

We appreciate the Reviewer's comments below and we have responded to the points in **bold text**.

Reviewer 1:

General Comments:

This paper employs GIS to define the terrain susceptible to active layer detachment slides and mud ejection features at a High Arctic site. The paper provides a suitable GIS tool to locate these features at Cape Bounty, an approach which may be applicable for similar terrain elsewhere. The paper is quite technical, with lots of jargon so I thought that it might be better suited for a GIS specific journal or PPP-Permafrost and Periglacial Processes where readers might be more knowledgeable about pore water pressure phenomena. If it is to be published in Cryosphere, more effort could be made to relate the research to other cryospheric types/regions where pore water pressure occurs to elucidate processes across diverse icy bodies. Clarification about distance to water, potential incoming solar radiation in the model is required. It was not clear from the paper whether one is concerned with upslope water or downslope water, or water sources in both directions. Also, what defines water (puddle, stream, lake or pond)? It was also not clear the time frame that PISR was calculated for (1 month, 2 months, 2 weeks)?

Response: Thank you for your comments. However, we disagree about the appropriateness of the journal. My coauthors and I feel that our paper is highly relevant to The Cryosphere as it presents new research on features that are unique to permafrost landscapes. Mud ejections in particular represent a significant gap in the literature. We have made an effort to relate the observations of the features we see at our site to other areas, in particular discussing how pore-water pressure (PWP) results in instability in other regions. We also clarified the model variables (distance to water, PISR, etc.) and believe that after incorporating the comments from the reviewers it will be suitable for publication in TC.

The study's introduction indicated that rainfall was an important factor in triggering pore water pressure but there was little information about this variable in the study. I think that more effort could also be made to get information about ground ice conditions at the site. I believe that there is a GSC report for this area, from the mid-70's which might report some of this information. Another look at field photos, or data from other studies in this location might provide clearer indication of ice content.

Response: The introduction has been reworded. Factors impacting PWP are either intrinsic (ex. slope, drainage, solar radiation) or extrinsic (temperature, rainfall) and although extrinsic factors are important, this model only identifies intrinsic factors.

Similarly, all areas across the landscape experience relatively homogeneous rainfall, and it is only certain locations which have high PWP, ALDs and MEs due to specific properties of the landscape at these locations. Therefore, we are using this model to identify these landscape variables. This section of the discussion has been removed, and the text has been reworded to clarify this.

The ground ice maps you mention don't have sufficient ground ice data for our area or detail. Permafrost cores have been taken at the site near and ALD, and the data shows ice enrichment from 60-80 cm bgs (Lamhonwah et al., 2017). Observations in the headwalls of ALDs show ~0.5m of massive ice starting at ~80cm. Additional information has been added to the text.

Specific Comments:

1) In the abstract you indicate distance to water but is that distance to water upslope of the feature or downslope or both? It is also not clear in the rest of the text.

Response: We are referring to distance to downslope water sources. Distance to water was calculated using the Euclidean Distance Tool in ArcGIS and distances were measured from a ALD or ME to a hydrological vector layer. Text has been clarified throughout the manuscript to ensure that the difference between distance to water and TWI is clear.

2) In your abstract perhaps indicate that the GAM model is a GIS-type model.

Response: The GAM model is not a GIS-type model, it is a statistical model. We used the terrain variables (which were derived using GIS) as inputs into the statistical model.

3) Be more specific in your abstract about PISR, instead of "relatively low PISR", perhaps put a value in. Is PISR calculated for the whole summer, a few weeks? It is also not clear in your paper. Did you measure solar radiation directly at your study site? If so, how do these values compare with PISR.

Response: A value has been added for PISR in the text.

4) In your abstract, perhaps put...Based on these results, this GIS method identifies....

Response: This has been changed.

5) At the beginning of the abstract, you indicate that late season precipitation is important for these features to develop but you don't use precipitation as an explanatory variable. In fact, I don't see any information about precipitation or late-season precipitation in the paper.

