Incidence of Late Pleistocene-Holocene Climate on the Concurrent Landscape and Permafrost Development of the Beaver Creek Region, Southwestern Yukon, Canada

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
The Beaver Region is located in southwestern Yukon and was not glaciated during the last glacial advance (Late Wisconsinian, 26-11.7Ky BP). The site lies on Middle Wisconsinian to Holocene deposits covering a disintegration moraine; prior cryostratigraphic investigations have shown the presence of ice-rich cryofacies and syngenetic ice wedges down to 10 m below the surface. The objective of this paper is to propose a conceptual model linking the permafrost cryostratigraphy to the post-glacial climate history. 29 boreholes have been analysed in relation to the topography, ecology and pedology. Five cryostratigraphic units have been defined, characterized and related to specific development stages. As results, the contemporary landscape can be defined in two contrasted zones; mesic convex, and humid concave areas. This differentiated geomorphology affects the modern landscape evolution from a geothermal, hydrologic, ecologic, pedogenic and cryogenic perspective.

RÉSUMÉ
La région de Beaver Creek est située au sud-ouest du Yukon et n'a pas été englacée lors de la dernière avancée glaciaire (Wisconsinien tardif, 26-11.7 ka BP). Le site repose sur des dépôts récents (du Wisconsinien Moyen à l'Holocène) recouvrant une moraine de désagrégation; des études cryostratigraphiques préalables ont montré la présence de cryofaciès riches en glace et de coins de glace jusqu'à 10 m sous la surface. L'objectif de cet article est de proposer un modèle conceptuel reliant la cryostratigraphie du site avec l'histoire post-glaciaire. 29 forages ont été analysés en relation avec la topographie, l'écologie et la pédologie. Cinq unités cryostratigraphiques ont été définies, caractérisées et assignées à autant de stages de développement spécifiques. Enfin, le paysage actuel peut être divisé en deux zones contrastées; un environnement à topographie convexe et mésique puis un concave et humide. La géomorphologie différenciée affecte l'évolution contemporaine du paysage d'une perspective géothermique, hydrologique, écologique, pédogénique et cryogénique.

INTRODUCTION

During the Pleistoscene, the landscape of southwestern Yukon (Canada) was extensively transformed by several regional glaciations (Jackson & al. 1991; Scudder 1997; Fuller & Jackson 2005). During the last glacial maximum (regionally referred as the McConnell glaciation ~24 ky BP – Jackson 1991), the Cordilleran Ice Sheet covered most of north-western America and merged with the Laurentide Ice Sheet up to southwestern North-West Territories (Dyke 2004). Extensive areas of Siberia, Alaska and Yukon remained ice-free. This region, Beringia, extended from the Lena River in Siberia (Russia) to the Mackenzie River in the North-West Territories (Canada) (Fig.1) (Anderson & Lozhkin 2001; Elias & Brigham-Grette 2013). Much of Beringia preserved an exceptional sedimentary record of Pleistocene environmental change as well as an important volume of ground ice and carbon (Schirrmeister et al. 2013).

This paper is concerned with periglacial terrains that remained unglaciated during the last glacial maximum in southwestern Yukon. Specifically, our study focused on the Beaver Creek area which is located in the Wellesley basin, north of the Kluane range and 10-20 km north of the Shakwak trench (Fig.2). The Wellesley basin sits at the base of the St-Elias Mountains, where the St-Elias glacial lobe ended as a piedmont glacier complex more than once during the Pleistocene (Fig.2) (Jackson & al. 1991).

Because of its particular location, this site was glaciated under the Mirror Creek glaciation, most probably until the end of Early Wisconsinian (55-50 ky BP for the Gladstone glaciation – Ward & al. 2007), but remained ice-free under the McConnell glaciation during the Late Wisconsinian (Fig.2) (Rampton 1971; Vermaire & Cwynar 2010). At the terminus of St-Elias piedmont glacier complex (Jackson & al. 1991), the Mirror Creek glaciation left a non-oriented hummocky disintegration moraine deposits 5 km south of the town of Beaver Creek (Rampton 1971).

