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# *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

**Rupesh Subedi**

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This is a high-level summary of the changes made in the revised manuscript, important relations with comments by Referees 1 and 2 and by Dr. Wolfe are referenced (R1, R2, W). We have expanded several sections with additional detail and the manuscript has increased in length and complexity. We undertook to preserve simplicity by creating a detailed Supplement and by minor reorganization and editing.

## 1 Regional context and characteristics of study area

Regional context has been expanded and illustrated with a new figure (R1.2, R1.4, R2.1, R2.14, R2.19, W4). The abundance of surficial geology classes is now tabulated for the study area and two surrounding map sheets (R1.14).

## 2 Glaciological context

More detailed explanation of the glaciological context and a new figure have been added. With this, the ambiguous notion of being 'near' an ice divide is now specified further in terms of distance and put into a geomorphic and glacial context (W1).

## 3 Information for individual boreholes

We have expanded Table 1 and added a Supplement that provides a detailed map of the study area, an overview plot comparing all boreholes, and individual plots of major results for each borehole (R1.5, R1.13, R1.15, R2.14, W19). The publicly available core photos are mentioned explicitly and one new figure with core photos has been added (R2.6). The original (but abandoned) sampling strategy has been described and the four terrain types we now use instead are justified (R2.4, R2.11, W10).

## 4 Accounting for large clasts in aggregated organic-carbon densities

We have derived the approximate proportion of large clasts from the core photographs and applied this to the aggregation of organic-carbon densities. The has lowered the values we report by up to 7%. (R1.8)

## 5 Comparison of cation concentrations with other studies

More background on the difficulties of comparing studies in the absence of consensus methods is now outlined (R2.7, R2.8, R2.12) and more studies, also from environments with similar material origins but differing depositional history, have been added (R2.3, W15).

## 6 Spatial abundance and mapping of preserved relict ground-ice

We now provide spatial aggregates of relict ice predictions by a previous model in a new table (W6, W7). We also estimate plausible ranges for the the spatial extent of relict ice (W20). We discuss the difference between our findings and a published prediction of relict ice abundance more explicitly and explain how the underlying scaling issue can be addressed to improve future models (W8, W16). The importance of the 'mosaic' character of the landscape is now emphasised more clearly throughout the manuscript, accordingly.

## 7 Conclusions

Our conclusions remain largely unchanged. The statement on spatially aggregated soil-organic carbon storage has been omitted, along with its background in the manuscript, to keep the manuscript length and complexity manageable.

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Reply to the interactive comment of Anonymous Referee 1 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 for the constructive and detailed comments provided. Here, we respond to each issue raised and outline how the comments led us to revise the manuscript. The entire original text of the interactive comment is shown in **bold font** and author responses in regular font. Each issue is identified with a code indicating "Referee 1" as well as a consecutive number, e.g., R1.1. This will help to revisit key issues raised by each of the three interactive comments in a summary reply that outlines the most important changes to the manuscript.

## 0.1 General comments

**This study presents unique and highly valuable data on ground ice, organic carbon and soluble cation contents in deep permafrost cores of the Central Canadian Arctic. The surprisingly high ground ice content found in some cores makes the landscape susceptible to potential (differential) ground subsidence and thermokarst formation allowing the remobilization of deep carbon and soluble cation stocks (as well as affecting infrastructure).**

**The authors should better explain why this particularly study area (Lac de Gras) was selected, as well as which approach was used to select specific core sites. This is important information to evaluate how representative this study is for the wider Slave Geological Province.**

**There are some issues with field and laboratory procedures, regarding the logging of field volumes collected in the active layer of soil pits, the application of a mean LOI value of 80% to organic samples in the top meter of the cores, disregarding coarse clast volume, the inferred zero organic carbon content of the soil fraction 0.5-5.0 mm, the indirectly inferred fine soil fraction ($<$ 0.5 mm) for about half of the samples, and the indirect derivation (regression) of dry bulk density values (when known volume samples are, or could have been, available for most of the samples). Particularly, SOC estimates for the 0-1 m depth interval are prone to large uncertainties and should not be the focus of the analysis. I feel it necessary to mention these concerns, even though in most cases they**

**cannot be addressed any longer.**

**The structure and use of language are adequate. I propose to move one subsection on field sampling to Methods. Figures and tables are generally fine, but I suggest to add an additional map to Figure 1 as well as a new figure in the Appendix with properties of a few selected individual permafrost cores.**

**Despite some methodological issues, this study is a very important scientific contribution that addresses important gaps in the knowledge of ground ice and organic carbon content in deep permafrost cores (other than deltaic and Yedoma deposits).**

## 0.2 Specific comments

**Title:...and soluble cations in deep tundra permafrost cores near a Laurentide... Note: the 0-1 m (and active layer) SOC estimate is highly uncertain (see below), the authors should focus on the valuable deep data**

*R1.1 – Deep cores:* Interpretation of the term 'deep' varies between academic communities and, as such, we prefer to not use it in the title. The abstract clarifies "Twenty-four boreholes with depths up to ten metres...".

**Page 1 (P1), Line 13-14 (L13-14): . . . and 0-3 m, respectively. Deeper deposits have C densities ranging from X-Y Kg C m-3, representing a significant additional C pool.**
Done

**P1, L16: ...and slightly less 0-3 m organic carbon stocks and fewer...**
Sentence omitted, now.

**P2, L45: ...consequences of permafrost thaw.**
Done

**P2; L47: (Hugelius et al., 2014)**
Done

**P3, L79: The authors should clarify why this particular study area was selected, especially since they compare their results to more generalized maps of permafrost/ground ice conditions and SOC storage for Canada and the northern circumpolar region. Is it a simple issue of accessibility, or was this area chosen because of special features of potential interest to infrastructure development (e.g., the occurrence of fossil thaw slumps as depicted in Fig. C1) ?. This is important in order to evaluate the representativity of the study area for the Slave Geological Province.**

*R1.2 – Selection of study site:* More detail on the selection of the study site and its relationship with surrounding areas is now provided, including new map figures.

**P3, L70: ...characterization of active layer and deep permafrost materials in...**
We prefer to avoid the term 'deep permafrost', see R1.1.

**P3, L82: ...and 14 C, respectively, and...**
Done

**P3, L83: cal yr BP ? (2 times)**

*R1.3 – Calibrated years:* The two references cited do not specify whether these are calibrated radiocarbon years. Presumably they are, but we prefer not to make that determination.

**P4, L95: I propose that the authors include a (simplified) surficial geological map of the 50x50 km study area as Fig. 1B, with location of the 24 permafrost cores. The current Canada map can be a small inset (Fig. 1A).**

*R1.4 – Map of study area:* This figure is now provided.

**P4, L100: Organic soils cover 5% and...**
This has now been replaced by table because the response to other comments required more specific data on spatial abundances.

**P5, Fig. 2 caption (and related references in text). Shift B and C, see Figures 3-6**
Done

**P5, L116: As with the study area, the authors should explain their selection of core sites. Were sites selected because of easy access, or because they were considered typical for the different surface geology units, or was there a degree of randomness in site selection. This is important to assess how representative sites are for scaling to the study area as a whole. See my point P8, L183-184.**

*R1.5 – Site selection and sampling strategy:* The original strategy for site selection is now explained in more detail.

**P5, L116: Permafrost cores with a diameter of 5 cm were obtained in mid-July 2015 using a ... Note: So, these samples had a known volume that could have been used for DBD calculations !**

*R1.6 – Volume of core:* Many of the recovered core sections were irregular due to reaming or partial melting. This is now clarified in more detail and with an additional

figure in the revised text.

**P5, L118: How was the active layer in soil pits sampled ? Sample depth interval?, using fixed volume cylinders (for DBD) ?**

*R1.7 – Volume of pit samples:* Pits were sampled, where possible, at depths of 10 cm, 20 cm and 30 cm. The use of sampling cylinders deviated from the intended protocol and the volume cannot be reconstructed with confidence. Clarified in revised text.

**P6, L129: The coarse clasts >5 cm that could not be recovered by the drill are not considered. The authors refer to this on P12, L238. This could result in a significant overestimation of OC densities, particularly in till. I wonder, are there no natural/excavated deep exposures in the general study area from which the volume proportion of large clasts can be (visually) estimated and then computed?**

*R1.8 – Bias from clasts larger than 5 cm* The average volume of clasts coarser than the drill barrel has now been estimated visually from the core photographs and applied as a correction in the aggregation of organic carbon densities and storage, accordingly.

**P6, L149: Using a LOI of 80% for those samples with no visible mineral component is highly questionable. Peat deposits will normally have a higher LOI, whereas topsoil organics in mineral soils will have generally a lower LOI. This introduces high uncertainty, which is one reason why the authors should not focus on the SOC 0-1 m stock.**

*R1.9 – Uncertainty from LOI estimate when no mineral content visible:* Yes. This now stated and referenced in the revised manuscript. Estimates actually only affected the pit samples in the top 0.3 m and this is also clarified, now.

**P6, L150: The LOI applies to the fine soil fraction ($<$0.5 mm), whereas the volume of the coarse fraction $>$5 mm – 5 cm is accounted for (P6, L129). But what happens to the fraction 0.5–5 mm, is this all considered 100% mineral ? It could include roots, or other plant remains / organic aggregates, etc. ?. Furthermore, the fine soil fraction ($<$0.5 mm) is only available for half of the samples and very indirect approaches are used to calculate this value for the remaining samples (P7, L166–167).**

*R1.10 – Carbon density bias from 0.5–5 mm grain-size fraction:* After drying the samples at 105 C, they were crushed with mortar and pestle before sieving; most root or plants residues would have been crushed and passed the sieve.

**P7, L160: It is rather unfortunate that DBD was not computed directly from dry weight and field volume of samples, at least for those samples in which no ground ice/materials were lost**
Agreed. At the same time, this is a unique set of data and we intend to make it as useful as is possible.

**P7, L174-175: The fine fraction and DBD deviations for calculating uncertainty ranges seem to be quite arbitrary**

*R1.11 – Arbitrary uncertainty ranges* They are based on reasoning and subjective decisions because no objective values can be determined. This is why we wrote 'The potential magnitude of this effect...' rather than calling it an estimation of uncertainty. More explanation has now been added in the revised manuscript to make the reasoning behind those ranges traceable, and therefor the resulting values more valuable.

**P8, L183-184: This section/subsection should be moved prior to subsection 3.1., starting with an explanation about the selection of sites (see my point P5, L116)**

*R1.12 – Moving Section 4.1 Study Sites* We have expanded the section on field observation and sampling to also describe the original sampling protocol and difficulties encountered.

**P8, L187+: For all boreholes, it should be indicated why coring was discontinued (hitting bedrock, logistical/time constraints, etc.). See also comment on Table A1 (below)**

*R1.13 – Expanding Table A1:* The table has been expanded and the Supplement now contains plots per borehole.

**P8, L218: Please add area proportion for each surface geology class (see P15, L316-317)**

*R1.14 – Abundance of surficial geology classes:* This is now in a new table.

**P9-12: In Figs. 3-6 the authors have grouped samples from all profiles belonging to one class in one and the same graph. The information from single profiles is lost. I propose to add graphs in the Appendix, providing data from Figs. 4-6 for a single/typical/most complete core for each surface geology class (New Appendix Figure C1-C4). It should be considered that data from individual profiles are more valuable than composites that cannot be disentangled anymore in its individual components.**

*R1.15 – Individual borehole profiles:* This has been added as supplementary material.

**P13, L264-265 and P14, L274-275: (currently Fig. C1)**
Fixed

**P18, Table A1: Add depth of core (and reason to stop drilling)**
Yes, see R1.13 above.

**P20, Fig. B2 caption. The peat in (A) would normally have a LOI of c. 95%. The default value of 80% does not generally apply**
Yes, see R1.9, above.

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# *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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Reply to the interactive comment of Anonymous Referee 2 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 for the comments provided. Here, we respond to each issue raised and outline how the comments led us to revise the manuscript. The entire original text

of the interactive comment is shown in **bold font** and author responses in regular font. Each issue is identified with a code indicating "Referee 2" as well as a consecutive number, e.g., R2.1. This will help to revisit key issues raised by each of the three interactive comments in a summary reply that outlines the most important changes to the manuscript.

## 0.1 Summary

**This paper is formally well written and presented, and describes unique data from an interesting environment that is under-represented in the literature. I think that the data from these cores should be published, but in its current form the paper does not do the material justice. The paper suffers from a mismatch between its stated goals and its delivered conclusions. There are also problems with the methods that are major enough to call some of the conclusions into question. I recommend that the paper be rejected and returned to the authors for re-working and potential re-submission after the problems have been addressed.**

## 0.2 Criticisms

### 0.2.1 Approach

**The context for this study requires more thinking and description. For example, the authors state that, contrary to published maps, there is significant excess ice in the "area" – what is the area? The paper requires a map showing the Keewatin Ice Divide, the "central Slave Geological Province", etc. Table A.1 would be informative if it were a map or, even better, mapped together with an optical satellite image to allow comparison with land cover. For what region do the authors believe that their results are representative? Demonstrate that the set of**

**cores is somehow representative for a region and communicate what region this is. How much of the region that you so identify is represented by the four terrain types for which you present data?**

*R2.1 – Maps and context:* An overview map figure has been added to the manuscript and an additional map figure with the local study area to the new Supplement. We decided against optical satellite data as surface cover does not correlate well with subsurface conditions.

**“Comparison with other permafrost regions...” is listed as the 3rd goal of the paper, but is not addressed and represents a central weakness. As an example, any reader of this paper would expect to find permafrost ONLY in those regions of the NWT and Yukon in which the authors have already worked, as well as in unglaciated portions of Alaska. Such myopia is not unique: many authors cite only papers within their national borders, but this criticism is a grave one for geoscientists, who should have a natural curiosity for the variability of expressions of their study objects on Earth. European, Alaskan and Russian research on permafrost is extensive, and offers many studies that deal with ALL of the study objects (glaciation, permafrost, ground ice, ground ice/water chemistry, etc.) and processes (thawing, landscape change, deglaciation, solute exclusion, thermokarst, etc.) in this study. Willfully ignoring most of the research in your field makes it impossible for the authors to demonstrate rigor in their approach, their knowledge of their field or an openness to the existing and potentially alternative interpretations of similar data sets. Comparing your results (e.g. Table D2) to only 2 previous studies (BOTH from your own research group!) cannot fulfill your stated goal to “...compare excess-ice content, organic-carbon density and soluble cation concentration with other permafrost environments...”. It certainly reduces the relevance of your work to a broader readership and would alone be reason enough not to publish this manuscript.**

*R2.2 – Comparison with other permafrost regions:* The full text for Objective iii was "compare excess-ice content, organic-carbon density and soluble cation concentration with other permafrost environments *and with compilations such as overview maps and databases*". Here, in order to keep the scope of the manuscript manageable, "compilations such as overview maps and databases" have been taken as current reflections of what may be expected in the study area. To avoid misunderstanding, we have adjusted our formulation to read "... other permafrost environments OR with compilations ..." in the revised manuscript. Beyond that, we do find it unreasonable to conduct a study where conditions are contrasted between two regions, especially if one is well studied and is similar in some but not all aspects. This is part of formulating tractable questions.