Response: The introduction has been reworded. Rainfall is a trigger for high PWP but does not explain sensitivity of the landscape to PWP, so less emphasis was put on rainfall in the introduction.

6) Again in your abstract, can you be more definite about distance...avoid saying....areas relatively far from water. Again is that upslope or downslope.

Response: This has been reworded.

7) Page 2, Line 20-21. Perhaps cut down on the number of references to GAM.

Response: Some of the older references have been removed.

8) Lines 27-28. Can you cut down on the references?

Response: Two of the references which weren't necessary have been removed.

10) Page 3 Line 10. Put <10 m. There are some other places where you need to leave spaces...see line 14, 27, etc.

Response: This has been fixed throughout the manuscript.

11) Line 13. Since you are concerned with the spring/summer period for slope failure, besides the mean annual temperature add information about the spring/summer temperature and also add information about these infrequent, high magnitude precipitation events.

Response: Mean July temperature has been added to the text, summer precipitation totals, and information regarding the major rainfall events.

12) Line 25. Provide information on the summer temperature in 2007 and heavy rainfall.

Response: Mean July temperatures have been added for 2007 and information about the major rainfall events.

13) Line 27. Again put the temperatures in for 2011 and 2012, and maybe indicate how these temperatures compare with other areas in the High Arctic, and what other scientists were observing (glacial ice loss, sea ice). This will help put your work in context of other cryospheric phenomena.

Response: Mean July temperature has been added for 2011 and 2012. Above average temperatures were recorded in 2007 and 2012 in other areas of the arctic, and reference has been made to the SWIPA report to put this in context.

14) Page 4, Line 24. Why did you select >10 m for distance to a water source and again was that upslope or downslope. Also, why did you select a distance to an ALD of > 20 m? Can you plot those randomly ArcGIS points in your map?

Response: On average the width of channels are Cape Bounty are substantially less than 10 m. To ensure that randomized points were not placed in a stream a rule of >10 m was selected. This refers to the downslope distance to a water source. Again, to ensure that randomized points were not placed within the boundary of existing ALDs a minimum distance of 20 m was selected. Points were generated using the “Random Point” tool in ArcGIS with the additional criteria (>10 m from a water source and >20 m from an initiation point) limiting to a minimal extent where they could be placed. The location of the random points has been added to Figure 4.

15) Page 5, Line 8. Can you plot the randomly generated control points for MEs (78).

Response: The location of the random points has been added to Figure 4.

16) Line 15. Do you have a reference to add to after....they all have the potential to contribute to areas having high PWPs?

Response: The relation of each variable to drainage, soil moisture, and thus PWP were explained individually throughout that section and references were included for each variable.

17) Line 20. Again, is it distance upslope or downslope? Be specific, in terms of water, is it water table or a creek or a stream or a lake, pond. How do you define water? Many hillslope creeks in the High Arctic dry up after snowmelt, or are intermittent. Do you still estimate distance to them?

Response: We are referring to distance to downslope water sources. Distance to water was calculated using the Euclidean Distance Tool in ArcGIS and distances were measured from an ALD or ME to a hydrological vector layer which included lakes and rivers (can be seen on Figure 4 and 5). Text has been clarified. These rivers are the larger streams and rivers in the area and remain active throughout the hydrological season.

18) Line 23. Are you able to compare PISR with measured incoming radiation at a level site to see how they compare over a summer season? If you had a cloudy, rainy season then radiation across the slopes/plateau might not have been critical.

Response: The mean value for PISR at our site is 1267 MJ/m², indicating that ALDs have higher probability of occurring where PISR is lower than the site average. More information has been added to put this in context in Section 5.1.

19) Lines 7-8. Can you say more about the TWI index? How does this compare to the new paradigm of 'spill and fill', which is perhaps a better theory of how water moves in arctic environments (Woo, 2012).

