The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2020-33-AC3, 2020

The Cryosphere
Discussions
Open Access

Interactive comment on “Ground ice, organic carbon and soluble cations in tundra permafrost and active-layer soils near a Laurentide ice divide in the Slave Geological Province, N.W.T., Canada” *by* Rupesh Subedi

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Received and published: 29 June 2020

Reply to the interactive comment of Dr. S. Wolfe concerning the manuscript “Ground ice, organic carbon and soluble cations in tundra permafrost and active-layer soils near a Laurentide ice divide in the Slave Geological Province, N.W.T., Canada” by R.Subedi, S.V. Kokelj and S. Gruber.

We are grateful to Dr. Wolfe for his comments. In this reply, we outline how the comments have led us to make corrections, clarifications or additions to the manuscript and

also, we provide specific explanation where we disagree with the statements made in the comment. The entire original text by Dr. Wolfe is shown in **bold font** and author responses in regular font.

1 Introduction

The paper under review by Subedi, Kokelj and Gruber provides data on ground ice, organic carbon, and soluble cations from drill holes in the Lac de Gras region of the Slave Geological Province, Canada. The authors indicate that their results differ from observations made in western Arctic Canada and they make specific comparisons to field studies within the Mackenzie Delta region. They further indicate that the study provides quantitative data for a region that has few previous studies.

However, several statements and conclusions by the authors require reappraisal and revision in light of existing literature. Three issues in particular merit attention. Regarding the glacial context, the authors contend that the site is near the Keewatin Ice Divide, although it is more than 500 km distant. In reporting ground ice, they interpret model outputs prepared at a national scale in a local context, and combine surficial units with critically different properties. Lastly, the authors overlook relevant studies published from the Slave Geological Province, including from the study area.

Literature from the Slave Geological Province is discussed here to assist the authors in their task.

2 Glacial Context

The authors represent the study site as near a Laurentide Ice divide and having been influenced directly by it when, in fact, the Keewatin Ice Divide is distal to the study area.

The title of the paper indicates that the study area is “near a Laurentide ice divide”, while line 29 states that the Lac de Gras region “is situated close to the Keewatin Ice divide of the Laurentide Ice Sheet”. The term “Laurentide ice divide” should not be used. “Laurentide Ice sheet ice divide” or” Keewatin Sector ice divide” are appropriate alternatives.

Laurentide Ice Sheet ice divides comprise named ice divides (with capital letters: Keewatin Ice Divide, Labrador Ice Divide, M’Clintock Ice Divide, etc.) and unnamed ice divides (see Dyke and Prest, 1987). However, the Keewatin Ice Divide (KID) is by definition “the zone occupied by the last glacial remnants of the Laurentide Ice Sheet west of Hudson Bay” (Lee et al., 1957). Therefore, the KID was situated at least 500 km east of the study area (e.g. McMartin and Henderson, 2004). All the other ice divide positions in Keewatin are not located closer to the study area and cannot be termed “Keewatin Ice Divide”.

W1 – Is the study area near a Laurentide ice divide? We take a broad view of the literature in geology and glaciology, and of the temporal extent during which the Laurentide Ice Sheet (and possible earlier continental ice sheets) has shaped the landscape we observe today. Ice divides move over time (Benn & Evans 2010) and angles between preserved flow features are large in the zone of shifting ice divides (Boulton & Clark 1990a). This is consistent with the differing directions of ice flow (southwest, west, and northwest) field-mapped in the study area (Dredge et al., 1994). Furthermore, simulation (Margold et al., 2018) and mapping (Boulton & Clark, 1990a) results suggest evolving positions of ice divides, with some closer than 500 km to the study area. Predominant zones of erosion and deposition are apparent at the continental scale

and have been hypothesized to be related with basal thermal zones and ice divides during glacials (Sugden 1978; Benn & Evans 2010; Boulton & Clark 1990b). These zones emerge in the long term even though ice divides move laterally in response to the evolution of ice sheets. Other work on surficial geology takes a similarly broad view and includes our study sites, for example Figure 3 "Generalized bedrock geology of the area around the Keewatin Ice Divide" of Aylsworth and Shilts (1989). Being ’near’ an ice divide expresses the quality of neither being near the margin of the ice sheet, nor beneath the ice divide, but rather in an inner area influenced by proximity to a spreading centre and increasing net erosion. The proximity to a spreading centre is not expressed well by using ’central’ or ’middle’ as these terms bear no relationship to overall ice flow and are misleading in an ice sheet with multiple domes. Nevertheless, the term ’near’ is ambiguous and we agree that this is difficult. A new figure and more explanation on the glaciological background relevant to clarify this will be added in the revised manuscript. Based on this context, the actual distance to the approximate ice divide / spreading centre will be stated instead of ’near’ throughout most of the revised manuscript.