*R2.3 – Comparison of solute contents with two studies is not enough:* Few other studies exist in formerly glaciated and nearby environments that can easily be compared. In part, this is due to the broad diversity of approaches in extracting soil water and reporting (normalizing) analytical results. This is also addressed in our responses R2.7 and R2.12, and now described in the revised manuscript. It also explains why two studies with overlap in authorship were chosen: here the methods are comparable. One study (Lacelle et al., 2019) has now additionally been quantitatively included as data was available digitally and could be converted. At the same time, the impact of differing lab methods is difficult to assess. Two additional studies from the vicinity of Yellowknife have also been included, although direct quantitative comparison is difficult.

**The study makes the a priori assumption that categorization of the soil cores by terrain types is justified and that averaging all borehole results within one terrain type is justififed. How were terrain types identified? Why were these four chosen? Why do the authors think that terrain type has an influence on ice content, organic carbon, and total soluble cations? Such questions are fundamental to study design and the means to reaching conclusions of broader**

**significance. Tellingly, there is no significance to the terrain types in the 6 conclusions reached. At this point, the authors should have re-examined the basis for their choices. The results for all four parameters as a function of depth do not provide enough information (Fig. 3-6) for the reader to assess whether the cores really differ between terrain types. It is not clear why only total soluble cations are analyzed and presented. Why not other dissolved species? Why not present profiles for individual boreholes and/or cations? This work is left to the reader.**

*R2.4 – Justification of terrain types* The initial field sampling design and reasons for it having limited utility for interpretation of results is now described briefly in the revised manuscript. Based on this, the distinction of the four terrain types used is justified as a better way to group the locations analysed. Plots of individual borehole logs and analytical results are included in a new Supplement to prevent the manuscript from becoming too long. We do not agree that conclusions specific to each terrain type are a measure of their utility. Along the same lines, one could ask why individual boreholes should be shown. Terrain types are a useful grouping to add explanation to observations.

*R2.5 – Why only total soluble cations?* This study has unique data and insight to offer in several domains (ice, carbon, cations). As it is subject to a number of imperfections, focusing on total soluble cations and few salient features of their distributions keeps this robust and concise.

### 0.2.2 Methods & Data treatment

**The field photos of the cores are very impressive and show a wide variety of compositions and cryostructures – I think the paper would be strengthened by more of these and closer examination of the results. The methods used in this paper are beset with problems. The authors should refer to standard texts and**

**guides on soil analyses for methods of analyses. It is not sufficient to cite previous studies by the same set of authors (using “cf.”?) to establish that standard accepted methods have been applied. Specific problems with the analytical methods are:**

*R2.6 – More core photos:* The published core photos are referenced in the description of the study region in the original manuscript. The data (more than 2.5 GB) is well organized by borehole and depth interval. Rather than include many more photos and increase the length of the manuscript, we point to this information with more specificity in the revised version and point-out sections with telling photographs in borehole plots. Photos of frozen ice-poor till have now been included as an additional important example in a new figure.

*R2.7 – Standard accepted methods:* Janzen (1993) and Dean (1974), cited in the original manuscript, are standard texts. At the same time, these and other standard texts on soil analyses known to us do not describe methods for permafrost materials specifically. This is relevant because the extension of standard procedures (usually based in agricultural considerations) to permafrost materials is not straightforward. In many instances, no consensus on how this is best done is apparent from the permafrost literature. Often, this problem is due to extreme ranges of water content when excess ice is present. For example, expressing water content on a dry gravimetric basis, as proposed in standard texts, can lead to high values that are difficult to interpret (Phillips et al., 2015). This is now also clarified in the revised manuscript.

**The are 2 sets of cation concentrations: those which underwent an arbitrary 1:1 dilution with water and those which did not. Diluting the solution affects the equilibrium between dissolved and adsorbed species. It is not acceptable to treat these data sets as equivalent expressions of some kind of concentration without at least testing for equivalence.**

*R2.8 – Comparing samples with and without added water:* In the revised manuscript, the known issues with differing extraction ratios are now described in the methods section. Additionally, Interpretation and Discussion now include test results about the effect of extraction ratio on our results.

**The creation of means as a function of depth is problematic and has not been justified – how is the 95% confidence limit calculated? In many cases MOST of the measurements lie outside of the 95% confidence limit. In what are the authors 95% confident? Anyone drilling in a similar location can be confident that most values lie outside of these limtis. With this kind of variability over depth, drawing a smoothed mean variation (the blue lines) over depth is nonsensical and masks real variability. It certainly requires examining each set of measurements on a per-borehole basis and on evaluating the data in detail.**

*R2.9 – Mean profiles:* Mean profiles make broad patterns emerging from multiple boreholes and/or samples more easily visible. Because the actual sample values are shown in the same graph, the real variability is not masked. The standard error of the average expresses the confidence in the average falling within this range, accounting for sample abundance and vertical extent. The majority of samples may be outside the standard error at 95% confidence for the mean profile.

**Similarly for Table D2: it is not clear how many samples are used to form the means, whether they are means, what the variability is, etc.**

*R2.10 – Data in Table D2:* The values from Kokelj and Burn (2005) are now identified as mean values in Table D2 of the revised manuscript. The number of samples or measures of spread are not included in the table of the original publication but, if desired, can be appreciated from the figures. Values from Kokelj et al. (2002) are now identified as 'estimated from figures'. For both, we prefer not to indicate statistical results that we estimate after the fact but rather report and interpret the publications' content in the

simplest way that supports our interpretation. The difficulty outlined here underscores the fact that finding more data for quantitative comparison is not straight forward.

**Presumably data from multiple cores is combined for each of the four regions – it is not clear and has not been established that these groups of cores are similar enough to be grouped, that the cores cover similar depth ranges, that the sampling frequency is similar, or that the sample sizes per terrain type have no effect. Present the data for individual cores, do not create means, etc. and then establish that the groups of cores are different using a test of significance. At the moment, all the work is left to the reader.**

*R2.11 – Combining multiple boreholes in a terrain type:* The justification for the terrain types is outlined in more detail in the revised manuscript and individual borehole plots are included in the Supplement. We also clarify that mean profiles are described for aiding quantitative description, rather than quantitative prediction, based on sometimes sparsely and unevenly sampled boreholes.

**The expression of concentration per dry weight of sediment is almost entirely meaningless. It is meaningless in terms of processes affecting concentration during freezing, thawing or in general in the field. Concentration gradients, moisture migration, and any other relevant processes will depend on concentrations in the pore space or pore water or liquid water. Concentrations should AT LEAST be reported in terms of the water volume obtained by thawing the samples.**

*R2.12 – Normalizing concentration per dry mass of sediment:* In the new Supplement to the revised manuscript, we now also plot concentrations in terms of the water volume obtained by thawing the samples, as requested (this was included in the supplementary materials digitally already before). Additionally, we explicitly mention the expression of results per dry weight in the conclusion to further prevent misunderstanding. We agree that this adds clarity as some results may depend on the method for normalization chosen. We do not, however, agree with the broad assertion about the utility of the approach we have chosen: Solute contents in the permafrost literature are expressed in a variety of ways, for example with respect to dry mass, volume, or soil water content. None of these ways, similar to the choice of solute extraction (R2.7), is obviously perfect. In our example, standardization by dry weight makes sense because it helps in comparing permafrost (some very ice rich) and actively-layer soils (some coarse-grained and in dry convex upland locations). Furthermore, assuming that some of our ice rich sediments partially derive from Laurentide ice implies that the majority of solute found there can be assumed to originate from its particle content, possibly after thawing. For clarification, we have expanded the glaciological background so that the possibility of finding solute poor ice mixed with frozen sediments becomes more obvious. In summary, the issue of normalizing results, together with the wide differences in extraction methods used (see R2.7 – Comparing samples with and without added water) makes comparison of soil chemistry difficult between individual permafrost studies. To further clarify, a brief summary of these problems has been included in the manuscript.

**The calculation of excess ice content based on the ratio of volumes of thawed, saturated, settled sediment and supernatant liquid is problematic since the volume of supernatant liquid depends on soil texture.**

*R2.13 – Determination of excess-ice content:* Certainly. Further refinement or discussion of the shortcoming of this method, however, are beyond the scope of the work presented and would not affect our conclusions. The method we use remains the accepted standard in permafrost science (Subcommittee on Permafrost 1988) and engineering (ASTM 2016). Furthermore, line 124 in the original manuscript used 'estimate' to acknowledge that this is not clear cut.

### 0.3 Conclusions

**Each conclusion has problems:**

**1. Without placing your borehole sites in a geographical context, it is difficult to evaluate whether this qualifies as a new regional insight.**

*R2.14 – Geographic context and regional insight:* The context has now been expanded considerably with new figures and much expanded background on glaciological setting.

**2. The method of measuring excess ice does not allow the conclusion that thick occurrences of excess ice were found in tills. The photos show excess ice, but make it difficult to believe the volumetric values obtained by this method.**

*R2.15 – Excess ice amounts:* We maintain (see R2.12) that the method chosen for estimating excess ice content does allow the conclusion that thick occurrences of excess ice were found. We hope that the inclusion of individual borehole profiles in the Supplement and the published core photographs will also help alleviate this concern. We have addressed the question of the aerial abundance of thick excess ice now explicitly. While this is speculative, it helps to avoid the perception that we claim thick sequences of excess ice would be found everywhere. Finally, the amounts of 84% and 71% shown in Figure B3 were an error, as can also appreciated from Figure 4A that has no values above 80%. The values have now been corrected and additionally, the estimated visible ice content is shown per borehole, all of which are near 40%.

**3. The soil cores go down to ten metres and have maximal ice contents of 60%. If the deepest core had the highest ice content, you would have subsidence of less 6 m. How then is subsidence of “tens of metres“ possible? Is this based on some kind of unmentioned extrapolation of observations?**

*R2.16 – 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".

**4. These are potentially interesting values, but would be made relevant if there was someway to know for what region the authors claim they are representative.**

*R2.17 – Area represented:* The field area shown on a map and specified by coordinates. The spatial aggregation of soil organic carbon storage has been dropped to keep the manuscript manageable.

**5. The cation concentration data are used only to establish in general "lower concentrations" when compared to a two studies from one other region and are entirely incidental to the paper's conclusions. There is no need to present terrain types, variation over depth or any of the data to reach this conclusion.**

*R2.18 – Conclusion concerning cation concentration:* Yes, we have chosen to remain with a simple indicator and analysis and a high level result that can be stated with some confidence. We report a summary that is true for all three terrain types that have mineral soils in permafrost and the active layer. We hope that the added detail in the explanation of terrain types will further alleviate the concern raised here.

**6. I agree that geological legacy is important. The data here are insufficiently linked to geological legacy.**

*R2.19 – Linking with geological legacy:* This should be more obvious now with more explicit geographic context, justification of terrain types, and individual profile data shown and discussed.

## 1 References

Phillips, M R, C R Burn, S A Wolfe, P D Morse, Adrian J. Gaanderse, H. B. O'Neill, D.H. Shugar, and S. Gruber. 2015. "Improving Water Content Description of Ice-Rich Permafrost Soils." In Proceedings of the GeoQuebec 2015 Conference, September 20-23, Quebec, Canada.

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# *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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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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# Ground ice, including preserved Laurentide basal 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

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This is the annotated manuscript with colour indicating deletions and new text added. In tables, only the headings of new columns are shown in blue.

**Abstract.** The central Slave Geological Province is situated near a divide 450–650 km from the presumed spreading centre of the Keewatin Dome of the Laurentide Ice Sheet, and it differs from the western Canadian Arctic, where recent thaw-induced landscape changes in Laurentide ice-marginal environments are already abundant. Although much of the terrain in the central Slave Geological Province is mapped as predominantly bedrock and ice-poor, glacial deposits of varying thickness occupy significant portions of the landscape, creating a mosaic of permafrost conditions. SomeLimited evidence of ice-rich ground, a key determinant of thaw-induced landscape change, exists. Carbon and soluble cation content in permafrost are largely unknown in the area. Twenty-four boreholes with depths up to ten metres were drilled in tundra north of Lac de Gras to address these regional gaps in knowledge and to better inform projections and generalizations at coarser scale. Excess-ice contents of 20–60 %, likely remnant Laurentide basal ice, are common found in upland till and suggesting that thaw subsidence of metres to more than ten metres is possible. Beneath organic terrain and in fluvially-reworked sediment, aggradational ice is found. The variability in abundantce of ground ice poses long-term challenges for engineering, and it makes the area susceptible to thaw-induced landscape change and mobilization of sediment, solutes and carbon several metres deep. The characteristics nature and spatial patterns of landscape changes, however, are expected to differ from ice-marginal landscapes of western Arctic Canada, for example, based on subsurface properties. Average soil organic-carbon storage is approximately 8 and 14 $kg\,C\,m^{-2}$ for the depth ranges 0–1 m and 0–3 mspatial and stratigraphic heterogeneity. Mean organic-carbon densities in the top 3 m of soil profiles near Lac de Gras are about half those reported in circumpolar statistics, deeper deposits have densities ranging from 1.3–10.1 $kg\,C\,m^{-3}$, representing a significant additional pool. The concentration of total soluble cations in mineral soils is much lower than at other previously studied locations in the western Canadian Arctic.

Permafrost in the study area contains much more ground ice than expected, and slightly less 0–3 m organic carbon and fewer soluble cations than well studied areas in the western Canadian Arctic. As these differences are strongly related to

geology and glacial history, t This study may inform permafrost investigations in other parts of the Slave Geological Province and its data can support scenario simulations of future trajectories of permafrost thaw at continental and circumpolar scales. Preserved Laurentide basal ice can support new ways of studying processes and phenomena at the base of an ice sheet as well as environmental conditions during the last interglacial.

