and contain proximally derived Cretaceous siliciclastic sedimentary rocks and distal exotic igneous clasts from undefined montane sources in the west.

Bedrock had an important influence on the iceflow dynamics: the presence of weak siliciclastic bedrock would have resulted in deformable, lubricated conditions beneath Cordilleran and Laurentide ice (Mathews, 1974; Boulton, 1987; Fisher et al., 1995; Stokes and Clark, 2001; van der Meer et al., 2003). Glacially sculpted landforms up to several kilometres in length (drumlins, fluted till ridges and furrows) imply tills were deposited beneath active, wet-based ice sheets that were prone to fast-flowing and, or surging conditions (cf. Ross et al., 2009; Cofaigh, et al., 2010; Shaw et al., 2010). Drumlins in the western Liard Plateau indicate that Cordilleran ice flowed southeast toward the Liard and Toad River valleys, where it was confluent with glaciers flowing from cirques in the Northern Rocky Mountains. Continental ice (and subglacial meltwater) flowed from the northeast and southeast, and then continued westward into the Liard River basin and southwest over the Tsoo Tablelands towards the Northern Rocky Mountains (Figure 10). Drumlinized terrain is most pronounced south of the Petitot River and west of the Maxhamish Escarpment where ice flowed up-hill, and thick accumulations of till were deposited over soft bedrock and unconsolidated advance-phase sediments. Maxhamish Lake and numerous smaller basins were excavated by erosion and ice-thrusting when Laurentide ice and subglacial meltwater scoured and deformed older glacial deposits and weak bedrock (Figure 6c).

Deglaciation (>18 C^{14} ka [>21.4 calendar ka] to 10 C^{14} ka [ca. 12 calendar ka])

Deglaciation began sometime after 18 ka, with retreating Laurentide and Cordilleran ice sheets, stagnant ice masses and landslide debris blocking and reordering regional drainage (Figures 3d, 11a to 11j). The mapped distribution of moraine ridges implies that ice margins receded to the northeast in the Petitot River valley and to the southeast in the Fort Nelson River valley (Huntley and Hickin, 2011). Some large end moraines are deformed and streamlined suggesting that receding lobes remained active during retreat and occasionally surged (Figures 11a to

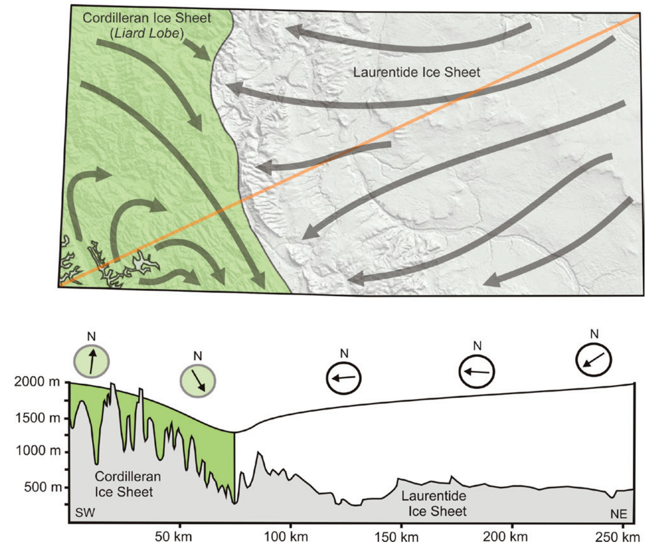


Figure 10. Greater than 18 C^{14} ka before Present (>21.4 calendar ka BP), upper limit to the Cordilleran Ice Sheet approximately 1800 m, terminal limit to Laurentide Ice Sheet approximately 1250 m elevation.

11j). Minor moraine ridges drape drumlins in cross cutting patterns, and are interpreted as crevasse fillings and minor moraines deposited shortly after surging and drumlinization ended, or as ice retreated from the map area (Sharp, 1985; Bednarski 2008; Figure 3i).

Hummocky till associated with short segments of subareal subglacial meltwater channels and eskers indicate that bodies of stagnant glacier ice remained in lowland areas on either side of the Maxhamish Escarpment and the Etsho Plateau. Eskers are composed of hummocky till and glaciofluvial gravelly sand, and likely exploited pre-existing crevasse patterns beneath the retreating ice sheet or stagnant ice bodies (Boulton et al., 2009; Utting et al., 2009). An extensive system of proglacial lakes was created in the Liard, Fort Nelson and Petitot river valleys, linked by spillways that drained meltwater into the Liard River valley and then northward into the Mackenzie River basin between 18 and 10 ka (Bednarski, 2008). In the map area, glaciolacustrine deposits and meltwater channel outlets incised into till and bedrock indicates that proglacial lakes had surface elevations of approximately 840 m, 720 m, 620 m, 540 m, 420 m, 380 m and <300 m throughout this interval (Figures 11a to 11k).