W2 – The term "Keewatin ice divide" We will omit the term "Keewatin Ice divide" (partially capitalized by mistake) to avoid an interpretation in terms of the field-mapped final position defined by (Lee et al., 1957). Instead, we will reformulate these sentences with reference to the "Keewatin Dome spreading centre". For the title, however, we prefer to keep the term "ice divide" because it is clearer in concisely expressing a relation to overall ice flow than the concepts of ice domes or spreading centres would be.

W3 – "Laurentide Ice sheet divide" vs "Laurentide ice divide": The comment does not state why “Laurentide ice divide” should not be used and “Laurentide Ice sheet ice divide” or” Keewatin Sector ice divide” are appropriate alternatives. Misinterpretation with respect to present day ice divides on the Canadian Shield is unlikely based on the specifier "Slave Geological Province, N.W.T., Canada", a region where no glaciers currently exist. We prefer to keep the concise title.

If the authors wish to consider features 500 km from their study area as proximal, then a reader would further expect literature that reports conditions in the glacial sediments near Yellowknife, only 310 km from the study area (line 79), to be fully considered. This is addressed further below.

W4 – Inclusion of environments near Yellowknife: The nature of the deposits and permafrost history near Yellowknife differ strongly from those in our study area. Comparing ('fully considered') across a transect in temperature conditions in addition to proximal versus distal location with respect to the Keewatin Dome spreading centre would complicate the manuscript. We now include two additional references from the Yellowknife area in the revised manuscript to provide context.

Basal ice sheet conditions, as discussed by Rampton (2000) and Utting et al. (2004), influence the source materials for shield-derived tills of the Slave Geological Province. Glacial conditions in the Slave Geological Province differed significantly from those of western Arctic Canada. Such differences had a profound effect on ground ice development (Wolfe et al., 2017). The authors compare their results with conditions in western Arctic Canada, where the source materials for till were derived from the sedimentary basins of the Interior Plains as opposed to the Canadian Shield. It is not evident why this setting is the primary reference for comparison with results from this study without relevant details on conditions in the Slave Province.

W5 – Why is the study area compared with conditions in western Arctic Canada? Western Arctic Canada is one of the most intensively studied areas and, as such, a natural point of comparison, especially with respect to solute concentrations in permafrost and the active layer. This is mentioned multiple times in the manuscript. In the revised version, we have added more detail on basal ice sheet conditions and the differences

to be expected between differing zones. Additionally, we now reference Gaanderse et al. (2018) for context with shield-derived sediments in the Slave Geological Province (see W14, below).

3 Ground ice reporting

3.1 Use of model outputs

The authors apply national-scale modelling results to local site conditions.
W6 – national-to-local comparison: This is not what we do. Local application would suggest extracting model values for the locations of boreholes. By contrast, we have been careful to avoid this, and by using a 50 km x 50 km area, we express the fact that what is found in the ground is not reflected in about 2500 model cells of 1 km x 1 km in the vicinity. The corresponding discussion has been expanded and a table added to prevent this misunderstanding.

The authors state that "the new Ground Ice Maps for Canada (O'Neill et al., 2019) show the study area (50 km x 50 km) to contain no or negligible wedge ice, negligible to low segregated ice and no relict ice, which includes buried glacier ice." (lines 40- 42). In fact, the new Ground Ice Maps for Canada depict wedge ice from none to low; segregated ice from none to medium, and relict ice (which includes buried glacier ice) from none to low (Figure 1). The authors thereby under-report the amount of ground ice depicted for the study areas by O'Neill et al. (2019).
W7 – Under-reported ground ice depicted by O'Neill et al. (2019): The values we report are true to those shown in O'Neill et al. (2019). The points shown by Figure 1 of Dr. Wolfe's comment do not match the locations we report in Table A1 of the original manuscript. We have added a map and more details to the revised manuscript to

underpin the values we report.

Nevertheless, differences between the authors' reporting and the model results are due, in part, to site-specific surficial geology. The surficial geology used in modelling is at scale of 1:5 M (GSC - Surficial Geology of Canada, 2014). For associations between ground ice and surficial geology to be appropriately considered at the local scale of 1:125,000, Dredge et al. (1995) and Ward et al. (1997) may be consulted.