## 1 Introduction

A unique drilling program sampling permafrost in the tundra north of Lac de Gras resulted in 24 boreholes with depths up to ten metres. It sampled permafrost and active-layer soils and allowed investigating their contents of ground ice, organic carbon and soluble cations. These three interrelated topics (e.g., Littlefair et al., 2017; Lacelle et al., 2019) are relevant for understanding the nature of permafrost and for anticipating consequences of its thaw, which are expected to become increasingly persistent and widespread due to anthropogenic global climate change.

The Lac de Gras region (Fig. 1), as part of the Slave Geological Province, is of interest because its geomorphic setting and Quaternary history differ from more intensively studied areas in the previously glaciated western Canadian Arctic and in unglaciated terrain in Yukon and Alaska (Dredge et al., 1999; Karunaratne, 2011). Its Holocene periglacial evolution spans only about 9,000 years, it is situated relatively close to the Keewatin Dome ice an ice divide of the Laurentide Ice Sheet. Even though ice divides shift over time (Margold et al., 2018; Boulton and Clark, 1990b), predominant zones of erosion and deposition by the Laurentide Ice Sheet, and likely previous ice sheets, are apparent at the continental scale and have been linked with continental patterns of ice flow and basal thermal regime (Sugden, 1977, 1978; Boulton and Clark, 1990a). The zone beneath the Keewatin Dome spreading centre, the predominant location of its ice divides, is characterized by low subglacial erosion rates and thick till. Areas near the margin of the ice sheet are frequently characterized by high deposition rates and these environments with thick till are relatively well accessible and studied in the western Canadian Arctic. Between both (Fig. 1) is a zone of increasing glacial erosion and basal conditions transitioning from melting to refreezing to fully frozen. The Slave Geological Province largely falls into this intermediate zone that is characterized by predominantly thin glacial sediments and mineral soils are often coarse and locally sourced from igneous and metamorphic rocks. The conditions in this zone likely result in high spatial and stratigraphic heterogeneity in the landscape, creating the need for detailed study of permafrost conditions and careful scaling approaches for coarse-scale models.

Several mines in the area as well as the planned Slave Geological Province Corridor (road, power transmission, communication) add applied relevance in the long term. This billion-dollar infrastructure project will connect Yellowknife with mines and future mineral resources in the study area and may eventually connect Canada's highway system to a deep-water port on the Arctic Ocean in Nunavut. The study presented here has been enabled by the Slave Province Surficial Materials and Permafrost Study, a large partnership of industry, government and academia.

The ice content of permafrost strongly determines the consequences of thaw such as subsidence or thermokarst development. It thereby also controls potential damage to infrastructure as well as the amount and timing of carbon fluxes into the atmosphere (Turetsky et al., 2019) and nutrient release into terrestrial and aquatic ecosystems (Lantz et al., 2009; Kokelj et al., 2013). The surroundings of Lac de Gras are shown as continuous permafrost with low (0–10 %) visible ice content in the upper 10–20 m and sparse ice wedges in the Permafrost Map of Canada (Heginbottom et al., 1995) and are designated as having thin overburden cover (<5–10 m) and exposed bedrock in the Circum-Arctic Map of Permafrost and Ground-Ice Conditions (Brown et al., 1997). For both, it is the lowest class of ground-ice content in continuous permafrost. The new Ground Ice Maps for Canada (O'Neill et al., 2019) show the study area (50 km × 50 km) to contain no or negligible wedge ice, negligible to low segregated ice and no relict ice, which includes buried glacier ice. By contrast, the thick and hummocky tills that cover about a quarter 20% of the study area have been hypothesized to contain large ice bodies, possibly of glacigenic origin (Dredge et al., 1999) as proposed also in other areas (e.g., Dyke and Savelle, 2000). Understanding the vertical distribution, spatial heterogeneity, and characteristics of ground-ice are a key prerequisite for simulating and anticipating the consequences or of permafrost thaw.

Large stocks of organic carbon that can be decomposed and transferred to the atmosphere upon thaw (Schuur et al., 2008) are held in permafrost (Hugelius et al., 2010) (Hugelius et al., 2014). The integration of organic carbon into the near-surface permafrost is related to either periods of deeper thaw, which can redistribute carbon within the soil profile, or to a rising permafrost table due to colluviation or alluviation, ecological succession, or climate cooling. These processes affect both carbon and geochemical profiles (Lacelle et al., 2019). To support the generation of future climate scenarios, the quantification and characterization of permafrost organic carbon storage is important and little information on soil organic carbon exists within a large area surrounding Lac de Gras, especially at depths exceeding one metre (Hugelius et al., 2014; Tarnocai et al., 2009).

Nutrients, organic materials and contaminants (natural and anthropogenic) can be released from permafrost during thaw (Dyke, 2001; Leibman and Streletskaya, 1997; Mackay, 1995), translating geomorphic disturbance, forest or tundra fire, or atmospheric warming into impacts on the chemistry of soils and surface water, and provoking noticeable ecological and downstream effects (e.g., Frey and McClelland, 2009; Kokelj and Burn, 2005; Kokelj et al., 2009; Littlefair et al., 2017; Malone et al., 2013; Tank et al., 2016). Studies from northwestern Canada report permafrost, the transient layer and the active layer to have distinct physical and geochemical characteristics (Kokelj et al., 2002; Kokelj and Burn, 2003, 2005; Lacelle et al., 2014) and sometimes distinguish relict/paleo-active layers (Burn, 1997; Lacelle et al., 2019). These vertical patterns are attributed to (a) past thawing causing loss of ground ice, leaching of solutes from thawed soils and redistribution of organic carbon by cryoturbation (Kokelj and Lewkowicz, 1999; Kokelj et al., 2002; Leibman and Streletskaya, 1997; Pewe and Sellmann, 1973), and (b) thermally-induced moisture migration during soil freezing redistributing water and soluble ions (Cary and Mayland, 1972; Qiu et al., 1988) contributing to solute enrichment in near-surface permafrost (Kokelj and Burn, 2005). These study areas, however, are different from the Slave Geological Province. For example, the alluvial materials derived from sedimentary and carbonate rock of the Taiga plain together with regular flooding produce solute rich active layer and permafrost deposits in the Mackenzie Delta. As another example, the sediments that comprise Herschel Island are silty-clay tills that include coastal and marine deposits excavated by the Laurentide Ice Sheet (Burn, 2017). In contrast to previous findings in these areas, we hypothesize that the tills in the Lac de Gras region are solute poor because they are locally sourced from granitic bedrock (Hu et al., 2003) and had limited potential for chemical weathering at depth. This is in line with sediments of similar origins, but contrasting depositional and permafrost history near Yellowknife reported to have low soil solute concentrations (Gaanderse et al., 2018) with variable trends in vertical profiles suggestive of active layer leaching and signs of evaporative concentration depending on site history (Paul et al., 2020).

This study aims to improve the understanding and quantitative characterization of permafrost and active layer materials in tundra environments near Lac de Gras and contribute to better understanding permafrost environments in the intermediate zone between the margins and the Keewatin Dome of the near Laurentide Ice Sheet ice divides and in the Slave Geological Province more broadly. The objectives are to *(i)* quantify the amounts and vertical patterns of excess ice, organic carbon and total soluble cations, *(ii)* explore factors contributing to the variation in physical and chemical characteristics between terrain types, and *(iii)* compare excess-ice content, organic-carbon density and total soluble cation concentration with other permafrost environments and or with compilations such as overview maps and databases. We interpret multiple boreholes grouped by terrain type and, with the data available, distinguish unfrozen (active layer) and frozen (predominantly permafrost) samples but do not additionally separate transient or relict active layers.

## 2 Study region

The study region (110.3° W, 64.7° N) is north of Lac de Gras, approximately 200 km south of the Arctic Circle and about 310 km northeast of Yellowknife. The regional climate is continental, with summers cool and short and winters cold and extremely long (Hu et al., 2003). Ekati, a diamond mine in the study region, has a mean annual and summer air temperature of -8.9 °C and 14.0 °C, respectively, and an annual precipitation sum of 275 mm during 1988–2008 (Environment Canada, 2019). Deglaciation occurred before 8,500 BP and between 6,000 and 3,000 BP, forest tundra extended to approximately the study area and then retreated again (Dyke, 2005; Dredge et al., 1999).

The region is in the zone of continuous permafrost (Figure 1) and mapped as having low (0–10 %) visible ice content in the upper 10–20 m (Heginbottom et al., 1995; Brown et al., 1997). One map indicates sparse ice wedges and the other thin overburden (<5–10 m) with exposed bedrock. A recent circumpolar compilation of permafrost carbon data (Hugelius et al., 2014) estimated soil organic-carbon storage (SOCs) to be 5–15 (0–1 m) and 15–30 $kg\ C\ m^{-2}$ (0–3 m). Recent work in the area has produced a wealth of permafrost stratigraphic (Gruber et al., 2018a) and thermal (Gruber et al., 2018b) data that enabled not only this contribution but also several simulation studies (Cao et al., 2019a; Melton et al., 2019; Cao et al., 2019b) predicting permafrost temperature driven by global atmospheric models.

For spatial context, we consider a 50 km × 50 km study area, and additionally, its surroundings as characterized by the 1:125,000 National Topographic System (NTS) of Canada maps on surficial geology 'Lac de Gras' (76-D, Geological Survey of Canada, 2014b) and 'Aylmer Lake' (76-C, Geological Survey of Canada, 2014a). These map areas are lLocated near the 450–650 km from the presumed mean spreading centre of the Keewatin Dome and about 100–300 km from the transition of thick to thin glacial sediments that is apparent on coarse-scale maps. Iice divide of the Keewatin sector of the Laurentide Ice Sheet, it generally is a source area for sediments, unlike ice marginal locations. The spatial abundance of surface materials

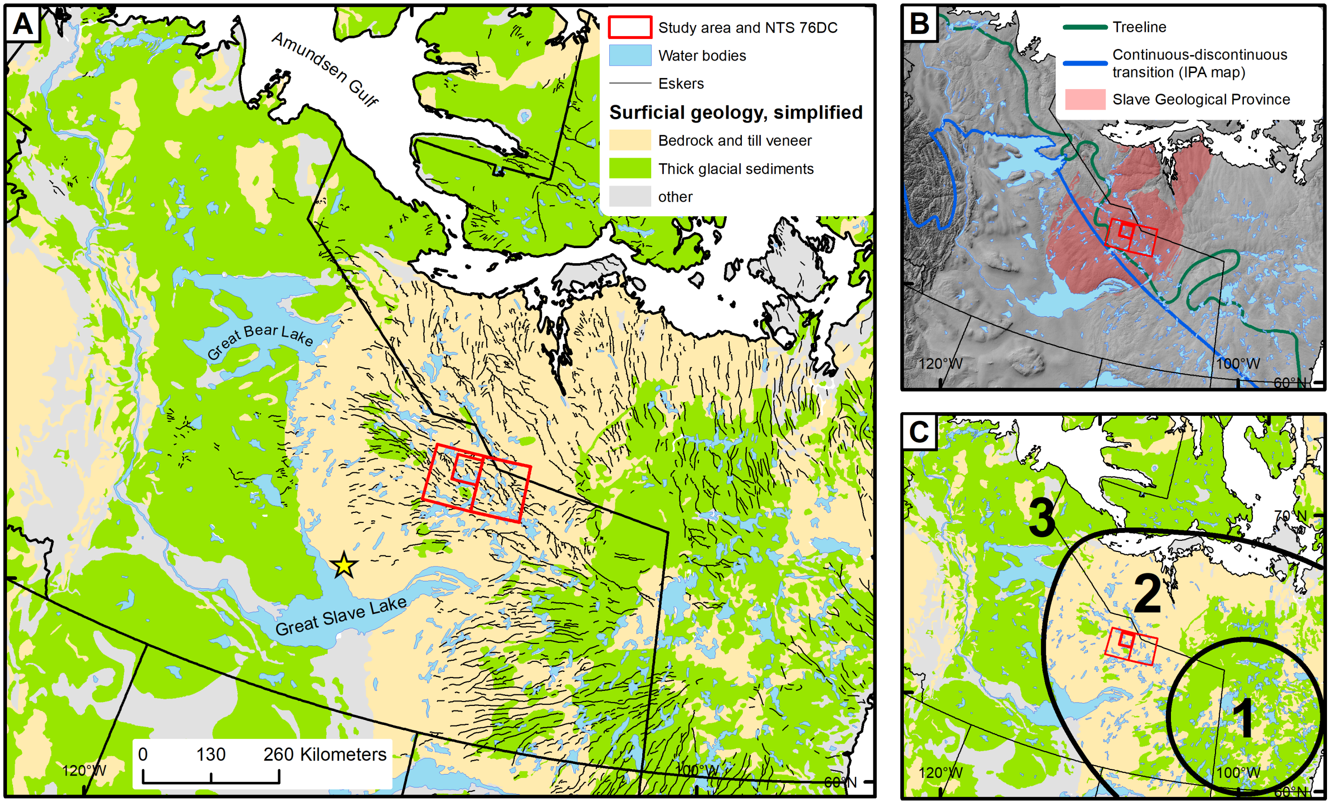

**Figure 1.** (A) Physiographic context of the 50 km × 50 km study area near Lac de Gras and the surrounding map sheets 76-D and 76-C. The simplified surficial geology legend distinguishes zones of thin and of thick till. Eskers indicate approximate late-glacial ice flow. (B) Location of the study area with respect to treeline, the mapped transition between continuous and discontinuous permafrost, and the Slave Geological Province. (C) Three zones of differing thickness of glacial sediment are apparent, zone (1) is assumed to correspond to the location of the the Keewatin Dome spreading centre. Data: Surficial Geology Map of Canada (Geological Survey of Canada, 2014c), Geological Map of Canada (Wheeler et al., 1996) and CanVec Hydro Features; Northern Canada Geodatabase (1.0); Circum-Arctic map of permafrost and ground-ice conditions (Brown et al., 1997).Location of the study area in the context of permafrost zones in Canada (modified from Heginbottom et al. 1995). Yellowknife is the closest city and indicated with a yellow star.

and previously predicted relict ice content is summarized in Table 1 (see also Fig. S1 in the Supplement). is derived from the surficial geology map 1:125,000 (110–112° W, 64–65° N) for Lac de Gras (NTS 76-D, Geological Survey of Canada, 2014b).

