

## ***Interactive comment on “Permafrost soils and carbon cycling” by C. L. Ping et al.***

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Interactive comment on “Permafrost soils and carbon cycling” by C. L. Ping et al. This review paper summarises concisely and (in general) clearly an eclectic literature on soils and carbon cycling in permafrost regions. This literature includes contributions from soil science, geocryology, biogeochemistry, periglacial geomorphology, Earth System modelling, Quaternary science, ecology and geology. Such breadth of coverage is a welcome contribution to help integrate our understanding of permafrost soils and carbon cycling, and the authors should be congratulated on bringing this together very nicely. I recommend that the review is published and suggest below some relatively small improvements that would help readers to place the work in the context of research questions, to understand more about the process(es) of cryoturbation, and to appreciate more clearly what the soil profiles look like. My only substantial criticism of

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the review is that it is structurally imbalanced: the narrative provides substantially more information than the figures, and I think with an appropriate call for photos amongst the five co-authors that it could make a visually important contribution to the literature, and balance the strong narrative impact.

We thank the reviewer for the constructive and very helpful comments and suggestions.

We will add pictures in the revised manuscript to show the profiles of each of the three suborders in the high and low arctic and the boreal regions to back up the narrative.

General comments 1. Research questions: I think the Introduction constitutes a later section and should instead stand back and summarise the main research questions that are driving recent research on permafrost soils and carbon cycling. These questions should lead readers into the subsequent sections of the review. We have provided an alternative Introduction that summarised the main research questions that are driving recent research on permafrost soils and carbon cycling. We also move the original Introduction section to Section 2. Permafrost Characteristics and Transformations. In light of this, we also moved the part of soil classification to Section 3. Cryoturbation: 3.4 Classification of Permafrost Soils. In the process we re-examined the structure of the manuscript and decided to combine all the carbon sections under a single Level 1 heading on Soil Carbon as Section 4.

2. Conclusions: after providing a fine review of the literature the paper again needs to step back and provide readers with some key conclusions and priorities for future research. At present, the review seems to me to start and end abruptly, and lacks a context that the co-authors, with their wealth of experience, are very well placed to provide. Basically, the narrative reads like an incomplete draft. We added the Conclusion section in the revised manuscript.

3. Cryoturbation: this process (which is fundamental to carbon cycling) could be explained more clearly in mechanistic terms that relate soil thermal and hydrological conditions to the resulting movement of mineral soil and organic matter in the soil pro-

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file. Generally the literature on cryoturbation (with a few exceptions like Mackay 1980, and Hallet & Prestrud) seems to me to be pretty vague and I think this paper could make a valuable contribution that explains cryoturbation simply and concisely in process terms. Bockheim (2007; *Soil Sci. Soc. Am. J.* 71:1335–1342) provides a useful starting point in his review of cryoturbation, although detail on process is scant. We revised the para on cryoturbation by adding the following: Cryoturbation is the term used to describe the lateral and vertical displacement of soil during seasonal and/or diurnal freezing and thawing (French, 1988). The genesis of cryoturbation has been attributed to loading, cryohydrostatic pressure and cryostatic pressure, and diapirism (Washburn, 1973; Rieger, 1983; French, 1988; Vandenberghe, 1988; Swanson et al., 1999). However, Mackay (1980) diffused the commonly accepted cryostatic pressure theory by using the cell circulation model to demonstrate the mechanism of cryoturbation through both equilibrium model and field experiment in hummock formation. He explained the upward displacement of material in the hummock by freeze-thaw of ice lenses at the top and bottom of the active layer with a gravity-induced cell-like movement, because the top and bottom freeze-thaw zones have opposite curvatures as described by Shilts (1978). Hummock is nonsorted circles which have uniform soil texture inside and outside the hummock (Washburn, 1973). Cryoturbation also manifests in sorted circles. Hallet and Prestrud (1986) used the circulation model to describe the mechanism involved in sorted circle formation. In their model, instabilities developed as the stone-soil surface grow upward. Then as soil plugs developed into sorted circles as they contact the ground surface, simultaneously elevating an encircling annulus of stone or gravel. Such surface gradients generated by the subsurface redistribution of stones by freezing and thawing can also cause downslope soil creep.

4. Soil profiles: a series of annotated colour photographs showing the main types of permafrost soil profiles (turbels, histels etc) developed on different substrates (clay, silt, sand) and associated with different permafrost types (epi- and syngenetic) and biomes (polar desert, tundra, boreal etc.) would be invaluable for readers. Remember that the paper is substantially aimed at the carbon community, and in my experience

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many 'carbonites' coming to work in permafrost settings are NOT very familiar with permafrost soils and find the soil nomenclature confusing.