W8 – Appropriate scale of application for the map by O'Neill et al. (2019): We fully agree with this statement. However, this scaling problem is best accounted for at the stage of model building, not in comparison with evidence. Coarse-scale maps must provide a useful generalization of ground conditions to have value for practical purposes and as scientific tools. If comparison with observations were deemed inappropriate, we would be on the slippery slope to an irrefutable hypothesis. The comparison of a map or model with observations is one of their key advantages. We agree that it must happen at, and appropriate to, the level of generalization used. In our manuscript, we compare the overall picture given by the map and not local patterns or point locations. In our 50 km x 50 km area, all 2500 1-km cells have class 'none' (not 'negligible') for ground ice. The entire Lac de Gras map sheet 76-D by Ward et al. (1997) (cited in the manuscript as "Geological Survey of Canada, 2014" in an updated version) has 97% of its cells classified as 'none', 3% cells classified 'low' and 0.08% classified as 'medium'. The adjacent Aylmer Lake map sheet 76-C by Dredge et al. (1995) is to 99.9 % classified as 'none'. Application of the mapping rules in O'Neill et al. (2019) at the scale of 1:125,000 as suggested would likely lead to drastically different abundance for relict ice. As such, our results may inform improved ground-ice mapping simply by bringing attention to this. In the revised manuscript, we now discuss this scaling issue and how it can be addressed in model applications based on the nationwide surficial geology at the scale of 1:5 M.

3.2 Use of surficial geological units

The authors combine surficial units with critically different properties in the context of reporting excess ice.

The authors combine drill cores into "upland tills", which they define as "smoothly rounded hills comprised of thick till and in till veneer over bedrock" (line 187-188). Combining drill cores from till veneers, which are tills that are less than 2 m in thickness, with the drill cores of thick till misrepresents the extent of "upland till" and therefore of ground ice contained within till terrain. To this end, Ward et al. (1997) and Dredge et al. (1995) provide more suitable spatial depiction of till veneer, till blankets, and hummocky till that permit the drill cores to be allocated to these specific till units. Such separation is appropriate for depicting depth versus water content and excess ice (as in Figure 3A and 4A). This approach may highlight the lower excess ice abundance in till veneers and at depths above 4 m, and higher amounts in thicker tills (and at depths below 5 m). These data may further inform understanding of the proportion of hummocky till, and thus potentially preserved Laurentide basal ice, in the area.

W9 – Misrepresenting the extent of upland till and therefore ground ice: We did not perform spatial aggregation of ground ice contents, nor did we state a spatial extent for upland tills. In the revision, we add clarity by always referring to our terrain type as 'upland tills' to avoid the ambiguity that existed when using the contracted 'tills'. Additionally, we now provide a first-order estimates for the spatial extent of upland tills with relict ice.

W10 – Combining the mapping units of 'till veneer', 'till blanket' and 'hummocky till' into 'upland tills': The mapping units of 'till veneer', 'till blanket' and 'hummocky till' are interpretations of till thickness and spatial extent derived largely from its surface expressions on aerial photographs. The lines drawn thereby represent a decision made by an experienced mapper, consistent with the level of spatial generalization required for a particular scale but not the actual conditions in the field. Our original field strategy followed these mapping classes and the map by Ward et al. (1997), as here proposed by Dr. Wolfe. The results however have shown that there is a difference between theory (or mapping) and reality (or field) and this has led us to use terrain types more suitable to conceptualize and interpret out results in the manuscript. In the revised manuscript, we now explain the original sampling approach briefly, as well as the reasons for deviating from the map units shown in Ward et al. (1997).

In addition, in presenting "fluvially reworked till (the Valley)" (line 185) where "silts and sands are well sorted and likely derived from fluvial reworking of local tills" (line 191) and in presenting evidence of post-glacial ground ice melt features (e.g. Figure C1) the authors might acknowledge alternative interpretations by Rampton (1999) and by Utting et al. (2009) to account for fluvial activity. Alternative classification of the terrain types is required because the current terms conflate categories of phenomena, e.g. till and valley.

W11 – Alternative interpretations: The interpretation of Rampton (2000) has been included, assuming that "Rampton (1999)" is a typo and in fact, refers to Rampton (2000). Utting et al. (2009) study glaciofluvial corridor hummocks; the relation to this manuscript is unclear.

W12 – Conflation of phenomena: The original manuscript consistently uses "the Valley", with both the definite article ("the") and capitalization indicating that this refer to one specific valley, as described in Section 4.1. For increased clarity, we now discuss in more detail how this terrain type differs from other locations.