The study area is characterized by low relief where irregular bedrock knobs and cuestas form hills up to 50 m high (Dredge et al., 1999). The northern part is dominated by till deposits, whereas the southern half consists more prominently of bedrock (8 %) with patches of till (Hu et al., 2003). Numerous eskers and outwash complexes (1 %), mostly composed of sand and gravel, are found in the area (Dredge et al., 1994). Till deposits are differentiated by their estimated thickness into till veneer (<2 m thick, 21 %), till blanket (2–10 m thick, 24 %), and hummocky till (5–30 m thick, 3 %). These deposits typically have a silty sand to sand matrix with low percentages of clay and 5–40 % gravel (Wilkinson et al., 2001). Organic material covers 5 %

**Table 1.** Spatial abundance of lakes, surficial geology and estimated relict ground ice for the 50 km × 50 km study area and surroundings (Fig. 1). Surficial geology is based on the 1:125,000 map sheets 76-D and 76-C, percentages are relative to exposed land area, whereas values in square brackets are relative to total surface area including lakes. The abundance of relict ground ice is from O'Neill et al. (2019), who use a model based on data products at the scale of 1:5,000,000.

| | study area | NTS 76-D | NTS 76-C |
|---|---|---|---|
| area (km$^2$) | 2,500 | 10,706 | 10,709 |
| Lakes (%) | [40] | [28] | [29] |
| Bedrock (%) | 12 [8] | 13 [10] | 8 [5] |
| Glaciofluvial (%) | 3 [2] | 2 [1] | 1 [1] |
| Till veneer (%) | 29 [17] | 34 [24] | 19 [13] |
| Till blanket (%) | 32 [19] | 40 [28] | 49 [35] |
| Hummocky till (%) | 19 [11] | 5 [4] | 17 [12] |
| Organic (%) | 5 [3] | 6 [5] | 6 [5] |
| Relict ice: none (%) | 100 | 96.1 | 99.9 |
| Relict ice: negligible (%) | 0 | 0 | 0 |
| Relict ice: low (%) | 0 | 3.8 | 0 |
| Relict ice: medium (%) | 0 | 0.1 | 0.1 |
| Relict ice: high (%) | 0 | 0 | 0 |

and lakes 38 % of the area. Overburden thickness is considerable in hummocky till and till blanket of the study area (Haiblen et al., 2018) and the two surrounding map sheets (Kerr and Knight, 2007).

Soils consist of till, glacio-fluvial sediments, or peat. Upland till surfaces are characterized by mud boils, earth hummocks and organic material, visible to depths of up to 80 cm, that has been redistributed within the active layer by cryoturbation (Dredge et al., 1994). The tills derived from granitic and gneissic terrain have a silty or sandy matrix, whereas those derived from metasedimentary rocks contain a higher silt-clay content (Dredge et al., 1999). Low-lying areas are mostly comprised of colluvium or alluvium rich in organics and wet areas often have peatlands (Karunaratne, 2011).

The area is in continuous shrub tundra (Wiken et al., 1996) and common shrubs include northern Labrador tea *(Rhododendron tomentosum)* and dwarf birch *(Betula glandulosa)*, while bog cranberry *(Vaccinium vitis-idaea)* and dwarf bog rosemary *(Andromeda polifolia)* often comprise the understory (Karunaratne, 2011). Well-drained upland areas are typically covered with a thin layer of lichens and mosses (Hu et al., 2003) (Figure 2A). Grasses and sedges with a ground cover of moss comprise the vegetation cover in valleys (Figure 2B) and some poorly-drained low-lying areas have thick peat associated with ice-wedge polygons and sedge meadows (Hu et al., 2003; Karunaratne, 2011) (Figure 2C). Frequently, low-lying areas have

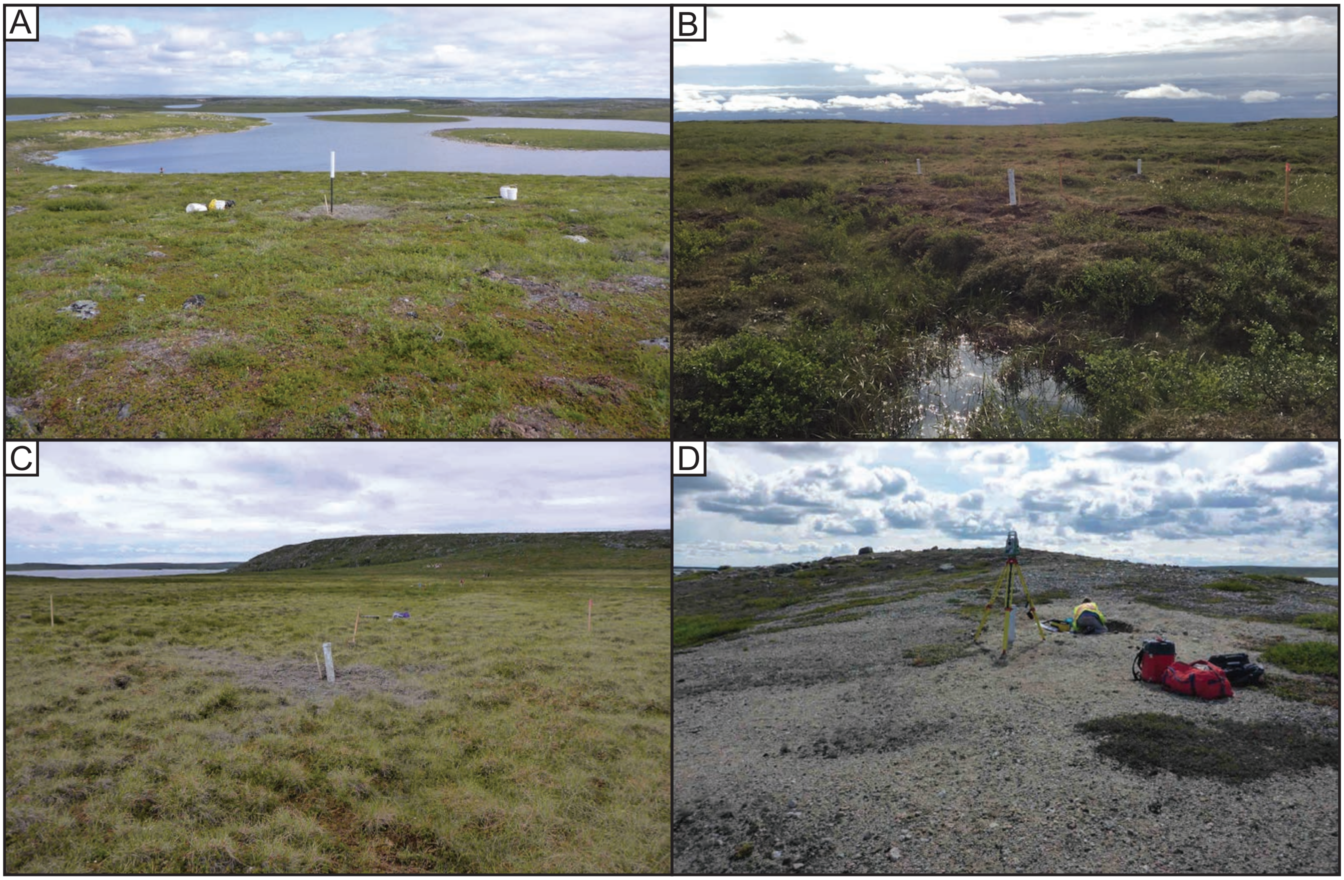

**Figure 2.** Examples of the four terrain types used: (A) upland tills, (B) the Valley organic deposits, (C) organic deposits the Valley, and (D) eskers.

tall shrubs along small streams and at the rise of steeper slopes. Esker tops have little vegetation and are often comprised of exposed soil (Figure 2D).

## 3 Field observation and sampling

In summer 2015, soil cores with a nominal diameter of 5 cm, but often irregular due to partial melting and reaming, were obtained using a diamond drill (Kryotek Compact Diamond Sampler), sectioned into 20 cm intervals and logged (soil texture, colour, ice content and visible organic matter) in the field while still frozen (Subedi, 2016; Gruber et al., 2018a). Esker locations were augered. Two soil pits were excavated within approximately 10 m of each borehole to describe and sample typical near-surface soil conditions. Where possible, samples were taken at depths of 10 cm, 20 cm, and 30 cm; exact sample volumes are not known. The depth of thaw at the time of sampling was estimated by probing, although this was often unsuccessful in coarse mineral soil. Drill core and pit samples were double-bagged for thawed shipment to the laboratory in Yellowknife.

Borehole locations were originally planned for investigating (a) vertical and spatial patterns of solute and organic-carbon content in soils, and (b) terrain effects on ground temperature based on thermistor chains installed after drilling. For site selection, we used the surface classes of the 1:125,000 surficial geology map 76-D, topographic position, aerial imagery revealing surface cover such as vegetation or boulders, and a Landsat derived index outlining the location of late-lying snow drifts. Locations were planned in clusters to simplify the logistics of moving equipment with a helicopter. The reverse-circulation winter drilling campaign during March and April 2015 (Normandeau et al., 2016) inspired the selection of site NGO-DD15-1014, where a thick sequence of ice rich ground was encountered.

During fieldwork, blocky surfaces could not be sampled as moving clasts jammed the drill rods. Sections with high gravel content or boulders resulted in slow progress and were often terminated at relatively shallow depth due to time constraints. Furthermore, these sections often resulted in low recovery, because the heating of the drill when cutting though hard rock would melt the frozen core and fines would be washed out. The complete drill logs and photographs revealed a cluster of boreholes with well-graded fine sands and pronounced ice lenses as well as till with high excess ice content beneath upland locations. These clusters, however, do not correspond well with the surficial mapping units used. Correspondingly, four terrain types (Figure 2) comprised of Upland Tills, fluvially reworked till (the Valley), Organic terrain and Eskers were sampled with are used as a grouping for describing and interpreting the drill cores and soil pits at 24 locations (Table A1, see also Fig. S1 in the Supplement). The uneven depth and sparse sampling within boreholes led us to report results from multiple boreholes in combined plots).

Upland Tills: Ten boreholes were sampled to depths of 2.5–9.5 m in smoothly rounded hills comprised of thick till and in till veneer over bedrock. The dominant cryostructure was wavy and suspended. The dominant plant species were dwarf shrubs, Labrador tea and grasses. Thaw depths were about 2 m on hill tops and nearly a meter at the bottom of hills.

The Valley: Eight boreholes were drilled to depths of 1–6 m in a gently sloped valley that contrasts with other terrain types because its silts and sands are well sorted and likely derived from fluvial reworking of local tills. Boreholes located on the more elevated sides of the Valley typically had coarser sediments, whereas those near its axis had mostly fine sediments with high silt contents and organics with ice-wedge polygons. The dominant cryostructure was lenticular. Few water logged sites contained tall shrubs with water channels. Sites were sparsely to moderately covered with plant species such as dwarf birch, Labrador tea and grasses. Thaw depths were 35–40 cm.

Organic terrain: Two boreholes to depths of about 4.5 m were drilled on the centres of ice-wedge polygons in peatlands with hummocky surface topographys. The dominant plant species were dwarf birch and Labrador tea, with plenty of low-lying grasses. The depth of thaw was 35 cm and the permafrost table 50–70 cm deep.

Eskers: Four boreholes were drilled to depths of 1.5–12 m at hilltop locations with sparse vegetation or exposed soil.

## 4 Methods

All samples were thawed and processed at ambient temperature. Samples were homogenized, poured into beakers, weighed, and allowed to settle for 12 h (cf. Kokelj and Burn, 2003). Volumes of sediment $V_s$ and supernatant water $V_w$ were recorded to estimate volumetric excess ice content (%) of the permafrost samples as

$$V_{ei} = \frac{1.09\,V_w}{V_s + 1.09\,V_w} \times 100, \tag{1}$$

where 1.09 approximates the density of water divided by that of ice. The volumetric percentages of coarse fragments (>5 mm), sand (0.074–5 mm) and fines (<0.074 mm) in the sediment was estimated visually to the nearest 5 %. The volumetric percentage of coarse fragments ($V_c$) relative to the total sample volume was obtained by multiplying the estimated coarse percentage with $1 - V_{ei}/100$. The length of solid rock cored per borehole was estimated from the core photographs.

Supernatant water was extracted directly from samples where sufficient volume was available and to all other samples, a known amount of deionized water was added (1:1 extraction ratio; Janzen, 1993). These samples were mixed thoroughly and then allowed to settle for 12 h. Water was collected with a syringe and filtered through 0.45 $\mu$m cellulose filter paper. The remainder of the sample was dried for 24 h at 105 °C to determine the gravimetric water content (%), expressed on a dry basis ($GWC_d$) and on a wet basis ($GWC_w$) (cf. Phillips et al., 2015).

The concentration (mg/l) of the soluble cations $Ca^{++}$, $Mg^{++}$, $Na^{+}$ and $K^{+}$ was determined by atomic adsorption spectrophotometer at the Taiga lab in Yellowknife. Measured soluble ion concentrations $C^m$ (mg/l) were converted to an expression $E$ using milli-equivalents per unit mass of soil (meq/ 100g of dry soil)

$$E = \frac{C^m}{M^e} \times M_w^{100g}, \tag{2}$$

where $M^e$ is the equivalent mass of ions (g) and $M_w^{100g}$ is the mass of water per 100 g of dry soil as present in the sample at the time of water extraction. Presentation of soluble cation concentrations per unit mass of dry soil facilitates comparison between samples of varying moisture contents. We sum the resulting four soluble cation concentrations to obtain total soluble cation concentration.

Organic-matter content $LOI$ (%) is expressed on a gravimetric dry basis and was determined using the sequential loss-on-ignition method (Sheldrick, 1984) at Carleton University. A small amount (2–3 g) of the homogenized and oven dried sample (< 0.5 mm soil fraction) was placed in a crucible and heated to 550 °C for 6 h to determine the organic-matter content as

$$LOI = \frac{M_S^{105} - M_S^{550}}{M_S^{105}} \times 100, \tag{3}$$

where $M_S^{105}$ is the mass of sediment after oven drying at 105 °C, and $M_S^{550}$ is the mass of sediment after ignition at 550 °C. To avoid combustion problems, reduced amounts (0.5–1 g) were processed when samples consisted of plant residue with very little visible mineral soil. When no mineral soil component was visible after coarse components were removed, samples were not processed and an LOI of 80% was estimated. This occurred only in the top 0.3 m metre and almost exclusively in samples from soil pits. The gravimetric percentage ($P_{0.5}$) of the <0.5 mm soil fraction has been lost from the original analysis. Later, this was determined again based on dry sieving for 183 of 357 samples.

