

August 2, 2024

For the attention of the Editor,

We have carefully considered the comments made by the two reviewers and thank you for the opportunity to respond. Our responses are detailed line by line in response to each reviewer's comment. We have submitted a copy of the manuscript with all changes accepted, for reference to this file. We are very grateful to the reviewers for their careful and insightful comments which have allowed us to improve the original submission and to clarify areas where our interpretations were not clearly expressed. As a result, we feel that the manuscript is now improved, and we hope that you will find that it is acceptable for publication.

We thank you for this opportunity to revise the manuscript. Please do not hesitate to contact us should any further clarification be required.

Sincerely,

Shannon M. Hibbard, Corresponding Author (*on behalf of all authors*)

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Referee #1

I am afraid that the genetic model proposed in this paper for the formation of VRFs is untenable and hence I have proposed a rejection.

I have attached an annotated pdf with specific comments on the text.

Whereas this paper presents a lot of good field data on some interesting landforms, the interpretive and analytical aspects are unconvincing and much of the material misconceived. Fundamental to this is the lengthy argument presented to reject a permafrost/periglacial origin of the landforms and then a very short and weakly justified case for a glacial origin. The latter appears to be based on a dated understanding of the glacial literature which is compounded by a lack of critical discussion of that literature with respect to ridge rimmed landforms, of which there are many types but few of which actually resemble those described by the authors. VRFs are common throughout the Canadian Arctic and occur on valley floors and coastal lowlands covered in deglacial sediments. Spatially they grade in and out of low-centred polygons and circles, the changing morphology being dictated by local material properties and standing water characteristics. In places you can see where old water channels link up with the depressions between parallel winding ridges, indicating that running water had some role in their evolution amongst developing ground ice features. The fact that the VRFs reported in this paper mostly lie on glaciofluvial outwash terraces clearly demonstrates that they have been constructed on those terraces after they formed - hence they cannot be derived from underlying dead ice even if it is present. Where stagnant glacier ice is present, the materials in which VRFs form has been released by supraglacial melt out. Any structure imparted on the material at this stage is subject to topographic reversal and flowage - no downwasting, debris-covered glacier surface has ever been reported to contain VRFs. Even if they did form they would not survive with such morphological clarity due to the continued melt-out of underlying ice. Moreover, once the material is thicker than the active layer it is subject to permafrost and periglacial processes for at least 8 ka. Reports on the surficial geology and landforms of deglaciaded terrain in the Canadian Arctic show that VRFs are inextricably linked to low centred ice wedge polygons, pingos and linear pingo complexes and lithalsa-type landforms developed in lowlands containing diamictic and poorly-sorted sand and gravel deposits laid down during and after deglaciation. They are therefore genetically related to those landforms. No evidence has been presented in this paper to justify any other interpretation. Nor has a specific glacial process been proposed in any detail other than differential ablation, which would form chaotic hummocky moraine or linear controlled moraine at best, not winding ridges.

Line 25: what does leading mean? And this sentence starts in the singular and finishes in the plural.

Thank you for bringing this to our attention. The sentence has been reworded with the correct pluralization.

Now Line 25

Line 27: another sentence with mixed singular and plural

Thank you for bringing this to our attention. The sentence has been reworded with the correct pluralization.

Now Line 27

Line 37: deglaciation and hence it is a predominantly paraglacial landscape that has experienced....

Agreed. Changed the wording to better express this.

Now Line 38

Line 43: 2003

Thank you for finding this error. Updated throughout.

Line 45: This is a very outdated citation - there is a large modern literature on this subject.

Thank you for your suggestion. Additional more recent references have been included.

Now Line 44

Line 47: Ditto - although older literature is valuable, it is inappropriate to be citing only papers that are more than 40 years old on this set of concepts.

Thank you for your suggestion. Additional more recent references have been included.

Now Lines 46-47

Line 51: is still

Updated.

Line 51: This paper is on features that have always been pingos/lithalsas and Ross et al. incorrectly re-interpret them. Why no other citations about the Welsh landforms here (i.e. all those that regard them as permafrost features)?

Thank you for your careful eye on references. We are only including one reference per argument to provide an example of landforms being debated on their glacial or periglacial origins.

Line 54: despite? Surely it's because?

We removed this word and section of the sentence to avoid confusion. Thank you.

Now Line 54

Line 147: are located - not reside

Thank you. Changed.

Now Line 147

Line 151: we don't need to know what you were doing at the time!

Agreed. Removed.