Response: In this study a FD8 flow algorithm was applied to allow water to flow into multiple neighbouring cells based on the concave or convex nature of the landscape. TWI is an indicator of the likelihood of saturated soil conditions during rain events, and represents hydrologic parameters influenced by slope morphology. TWI provides us with information on where soil moisture is likely to be higher as a result of the accumulation of surface water. This is important as an increase in subsurface water content can lead to increased porewater pressure which is a triggering factor for ALDs and MEs. More detail has been added to the manuscript. Woo (2012) discusses the fill-and-spill concept, and logically this is happening in our area to some extent, however, these subtleties of storage heterogeneity in hillslopes and catchments are difficult to account for using spatially derived data and the landscape scale. However, the TWI index does consider convexity and concavity, and in this manner partitions the slope into various segments.

20) Lines 10-11. Are you sure that you don't have any information about ground ice content. There must be some geology maps of this area which give an indication of ice content. During your fieldwork, did you not dig a hole in these different landscapes to examine where the ice and moisture were accumulating? Perhaps, look at some of your pictures, particularly, active layer detachment slides. The headwall scarps might give you an indication of where the ice rich depths occur.

Response: The ground ice maps available for the field area are highly generalized. Permafrost cores have been taken at the site, but the data is unpublished. Observations in the headwalls of ALDs provide further information about ground ice which has been added to the text.

21) Line 13. Do you really need ρ in front of Sp? Do you have a reference for VIFs?

Response: The ρ in front of Sp is necessary as this is the notation for this coefficient. The reference Neter et al., 1996 has been added for VIFs.

22) Page 8. Line 14. Do you have a reference for a confusion matrix?

Response: There is no reference needed for the confusion matrix as it is a standard methodology (a more complex contingency table).

23) Lines 20-23. Is this a standard framework for susceptibility/sensitivity? Should you add a reference here?

Response: It is the dominant method for susceptibility modelling used in the literature. References have been added.

22) Line 3. In terms of PISR, how does 1100 MJ/m² compare with what is generally measured during a summer season, and what is the time frame for the PISR estimate (i.e. is this over 30, 60 or 90 days). Do you start your calculations in late August, since you said these features often occur then?

Response: Total PISR is only calculated for the snow free period which is July 15 – September 15, and this information has been added to the text. The mean value for PISR at our site is 1267 MJ/m², indicating that ALDs have higher probability of occurring where PISR is lower than the site average. More information has been added to put this in context in Section 5.1.

23) Line 6. Again are you referring to upslope distance or downslope distance? I would think that upslope distance to water would be more important than downslope.

Response: Distance to water refers to the downslope distance to a water source and TWI incorporates the upslope contributing area. Downslope distance to water is an indication of drainage and wetness of the landscape, and water sources have the potential to erode banks and cause ALD initiation. This has been added to the text.

24) Line 16. Indicate the amount of rain which fell late July, also indicate the depth of ground thaw.

Response: General information about the frequency and magnitude of rainfall has been added throughout the text.

25) Line 26. What kind of soil structure did you have which allowed these slurries to occur?

Response: The soils are composed of mineral fines formed in glacial and marine sediments. We observed desiccation cracking at the site and MEs coming out of cracks in the ground. More information on this has been added.

Reviewer 2:

The paper uses a general additive model and terrain characteristics derived from remote sensing to map susceptibility of permafrost disturbances (active layer detachment and mud ejection). The GIS-based analysis was successful at identifying important terrain controls at the study site, and the approach seems to have potential for application at other sites. The results are interesting and well executed and the topic is of interest to readers of *The Cryosphere*, but I'm not convinced *The Cryosphere* is the most appropriate journal. The paper is quite technical and might be appropriate for a remote sensing journal or for *Permafrost and Periglacial Processes*, which has a geomorphology focus. An indicator here is that not a single *Cryosphere* paper was cited. This paper could be made more relevant to *The Cryosphere* by expanding the discussion to explore consequences for other sites, and by discussing in more depth the physical reasons for the observed explanatory power of the various terrain characteristics.