The cold continental climate of the area is characterized by short, warm and dry summers, and long, cold, and dry winters (Scudder 1997). The mean annual air temperature is -4.9 °C (Environment Canada 2015). The vegetation in the ecoregion includes boreal black and white spruce forest, subalpine spruce-willow-birch shrubland and alpine tundra at higher elevations (Scudder 1997). The surficial geology was described as dominated by till with rounded and angular boulders in a sandy matrix covered by fibric organic material (Lipovsky and Bond 2014).

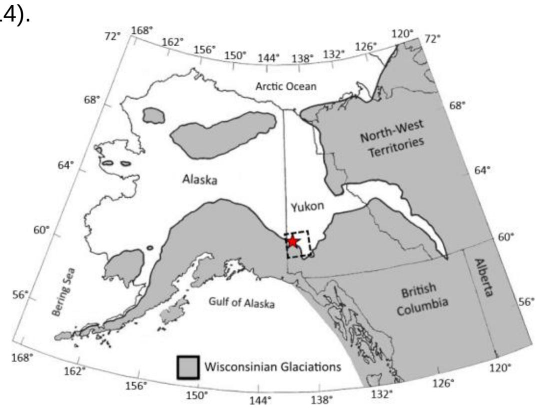

Figure 1. Localization of the study site in relation with the general Wisconsinian Glaciation limit (map from Scudder 1997). The white area in the continent refers to Eastern Beringia, the dashed square outlines the contour of Fig.2 and the red star locates the study site.

Since 2008, permafrost research has been conducted at the Beaver Creek Road Experimental Site, known as BC-RES (62° 20´ N - 140° 50´ W) which is located in the extensive discontinuous permafrost zone (Brown & al. 1998). Prior cryostratigraphic investigations at the site have shown the presence of ice-rich cryofacies and syngenetic ice wedges down to 10 m below the surface (de Grandpré & al. 2012; Stephani 2013; Stephani & al. 2014).

The present paper aims at presenting the cryostratigraphy at the Beaver Creek study site and to propose a model of concurrent landscape and permafrost development in relation to past climatic events during the Late Pleistocene-Holocene period.

METHODOLOGY

Vegetation and topographic surveys were conducted as well as pedologic and cryostratigraphic investigations of the terrain to interpret local landscape and permafrost development through time.

The plant communities and their spatial distributions were characterized during field survey and by the interpretation of a high resolution 4-colors satellite image (©WorldViewII, acquired on July 4th, 2008) and aerial pictures (flight line A24208, images 44 to 64, from the Yukon Geological Survey Library). The resulting map was created by digitizing the interpretation over the satellite image using ©ArcInfo 10.2. The topography of the site was measured with a ©Trimble R8 Differential GPS (8 mm vertical and 15 mm horizontal precisions). Data were processed using the ''Spline With Barrier'' tool in ArcInfo to develop a digital elevation model of the site. Soils were surveyed and classified using the Canadian Soil Classification System (SCWG 2002).

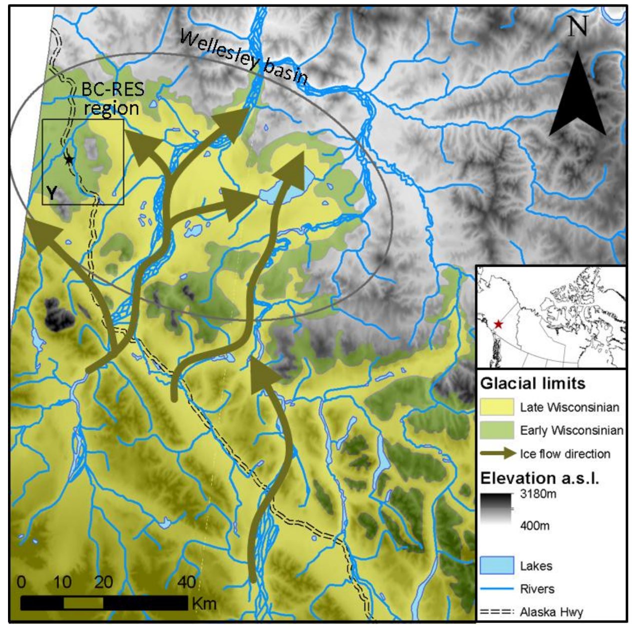

Figure 2. Glacial limits and ice flow direction over the regional topography. Study site location (star).