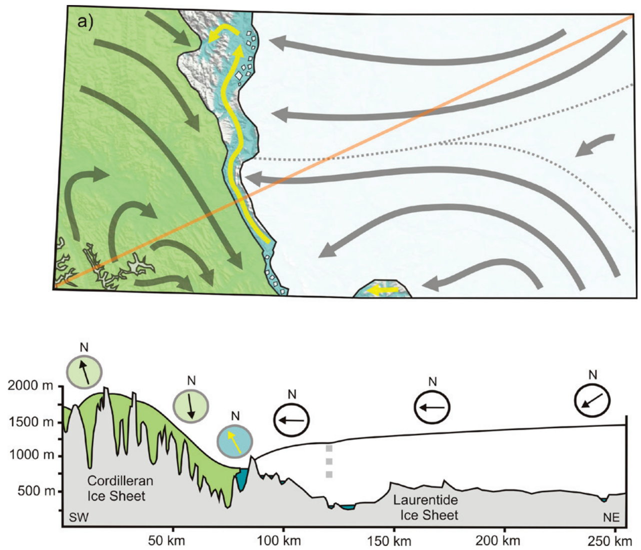


Figure 11 a) Greater 18 C^{14} ka BP (21.4 calendar ka BP) to 13.5 C^{14} ka BP (16.2 cal ka BP), early deglaciation, ice-marginal glacial lake still-stand elevation approximately 840 m.

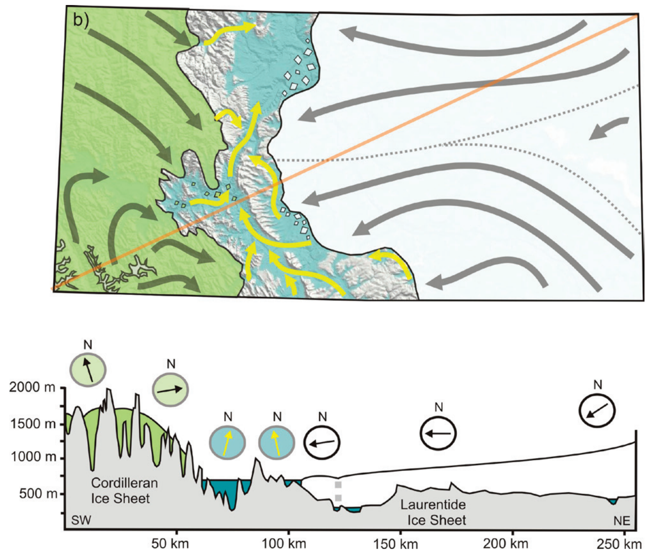


Figure 11 b) 13 C^{14} ka BP (15.6 calendar ka BP) to 12.5 C^{14} ka BP (15.2-14.4 calendar ka BP), Glacial Lake Liard still-stand elevation approximately 720 m.

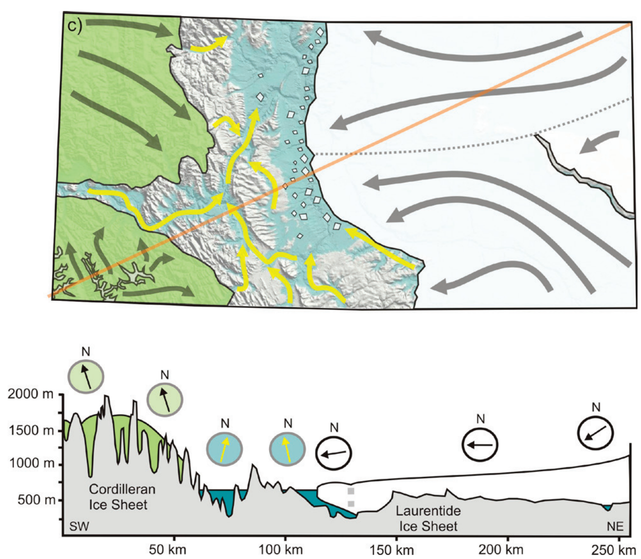


Figure 11c) 12.5 C^{14} ka BP (15.2-14.4 calendar ka BP) to 12 C^{14} ka BP (14.1 calendar ka BP), Glacial Lake Liard still-stand elevation approximately 620 m.