Response: We thank the reviewer for their comments, but disagree about the appropriateness of the journal. My coauthors and I feel that our paper is highly relevant to *The Cryosphere* as it presents new research on features that are unique to permafrost landscapes. Mud ejections in particular represent a significant gap in the literature. We have added information to expand the discussion and think that after incorporating the comments from the reviewers it will be suitable for publication in TC. We have made an effort to relate the observations of the features we see at our site to other areas, in particular discussing how PWP results in instability in other regions. We have added more discussion about the terrain variables to Section 5.1 (see specific comments below).

Specific comments

The title, abstract, and beginning of the paper focuses on pore water pressure, but the effect of interest is disturbance. High pore-water pressure is not observable directly, and it's possible to have high pore-water pressure without an ALD or ME. The title and the introduction should be revised to better reflect the topic of the paper - susceptibility to disturbance, not pore-water pressure.

Response: Without high PWP there would be no ALDs or MEs, so we are using the presence of ALDs and MEs as the surface expression of PWP. It is widely accepted in the

literature that ALDs and MEs form from high PWP (Washburn, 1956; Shilts, 1978; Zoltai, 1978; French, 2007; Lewkowicz, 2007). We used the presence of ALDs and MEs to predict areas across the landscape that are susceptible to high PWP, and therefore potentially future formation of ALDs and MEs. In this way we feel that the title is appropriate. The introduction has been reworded for clarity.

Some of the observed relationships between the terrain variables make sense physically and some are counterintuitive. For example, why would ALD be more likely in areas of low PISR? Why would ME's be more likely in drier locations and higher elevations? Physical reasons for all the observed relationships and especially the counterintuitive ones should be explained to convince the reader that those relationships are real and not spurious correlations.

Response: Section 5.1 has been elaborated to explain observed relationships between the high susceptibility zones for ALDs and MEs and the terrain variables.

The probability of observing an ALD approaches 100% for low PISR. This is clearly site-specific and raises concerns about the transferability of the results. Please explain.

Response: Based on our field mapping, modelling and the subsequent terrain analysis we believe that this research identifies a link between PISR and slope disturbance that can't be ruled out without further examination. While this link may not be a direct relationship, PISR may act as a proxy for additional processes associated with ALD initiation. This is not a new observation as evidence of this relation has been noted at other locations and is cited in the manuscript (Leibman, 1995; Huscroft *et al.*, 2004; Lipovsky and Huscroft, 2007; Niu *et al.*, 2014). This relation has also been documented at other sites in the High Arctic through the development of susceptibility models (Rudy *et al.*, 2016a and 2016b). More text has been added to section 5.1 discussing the relation of ALDs to low PISR.

Rainfall is likely to be an important controlling variable. This needs to be discussed, since it is not addressed.

Response: More specific details have been added about the frequency and magnitude of rainfall events, but rainfall wasn't a variable we looked at in this study. Factors impacting PWP are either intrinsic (ex. slope, drainage, solar radiation) or extrinsic (temperature, rainfall) and although extrinsic factors are important, this model only identifies intrinsic factors. Similarly, all areas across the landscape experience relatively homogeneous rainfall, and it is only certain locations which have high PWP, ALDs and MEs due to specific qualities of the landscape at these locations. Therefore, we are using this model to identify these landscape variables. This section of the discussion has been removed, and the text has been reworded to clarify this.

Pg 4 Line 24: what's the basis for the constraints >10 m from water source and >20m from an ALD?

Response: On average the width of channels at Cape Bounty are less than 10 m, to ensure that randomized points were not placed in a stream a rule of >10 m was selected. Again, to ensure that randomized points were not placed within the boundary of existing ALDs a minimum distance of 20 m was selected. Points were generated using the “Random Point” tool in ArcGIS with the additional criteria (>10 m from a water source and >20 m from an initiation point). The text has been clarified.

Pg 5 Line 4-7: The description of the declustering process is difficult to follow and should be explained more clearly. As I understand it, because closely located features carry redundant information, spatial clusters of features are replaced by representative features.

Response: The reviewer is correct, dense clusters of MEs were removed to avoid redundancy and statistical bias. Declustering was achieved by creating a 10 m buffer zone around each mapped ME feature in ArcGIS, and areas where buffer zones intersected were treated as one large polygon to represent the region of the cluster. A single point representing a ME was randomly generated as a representative point for every 10 clustered points within the polygon (i.e., a cluster of 25 MEs would result in 3 points). This has been reworded in the text for clarification.