The cryostratigraphy was described from a compilation of 29 boreholes that were drilled along the X – X' cross-section (Fig.3). Originally, the objective of the drilling campaign was to characterize permafrost sensitivity to thawing for a road mitigation project conducted by the Engineering Branch of Yukon Highways and Public Works (Reimchen & al. 2009). The cores were extracted using a modified SIPRE core barrel 10.2 cm (4 in) in diameter. Additional boreholes were made using a standard SIPRE core 7.6 cm (3 in) in diameter. The samples were kept frozen and described in detail using a cryostratigraphic approach (Stephani 2013; 2014). Recurrent cryofacies were identified and described, cryostratigraphic units were distinguished and every core was classified according to the principles of cryostratigraphy (French & Shur 2010). Once classified, core logs were displayed on a topographic profile of the site. The cryostratigraphic units were determined based on sediment composition and organization, cryofacies, textural composition, ice and organic matter contents, wood fragments and ice wedge occurrences. The units' localization, vertical contact, lateral variations, depth and thickness were characterized and logged. Some representative cores also used to get an averaged grain-size, textural proportions and gravimetric ice and organic matter content. The grain-size distribution was measured according to ASTM D-422-63e02 (2007) and statistics were computed using the Gradistat software (Blott and Pye 2001). The ice and organic matter content measurements were based on ASTM D-2974 (2014). Finally, for each unit, some representative cores were photographed and imaged by micro-computed tomography using a ©Siemens ''SOMATOM – Definition AS+ 128'' scanner (resolution of 97 x 97 x 300 µm/voxel for images of 512 x 512 voxels maximum dimension). Hounsfield (1973) and Knoll (1989) can be consulted for further information about tomography. Specifically, Calmels and Allard (2004) used this technique to analyze the cryostructures of permafrost.

RESULTS

Figure 3 shows the ecological and geomorphological interpretation of the study area. A clear distinction appears between two typical environments: 1) the muskeg (orange zone on Fig. 3) and 2) the forest (pink patches on Fig. 3). The transition from the muskeg to the forest is gradual.

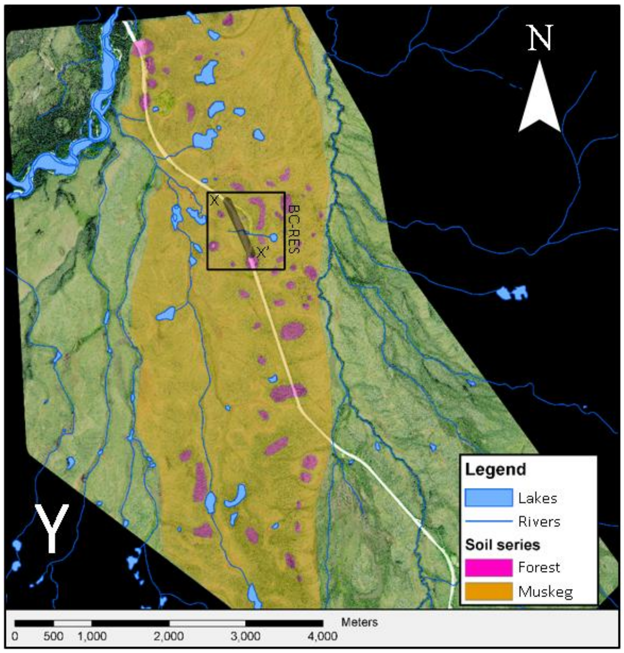

Figure 3. Satellite image of the of BC-RES vicinity (region previously framed by a black square 'Y' on Fig. 2). The orange and pink masks cover only the part of the moraine that remained essentially unaffected by any wider scale fluvial geosystems (in green). Pink represents the forest ecosystem while orange represents the muskeg and transitory ecosystem between forest and muskeg. The black square indicates the study site and the X – X' line defines the cryostratigraphic cross-section.