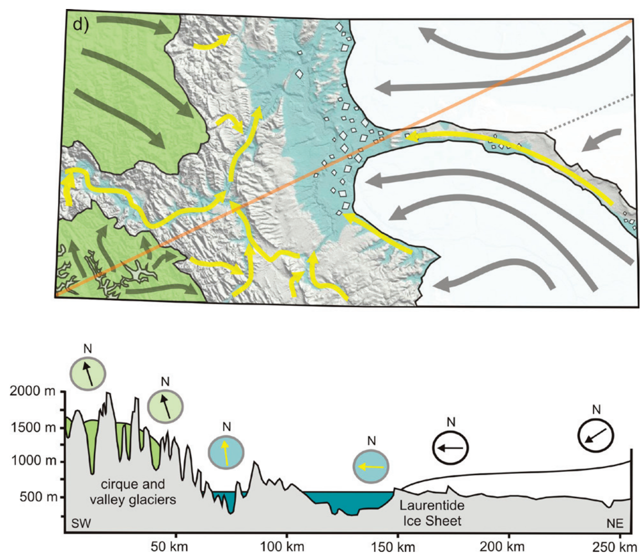


Figure 11 d) 12 C^{14} ka BP (14.1 calendar ka BP) to 11.5 C^{14} ka BP (13.45 calendar ka BP), Glacial Lake Liard still-stand elevation approximately 540 m.

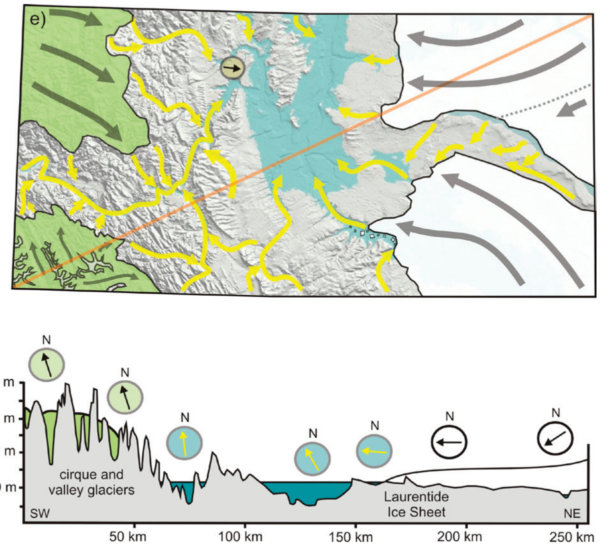


Figure 11e) 11.5 C^{14} ka BP (13.45 calendar ka BP) to 11 C^{14} ka BP (13 calendar ka BP), Glacial Lake Liard and Glacial Lake Fort Nelson still-stand elevation approximately 420 m.

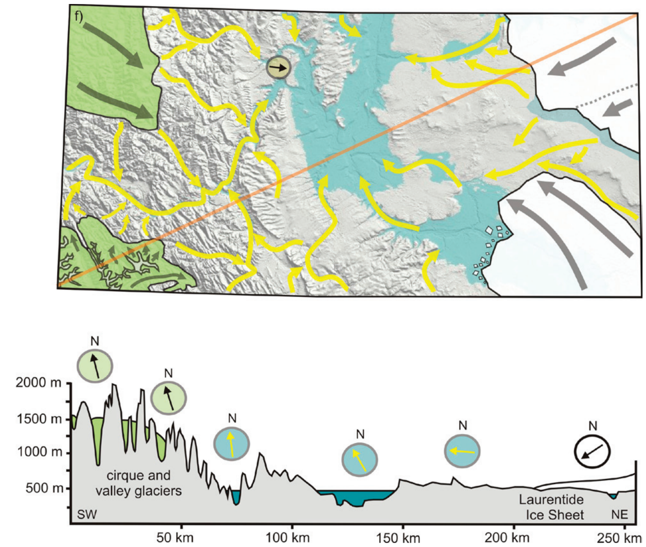


Figure 11f) 11.5 C^{14} ka BP (13.45 calendar ka BP) to 11 C^{14} ka BP (13 calendar ka BP), Glacial Lake Liard and Glacial Lake Fort Nelson still-stand elevation approximately 420 m.