Now Line 151

Line 274: They are not unusual. They occur in all permafrost landscapes where poorly sorted materials, predominantly created during deglaciation and often overlying ground ice of various origins, have been reworked into lithalsa-type forms and elongate ice wedge guided ridges and depressions. They often occur in association with, and grade in and out of, raised rim ice-wedge polygons and circles on valley floors and coastal lowlands - the plan forms and sizes vary according to local grain size properties and surface water characteristics.

Thank you for your input. Since there are many analogous landforms to our, we removed the word “unusual.” However, to our knowledge, these features, nor any just like it, have been documented in the literature to date.

Now Line 273

Line 301: lens

Corrected

Line 303: It's not actually till - it's outwash that has been cryoturbated.

Thank you. We have removed the word “till” and avoided giving the sediments an interpretation.

Now Line 307

Line 308: I see no reason why these are anything other than lithalsa-type and ice wedge related ridges and depressions. Statements about water supply and continuous permafrost are not justifiable, because these features have been described from a range of settings in the Canadian Arctic. Huge volumes of water were supplied to these environments during deglaciation and the area contains large amounts of water during spring melt and during early deglaciation from the melt of buried glacier ice.

Thank you for your input. Based on our review of the literature and from observations many of us have made in the field, Axel Heiberg Island shows very little evidence of any warm-based glaciation, indicative of a polythermal to cold based glacial environment. While you are correct that large volumes of water would need to be present to form lithalsas, we remain unconvinced that such volumes were present. This conclusion is based on both the literature and the lack of geomorphological evidence for a wet deglaciating environment. Furthermore, continuous permafrost does pose a problem without talik development which we now discuss.

We have expanded our discussion on the landscape evolution and the conditions necessary for the formation of these features, whether glacial or periglacial lithalsas, in the Discussion section, including a new subsection (5.3). We have also revised our language to more inclusively consider a lithalsa origin as a strong possibility without ruling it out. We are confident that we have thoroughly defended both glacial and periglacial origins and have presented our preferred interpretation in depth.

Line 319: Not sure what polythermal glaciers have got to do with the argument here? The glaciers were long gone after ridge formation.

Thank you for your question. Please refer to the response above.

Line 326: Yes, indeed.

Line 332: No they can't. Can you provide a modern analogue for this? These features form in the accumulating debris over the melting dead ice - they are certainly forming in supraglacial debris but, in contrast to non-permafrost environments, they are not hummocky moraine created by topographic inversion - instead they are permafrost and periglacial features created in the accumulating meltout debris.

Thank you for your input. We discuss a variety of morphologically similar glacial features formed by different glacial processes in subsection 5.2 in more detail since the revision.

Line 337: Which mostly don't look like the features you are describing.

We appreciate your input and compare these features in Table 1.

Line 342: ; or 2)

Corrected for all instances

Line 342: Lundqvist? Why no citation of those who have worked on the prairie forms here?

Thank you for your suggestion. We provided many additional examples in the literature.

Now Lines 359-378

Line 343: Most of these are not relevant here because they bear no resemblance to your VRFs. You have missed a lot of literature that has interpreted prairie forms as postglacial artesian features as well as the work of Parizek and Bik, who provide glacial and periglacial interpretations.

Thank you for your suggestion. We provided many additional examples in the literature.

Now Lines 359-378

Line 344: You have put Pulju moraines in both categories?

Thank you for pointing this out. We now have Pulju moraines only in the subglacial category

Line 345: Rogen are not relevant here - they are subglacial and are not rimmed ridges

Thank you for identifying this. We have removed Rogen moraines from the manuscript.

Line 347: 2003

Corrected

Line 351: "comprises" or "composed of" - the two can't be mixed.

We have changed this to "composed of" throughout

Line 354: Celtic?

Corrected to the British-Irish Ice Sheet

Now Line 384

Line 407: This justification of a glacial origin is weakly developed. You have demonstrated in the paragraphs above simply that your landforms have developed in glacial materials, some of which overlies dead ice. As debris is released at the surface of the dead ice it forms a blanket that becomes susceptible to periglacial and permafrost processes and is continuously fed by nival melt and buried ice melt, the latter ceasing once the debris cover exceeds the active layer thickness. Once the debris thickness exceeds the active layer thickness, it is in the periglacial/permafrost process-form regime and then ice wedge, pingo and lithalsa development takes over. The alternative, which you are inferring, is that the VRFs are inherited from underlying glacier structure and supraglacial processes and that no periglacial and permafrost processes have been active on that debris cover since deglaciation - this is just untenable. The GSC memoirs and bulletins on Canadian Arctic surficial geology clearly identify the impact of periglacial and permafrost processes in creating patterned ground on supraglacial debris covers (i.e. buried glacier ice). Such literature should be used to question earlier publications on those ring ridge landforms (purported to be moraines) that resemble lithalsas and related features - indeed, such a critique should be assembled here.