The muskeg, including its transition zone, covers most of the terrain over the surface of the moraine. It occupies the concave topography and represents the lower relative elevation (690-700 m). The typical vegetal community comprised 0.3-0.5 m high cotton-grass tussock, with sphagnum and brown mosses growing in the inter-tussock channels. Many 0.5-1 m dwarf birch and willow shrubs were observed in the most humid patches, while green alder and bigger willow shrubs were preferentially located along subsurface flow paths (water tracks). Stunted black spruces were distributed sparsely over the muskeg and their development and density progressively increased toward the forest. The muskeg soils were dominated by either a glacic, mesic or terric organic cryosol with a very thin cryic phase; the average active layer thickness was 0.5 m (min=0.3; max=0.9; Standard Deviation (SD)=0.2; n=64).

Comparatively, the forest was associated with the small hills protruding the general topography and with steeper slopes; hills' elevation approximated 5-10 m above the surrounding muskeg elevation. Their typical plant community was composed by 3-10 m clustered spruces sitting on woodland moss cushions surrounded by lichen mat. Many 2-3 m willow and white alder shrubs were observed around it. The soil generally found was a gleysolic static cryosol with a slightly gravelly and very thixothropic phase. In some places, the permafrost table was not encountered with the 1.2 m frost probe or hand auger (6 occurrences) but, if this was neglected, the active layer averaged thickness would have been 0.7 m (min=0.3; max=1.2; SD=0.2; n=71).

The cryostratigraphy is classified in five units from bottom to top (the numbers in parenthesis after titles is for the approximate depth range of each unit) : A) the diamicton, B) the stratified sediments, C) the lower ice-rich silt, D) the massive ice-poor silt and E) the upper ice-rich silt. The active layer was not considered in this classification, although it is genetically linked to the permafrost.

Unit A – Diamicton (>12-6+ m)

Unit A consists in a diamicton characterized by sub-angular to sub-rounded rock fragments in a grey silty to sandy matrix. The particle size distribution is coarse, unsorted and contains a significant mud fraction. The dominant cryostructure is porous-visible and the permafrost is relatively ice-poor.

The average grain size is 385 μm and the gravel and coarser fraction is 25.8 %, the sand fraction is 33.8 %, the silt fraction is 31.2 % and the clay fraction is 9.2 %. There is no ice in excess of the porosity, organic matter, tephra, ice wedge nor wood fragment.

This unit was rarely encountered, occurring in only 5 % of the total 145 m of core extracted. It was always the deepest material to be recovered from boreholes and its thickness was out of reach of the coring equipment (Fig.4). Being closer to a forested hill, diamicton at YG12-2 represents the shallowest occurrence (6.15 m below the surface) while diamicton at YG5-1 represents the deepest (11.8 m below the surface). This is explained by the rolling topography of the disintegration moraine. Some rock fragments similar to the diamicton also outcrop at several locations in the forest uniquely. The surface elevation of Unit A at the site ranges from <680 m to >700 m.

Unit B – Stratified sediments (>10-5 m)

Unit B consists in a blend of ice-poor finely stratified and/or distorted sandy to silty organic sediments that sometimes includes sand and reworked gravels. Its cryostructure ranges from porous invisible to poorly developped stratified-lenticular. It also includes crustal ice around rocks and branches.

No measurements were made on the material grain size proportions due to their high variability and very finely stratified aspect. However, it includes a significant portion of wood fragments (~37 %), some organic-rich parts, a trace of tephra and no ice-wedge.

This unit is well represented among the boreholes (in 9/29 of them), occurring in 19 % of all the core length recovered, and was found directly over unit A every time the latter was found, plus at the bottom of YG2-1, YG1-2 and YG1-3 (Fig.4). Its thickness varies around 2-3 m and its transition with the underlying unit A is different from a sedimentary and a cryogenic perspective. In terms of sediment type and organization, the transition is very sharp while in terms of ice, porous invisible cryostructure (ice-poor permafrost) remains dominant.