As the reviewer pointed out that there is an imbalance between the narrative and the photos, we added 4 photos representing permafrost soils formed in epigenetic and syngenetic permafrost, permafrost-affected organic soils and sample of cryoturbated organic matter imbedded in a mineral matrix with cryostructure.

Specific comments Note for the journal production: the absence of cumulative line numbers on the paper wastes reviewer time counting lines, and author time checking. The journal really ought to fix this problem. 1. Page 710, section 1, paragraph 1, line 5: I think you mean that the permafrost region occupies 24% of the exposed land surface; the actual area of permafrost is considerably less (see Zhang et al. 2000, 2008). We revised the sentence as "Permafrost underlies approximately 22.79x106 km<sup>2</sup>, nearly 24% of the landmass of northern hemisphere or ~15% of the Earth landmass (Zhang et al., 2008)." 2. Page 710, section 1, paragraph 1, penultimate line: by ice free do you mean free of glacier ice or all forms of ice? We changed "ice-free" to "non-ice covered". 3. P. 711, last para, line 3: define IUSS We defined as suggested "International Union of Soil Scientists". 4. P. 712, last para, line 4: 'notable' in terms of carbon. But there is lots of relict epigenetic permafrost too. We revised this statement to include both syngenetic and epigenetic permafrost. There is more relict epigenetic than syngenetic permafrost. Even relict syngenetic permafrost is over relict epigenetic and their combination is called polygenetic.

5. P. 713, first para, line 9: I think you mean permafrost in non-glaciated regions. Permafrost probably degraded widely under thick glacial ice of the Laurentide Ice Sheet and other ice sheets. Yes, we amended the statement by pointing out permafrost in the non-glaciated regions.

6. P. 714, final para, third line up from bottom: 3 to 4 months is right at the maximum of the zero curtain; it more commonly lasts in the order of weeks. Better to cite research

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papers by e.g. Outcalt et al 1990 than Davis 1991. We revised the discussion on zero curtain “The zero curtain in the active layer lasts from the beginning of its freezing to its ultimate freezing. In Arctic, for example at Barrow, Alaska, the zero curtain lasts during several weeks (Outcalt et al., 1990). In the discontinuous permafrost zone, for example in Fairbanks, the zero curtain occurs during several months and in especially warm or winters with a thick snow cover, a part of the active layer remains still unfrozen in the end of a winter (Jorgenson et al., 2000) and consequently the zero curtain effect occurs through the entire winter.”

7. P. 715, para 2, line 7: cryostatic pressures refers to ice pressure, whereas I think you're suggesting (through usage of 'saturated zone' either an artesian pressure (in last to freeze parts of the active layer near the base of hillslopes, with water flowing downslope through the active layer) or hydrostatic pressure (during 2-sided freezing of saturated non-frost susceptible material like sand or gravel on flattish ground)). The cryostatic pressure hypothesis of involution formation (at least in frost-susceptible sediment on hummocky flattish ground) was debunked in 1976 and 1980 by Mackay, who failed to measure high porewater pressure during 2-sided freezing within earth hummocks. 2-sided freezing sucks water away from the last to freeze part of the active layer (some upward, some downward), consolidating it and increasing the shear strength of the central active layer, making cryoturbation of this part less likely at this time of year. We thank the reviewer for pointing out that we mixed cryostatic pressure with hydropressure. We revise the para as “Frost heave is a volume change from ice segregation and ice lens formation. It often results in the deformation of the ground surface. With horizontal expansion limited, there is often enough stress to produce crooked or tilted lenticular and reticulate structures (French and Shur, 2010). Differential frost heave eventually deforms originally flat horizons into warped or wavy horizons. When freezing occurs in saturated coarse grained soil, the cryostatic pressure pushes water out of soil, thus producing in features such as icing and frost blister (Tsytoich, 1975). Soil deformation occurs during the active layer freezing. When fine grained soil of the active layer freezes on two freezing fronts as a closed system, water moves to

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two freezing fronts and the upper and the lower parts of the active layer become saturated with ice and vertical cracks are formed in the desiccated part of the active layer. Whereas in an open system when the active layer freezes near the base of hillslopes the artesian pressure forces the water out and freeze, thus crack and broken the surface soil horizons (Zhestkova, 1982). When ice-rich layers below the active layer thaw, the release and movement of water leads to a type of micro-scale diapirism where water and saturated materials are forced through brittle layers or cracks while heavier mineral and organic rich soils fill the ensuing voids (Swanson et al., 1999).