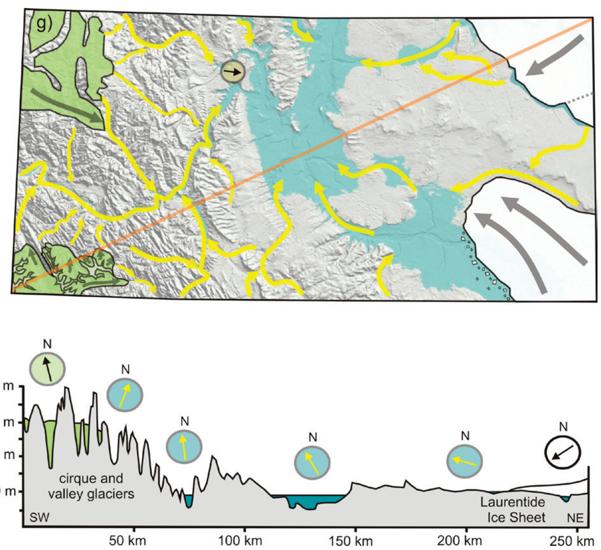


Figure 11g) 11.5 C^{14} ka BP (13.45 calendar ka BP) to 11 C^{14} ka BP (13 calendar ka BP), Glacial Lake Liard and Glacial Lake Fort Nelson still-stand elevation approximately 420 m.

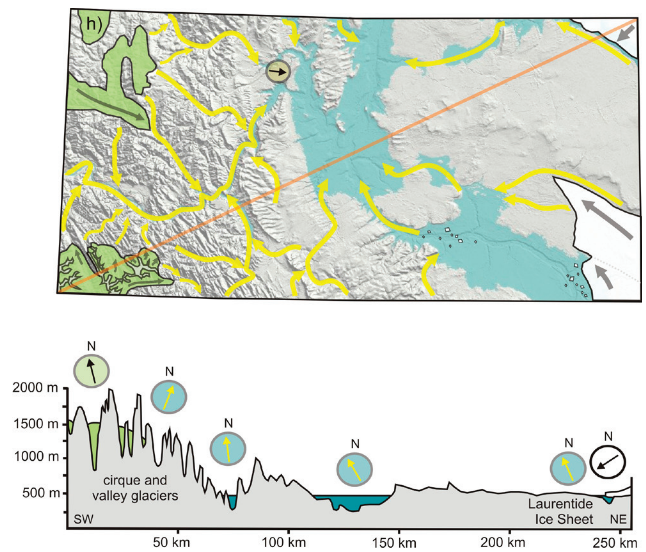


Figure 11h) 11.5 C^{14} ka BP (13.45 calendar ka BP) to 11 C^{14} ka BP (13 calendar ka BP), Glacial Lake Liard and Glacial Lake Fort Nelson still-stand elevation approximately 420 m;

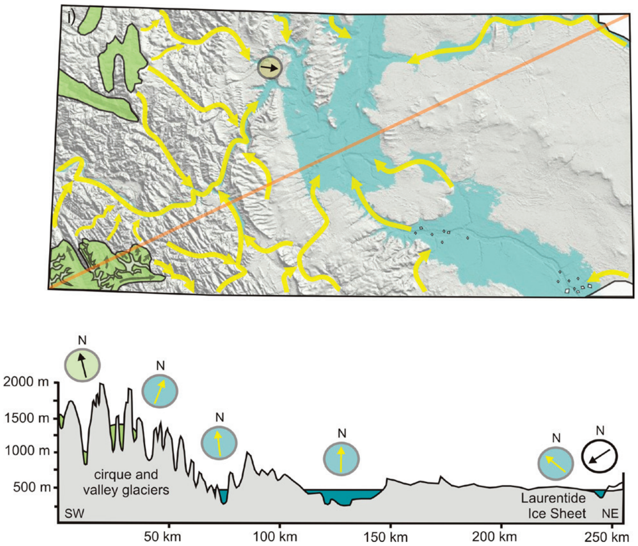


Figure 11i) 11.5 C^{14} ka BP (13.45 calendar ka BP) to 11 C^{14} ka BP (13 calendar ka BP), Glacial Lake Liard and Glacial Lake Fort Nelson still-stand elevation approximately 420 m