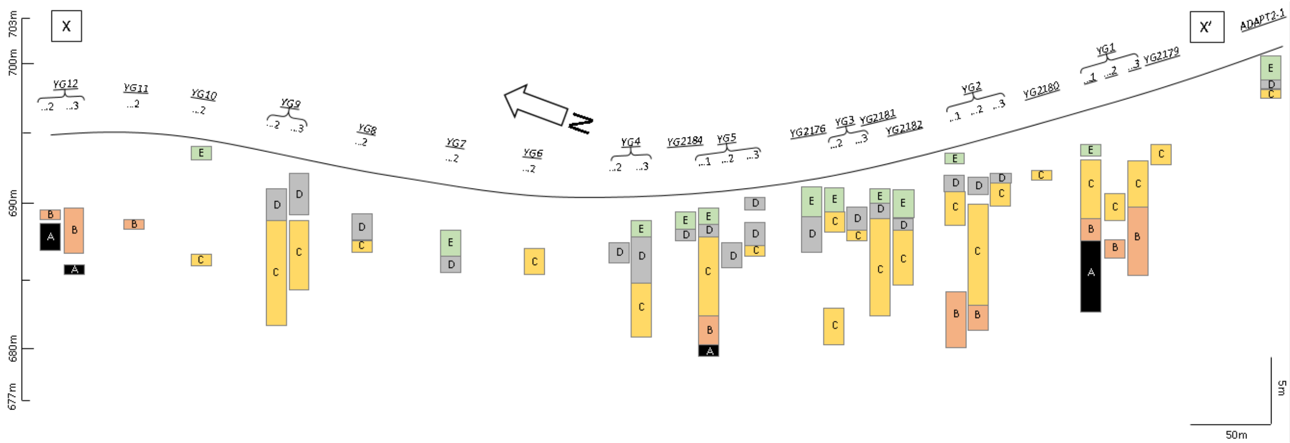

Figure 3. Cross section X – X' of the terrain showing relevant boreholes and interpreted cryostratigraphic units (A to E).

Figure 4. Typical internal structure of permafrost and appearance shown by a tomographic images (left side) and a picture (right side) of each cryostratigraphic unit (A to E). For tomographic images, white indicates dense mineral matter, dark gray indicates ice and mid-tones are proportional to the mixture proportion. The chromatic scale is not fixed and/or absolute but rather individually modulated to increase contrasts and highlight cryostructures.

Unit C – Lower ice-rich silt (4-2 m)

Unit C consists in an ice and organic-rich silt with well-developed microlenticular to stratified-lenticular (belt-like) and ataxitic cryostructures or a porous-visible organic matrix.

The average grain size is 19.0 µm and the gravel fraction is 1.5 %, sand fraction is 11.5 %, silt fraction is 76.1 % and clay fraction is 10.9 %. The gravimetric ice and organic matter content were respectively measured at 109 % and 7.7 %. In this unit, most of the wood fragments (~49 %), most of the ice wedges (74 %) and traces of tephra were encountered. Additionally, many cores show strata affected by ice-wedge growth.

This unit is the most widely represented, making 51 % of the 145 m of core recuperated (in 21/29 boreholes). Its general thickness was difficult to evaluate due to the lack of clear contact with the cryostratigraphic unit B. However, the data are sufficient to estimate a minimum thickness of 6 m under the lower part of the muskeg and a tendency to decrease when moving toward the forest. Where the contact with the underlying unit B was found (YG5-1 and YG1-1 – Fig.4), a gradual refinement of the particle size was observed co-occurring with well-developed stratifications, a gradual density decrease and a quick shift toward ataxitic, stratified-lenticular and microlenticular cryostructures (ice-rich permafrost).

Unit D – Massive silt (3-1 m)

Unit D consists in an ice-poor grey silt. A few black spots associated to rotten rootlets and some oxidation along faults are also characteristic of this unit. The dominant cryostructure is porous-invisible with very few thin and long lenticular cryostructure in the upper portion of the unit.

The average grain size is 19.0 µm. The gravel fraction is 0.1 %, the sand fraction 17.1 %, the silt fraction 68.2 % and the clay fraction 14.0 %. The gravimetric ice and organic matter content were respectively measured at 47 % and 3 %. In this unit, only few wood fragments (~7 %), some ice-wedges (20 % of all ice-wedge compiled) and one occurrence of tephra were found.

This unit is well represented, making 19% of the 145 m core recovered (in 18/29 boreholes). It was found at a depth between 5-1 m and its general thickness was less than 1-3 m (Fig.4). The cryostratigraphic contact with the underlying unit C was clear and frequently observed by the recognition of a thaw unconformity. From unit C upward, the mineral texture does not change but the unit is characterized by porous invisible cryostructure (ice-poor permafrost).