Pg 5. Line 4-7. The declustering algorithm seems arbitrary. Are the results sensitive to how that is done?

Response: Analysis was done both with and without declustering, and was more representative of the study area with the declustering as it reduced statistical bias to the landscapes where the clusters were found. Clusters of MEs were mapped as a polygon, and then one point for every 10 MEs within the polygon were randomly generated within the area as a representative point.

Pg 6. Line 21. How were the features partitioned between the calibration and validation subsets? Random?

Response: The total (combined disturbed and undisturbed points) datasets for each MEs and ALDs were randomly subdivided into 70 per cent calibration and 30 per cent validation subsets. The text has been clarified.

Pg 26. Line 1. What is an “explained deviance”?

Response: Relative importance of variables was evaluated by the change in explained deviance from the full model as variables were removed individually. If the variable is important for the model it will result in a higher explained deviance. For example, the slope variable had the greatest explained deviance from the full ALD model. It is the equivalent of R^2 in a linear-regression model. This has been clarified and some references have been added.

Final sentence: The phrase “incentive and potential to move towards: : :” makes for a weak conclusion. Is it not possible to say something more definitive?

Response: This has been reworded.

Anonymous Referee #3:

General comments:

In their paper, the authors evaluate the susceptibility of High-Arctic permafrost terrain to disturbances (ALD and ME) related to high pore water pressure. To do so, they used a GIS-based approach, statistics, and field validation, and made the demonstration that such an approach is exportable to other sites. The results indicate that terrain characteristics of ALDs and MEs differed in the modelled high susceptibility zones, whereas they were similar in low susceptibility zones. They have shown that slope was the main variable driving ALD initiation and distance to water was the most important variable explaining ME formation. Although this paper makes an interesting contribution to permafrost landscape hazards and permafrost landscape dynamics studies, I think it would be better suited for a GIS-dedicated journal or a hazards-dedicated journal. Indeed, my impression is that the cryospheric components in this article are not developed sufficiently to justify a publication in *Cryosphere*. If the editor decides differently, then the authors should develop a section on ground ice and particularly clarify the concept of ‘transient layer’ and how it applies at the landscape scale, how to model it and how to incorporate it in their GIS-based approach. A point should be made about the distribution of ground ice in a given watershed and along topo-sequences. Unfortunately, it is mentioned in the paper that ground ice was not specifically taken into account in the analysis due to a lack of data about this aspect. Some of the results of the modelling makes a lot of sense although other are very surprising. I think the authors should explain better the ‘correlations’ they obtained. In particular, I would like to see more explanations on the 1) PISR: the peak for ME and the fact that the probability decreases as PISR increase for ALD (is this a ground ice effect? Less PISR, ice closer to the surface?), 2) distance to water (probability decreases and then increases with distance to water for ME and ALD), 3) TWI for ME: probability increases and decreases with rise of TWI. Again, I would like to stress that I consider the quality of this paper to be good to

very good but that the authors would benefit in terms of dissemination and citations to publish it in a different journal with a better-targeted readership.

Response: We thank the anonymous referee for their constructive comments. We have added as much information about ground ice as is available at our study site currently. This includes permafrost cores which have recently been taken at the site near an ALD, and the data shows ice enrichment from 60-80 cm bgs (Lamhonwah et al., 2017). Secondly, observations in the headwalls of ALDs show ~0.5 m of massive ice starting at ~80 cm.

Section 5.1 has been elaborated to explain observed relationships between the high susceptibility zones for ALDs and MEs and the terrain variables.

Specific comments:

Abstract, L12 : The link between high pore water pressure and landscape degradation isn't clear. I understand it but it is implicit in the text. The authors should clarify this in the abstract and later in the text. Perhaps by stressing which geomorphological processes can be triggered by high pore water pressure, how high PWP are generated and how these geomorphological processes can have an impact on landscape evolution, landforms, or, to a different scale, active-layer/surface dynamics.