4 Incorporation of comparative literature

The authors overlook existing regional and local literature with similar conclusions, thereby claiming undue precedence.

4.1 Solutes in mineral soils

The authors' state that "the concentration of total soluble cations in mineral soils is much lower than at other previously studied locations in the western Canadian Arctic" (lines 14-15) and that "the absolute concentrations of soluble cations obtained in the study area near Lac de Gras are low compared to previous studies from northwestern Canada that report higher concentrations in active layer and permafrost across diverse terrain types (Table D2)." (lines 302-304). These remarks assume that all comparable previous studies have taken place in the Mackenzie delta area or Herschel Island (Table D2). The authors indicate that "The low concentrations in our study area are associated with the contrasting nature and origins of surficial materials. Tills in our study region are generally coarser grained than many glacial deposits studied in the western Arctic, are regionally sourced from mostly granitic rocks and have been exposed only to minor postglacial landscape modification (Haiblen et al., 2018; Rampton and Sharpe, 2014)". (lines 311-314).

W13 – Assumption that all comparable previous studies have taken place in the Mackenzie delta area or Herschel Island: We disagree with this assertion. The statements that Dr. Wolfe cites are true based on the two (now three) studies we compare with. It is not the remarks that do the assuming of 'all'.

Gaanderse et al. (2018) originally reported on solute concentrations from glaciolacustrine deposits within the shield area that indicate low values similar to the

Lac de Gras area. Gaanderse et al. (2018, p. 1039 noted that "Total soluble ions concentrations decreased with depth from the active layer to the underlying glaciolacustrine clays in permafrost (Figure 8). This trend contrasts with observations in the western Arctic, where low ion concentrations occur within sediments of the active layer and near-surface permafrost, relative to the underlying permafrost (Kokelj et al., 2002; Kokelj and Burn 2003, 2005; Lacelle et al., 2014). Unlike the predominantly marine origin and the mixed-layered clays of the western Arctic (Dewis et al., 1972; Kodama, 1979), the glaciolacustrine clays of the Great Slave region are not inherently solute-rich or weathered." And "These fine-grained glaciolacustrine, lacustrine and alluvial sediments belong to the same generation of glacially-derived sediments with a regional mineralogical composition from igneous and metamorphic sources (Aden et al., 2015). The clays and clay-sized glaciolacustrine sediments are predominantly unweathered, with major soil ion abundances likely reflecting the mineralogy of local rocks, including Ca2+, Na2+, and K+ from the weathering of feldspars; Mg2+ and Ca2+ from amphiboles, pyroxenes and olivine; S042- from sulphides and Cl- from igneous sources."

W14 – Gaanderse et al. (2018) We now reference Gaanderse et al. (2018) to provide context of low solute concentrations in shield-derived sediments from the Slave Geological Province. Two caveats remain: (1) the nature of the deposits and permafrost history differ from the Lac de Gras area and (2) quantitative comparison is difficult because they extract and report solutes with respect to saturated paste and we do not know the saturated-paste water content for our samples. We now give more details on the various methods of extracting and reporting solute contents to further explain why few studies are used for comparison and to provide context for these caveats.

Additional supporting data on low concentrations of soluble cations from the Slave Geological Province and in the Lac de Gras area are also presented in Wolfe et al. (1997a) and Wolfe (1998) who describe low cation concentrations

in buried ground ice in glaciofluvial delta sediments, and in Wolfe et al. (1997b), who include borehole logs, geophysical surveys, cation concentrations and oxygen isotopes from a 14-m borehole at the BHP Airstrip Esker within the authors' Lac de Gras study area.

W15 – additional data published by Dr. S. Wolfe: In the revised manuscript, we have now included a reference to the solute concentrations summarized in Wolfe (1998), although the comparison requires some assumptions about the method of water extraction and reporting. Wolfe et al. (1997a) describe oxygen isotopes and cation concentrations for ground ice, whereas our contribution describes soils samples. It is difficult to make a meaningful comparison with this contributions. Its insight that massive ice exists in glaciofluvial sediments in the area is already included in our manuscript via the citation to Dredge et al. (1999) who summarise key insights on ground ice from this work, as well as from BHP Diamonds Inc (1995) and EBA (1995). Wolfe et al. (1997b) appears to be a work report that was then distilled in the other two papers by its authors.