Unit E – Upper ice-rich silt (0.7-0.3 m)

Unit E consists in an ice and organic-rich sandy coarse silt. The particle size is very similar to unit D, however, the cryostructures differ: the microlenticular cryostructure content progressively increases from unit D upward to reach an elevated ice content zone where the cryostructure appeared as ataxitic and stratified-lenticular. The latter zone is delimitated by two thick ice lenses (>1 cm).

The average grain size is 27.2 µm. It includes no gravel, 19 % sand, 75 % silt and 6 % clay. In the forest, the same sediments can include up to 15 % of sparse reworked gravels. The average gravimetric ice content is 184 % and tephra is found very often near the permafrost table. The average organic matter content is 17.5 % and tends to reach its maximum near the permafrost table.

This unit is present all over the terrain, but has not been recovered very often in the X – X' cross-section. It was found in 11/29 boreholes, representing only 12 % of the total recovered length. When accessible, its bottom was encountered at about 2-3 m below the surface (Fig.4). The cryostructure transition from the underlying unit D is gradual. This unit includes ice-wedges 1 m below the muskeg surface, and none was observed in the forest. This unit could be present in a greater extent, under the hilltops where it was impossible to drill with a portable SIPRE Corer due to the presence of coarse fragments in the slightly gravelly static cryosol.

INTERPRETATION AND DISCUSSION

Each cryostratigraphic unit is concordant with a climatic event of the Late Pleistocene. Five general development stages were deducted: 1) the ice retreat, 2) the interstadial soil development, 3) the yedoma build-up, 4) the partial thaw and 5) the contemporary permafrost aggradation (Fig.5).

Stage 1 – Ice Retreat

Stage 1 corresponds with unit A and refers to the period when and where the glacier recessed and set the Mirror Creek hummocky disintegration moraine landscape composed of ablation and lodgement till. It most probably occurred at the end of Early Wisconsinian.

Considering the general absence of permafrost under ice lobes (French 2007) and the low ice content found in such a fine-rich diamicton, the permafrost could be interpreted as epigenetic and the moraine would have remained partially unfrozen during this stage. Residual ice in the moraine is probable according to the regional tendency of glacier to end on ice-cored moraines (Rampton 1970; Johnson 1971). In this first step, the landscape might have been very uneven (Rampton 1971) and important slope processes would have quickly reworked the hummocks to fill the base of depressions. Obviously, no vegetation was present at the beginning but quite soon, organic matter could have started to accumulate in stable areas.

Stage 2 – Interstadial soil development

Stage 2 corresponds to unit B and refers to peatland and lacustrine environment development on a relatively stabilized moraine complex. Moreover, the stratified cores suggest some alluvial activity and probably solifluxion and sheet erosion towards depressions.

Being defined by a fine material and a porous invisible cryostructure, the permafrost here is interpreted as epigenetic and ice-poor. Directly postdating the Early Wisconsinian, Stage 2 marks the beginning of the Middle Wisconsinian. In Beringia, it is characterized by a general warming where conditions remained however colder and drier than presently, sustained an open herb tundra vegetation and, near the end, sustained some tree patches (Anderson & Lozhkin 2001; Vermaire & Cwynar 2010; Elias & Brigham-Grette 2013).

Stage 3 – Yedoma build-up

Stage 3 corresponds to unit C and refers to the aggradation of a yedoma deposit. This specific term refers to Late Pleistocene ice-rich syngenetic permafrost of Beringia (Elias & Brigham-Grette 2013; Schirrmeister & al. 2013). The dominant silty texture of this unit and the proximity of the site to a prior outwash plain suggests that periglacial aeolian processes had a strong geomorphic influence on permafrost aggradation (Seppälä 2004). Locally, it indicates severe, cold, and xeric periglacial climatic conditions during the Late Wisconsinian. These conditions may reflect the glacial advance recognized at Silver Creek, about 200 km southward in the Shakwak trench, as early as 29.6 ky BP (Denton & Stuiver 1967).