Response: This has been reworded. We have also re-written the introduction to be more clear about how PWP are generated and the impacts of ALDs and MEs on the landscape.

Abstract, L17-18: 'distance to water' repeated in the same sentence. Correct please.

Response: This has been corrected.

Abstract, L20: delete 'accurately'. Let the reader judge if this was indeed 'accurately modelled'.

Response: This has been deleted.

Abstract, L22-23: the authors use the term 'relatively' (. . . low PISR, . . . far from water). I propose to eliminate relatively and suggest to change to something like 'lowest PISR' or simply 'low PISR' and 'far from water' or 'farthest away from water'.

Response: More specific details have been added to this section.

Abstract, L23: ' . . . areas that may be sensitive to high PWP'. This sentence weakens the abstract. I think it is reasonable to say: ' . . . areas sensitive to high PWP' without 'that may be' .

Response: This has been changed.

Introduction, L30: delete 'seasonal'. The active layer is a seasonal phenomenon.

Response: This has been deleted.

Introduction, L31: 'water and ice enrichment at the base of the active layer'. I believe the authors should add 'and in the upper part of permafrost'.

Response: This has been added.

p. 2, L3: 'during the summer months'. This should be either deleted or 'beginning of winter' be added. Indeed, the bottom of the active layer often thaws as the top of the active layer is refreezing.

Response: It has been deleted.

p. 2, L4-5: 'During the fall freeze-back period this water undergoes refreezing, consequently developing an ice-rich transient layer at the base of the active layer (Hinkel et al., 2001; Kokelj and Burn, 2003, Shur et al., 2005).' The transient layer is not explained properly here. The authors have to explain that this water refreezes and remains in the 'permafrost portion' of the soil column during cold year (s) whereas during warm years the transient layer thaws partially, that is the active layer deepens (thawing of the active layer and upper portion of permafrost). The following two years (or more), depending if these years are colder or warmer than the previous ones, the active layer will continue to deepen or the lower portion of it will not thaw and then will be part of the upper permafrost. The authors should re-write the text around the concept of transient layer.

Response: We have reworded the text and better explained the idea of the transient layer.

p. 2, L7-8: 'This addition of moisture, as well as infiltration from late season precipitation, results in high pore-water pressures (PWP) at the base of the active layer'. This is the case for saturated (porosity filled with ice and, upon melt, with water) fine-grained soils essentially. Unsaturated sediment will not develop high pore water pressure upon thaw and coarse sediment will usually drain and won't develop high pore water pressure. Please specify. The reference cited could be improved, perhaps cite specific studies concerning pore water pressure in permafrost environment or classic geotechnical literature about PWP and mass movements.

Response: This is a general statement about how high PWP is generated in areas with ice-rich transient layers. Previous work in the study site indicates fine-grained soils throughout

the area. Similarly an ice-rich layer at the top of the permafrost has been observed at the site from cores (Lamhonwah et al., 2017). This information has been added to the study site section and expanded on throughout the text. The references have been updated to include more classic geotechnical literature about slope instability, and this section of the introduction has been rewritten for clarity.

p. 3, L20-22: 'The site is underlain by Devonian sandstone and siltstone bedrock comprising the Weatherall, 20 Hecla Bay, Beverley Inlet and Parry Islands (Burnett Point Member) formations (Harrison, 1995), but outcrops are uncommon'. I suggest to change for: 'The site is underlain by sandstone and siltstone bedrock but outcrops are uncommon (Harrison, 1995).'

Response: Thank you for the constructive suggestion and this has been changed.

p. 4, L24-25: the reason why distance to water (10 m) and distance to ALD (20 m) needs to be explained. 10 m from water appears close to me for the topic and scale of the study.