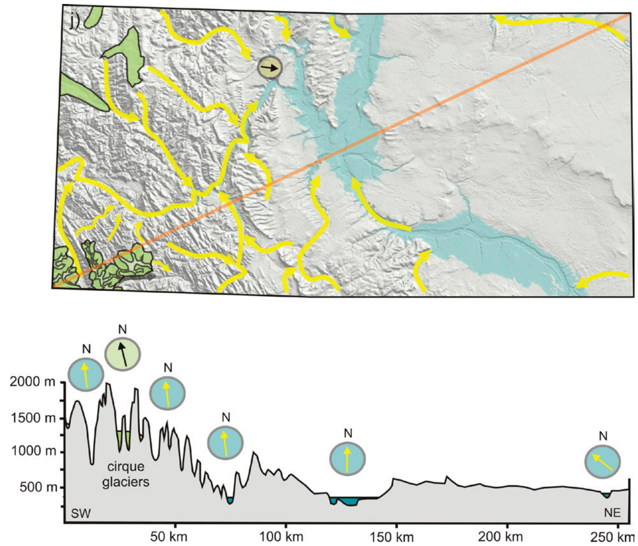


Figure 11j) 11 C^{14} ka BP (13 calendar ka BP) to 10.5 C^{14} ka BP (12.65 - 12.75 calendar ka BP), Glacial Lake Liard and Glacial Lake Fort Nelson still-stand elevation approximately 380 m.

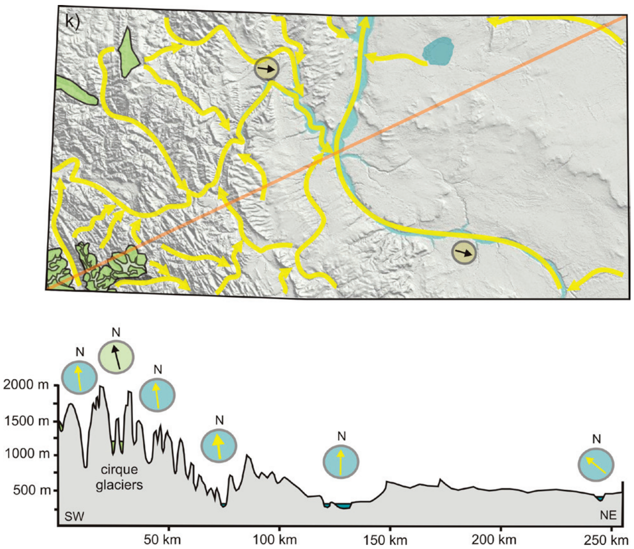


Figure 11k) 10.5 C^{14} ka BP (12.65 - 12.75 calendar ka BP) to 10 C^{14} ka BP (11.95 - 12.05 calendar ka BP), Liard and Fort Nelson spillways draining into Glacial Lake Mackenzie with a surface elevation less than 300 m.

Post-glaciation (10 C^{14} ka [ca. 12 calendar ka] to Present)

After 10 ka, changes in regional base-level led to episodes of channel incision and aggradation, resulting in the formation of drift terraces along most stream and river valleys (Figure 12). In the early Holocene, pulses of fluvial terrace building followed initial valley incision by the Liard, Toad, Fort Nelson, Petitot and other major rivers. Most streams and rivers have alluvial terraces <5 m above active floodplains consisting of gravel overlain by silt and sand. Poorly drained clay-rich till on the plateaus and glaciolacustrine sediments in lowland areas are covered by extensive postglacial peat deposits and fens. Discontinuous permafrost is sporadically encountered in glaciolacustrine and some peat deposits. Charcoal, observed in dug pits on alluvial terraces, suggest forest fires may have contributed to periods of landslide activity on slopes and local fluvial aggradation. Landslides and colluviated deposits are common where bedrock outcrops form escarpments, and where shale or fine-grained glacial deposits are exposed along steep cutbanks. Stream networks draining lowland and plateau watersheds are disrupted by beaver activity, and to a lesser extent where roads, pipelines and other infrastructure cross streams, rivers and organic deposits (Huntley and Hickin, 2010; Huntley and Hickin, 2011).

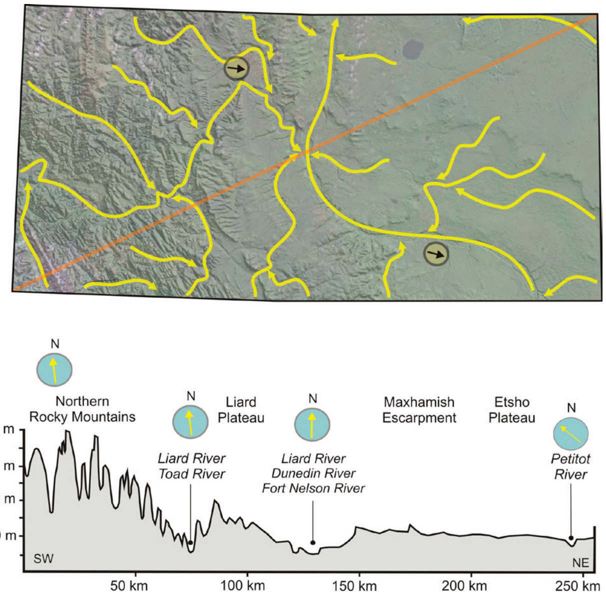


Figure 12. 10 C^{14} ka BP (11.95 - 12.05 calendar ka BP) to Present; modern drainage network established.