Data quality was assessed in a second analysis on the samples using the same procedures and tools as during the original processing. Based on measured blanks, the accuracy is about 0.03 % LOI, the median accuracy based on doubles is 0.04 % LOI with the highest difference being 0.30 % LOI.

Soil organic-carbon storage (SOCs, $kg\,C\,m^{-2}$) was computed for comparison with soil carbon inventories (e.g., Hugelius et al., 2014). For this, soil organic-carbon concentration (SOCc, % mass) was computed as

$$SOCc = \frac{LOI}{2.13}, \tag{4}$$

following Dean (1974) and dry bulk density (DBD, $kg\,m^{-3}$), which is known to correlate with SOCc (e.g., Alexander, 1989; Bockheim et al., 2003), was approximated as

$$DBD = 71 + 1322 \times e^{(-0.071 \times SOCc)}, \tag{5}$$

following Hossain et al. (2015), who conducted their study in geologic settings similar to the project area. This resulted in an estimated DBD for the fine-grained soil, i.e. excluding the volumes $V_{ei}$ and $V_c$. To account for this, soil organic-carbon density (SOCd, $kg\,C\,m^{-3}$) was derived as

$$SOCd = \frac{SOCc}{100} \times \frac{P_{0.5}}{100} \times DBD \times \left(1 - \frac{V_{ei} + V_c}{100}\right), \tag{6}$$

and finally applied as average values over depth intervals within each terrain type to obtain SOCs. Aggregated SOCd and SOCs were reduced by the average proportion of solid rock cored though in Upland Tills and in Organic terrain below 2 m. For the samples without measured values, $P_{0.5}$ was estimated by beta regression (Cribari-Neto and Zeileis, 2010) with $LOI$, $GWC_w$ as well as the visually-estimated proportions of sand and fines as independent variables. Predictors are significant at the 0.1 %-level and residuals have a standard deviation of 11 %. The spatial average of soil organic-carbon storage is estimated by aggregating SOCd with the spatial abundance and estimated depths of surface materials (NTS 76-D, Geological Survey of Canada, 2014b) for the study area. Depths are restricted to the available observations, and for the three till classes restricted or extrapolated to their mean depths.

Estimating $P_{0.5}$ for 176 of 357 samples statistically, parameterizing $DBD$ and estimating $V_c$ visually introduce uncertainty in the resulting values for $SOCd$ and $SOCs$. The potential magnitude of this effect on average values is estimated by computing a low-carbon scenario and a high-carbon scenario by varying $V_c$ and $P_{0.5}$ by ±10 percentage points each and $DBD$ by ±50 $kg\,m^{-3}$. These deviations are subjective choices and correspond to a bias of twice the recorded precision for $V_c$ and approximately the standard deviation of model residuals for $P_{0.5}$. The deviation for $DBD$ is chosen to be considerable while within the variation observed by Hossain et al. (2015, Fig 6). The averages of the resulting scenario values are 37 % lower and 38 % higher than the best estimate for SOCd that is reported and interpreted in the following sections.

Detailed grain-size distribution was measured on selected samples using a Beckman Coulter LS 13320 laser-diffraction particle-size analyzer. Samples were first oven-dried at 105 °C and then crushed and homogenized with a mortar and pestle. Samples were then passed through a 2 mm sieve to remove the coarse fraction that was then weighed. Organic matter was removed from the fines using hydrogen peroxide. The samples were then mixed with Calgon to prevent flocculation and passed through the particle-size analyzer. Results were classified according to the USDA textural classification system (2 mm > sand > 53 $\mu$m > silt > 2 $\mu$m > clay).

## 5 Results

### 5.1 Soil texture

Approximately 7 % of upland tills (3.4 of 49.4 m of borehole depth, Table A1), consist of rock clasts larger than the core barrel. Eskers were augered rather than cored and large clasts would have terminated the borehole and not be recovered. The majority of the Valley cores was free of large clasts. Most soils consisted of poorly to very poorly sorted silt and sand. The relative proportion of silt was high in samples from mineral soils beneath organic terrain and in valley bottom sites with average values exceeding 40 %. Clay content was low and always below 20 %.

### 5.2 Ground ice

Field logged visible-ice content is available for 113 core sections. The average, weighted by the length of core sections, is 24 %. Cryostructure is discussed in Section 6. Details about individual boreholes are in the Supplement and all core photographs are available in Gruber et al. (2018a). Laboratory analyses show that water and excess-ice contents increase progressively with depth in Upland Till. Zones of high moisture content (Figures 3A and 4A) were often associated with ice lenses, several centimeters thick (e.g., Figures B1 and B3). Excess-ice content greater than 50 % in Upland Till became increasingly common below 4 m depth.; 5 boreholes terminated in ice-rich material and 5 in rock. In organic terrain, high moisture content (>80 %) but low excess-ice content in permafrost reflect saturated organic soils with low bulk density (Figure 3B). The sharp decline in water content below 2 m depth coincides with a decline in organic matter contents (Figure 4B). A notable increase in moisture and excess ice content from 2.5–4 m depth occurred in underlying mineral soils. Profiles from the Valley showed high moisture content near the surface, where organics were present, and deeper down (Figure 3C) due to 20–50 % excess ice in mineral soil (Figure 4C). Frozen and ice poor till has been recovered near the bottom of boreholes in Organic terrain and in the Valley (Figure B4). In eskers, water content was mostly below 20 % and pore ice the dominant ground-ice type (Figure 3D).

### 5.3 Organic carbon

Organic-carbon density in the active layer was typically greater than at depth in permafrost (Figure 5). Statistics of soil organic-carbon density and storage are given for consistent depth intervals and the four terrain types in Table 2. The spatial average of soil organic-carbon storage in the study area, accounting for the abundance of bedrock and lakes, is estimated as 8 and 14 $kg\,C\,m^{-2}$ for the depth ranges 0–1 m and 0–3 m, respectively.

### 5.4 Total soluble cations

The concentrations of soluble cations (meq /100g dry soil) in organic-rich, shallow soils were mostly higher and more variable than those in mineral permafrost soils at depth (Figure 6). In organic materials, the concentration of soluble cations near the top of permafrost was relatively high (Figure 5B and 6B). In Upland Till, soluble cation concentrations, as with ice content, increased gradually with depth (Figure 4A and 6A). Differences between active layer and permafrost, as well as between

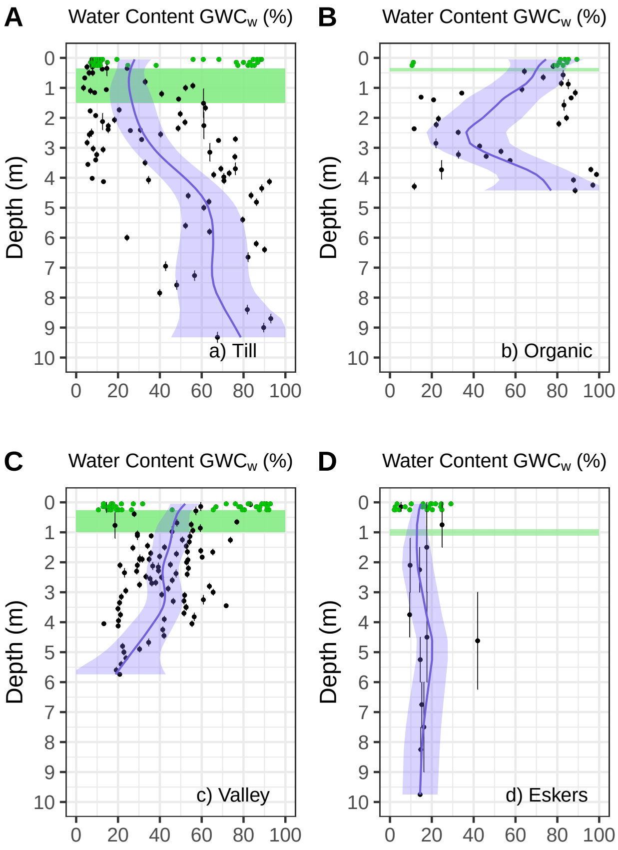

**Figure 3.** Gravimetric water content from four terrain types near Lac de Gras, N.W.T. Black points and their vertical lines represent borehole samples and their depth intervals, the number and individual characteristics of boreholes are in Table A1 and in the Supplement. Green points show pit samples. Blue lines represent averaged values, taking into account sample depth intervals, with shaded blue areas indicating the standard error at 95% confidence. Green shaded areas indicate the range of thaw depths for the boreholes at the time of sampling.

organic and mineral soils are apparent from their median concentration of soluble cations; organic samples are distinguished using a threshold of 30 % LOI (cf. CSSC, 1998) and permafrost considered when logged as frozen. In organic samples the contrast (permafrost to active layer) was 2.02 to 0.34 meq/100 g dry soil and in mineral samples 0.26 to 0.09 meq/100 g dry soil. The four group medians are all significantly ($p < 0.01$) different from each other based on Kruskal-Wallis tests. Although the dry bulk density of organic soil is lower than that of mineral soil, these patterns persist even when expressed relative to wet soil mass ($p<0.01$) or the volume of water contained in the thawed sample ($p<0.05$).

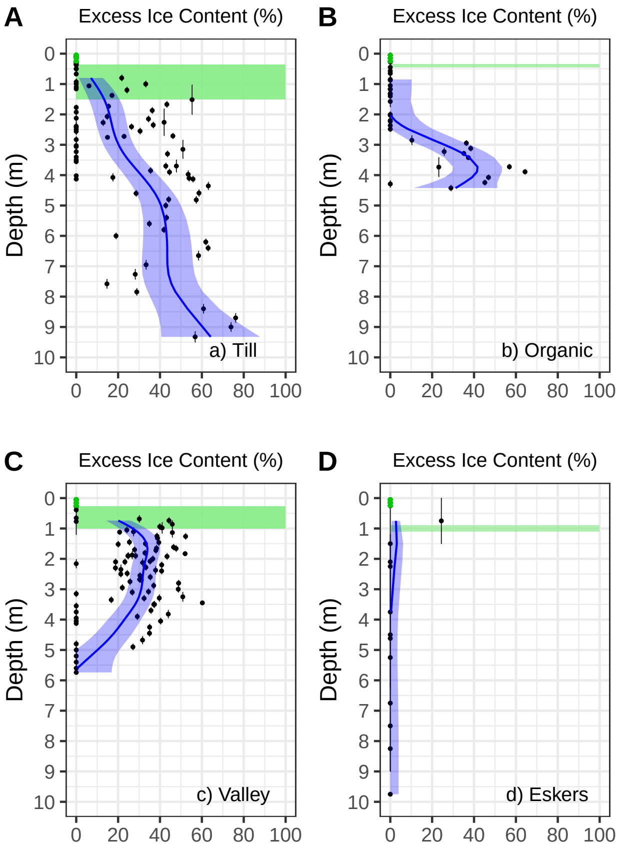

**Figure 4.** Excess-ice content from four terrain types near Lac de Gras, N.W.T. Black points and their vertical lines represent borehole samples and their depth intervals, the number and individual characteristics of boreholes are in Table A1 and in the Supplement. Green points show pit samples. Blue lines represent averaged values, taking into account sample depth intervals, with shaded blue areas indicating the standard error at 95% confidence. Green shaded areas indicate the range of thaw depths for the boreholes at the time of sampling.

## 6 Interpretation and discussion

### 6.1 Ground ice

The results presented are subject to a number of biases compared to a perfectly randomized sampling within each terrain type and perfect recovery of samples during drilling. Drilling induced errors in the recovery of ground ice where excessive heating of the drill barrel caused partial or complete thaw of the core (Figure 7). Depending on the degree of thaw and core composition, this resulted in intervals erroneously shown with reduced or no excess ice content (Figure 4C). The results are, therefore, likely to be conservative (low biased) estimates of excess ice and gravimetric water content at the locations sampled. The difficulty of drilling though large clasts, on the other hand, may have caused bias towards sampling locations with higher contents of

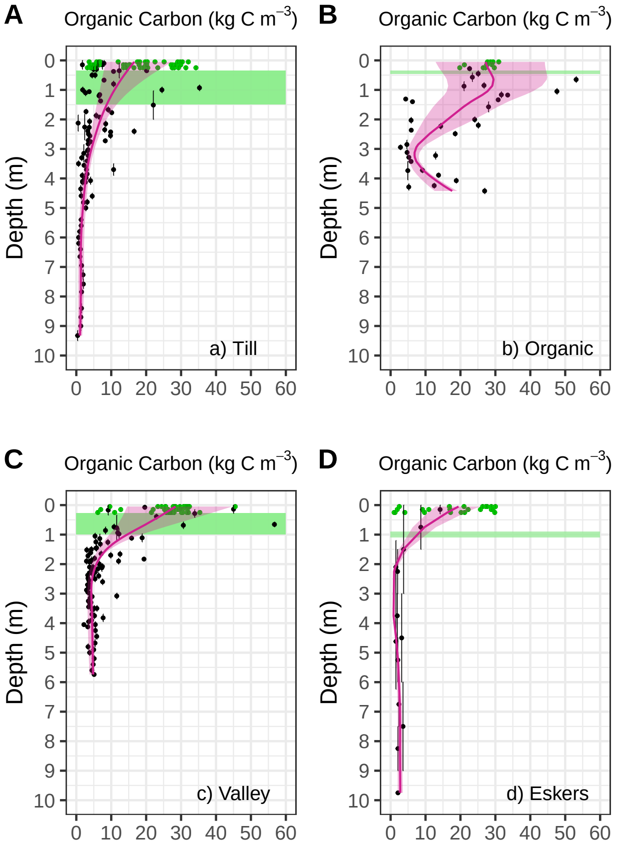

**Figure 5.** Soil organic-carbon density ($kg\ C\ m^{-3}$) from four terrain types near Lac de Gras, N.W.T. Black points and their vertical lines represent borehole samples and their depth intervals, the number and individual characteristics of boreholes are in Table A1 and in the Supplement. Green points show pit samples with approximated values for the organic terrain. Magenta lines represent averaged values, taking into account sample depth intervals, with shaded magenta indicating the high/low-carbon scenarios used to estimate the uncertainty inherent in estimating and parameterizing some of the values used in calculations. Green shaded areas indicate the range of thaw depths for the boreholes at the time of sampling.

excess ice and of fines. When drilling organics within polygon networks, the drill rig was placed on polygon centres. As a consequence, wedge ice, which is known to be present in the area based on the surface expression of polygon networks, is systematically avoided in sampling and, therefore, largely excluded from the present quantitative data and interpretation.