8. Page 715, penult para, line 5: 'create' (in singular) as contraction and expansion are plural. Corrected as suggested. 9. Page 716, penult para, lines 3-4: Please clarify: frost jacking ejects elongate stones towards ground surface, with the long (a) axes vertical to subvertical (perpendicular to freezing front). That's why in Pleistocene periglacial sedimentary sequences, elongate stones are commonly oriented vertically to subvertically. We corrected by switching places for “parallel” and “perpendicular”. 10. Page 716, last para, line 1: delete comma after 'formation' Deleted as suggested. 11. 3 lines later: my understanding is that 'organic' is an adjective, not a noun, although it is commonly used incorrectly as a noun Corrected as suggested “organics” to “organic matter”. 12. P. 717, line 5: replace 'water' with 'volume' Changed as suggested. 13. P. 718, line 3: add 'and melting' after 'the formation' Added as suggested. 14. P. 718, para 2, last few lines: are Mn nodules common in permafrost soils? Where in soils does the ferrihydrite tend to form? We did not mention Mn nodules because the arctic environment disfavor the formation of this compound. We also added the statement of the condition in which ferrihydrite form and changed the reference: In the presence of high concentration of organic matter, the reduced iron (Fe<sup>2+</sup>) is rapidly oxidized upon in contact with air and forms a poorly ordered Fe<sup>3+</sup> oxide called ferrihydrite (Schwertmann and Taylor, 1989). 15. P. 719: lines 1-3: usage of 'different' three times in a sentence is excessive Yes, indeed. We changed the first “different” to “various”. 16. P. 719, para 2, line 1: please clarify usage of terminology: here 'transition layer' is used, whereas section 2.2 uses 'transient'. We changed to “transient”. 17. P. 720, last para,

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line 1: I think you mean 'the formation of ice' (at the start of the para), because ice is not a process. Yes. But we revised this sentence as "Cryogenic processes that result in redistribution or mixing of soil horizons are generically termed cryoturbation." 18. P. 721, para 2, line 4: not sure I understand what you mean by 'thermal convection'. The process-based permafrost literature by Mackay, Peterson and others tends to refer to 'soil circulation' and 'differential frost heave' etc, but not 'thermal convection' as convecting heat has no direct impact on frost sorting and the water convection of Ray et al. is doubtful in all by coarse sand and gravel. We changed "thermal convection" to "differential frost heave". 19. P. 722, line 5: Didn't Mackay identify in the 1950s a buried organic layer formed by hummocks moving downslope? We added citation of Mackay (1980). 20. P.722, penult. Line: I'm not really clear from reading the narrative above exactly how cryoturbation redistributes SOC. Could you insert a sentence or two that explains this process mechanically in simple terms. We added the sentence "In the process, the surface organic matter is entrapped into the cracks along the edge of the pattern grounds due to differential frost heave.". 21. P.723, para 2, line 1: 'was' (a series is singular) Corrected. 22. P. 723, last line: what are these subzones? It is confusing having C (for carbon) and subzone C (for a soil layer?) in the same sentence; best use another way of describing the subzone. The subzone is an ecological subdivision of the arctic tundra developed by the circumpolar vegetation group. The subzone describes vegetation community in association with landscape processes and climate parameters. To avoid the confusion of C (carbon) and the C in subzone C, we keep the consistency of using SOC, OC but whenever it comes to "carbon" we avoid using "C", instead we spell out "carbon". 23. P. 724: line 1: please explain this increased insulation effect in process terms. This whole paragraph is not easy to follow because it is not clear (to me at least) what all 5 the different subzones are. It would clarify things if the vegetation and land surface characteristics were specified, so changes from subzone C to D were explicit for the reader. We revised the last sentence to clarify the relationship between organic matter insulation and cryoturbation: "Such drop is caused by decreased cryoturbation, thus decreased frost heave due to increased insulation of the

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surface organic horizon which increased its thickness from the sedge to shrub tundra (Kade and Walker, 2008)." 24. P.724, para 2, 6 up from bottom: please explain why cryoturbation occurs beneath ridges but not beneath centers. We revised the sentence to explain why: "(3), soils lacking cryoturbation in the flat centers of newly formed polygons (Aquorthels, Historthels). However, with time, the flat centers experience cracking and increased cryoturbation. Turbels such as Histoturbels or Aquiturbels will form." 25. P.724, para 2, 3 up from bottom: please explain why 'greater cryoturbation leads to formation of soils....' We revised the sentence as: Also with time, the ice wedges can degrade, forming deep troughs (Jorgenson et al., 2006), then the polygon interiors become high centered, where thick organic layers accumulate due to slightly improved drainage and form either Histels or Histoturbels (Ping et al., 2008a; 2011; Zubrzycki et al., 2013) (Fig. 3)." 26. P.725, penultimate line: prefix 'ice' with 'volumetric' Changed as suggested.

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