Stage 4 – Permafrost degradation

Stage 4 corresponds to unit D and refers to a paleoactive layer interpreted on the base of a secondary thaw unconformity (French & Shur 2010) where it reaches into unit C. More precisely, the invisible porous cryostructure, truncated ice-wedges, oxydized faults and gleyfications suggest that a generalized warming would have triggered permafrost degradation, active layer deepening, and the thaw-settlement and drainage of soils. The original cryostructure of this section of the yedoma disappeared (melted) and current conditions suggest epigenetic permafrost recovery (refreezing) in the past.

Stage 5 – Contemporary permafrost aggradation

Stage 5 corresponds to unit E and refers to the most recent climate conditions. The ashes found near the permafrost table are most likely associated with the White River tephra (1.40 & 1.25 ky BP – Fuller & Jackson 2005; Turner et al. 2013). The base of Unit E is relatively organic-poor and the microlenticular ice content increases upward. This suggests decelerating syngenetic aggradation of aeolian silt (Kanevskiy 1993). The fact that mineral syngenetic permafrost buries the refrozen unit D demonstrates that the aeolian source was still active after the thaw event of Stage 4. However the timing of this event is unknown.

Upon subsequent cooling, the ice-wedges observed in the muskeg zone have extended downward (epigenetically) in the refrozen unit D and upward (syngenetically). The upper ataxitic zone at the permafrost table is interpreted as the intermediate layer and corresponds to the cessation of silt deposition and related ecosystemic stabilization (Kanevskiy, 2003; Shur & al. 2005; French & Shur 2010).

Topographic signifiance

During the Stage 1, the post-glacial topography likely remained quite complex and chaotic. At the end of the Early Wisconsinian, various geomorphic processes contributed to hill denudation and infilling of hollows. The terrain readjustment during stage 2 is interpreted as a period of solifluxion and alluvial activity. The onset of stage 3 during the Middle Wisconsinian was characterized by important silt, peat and ice accumulation, especially in topographic lows. Humid ground conditions and active layer development favoured peat accumulation and was accompanied by aeolian sedimentation. While it happened, solifluxion contributed to the sedimentary budget as the material is thixotropic (Unit 2C - Stephani 2013; Stephani et al. 2014). During permafrost degradation at stage 4, the upper portion of the ice-wedge network have partially melted and the ground surface experienced thermokarst subsidence and gullying (Kokelj & Jorgenson 2013). Finally at stage 5, the silt, peat and ice accumulation resumed preferentially in hollows where conditions were conducive to permafrost aggradation.