While this study was not designed to elucidate the origin of ground ice, a number of observations merit discussion. In organic terrain, the excess ice recovered resembles pool ice (clear with small bubbles and embedded peat filaments) and wedge ice (foliated with bubbles and some sediment, Figure B2 panels B and C) as previously reported for polygonal ground in organics (Mackay, 2000; Morse and Burn, 2013). In the Valley and in Organic terrain, the increase in water and excess-ice

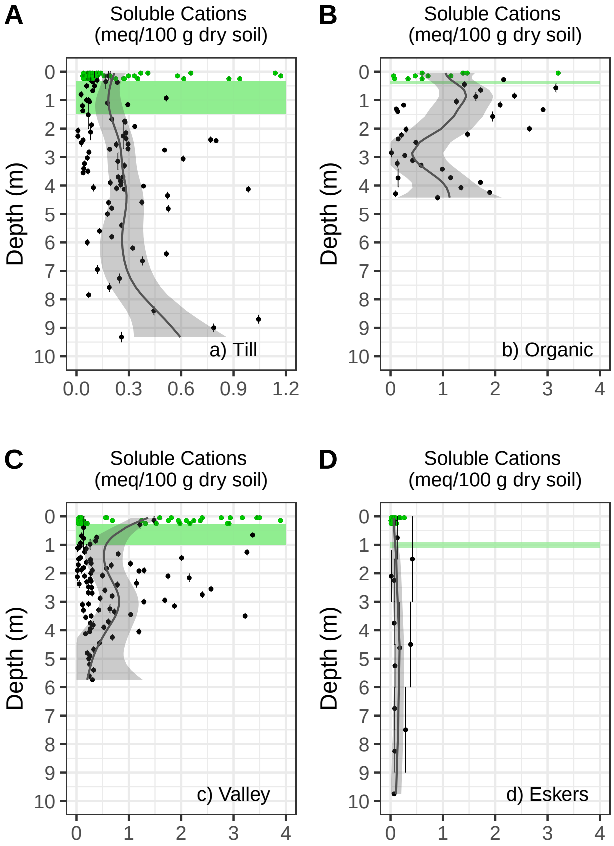

**Figure 6.** Total soluble cation concentration (meq/100 g dry soil) from four terrain types near Lac de Gras, N.W.T. Black points and their vertical lines represent borehole samples and their depth intervals, the number and individual characteristics of boreholes are in Table A1 and in the Supplement. Green points show pit samples. Smooth black lines represent averaged values, taking into account sample depth intervals, shaded grey areas indicate the standard error at 95% confidence. Green shaded areas indicate the range of thaw depths for the boreholes at the time of sampling. Note differences in horizontal scales.

content with depth (Figures 3 and 4) is likely due to ice segregation in frost susceptible and relatively well graded mineral soil (Figures B1 and B2 panel D) with frequent reticulate cryostructure. Both the Valley site, with well-graded materials that are likely to be fluvially-reworked tills, and Organic terrain represent aggradational environments in low lying areas where water tends to accumulate and the terrain surface gained material either through the growth of peat or fluvial deposition. Shallow permafrost aggraded in these settings, as such, does not contain relict or preserved ice within the depth of thaw prior to and 305 during aggradation. Similarly, permafrost has aggraded in the sediment of eskers, where less fine material together with convex topography explains the absence of aggradational ice. Eskers in the study area occasionally contain relict ice, interpreted as

**Table 2.** Mean observed sSoil organic-carbon density (SOCd, $kg\,C\,m^{-3}$) per depth interval and soil organic-carbon storage (SOCs, $kg\,C\,m^{-2}$) for the four terrain types investigated. SOCs is based on average SOCd accumulated from the surface down to the specified maximum depth. Ranges in parentheses indicate minimum and maximum values rounded to the nearest integer, the number of samples is indicated in square brackets. Values for Upland Tills and at depths below 2 m in organics account for the abundance of rock clasts larger than the core barrel. The top 0.3 m are subject to high uncertainty arising from the uniform estimation of 80 % LOI for organic-only samples.

| | Organics | | The Valley | | Upland Till | | Eskers | |
|---|---|---|---|---|---|---|---|---|
| Depth | SOCd | SOCs | SOCd | SOCs | SOCd | SOCs | SOCd | SOCs |
| 0–0.3 m | 26.5 (19–31) [13] | 8 | 26.5 (6–45) [52] | 8 | 14.8 (2–31) [59] | 4 | 17.5 (1–30) [25] | 5 |
| 0.3–1 m | 29.9 (21–53) [5] | 29 | 20.6 (8–57) [8] | 22 | 10.9 (4–33) [10] | 12 | 8.7 (9–9) [1] | 11 |
| 1–2 m | 25.6 (4–48) [9] | 54 | 7.6 (3–19) [23] | 30 | 7.8 (2–23) [13] | 20 | 3.7 (4–4) [1] | 15 |
| 2–3 m | 11.8 (3–23) [8] | 66 | 4.8 (3–8) [22] | 35 | 5.4 (1–15) [16] | 25 | 1.8 (2–2) [2] | 17 |
| 3–5 m | 10.1 (4–25) [11] | 87 | 4.8 (2–12) [25] | 44 | 2.7 (1–10) [23] | 31 | 2.2 (2–3) [3] | 21 |
| 5–10 m | | | | | 1.3 (0–3) [16] | 37 | 2.4 (2–4) [5] | 34 |

**Figure 7.** Heating of the drill barrel, likely due to cutting through the rock near the middle of this section, caused complete melt of ground ice in the left part of the core shown. Here, gravel was recovered but fines were likely washed out with melt water and drilling fluids. The right side of the core is partially thawed and ice rich. This recovered section of less than 0.5 m represents 1.3 m in borehole NGO-DD15-2033.

partially derived from of glacial meltwater and deposited together with the esker sediments (Dredge et al., 1999; Hu et al., 2003) and show geomorphic evidence of melt-out (Prowse, 2017).

Cores from upland hummocky till, analyzed to 9 m depth (Figure B3), were often associated with high amounts of excess ice. Ice occurred in wavy layers and sometimes as massive clear ice several centimetres thick (similar to Fig. 3.8c in Gruber and Haeberli, 2009). In contrast to the Valley site and Organic terrain, no reticulate structure and no apparent separation of consolidated fines and clear ice were visible in most Upland Till cores. Sediment was coarser and more poorly sorted in Upland Till than at the Valley site or beneath Organics. Particles appeared to be suspended in the ice matrix, giving it a visual appearance of much lower ice content than it actually has, as reported previously for basal glacier ice facies (Knight, 1997; Murton et al., 2005). Soluble cation contents are lower in mineral soil active layers and near-surface permafrost than at depth, consistent with near-surface leaching and preservation of underlying materials in the frozen state since deglaciation. Finally, the convex topography of Upland Till sites makes them well drained and differentiates them from the Valley and from Organic sites. These differences in cryostructure, cation content and sedimentological properties point to ice of differing origin and deposit type. The presence of hummocky topography, thermokarst lakes and thaw-slump like features (Fig. C1), suggest indicating melt-out of ice-rich till, and the involuted nature of some hilltop surfaces resemble other permafrost preserved glaciated landscapes in northwestern Canada, which are known to host relict Pleistocene ground ice (Dyke and Savelle, 2000; Rampton, 1988; St-Onge and McMartin, 1999). By contrast, Rampton (2000) invoked subglacial hydrology rather than ground-ice melt in interpreting features such as the one shown in Fig. C1, calling them (inverted) plunge pools that were caused by scouring where pressurized turbulent water was forced to change direction. Both, ground ice characteristics and geomorphic features suggests that a large proportion of the excess ice in this hummocky till is Laurentide basal ice preserved beneath ablation till.

The excess ice contents encountered in mineral soil were often 20–60%. As a first-order estimate, this implies that complete thaw of permafrost can cause about 0.2–0.6 m of subsidence for each vertical meterof permafrost in till. The boreholes in upland hummocky till, which is estimated to be 10–30 m thick in the area (Haiblen et al., 2018) show an increasing trend of excess ice content with depth, based on our limited sampling to 9 m, alone. Half the boreholes terminate in ice rich ground and the other half in rock. Not having boreholes terminate in ice poor till indicates that thicker sequences of ice rich material than what has been recovered can be expected. Furthermore, an earlier winter drilling campaign (Normandeau et al., 2016) produced six boreholes in upland tills. NGO-RD15-150, co-located with NGO-DD15-1014, logged 13 m of 'ice' with bedrock at 16.7 m. The other boreholes (NGO-RD15-148, 155, 160) only returned minor ice content with depths between 5.5 and 7.9 m. While this provides additional context, the absence of logged ice needs to be interpreted with care give the combined difficulties of logging reverse circulation recovery and winter conditions, and because logging ice content has not been a priority of that campaign. A potential surface lowering of many meters, up to more than ten meters, is thus to be expected from areas of thick Surface lowering of several meters, with potential of up to more than ten metres, could thus be expected from areas of thick upland till if this permafrost was to thaw completely. This includes the potential for thermokarst processes to mobilize sediments, solutes and organic carbon at depth more quickly than expected in strictly conductive one-dimensional thaw. A number of geomorphic features reminiscent of retrogressive thaw slumps (Fig. C1) and the presence of kettle lakes (Prowse, 2017) in the area both exhibit local relief that suggest meltout of massive ice several metres in thickness.

#### 6.1.1 Glaciological context

In the interior of the Laurentide Ice Sheet, no supraglacial sources of debris existed. If the ice found in Upland Tills is indeed Laurentide basal ice, then its mineral content must derive from basal entrainment. Debris rich basal ice can result from a variety of processes that occur at glacier beds with net freezing or net melting (Alley et al., 1997; Cuffey et al., 2000). Some of the processes of freezing involve the migration of liquid water akin to permafrost aggradation and ice lensing studied in periglacial environments (Christoffersen and Tulaczyk, 2003).

Using ice samples from of the Greenland Ice Sheet, Herron et al. (1979) showed debris-laden ice in the lowermost 15 m beneath a divide and Souchez et al. (1995) showed vertical mechanical mixing of clean ice and basal ice beneath the summit. Furthermore, they pointed to the similarity of the anomalously high gas content ($CO_2$ and $CH_4$) to that in permafrost soils, invoking the mobilization of soils predating the ice sheet. The original basal ice prior to upward mixing has partially formed at the ground surface and is hypothesized to be a remnant of the growing stage or the original build up of the ice sheet (Souchez et al., 1994). Assuming vertical mixing near the bed of the ice sheet, the lowermost meters of ice may thus be composed to varying degrees of ice derived from precipitation and metamorphism at the surface of the ice sheet and of materials formed from the freezing of liquid water in debris (cf. Gow et al., 1979). The hypothesized basal ice in the project area, however, is richer in sediment, contains coarser clasts, and is thicker than that reported from ice cores beneath the summit of Greenland (Gow et al., 1997), especially when accounting for previously thawed material that overlies the remnant ice found today.

Most studies of basal ice from ice sheets originate from either ice coring at modern ice divides, modern margins of Arctic ice caps that have preserved basal ice-sheet ice (LeB. Hooke, 1976), or from studies near the margins of former ice sheets, where the presence of buried basal ice in permafrost (Murton et al., 2004) is well established. The present study may provide the first evidence of basal ice in the zone a few hundred kilometers from ice divides (as conceptualized in Figure 1C, Zone 2) where rates of erosion increase and the thermal regime at the base varies (Sugden, 1977, 1978; Boulton, 1996). These conditions are described by Hooke et al. (2013) who reconcile glaciological theory with observations from mineral prospecting. They predict the formation of thick dispersal plumes in the transition zone from basal melting to basal refreezing to a fully frozen bed, that is likely to have occurred in the study area. Sediment plumes are thus likely composed of directly eroded bedrock incorporated into the basal ice by, and together with, refreezing basal melt water. Additionally, regolith and organics predating the ice sheet may be incorporated. The model of Hooke et al. (2013) is useful in explaining why we find a spatial patchwork of preserved excess ice. First, the thermal conditions at the bed of the ice sheet likely had a patchwork character in this transitions zone, making the distribution of sediment plumes uneven. Second, basal ice can only be preserved where it is overlain by sediment thicker than the maximum depth of thaw during the Holocene. As spatial patterns of plume thickness, mineral content, and vertical structure are expected to vary, so will the likelihood of preserving ice until today.

#### 6.1.2 Estimated spatial abundance of relict ice and implications for mapping and modelling at coarse scale

Although our results suggest of relict ice preserved in areas of thick upland till, they do not easily support quantitative conclusions on the spatial extent over which this occurs. Nevertheless, we can constrain the range of plausible extent based on a few assumptions. Let us express the areal proportion underlain by some amount of relict ice as $P_{ice} = P_{up} \times P_{pre}$, with $P_{up}$ being the proportion of upland in a particular class of till and $P_{pre}$ being the proportion of area within the upland portion where preserved ice is found. Based on visual interpretation of maps and imagery, we assume $P_{up}$ to be 30–70 % in hummocky till and 5–30 % in till blanket. We can attempt to estimate $P_{pre}$ based on what we interpret as preserved ice at three drilling locations (Figure S1, NGO-DD15-1014 and around NGO-DD15-2004 and NGO-DD15-2033) and not finding it during winter drilling at three other locations (NGO-RC15-148, 156, 160). Winter drilling with reverse circulation may produce false negatives, whereas one could argue that NGO-DD15-2004 and NGO-DD15-2033 are close and should not be counted separately. With these biases, the low number of locations sampled, and the implications of varying sediment-plume characteristics in mind, let us assume $P_{pre}$ to be 25–75 %. Correspondingly, $P_{ice}$ is 7–53 % for hummocky till and 1–23 % for till blanket, considering till veneer and bedrock are negligible by comparison. This leads to estimated areal proportions of the land surface underlain by some relict ice of 2–17 % for the study area, 1–12 % for NTS sheet 76-D, and 2–20 % for NTS sheet 76-C (Table 1).