4.2 Ground ice expectations

The authors state that "permafrost in the study area contains much more ground ice than expected" (line 16). As noted above, several studies have illustrated the presence of high ground ice contents in outwash sediments in the area. In addition to these, Dredge et al. (1999), referenced by the authors, clearly present expected ground ice conditions and terrain sensitivity in line with the authors observations. The importance of the geological legacy in determining the characteristics of permafrost and potential responses of this system of disturbance and change is further summarized in Wolfe et al. (2017), who conclude that "Glacially-derived ground ice includes buried glacial ice within glaciofluvial outwash deposits and buried glacial and meltwater ice

within eskers. Sediment-rich ice has also been encountered within hummocky till terrain during mine development operations. Surficial features attributed to partial thawing and creep of massive ground ice are regionally apparent. Although massive ice has been encountered in only a few locations to date, buried ground ice may be common within this glaciated region of the Tundra Shield."

W16 – Is there more relict ground ice in the study area than expected? The new ground ice maps for Canada by O'Neill et al. (2019) show the project area, and most of its surroundings (see comment W6), as having no relict ice. This is despite the alternative classes 'negligible' and 'low' being available in the map. The rules formulated in a model and the results accepted in its evaluation express the expectations held by the authors (including Dr. Wolfe) and accepted by its internal and external reviewers. Similarly, a user of this map that is available digitally, will form their expectations based on what the legend states. These expectations match with those formulated in earlier maps but not with our findings.

Nevertheless, the authors are still cautioned about asserting that "Tills in our study areas . . . have been exposed to only minor post-glacial modification (Haiblen et al., 2018; Rampton and Sharpe, 2014)", noting the evidence of Holocene warming and tree-line advance in the region as noted by the authors (lines 83-84) and in Moser and MacDonald (1990) and MacDonald et al. (1993).

W17 – Post-glacial modification: Yes, this sentence applies to the majority of only UPLAND tills and has been clarified accordingly.

The authors state in the abstract that "thaw subsidence of metres to more than ten metres is possible" due to ground ice that may be buried Laurentide

basal ice (line 8 – 9). Within the paper, the authors write: "A potential surface lowering of many metres, up to more than ten metres, is thus to be expected from areas of thick till if this permafrost was to thaw completely" (lines 271-272). Again, in the conclusions, the authors state: "Thaw-induced terrain subsidence on the order of metres to tens of metres is possible in ice-rich till" (line 326). The statements are based upon data from only one borehole with samples from below 6 m depth. The borehole terminated at 9.5 m depth. The authors assume that conditions in this borehole are representative of all till "estimated to be 10-30 m thick in the area (Haiblen et al. 2018)" (line 270). In other words, the authors assume, without disclosed evidence, that the excess ice profile presented in Fig. 4 extends indefinitely downwards with high values, that it applies consistently throughout an extensive till unit, and that the unit is sufficiently thick to contain excess ice tens of metres thick. Readers should be made aware of the assumptions upon which these statements are based and, in particular, should be able to recognize that the principal data contributing to these assertions are derived from 3.5 m of drill core, from 6 to 9.5 m in the profile.

W18 – TenS of meters: The formulation of tenS of metres in line 326 was unintentional and has been corrected. Lines 9 (abstract) and 271, correctly read "metres to more than ten metres" and "up to more than ten meters".

W19 – Only one borehole with samples from below 6m depth: More detail supporting our conclusion has been inserted in the revised manuscript: (1) Table A1 now shows that 5/10 boreholes in upland tills terminate in bedrock or a boulder and the remaining 5/10 terminate in ice rich material. This supports the expectation of some continuation with depth. (2) Information for individual boreholes in now included as a plot in Supplementary Materials. (3) One more borehole from an earlier campaign has been added to the discussion. The geomorphological argument in Figure C1, although hypothetical, adds some further support.

W20 – Assumptions of the authors: We do not hold the assumptions ('representative of all till', 'extends indefinitely downwards', 'applies consistently throughout an extensive till unit') ascribed to us here. In the revised manuscript we improve clarity by including an estimate of plausible ranges for the extent of relict ice. While uncertain, this will prevent misunderstanding.

5 Summary and Conclusion

The paper by Subedi, Kokelj and Gruber (in review) provides an added contribution to the growing knowledge of permafrost and ground ice in the Slave Geological Province. The purpose of these comments is to provide an appropriate regional context for the observations. The authors may take advantage of these comments so that their contribution to the literature will complement, and be informed by, the existing knowledge of permafrost, environmental change and ground ice conditions in this region.

6 Acknowledgements

These comments benefitted from discussion and input with several colleagues. In particular, Drs. Chris Burn, Brendan O'Neill, Peter Morse, Dan Kerr and Isabelle McMartin are gratefully acknowledged.

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Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-33, 2020.