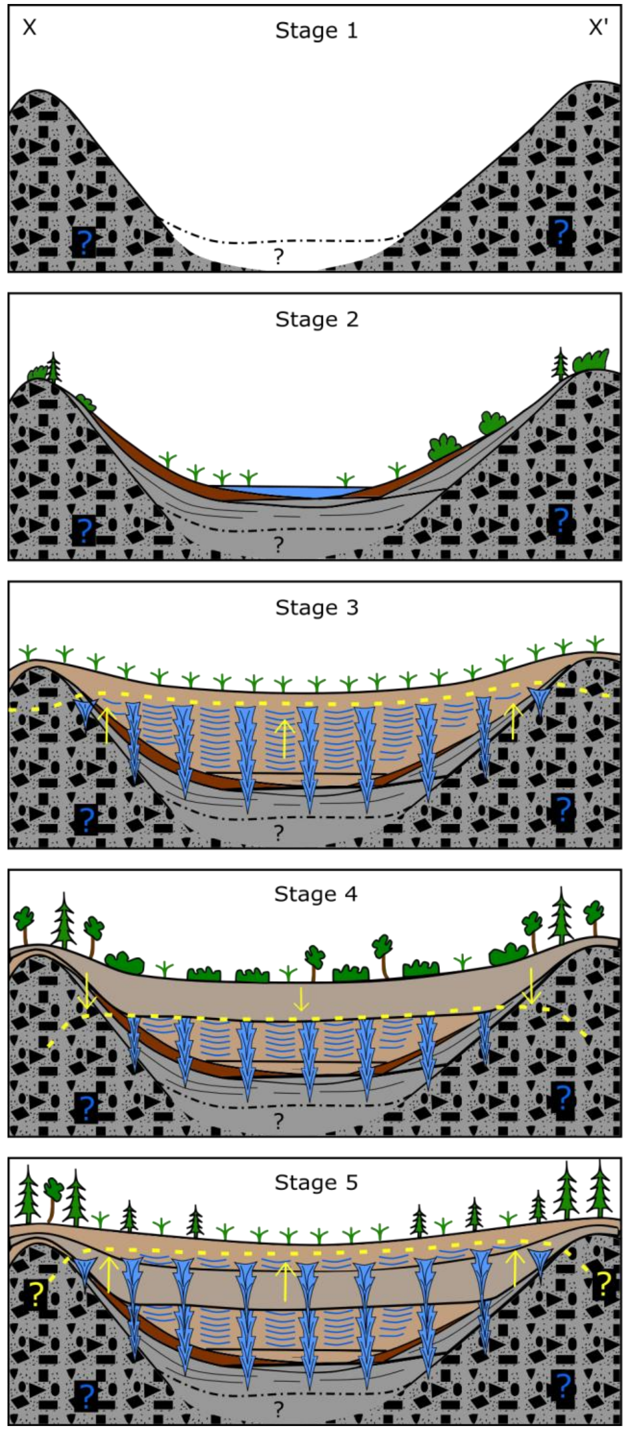

Figure 5. Landscape development and permafrost aggradation sequence at the study site across the section X – X' (Figs. 2 and 3). The drawing of Stage 5 reflects our understanding of the cryostratigraphic framework. Note that the vertical exaggeration is about one third that of Figure 3. The arrows and dashed yellow line represent the permafrost table elevation (lowering for stage 4). Blue interrogation marks indicates uncertain cryostratigraphic conditions and the yellow ones denote the questionable presence of permafrost.

The contrast between the forested hills and the muskeg depressions is of primary importance since differential topography, ecology, pedology and cryostratigraphy, directly linked with the original moraine setup, induces differential landscape evolution.

CONCLUSION

Two permafrost zones are fundamentally contrasted at the Beaver Creek study site. The muskeg and transitory areas are concave, have a thin active layer and sit on an organic cryosol covering a polygenetic Late-Pleistocene-Holocene permafrost sequence. In contrast, the forested zones are convex and protruding, have a thick active layer (sometimes >1.2 m) and sit on a static cryosol covering a relatively thin (<6 m) and potentially discontinuous epigenetic permafrost where the cryostratigraphic sequence is thinner and possibly incomplete.

The cryostratigraphy indicates that the Mirror Creek disintegration moraine, likely formed at the end of the Early Wisconsinien, played a major structural role in the permafrost aggradation history. Reworking of glacial deposits by alluvial and solifluction activity and peat accumulation in the depression of the hummocky moraine likely occurred during the Middle Wisconsinian period and was followed during the Late Pleistocene by the yedoma build-up. A major thaw event, the timing of which is unknown, interrupted the syngenetic permafrost aggradation. The latter resumed, and ice wedges extended upwards. During the Holocene, the aeolian sedimentation and ice wedge growth decreased significantly and peat accumulation promoted the development of a very ice-rich zone, known as the intermediate layer.

Today, the differentiated geomorphology of hills and depressions inherited from the Mirror Creek disintegration moraine continues to affect the geosystem evolution. Specific eco-geomorphological units, with distinct geothermal, hydrologic, ecologic, pedogenic, and cryogenic dynamics characterize the landscape of the Beaver Creek area. The model outlined in this paper provides a framework for conceptualizing long-term terrain dynamics and permafrost history.

ACKNOWLEDGEMENTS

We are grateful to R. Daanen, M. Darrow, J. Malenfant-Lepage, B. Loranger, L-P. Roy, E. Stephani and J. Zottola for their help in the field: We also thank the Engineering Branch of Yukon Highways and Public Works for logistical support and access to the Beaver Creek test site. This project was funded by Transport Canada, ArcticNet, the Natural Sciences and Engineering Research Council of Canada (NSERC), the Northern Scientific Training Program (NSTP) of the Canadian Polar Commission, the NSERC Discovery Frontiers grant 'Arctic Development and Adaptation to Permafrost in Transition' (ADAPT).

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