Even though the areal proportion underlain by relict ice is uncertain, the contrast with the recent map of O'Neill et al. (2019) is striking (Table 1). It highlights the importance of spatial heterogeneity and of representing it at coarse scale, where the dominant surface type alone may not be a good predictor of actual relict ice content. This scale mismatch is a common challenge for permafrost models (Gruber, 2012) and more generally for models of non-linear processes (Giorgi and Avissar, 1997). The rules proposed by O'Neill et al. (2019) would likely predict relict ice in the project area similar to observations if used with the surficial geology at 1:125,000 scale. By contrast, the study area has been generalized into the classes of till veneer and bedrock, exclusively, in the surficial geology map 1:5,000,000 that was used as input for the nation wide map of O'Neill et al. (2019). In earlier permafrost maps and models, uncertainty and variability at the sub-grid scale have been propagated into model results with high/low cases on assumed sub-grid processes and with the presentation of additional instructions for field interpretation (e.g., Boeckli et al., 2012; Gruber, 2012). Analogously, introducing a scaling relationship between the surficial geology at 1:125,000 and 1:5,000,000 would allow to apply the rules of O'Neill et al. (2019) at the national scale while improving the representation of heterogeneity. For example, a fractional sub-grid proportion of hummocky till in till veneer at 1:5,000,000 could be assumed. Extending this to other classes and introducing best, high and low estimates would make the scaling issue a part of the modeling process and propagate its effects into the final results.

### 6.2 Organic carbon

Terrain variation in organic-carbon density and in organic matter content in fine material occur in association with surficial material and topographic setting. Organic terrain is frequently characterized by peat deposits up to 2.5 m thick and associated with low lying, poorly drained portions of the landscape. In other terrain types, organic materials may have become vertically redistributed in the top few metres of soil profiles by cryoturbation (Dredge et al., 1994; Kokelj et al., 2007; Haiblen et al., 2018) and by burial during permafrost aggradation due to colluviation/alluviation (e.g., Lacelle et al., 2019). The low organic-carbon density at depth likely indicates the absence of sediment reworking and permafrost preservation in upland tills during the Holocene.

Mean organic-carbon density in the top 3 m of soil profiles near Lac de Gras is about half that reported in recent circumpolar statistics (Table D1). This is similar to the mean of about 12 ($kg\,C\,m^{-3}$) for the top 1 m in the northern Canadian Arctic and its difference to about 30 ($kg\,C\,m^{-3}$) in the southern Canadian Arctic reported by Hossain et al. (2015, Fig. 5D). A recent circumpolar compilation of permafrost carbon data (Hugelius et al., 2014) estimated SOCs for the study area to be 5–15 (0–1 m) and 15–30 (0–3 m) $kg\,C\,m^{-2}$. These values are similar (0–1 m) and slightly higher (0–3 m) than the spatially-averaged results of this study, that include zero SOCs in bedrock and in lakes. The low organic-carbon density in the study area, especially at depth, is interpreted to derive from the short duration of Holocene carbon accumulation following at least partial evacuation of older soil carbon by the Keewatin sector of the Laurentide Ice Sheetduring Marine Isotope Stage 2. While deep carbon pools are important (Koven et al., 2015), corresponding data, as reported here, is rare (Hugelius et al., 2014; Tarnocai et al., 2009). Values reported here on organic-carbon density in the top 0.3 m are subject to high uncertainty arising from the uniform estimation of 80% LOI for organic-only samples. This is because peat usually has higher (Treat et al., 2016) and non-peat organic material lower (Hossain et al., 2015) LOI.

### 6.3 Total soluble cations

In mineral soil, the lower concentration of total soluble cations in the active layer (median of 0.05 meq/100 g dry soil) compared with permafrost (median of 0.25 meq/100 g dry soil) is interpreted to be caused by leaching of ions from unfrozen soil, and is similar to observations in other regions (Table D2). This large contrast between mineral soil active layers and permafrost is likely robust even though variable extraction ratios were used. Fitting a model to predict total soluble cation concentration in mineral soil from $GWCw$ and the extraction ratio shows $GWCw$ as a highly significant predictor, while the extraction ratio is not significant ($p>0.05$). Additionally, the redistribution of ions along thermal gradients during freezing may have caused solute enrichment during the development of segregated ice (Figure B1 and B2) in aggrading permafrost (cf. Kokelj and Burn, 2005) in mineral soils of the Valley and beneath peat in organic terrain. There, zones of increased cation concentrations at depth corresponded with ice-rich intervals in permafrost , especially at sites in till and in organic terrain (Figure 4 and 6). Where high amounts of organic matter are present, also the concentration of total soluble cations is high. As a consequence, mineral-soil permafrost has lower concentrations of soluble cations than organic active-layer soils but higher concentrations than mineral active-layer soils.

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). In the Mackenzie Delta, alluvial materials derived from sedimentary and carbonate rock of the Taiga plain and regular flooding produce solute rich active layer and permafrost deposits. A range of forest-terrain types contained more soluble cations, often several times higher, in the active layer and permafrost than the mineral soils in this study. Also in comparison with undisturbed terrain on Herschel Island, the absolute concentrations of soluble cations in our study are low. Sediments on Herschel Island are silty-clay tills that include coastal and marine deposits excavated by the Laurentide Ice Sheet (Burn, 2017). These materials are frequently saline below the thaw unconformity indicating permafrost preservation of soluble materials below the maximum depth of early Holocene thaw (Kokelj et al., 2002) or their concentration in colluviated materials (Lacelle et al., 2019). 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 in many upland locations have been exposed to only minor postglacial landscape modification (Haiblen et al., 2018; Rampton and Sharpe, 2014). Although analytical methods are different, studies near Yellowknife (Gaanderse et al., 2018; Paul et al., 2020) also suggest low soluble cation concentrations in materials of similar origins but with contrasting depositional environments, terrain history and ecological conditions. Water from glaciolacustrine delta sediments west of Contwoyto Lake, about 120 km north of the study area, has been reported with an average concentration of 6.2 meq/l for 8 samples from 3–12.4 m (Wolfe, 1998), similar to the average value of 7.5 meq/l resulting from 10 Esker samples of our study in the same depth range.

The values reported must be interpreted in light of the ambiguity involved in the choice of method for extracting water from samples and in normalizing analytical results for comparison. Non-uniform extraction ratios can add uncertainty due to increased uptake of solutes from soil where water content is high (Toner et al., 2013). This effect is difficult to prevent with multiple samples having $GWCw$ larger than 90% and standardization by extraction from a saturated paste as used in soil science is impractical with large clasts and high ice content. As such, the values obtained provide an imperfect comparison of the total cations that can be dissolved from the sediment within each sample. For comparison of samples, analytical results from permafrost studies are often normalized to dry soil mass (common in soil science) or water volume (common in studies of water chemistry or glaciology), either that contained in the sample or that used during extraction of solutes. Because no uniformly accepted protocol exists, comparison between studies is often challenged by differences in their methods.

Sections with relatively high solute concentrations exist in several boreholes. We hypothesize that those are, at least partially, caused by fresh rock flour produced when the diamond drill bit cuts though clasts, e.g., in NGO-DD15-2006 near 2.4 m depth. As such, the summarized concentrations we report may have a high bias.

## 7 Conclusions

The research area near Lac de Gras is characterized by a mosaic of terrain types (48 % till, 38 % lakes, 8 % bedrock, 5 % organic material and 1 % eskers and outwash complexes) with a high degree of fine-scale spatial variability in subsurface conditions. Permafrost there contains much more ground ice, slightly less organic carbon and fewer soluble cations compared with global compilation products or published research from sites in the western Canadian Arctic. This study provides quantitative data in a region with few previous studies and it supports six specific conclusions:

1. Excess-ice contents of 20–60 % are common, especially in samples from upland till and till-derived sediments, and the average field logged visible-ice content is 24 %. This new regional insight improves upon coarse-scale compilations that rate map the area north of Lac de Gras as ice poor (O'Neill et al., 2019; Brown et al., 1997; Heginbottom et al., 1995). Specifically, it points to the importance of scaling issues when applying models with coarse-scale input data.

2. Thick occurrences of excess ice found in upland tills are likely remnant Laurentide basal ice, and aggradational ice is found beneath organic terrain and in fluvially-reworked till.

3. Thaw-induced terrain subsidence on the order of metres to more than tens of metres is possible in ice-rich till. Even though this study did not investigate the spatial abundance of ice rich till, it can be estimated as 2–17 % for the study area. Organic terrain hosts wedge ice and is typically underlain by ice-rich mineral deposits. Future thermokarst processes may therefore result in significant landscape change and fast mobilization of sediment, solutes and carbon several metres deep. Geomorphic evidence of past ground-ice melt, including retrogressive thaw slumping thaw-induced mass wasting exists.

4. Peatlands are were found to be up to 2.5 m thick and in till, cryoturbation and colluviation/alluviation have redistributed modest amounts of organic carbon locally to depths of 2–4 m. Mean organic-carbon density in the top 3 m of soil profiles near Lac de Gras is about half that reported in recent circumpolar statistics (Hugelius et al., 2014). Estimated areal means, accounting for the abundance of bedrock and lakes, of soil organic-carbon storage are 8 and 14 $kg\,C\,m^{-2}$ for the depth ranges 0–1 m and 0–3 m, respectively, similar to or slightly lower than in a global estimate (Hugelius et al., 2014).

5. The concentration of total soluble cations, expressed as meq/100 g dry soil, in active layer and permafrost mineral soils is markedly, often by one order of magnitude, lower in the Lac de Gras area than at other previously studied locations in the western Canadian Arctic. Mineral-soil active layers have a lower concentration of total soluble cations than permafrost. Total soluble cation concentrations are higher where soils are rich in organic matter.

6. Abundant relict ground ice and glacigenic sediments exist at locations in the interior of the Laurentide Ice Sheet and are poised for climate-driven thaw and landscape transformation change, similar to permafrost-preserved ice-marginal glaciated landscapes where dramatic major geomorphic transformations are already observed (e.g., Kokelj et al., 2017; Rudy et al., 2017). The characteristics of thaw-driven landscape change, however, are expected to differ from observations in ice-marginal positions due to differences in topography and climate affecting location and timing, geotechnical properties affecting stability and mobility of sediments, and geochemistry affecting solute and carbon release to surface water, ecosystems and the atmosphere.

These findings highlight the importance of geological and glaciological legacy in determining the characteristics of permafrost and the potential responses of permafrost systems to disturbance and climate change. The existence of preserved Laurentide basal ice offers a unique chance to better study processes and phenomena at the base of an ice sheet as well as environmental conditions during last interglacial. This opportunity will gradually diminish as the ice can be expected to progressively melt in the future. This future melt will partially reveal subsurface conditions through the nature and magnitude of change. Continued research on permafrost and landscape response to warming at locations in the interior of the Laurentide Ice Sheet will help to understand and predict changes specific to these landscapes characterized by a mosaic of contrasting permafrost conditions, and how they affect ecology, climate, land use and infrastructure.

*Code and data availability.* Drill logs, visible ice content and core photos from the 2015 campaign are published (Gruber et al., 2018a). Data and code for reproducing the main figures, constructed using GG-plot in R, are available at https://doi.org/10.5281/zenodo.3628070

*Author contributions.* SG and RS wrote the manuscript together with SVK. RS conducted the initial study, performed or oversaw the laboratory analyses, and produced the scripts for plotting Figures 3–6. SG produced Figure 1, the Supplement, the sections on ground ice, glaciology, soil organic-carbon density as well as framing and conclusions.

*Competing interests.* No competing interests are present.

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## Appendix A: Sample locations

Table A1 details on borehole locations and sampling dates.

**Table A1.** Borehole locations and times drilling dates, detailed plots are contained in the Supplement (Fig. S1–3). Full ID codes have the prefix 'NGO-DD15-'. Map units correspond to surficial geology at the scale of 1:125,000 (Geological Survey of Canada, 2014b). The depth and material at the end of hole (EOH) are indicated. The length of rock drilled though is estimated to the nearest 5 cm.

| ID | Terrain Type | Map Unit | Depth m | EOH material | Rock m | Longitude WGS84 | Latitude WGS84 | Elev. m | Date 2015 | Thaw depth m |
|---|---|---|---|---|---|---|---|---|---|---|
| 2008 | Eskers | GFr | 6.2 | ice poor | auger | -110.1851 | 64.6003 | 458 | 12 Jul | – |
| 2028 | Eskers | GFr | 11.7 | thawed | auger | -110.1851 | 64.6003 | 458 | 19 Jul | – |
| 2029 | Eskers | GFr | 12.1 | thawed | auger | -110.1846 | 64.6002 | 458 | 20 Jul | – |
| 2026 | Eskers | GFr | 1.5 | boulder | auger | -110.3451 | 64.7246 | 437 | 19 Jul | – |
| 1006 | Organic | Th | 4.4 | ice rich | 0.20 | -110.2333 | 64.6037 | 443 | 12 Jul | 0.35 |
| 1005 | Organic | Tv | 4.9 | ice | 0.00 | -110.2356 | 64.5999 | 440 | 10 Jul | 0.35 |
| 2009 | Till | Th | 5.0 | ice | 0.40 | -110.2169 | 64.6041 | 446 | 12 Jul | >0.34 |
| 2033 | Till | Th | 5.1 | ice rich | 0.45 | -110.2152 | 64.6055 | 458 | 22 Jul | >0.40 |
| 1004 | Till | Th | 4.3 | boulder | 0.75 | -110.2381 | 64.5951 | 471 | 9 Jul | – |
| 1007 | Till | Th | 4.3 | boulder | 0.25 | -110.2328 | 64.6037 | 442 | 12 Jul | 0.35 |
| 2004 | Till | Th | 6.0 | bedrock | 0.25 | -110.2363 | 64.5963 | 480 | 10 Jul | – |
| 2005 | Till | Th | 4.2 | ice rich | 0.05 | -110.2332 | 64.5966 | 472 | 11 Jul | >0.40 |
| 2006 | Till | Th | 4.3 | ice rich | 0.05 | -110.2307 | 64.5968 | 453 | 11 Jul | >0.47 |
| 2007 | Till | Th | 3.7 | boulder | 0.65 | -110.2354 | 64.5985 | 459 | 11 Jul | >0.40 |
| 1014 | Till | Th | 9.5 | ice | 0.50 | -110.7354 | 64.6254 | 489 | 21 Jul | – |
| 2018 | Till | R2 | 3.0 | bedrock | 0.00 | -110.4360 | 64.7136 | 461 | 16 Jul | 0.40 |
| 1009 | Valley | Tb | 5.3 | thawed | 0.10 | -110.4430 | 64.7015 | 432 | 14 Jul | 0.36 |
| 1010 | Valley | Tb | 5.0 | thawed | 0.00 | -110.4398 | 64.7027 | 426 | 14 Jul | 0.34 |
| 2011 | Valley | Tb | 5.8 | bedrock | 0.00 | -110.4479 | 64.7023 | 432 | 13 Jul | 0.27 |
| 2012 | Valley | O | 4.1 | bedrock | 0.00 | -110.4459 | 64.7021 | 433 | 13 Jul | >0.35 |
| 2013 | Valley | Tb | 3.3 | bedrock | 0.15 | -110.4501 | 64.7028 | 440 | 14 Jul | >0.40 |
| 2015 | Valley | O | 2.8 | thawed | 0.05 | -110.4421 | 64.7035 | 425 | 14 Jul | >0.40 |
| 2016 | Valley | Tb | 2.0 | boulder | 0.00 | -110.4441 | 64.7045 | 431 | 14 Jul | >0.40 |
| 2019 | Valley | R2 | 2.8 | ice rich | 0.70 | -110.4357 | 64.7021 | 428 | 16 Jul | 0.40 |

## Appendix B: Typical core

Figures B1, B2, and B3 show typical core.