Thank you for your concerns and suggestions. While we acknowledge the potential for nival and buried ice melt as water sources (Lines 297-299 and 528), we have not explored this in depth. It is challenging to consider these as significant water sources capable of forming injection ice alone in a continuous permafrost cold desert climate, similar to the difficulties encountered in explaining pingos in Greenland. However, if you have additional papers you would like us to explore we are open to your suggestions.

Line 422: This paper, I have to point out again, formulates a similarly flawed argument.

We appreciate your concern. In the revised text, we have relied less heavily on this paper.

Line 423: This paragraph finally hints at an important issue but then sits of the fence by using the term equifinality. There is enough literature to formulate a critique of VRF types and their genesis, and indeed you have cited some, but your preceding arguments have been largely pre-determined in favour of a glacial origin.

Thank you for your concern. We have elaborated on both arguments throughout the discussion and have included a new figure (Fig. 9) and subsection (5.3) to describe our two proposed mechanisms in more detail.

Line 426: This has not been justified in any detail. Why would the supraglacial and englacial debris be arranged in vermicular ridges? There is no modern analogue for this. The ridges have been created in the debris after it was deposited - otherwise why would the host material be arranged in terraces?

Thank you for your concern. We have elaborated on both arguments throughout the discussion and have included a new figure (Fig. 9) and subsection (5.3) to describe our two proposed mechanisms in more detail.

Line 613: 2003 Book author/editor?

Reference updated.

Referee #2

This paper provides a contribution to the discussion about periglacial vs glacial origin of vermicular ridge features in the Canadian high Arctic.

The authors make a huge and solid effort in field work and data collection, on the ground and remotely. They also give a good description of a complicated set of landforms.

I think this paper has potential, but I suggest a major revision, with an in-depth discussion of the possible formation mechanisms. Especially, the authors should provide a schematic step-by-step drawing/description of their chosen formation suggestion (or two contradictory ones). That is, about the possible origins of buried ice, that seems to be the key in figuring out formation mechanisms. About formation timing of the terrasses where these features are located, thus the transport of the glaci-fluvial material you describe, and how this relates, in time and space, to the possible buried ice.

Thank you for your suggestion. We have added a new subsection (5.3) and a supporting figure outlining the possible formation mechanisms we propose. Additionally, we elaborate on the periglacial and glacial literature in subsections 5.1 and 5.2. We are confident that these additions provide helpful details for the reader and contribute meaningfully to the field.

Line 34: can you really say that many of these were associated with massive ice? What does massive mean? Only ice would be sufficient?

Massive ice refers to large masses of ground ice, encompassing both glacially and periglacially derived ice without specifying which. As we discuss massive ice features throughout the text, we have chosen to retain this terminology.

First section, any references to the ongoing debate about the Canadian high Arctic?

Thank you for your suggestion. To our knowledge, topographic inversion features have not been heavily debated in the Canadian High Arctic. However, massive ice origins have. We provided a reference to this struggle in Line 35.

Line 89 of our field study

Changed.

Now Line 89

In Line 330 you give a crucial part of your argumentation: “Axel Heiberg Island lies within a recently deglaciated landscape where large amounts of dead glacial ice are likely preserved in the continuous permafrost zone under the protection of surface debris cover”. Could you please elaborate on this argument and give references? You describe some of the glacial history in chapter 2, Geologic and Geomorphic Setting, but nothing that tells the likeliness of large amounts of dead glacial ice. In chapter 6, Summary and Conclusions, first section, you suggest the presence of buried ice, but that the origin of the ice is unknown.

Thank you for your suggestion. We included references for this sentence in particular and touch on the glacial history of the area in the Discussion, particularly in the new subsection (5.3).

Now Line 353

An interesting point is that you did not observe grain sorting where you were digging. Would you say this applies to the entire area?

We suspect that there should be some degree of sorting in the deposit, given its location within the outwash plain and its likely glaciofluvial origin. However, we cannot confirm this based on our single observation.

5.2 Glacial Origins, Line 393 and onwards: please read the references you give, and which formation hypothesis is given in which reference, and sort them correctly in 1) leftover from stagnant ice, and 2) subglacial diapirism (or if needed, add a third formation class).

Thank you for your suggestion. We carefully reviewed all references and included additional references for each category. We also included additional categories.

Now Lines 359-378