Response: On average the width of channels at Cape Bounty are less than 10 m, to ensure that randomized points were not placed in a stream a rule of >10 m was selected. Again, to ensure that randomized points were not placed within the boundary of existing ALDs a minimum distance of 20 m was selected. Points were generated using the "Random Point" tool in ArcGIS with the additional criteria (>10 m from a water source and >20 m from an initiation point). The text has been clarified.

p. 5, L4-5: the reason why large spatial clusters of ME were removed from the analysis needs to be explained. It could indeed be interesting to see these large clusters.

Response: Analysis was done with and without declustering, and was more representative of the study area with the declustering as it reduced statistical bias to the landscapes where the clusters were found. Declustering was achieved by creating a 10 m buffer zone around each mapped ME feature in ArcGIS 10.1, and areas where buffer zones intersected were treated as one large polygon to represent the region of the cluster. A single point representing a ME was randomly generated as a representative point for every 10 clustered points within the polygon (i.e., a cluster of 25 MEs would result in 3 points). This has been reworded in the text for clarification.

p. 6, L5-6: what is the scale of the surficial deposit map used? Could this map along with the marine limit elevation be used to infer, although very generally, the potential distribution of ground ice, given the general relation between grain-size distribution, frost-susceptibility and ground ice? The lack of data on ground ice is, in my view, one of the main weakness of that paper.

Response: We did not use a surficial deposit map for this analysis, and such a map does not exist for this site. We did use marine limit (elevation) as a proxy for ground ice, as generally there will be finer-grained sediment below marine limit and thus more ground ice. This is stated in section 3.3 of the methods. We've added more data on the ground ice conditions at the site.

p. 6, L10-11: 'While ground ice content is linked to high PWPs, it is not used as an input variable as ground ice maps were unavailable and impractical to attain'. The authors mentioned that ground ice is more abundant below the marine limit (p. 5, L17-19). Was there a factor/weight added to the cells below the marine limit as PWP is more likely to be generated in areas with high ground ice content? Please describe surficial sediment/(cryo) stratigraphy above and below the marine limit. Models indicated 50 and 80 m as key elevations. What's going on around these elevations that could help understand the output of the model better?

Response: The estimation of marine limit at the site is approximately 60-80 m, but it is a diffuse gradient that is not clearly defined, so we didn't put any weight on the cells below marine limit. We do not have data for ground ice conditions above and below marine limit, and the surficial sediments do not show a clear difference above and below marine limit.

Note that table 2 has been updated and 60m is a key elevation for MEs, attributed to drier, barren, plateau environments which have deeper annual thaw. Results indicate that 50 m is a key elevation for ALDs, which is below the marine limit of 60-80 m for the site indicating that ground ice likely plays a role here. More information has been added to section 5.1 on this matter.

p. 11, L20: 'Landscapes composed of fine-grained surficial sediments are susceptible to a wide range of permafrost degradation processes, including the development of high PWP in the active layer'. The development of high PWP is not a permafrost degradation process. High PWP and excess PWP lead to the development of mass movement and this could be included as a 'permafrost degradation process'. Please change.

Response: This has been reworded.

p. 11, L25-26: 'While soil PWP measurements are not available to confirm pressurization in these instances, the inferred mechanism is diapirisation of sediment slurries from the base of the active layer caused by pore-water pressurization due to ice thaw' Diapirism of sediment slurries can be from the base of the active layer or from lateral mass movement originating from upslope (there will be mass transfer, at least water, even with low angle slope). I also agree that is it probably more related to the base of the active layer, however the authors haven't shown data to

support it. Furthermore, the liquid limit threshold can be attained due to water release upon ice thaw but it can also be attained by the infiltration of rain in the active layer or from subsurface flow. This should be mentioned.

Response: Holloway et al. (2016) show evidence for MEs originating at the base of the active layer, and we have referenced this work. MEs mainly occur on flat terrain, so upslope contributions would be limited. There is very limited literature on MEs. We have removed discussion of liquid limits and have clarified the text.

p. 12, L11-13: 'Hence, while surficial materials are broadly similar across CBAWO, the landscape zonation of these two features appears to follow a slope continuum.' I agree and I think the authors should expand their explanation here. Please put this sentence in the context of High-Arctic polar desert watershed/toposequence so that readers could verify if these observations apply in other similar landscape settings. Clarify the link between toposequence, hydrology, moisture and the thermal regime of the active layer.