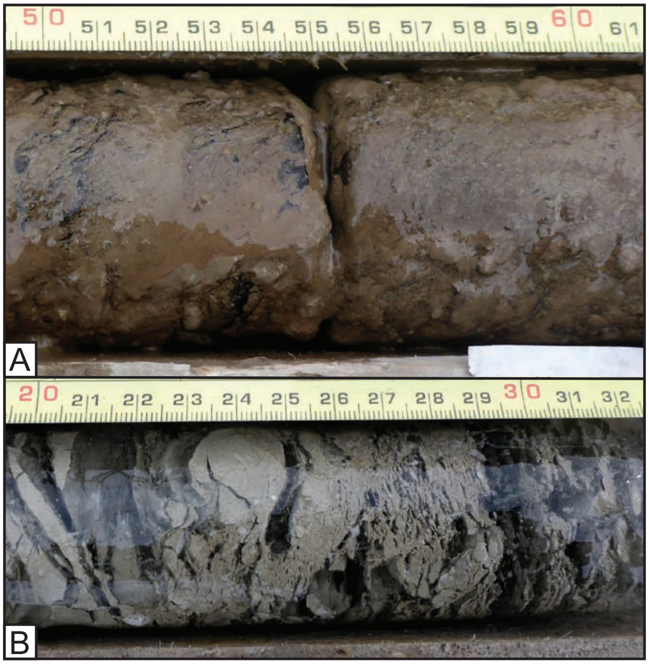

**Figure B1.** Drill core recovered from borehole NGO-DD15-1010 in the Valley. (A) shows core from 1.6 m depth with 7146% excess ice and 1.3% organic matter. (B) is about 3.5 m depth with 7760% excess ice and 1.5% organic matter. Scale bars are in cm.

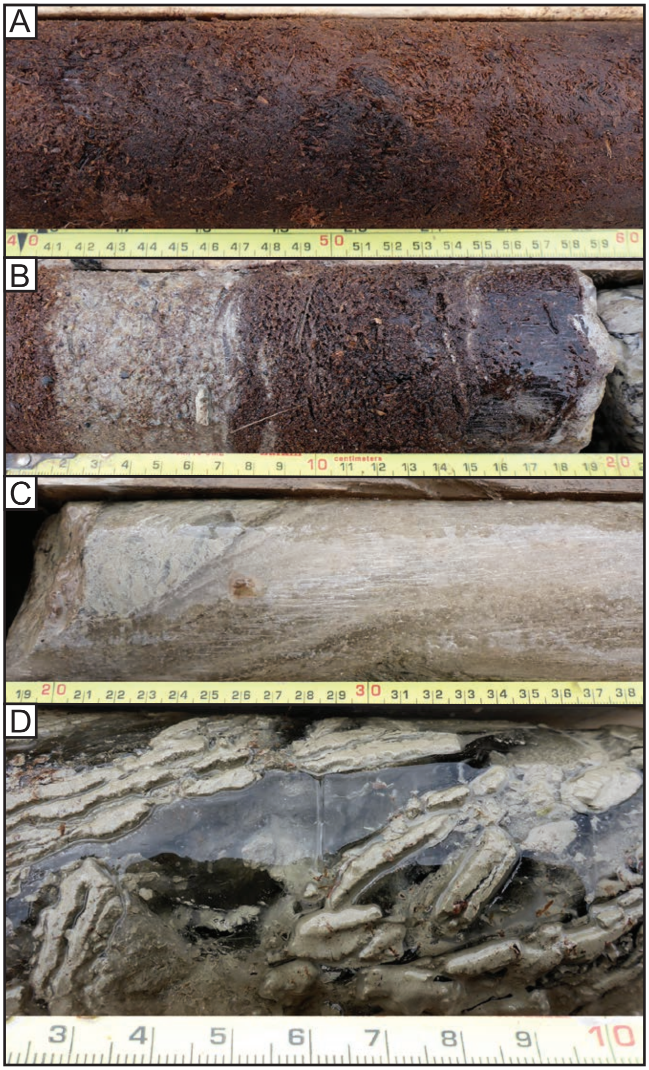

**Figure B2.** Drill core recovered from borehole NGO-DD15-1005 in organic terrain. (A) Compact frozen organics near 0.85 m without excess ice and 80% organic matter. (B) Alternating layers of organics and mineral soil near 1.6 m with 19% excess ice and 9.2% organic matter. (C) Nearly pure ice around 2.7 m, no analyses available. (D) Ice in mineral soil, 3.5 m deep with 537% excess ice and 1.6% organic matter. Scale bars are in cm.

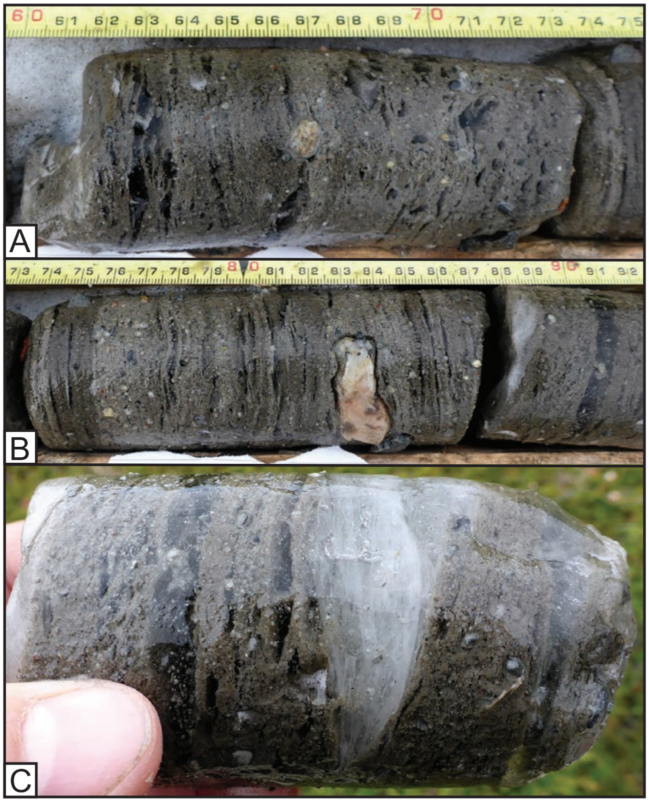

**Figure B3.** Drill core recovered from borehole NGO-DD15-2005 in hummocky till near a hilltop and logged as 40% visible ice. (A) Core near 3.8 m depth with 84% 43% excess ice and 1% organic matter. (B) Core near 4.0 m depth with 71% 45% excess ice and 0.6% organic matter. (C) Closeup of the right side of the core shown in (B). Scale bars are in cm.

**Figure B4.** Evidence of permafrost in previously thawed till. (A) Thin lenses of segregated ice at 3.3–3.5 m in NGO-DD15-1007 indicate refreezing of thawed till and illustrate the different appearance when compared to the cryostructure in Fig. B3. (B) The contact between the well sorted silt/sand and coarser material a6 3.7–4.1 m in NGO-DD15-2012.

## Appendix C: Geomorphic evidence of post-glacial melt of ground ice

Figure C1 shows evidence of post-glacial ground-ice melt.

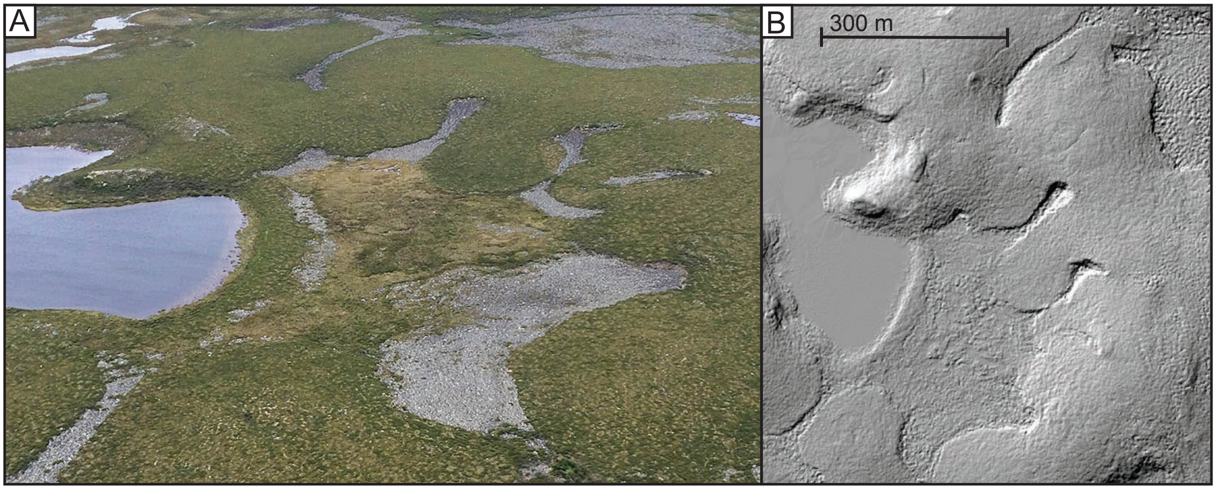

**Figure C1.** Terrain features that may indicate post-glacial ground-ice melt (see also McWade et al., 2017) shown in oblique aerial photograph from July 13, 2015 (A) and hillshade image with 1 m resolution (B). Lower elevation areas expose many large boulders. The elevation difference between the concave features and the smooth upland tills is 5–10 m and hypothesized to derive largely from loss of ice in the ground. The centre of the area shown is 109.944° W, 64.615° N. The hillshade is based on a digital elevation model kindly provided by Dominion Diamond Mines.

## Appendix D: Tabulated comparison with previous studies

Table D1 compares soil organic-carbon densities and Table D2 soluble cation concentrations between this and previous studies.

**Table D1.** Soil organic-carbon density (SOCd, $kg\,C\,m^{-3}$) per depth interval for three terrain types from the Lac de Gras study area (Table 2) compared with similar soils reported in a circumpolar compilation (Hugelius et al., 2014, Table 2). Upland Tills are compared to Turbels (cryoturbated permafrost soils), Eskers with Orthels (mineral permafrost soils unaffected by cryoturbation) and Organics with Histels (organic permafrost soils). Circumpolar values below 1 m are for "Thin sediment". For Orthels, values in "Thick sediment" are more than ten times larger.

| Depth | Histels | Organics | Turbels | Upland Till | Orthels | Eskers |
|---|---|---|---|---|---|---|
| 0–0.3 m | 60.3±10.0 | 26.5 | 49.0±5.0 | 14.8 | 52.7±8.7 | 17.8 |
| 0–1 m | 49.3±8.4 | 28.9 | 33.0±3.5 | 12.1 | 25.3±4.1 | 11.4 |
| 1–2 m | 49.0±9.2 | 25.6 | 31.6±33.1 | 7.8 | 2.6±2.0 | 3.7 |
| 2–3 m | 30.5±8.8 | 11.8 | 19.5±17.5 | 5.4 | 1.3±16.9 | 1.8 |

**Table D2.** Concentration of soluble cations in active layer and permafrost in mineral soils compared with previous studies in northwestern Canada that employ a comparable analytical approach. In this study, active-layer values derive from pit samples and permafrost values from frozen core sections, samples below 2 m depth were used on Eskers. Values from Lacelle et al. (2019) were derived using three sequential extractions in a 1:10 soil water ratio on dried soils, likely yielding higher concentrations (cf. Toner et al., 2013), possibly by a factor of two or more, than what would be obtained with the method described in this study.

| | *Total soluble cations (meq/100 g dry soil)* | |
|---|---|---|
| Terrain type | Active layer | Permafrost |
| *Lac de Gras area (this study), mean (median, n)* | | |
| Upland till | 0.06 (0.06, 18) | 0.24 (0.20, 59) |
| The Valley | 0.19 (0.10, 6) | 0.59 (0.29, 79) |
| Eskers | 0.05 (0.04, 18) | 0.15 (0.09, 10) |
| *Mackenzie Delta (Kokelj and Burn, 2005), mean values* | | |
| Point-bar willow | 2.06 | 3.83 |
| Point-bar alder | 1.54 | 2.15 |
| Spruce-alder-bearberry | 0.64 | 2.09 |
| Spruce-feathermoss | 0.49 | 1.24 |
| Spruce-crowberry-lich. | 0.38 | 1.62 |
| *Herschel Island (Kokelj et al., 2002), estimated from figures* | | |
| Undisturbed plateau | 0.25–1.5 | 12–14 |
| Undisturbed plateau | 0.25–6 | 8–14 |
| Undisturbed stable sl. | <0.25 | 5 |
| Disturbed AL detachm. | 2–10 | 12 |
| Disturbed AL detachm. | 2–12 | 12 |
| *Richardson Mountains–Peel Plateau, mean (median, n) (Lacelle et al., 2019)* | | |
| CB thaw slump | 1.21 (1.2, 12) | 7.0 (6.5, 12) |
| paleo AL | | 4.0 (3.8, 5) |
| Wilson slump | 2.12 (1.7, 5) | 6.4 (6.0, 6) |
| paleo AL | | 4.5 (4.1, 10) |
| WR-03 slump | | 10.4 (9.6, 9) |
| paleo AL | | 17.5 (15.4, 6) |
| WR-05 slump | | 11.6 (10.9, 7) |
| paleo AL | | 19.9 (21, 23) |

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