SUMMARY AND FURTHER RESEARCH

Knowledge of the extent and iceflow patterns of the Laurentide and Cordilleran ice sheets; the distribution of glaciofluvial and glaciolacustrine deposits, meltwater features and drainage directions; the distribution of colluvial deposits, landslides and permafrost; and the extent and nature of eolian deposits is critical to reduce the risks for exploration of energy, mineral and forest resources, sustainable long-term investment and economic development in northeastern British Columbia (Huntley and Hickin, 2010; Huntley and Hickin, 2011). The public geoscience data model created as part of the GEM-Energy Yukon Basins project is an important source of information for targeted exploration of granular aggregate, frac sand and groundwater resources; recognizing geological hazards that could influence surface engineering practices (e.g., road design, well pad locations, pipeline and power-line routing); understanding the long-term impacts of climate change on landscape evolution; land management decisions on energy and mineral resource development in the region; and e) innovative geoscience initiatives to encourage community engagement (e.g., Figure 13; Huntley, 2010).

New insights into the glacial history and paleogeography of the Toad River (NTS 094N) and Maxhamish Lake (NTS 094O) map areas (Figures 10 to 12) are provided by the regional-scale overview of the bedrock geology, surficial earth materials and landforms presented here (Figures 1 to 9). The distinctive landscape of northeastern B.C. is (in part) the product of the Late Wisconsinan Glaciation, beginning >18 C^{14} ka (21.4 calendar ka) and terminating in this region at approximately 10 C^{14} ka (ca. 12 calendar ka) before present. Topography and drainage patterns were greatly modified during the last glaciation. Underfit modern rivers occupy Late Pleistocene glacial spillways that drained into the Liard River basin (Figure 3). Maxhamish Lake and numerous smaller basins were excavated when ice sheets and subglacial meltwater scoured older glacial deposits and weak bedrock (Figures 2 to 4). During deglaciation, and into the Holocene, changes in regional base-level led to episodes of channel incision and aggradation, resulting in the formation of terraces along most stream and river valleys (Figures 6 to 9). Forest fires may have been a key trigger for landslide activity on slopes. Watersheds are prone to disruption by beavers, and to a lesser extent, by humans.

Based on remote predictive mapping and field observations from 2003 to 2010, our landscape evolution model is geomorphologically robust, although the details and interpretations may change as new information is acquired. Results are pending for lithogeochemistry and sedimentological analyses on glacial erratic boulders, potential frac sand sources and granular aggregates sampled in 2009 and 2010 (Hickin and Huntley, 2011). A future research focus should be to improve the age control of events and

Figure 13 Scatter River Fly Camp (2010): the original work in acrylic (by D.H. Huntley) is a 10x16 inch canvas that resides in a private collection. The painting depicts a joint BC Ministry of Energy and GSC summer field camp at the base of large translational bedrock slide involving failure of Paleozoic and Mesozoic clastic sedimentary rocks; successively lower terraces in the valley are related to the periodic blockage of the valley by landslides downstream (see also Figure 3d).

place the relative sequence of events presented here in regional chronolithostratigraphical context. Further, detailed investigation of bedrock and drift sections in the Liard, Toad and Dunedin river valleys; exposures in borrow pits and other anthropogenic sites; and at elevation is required to collect samples for detailed sedimentological analyses, organic material for radiocarbon dating, or to obtain optically stimulated luminescence dates and cosmogenic ages on sand (loess) dunes and large erratic boulders on mountain tops and ridges. Another focus could be the application of our digital surficial geology data model to other methods of drift exploration, including LiDAR, seismic shothole records, petrophysical logs, auger drilling, test pitting, ground-penetrating radar and airborne electromagnetic surveys (cf. Best et al., 2004; Levson et al., 2004; Smith et al., 2006, Hickin et al., 2008; Smith and Lesk-Winfield, 2009).

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