Response: Text has been added to describe the toposequence at our site. We've added information about the hydrology and active layer in the zones of high susceptibility in Section 5.1.

p. 12, L15-17: 'In 2007, the warmest year since regional records began in 1949, deep active layer development and late July rainfall triggered widespread ALD formation.' I would like to have more information about the effect of rainfall on ALD. There's not enough information about it in the paper, even though it could be an important factor. If rainfall data are available, they should be included in the results and discussed later in the paper.

Response: Response: More specific details have been added about the frequency and magnitude of rainfall events, but rainfall wasn't a variable we looked at in this study. Factors impacting PWP are either intrinsic (ex. slope, drainage, solar radiation) or extrinsic (temperature, rainfall) and although extrinsic factors are important, this model only identifies intrinsic factors. Similarly, all areas across the landscape experience relatively homogeneous rainfall, and it is only certain locations which have high PWP, ALDs and MEs due to specific qualities of the landscape at these locations. Therefore, we are using this model to identify these landscape variables. This section of the discussion has been removed, and the text has been reworded to clarify this.

p. 12, L20-22: 'Similar conditions were observed with MEs associated with terminated active layer fractures in 2012 further suggesting the presence of fluid slurries in situations approaching those that generate ALDs.' . . . These observations suggest that MEs, while clearly reflecting evidence for subsurface soil water pressurization also likely play a stabilization role through

pressure release to the surface.' 'By contrast, ALDs are associated with sufficient pressurization to induce slope fracturing and downslope movement.' Are the authors suggesting that ME reduced the PWP and reduced therefore the occurrence of ALD? Please make it clear. Is it possible that ME occurred at the location of ALD prior to the slide? I would like the authors to provide their interpretation/opinion about this point. This can form interesting working hypotheses for future studies.

Response: We go into further detail in the subsequent section 5.2 about MEs possibly releasing pressures and stabilizing slopes. The text here has been reworded for clarity.

p. 14, L23-25: 'The susceptibility models demonstrate that ALDs are most probable on hillslopes with gradual to steep slopes and relatively low PISR, whereas MEs are associated with higher elevation areas, low slope angles and in areas relatively far from water (drier)'. I suggest to add concave slope for ALD and convex slope for ME.

Response: This has been added.

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For all the text: add space between number and unit. Ex: 100 m.

Response: This has been corrected.

In the pdf version, at several places, space is missing between words, punctuation, units, etc.

Response: This has been corrected.

Figure 1: add scale (1a, d), add complete date (a, b, c, d).

Response: Scale has been added to Figure 1 a and d, and complete dates have been added to the figure caption.

Figure 6: add scale and complete date. Is the ALD visible in the background or are they more MEs? Please clarify in the figure caption or directly in the figure.

Response: Scale and complete date have been added. The picture is taken at the edge of the ALD looking out towards the adjacent terrain (the ALD is not visible). This has been clarified.

Table 2. It would be interesting to add some basic statistics to this table. The table provides mean values of terrain variables. Please add the range, the median and the standard deviation for these

variables. It would be very useful if one's want to compare this study with other studies conducted in similar/different environmental set-ups.

Response: Table 2 has been updated with standard deviation. We did not add all these statistics as these values are for our specific modelled susceptibility zones and therefore not directly comparable to other sites.

Determining the terrain characteristics related to the surface expression of subsurface water pressurization in permafrost landscapes using susceptibility modelling

Abstract. As the Arctic warms, deepening active layers and thaw of ice-rich permafrost can lead to various forms of degradation, including slope failures referred to as active layer detachments (ALDs) and expulsions of pressurized slurries called mud ejections (MEs). ALDs and MEs both form from high pore-water pressures (PWP) caused by rainfall events and rapid thawing of ice-lenses at the base of deep active layers. To predict areas that have the potential for high PWP, we use susceptibility maps generated using a generalized additive model (GAM). As model response variables, we used ALDs and MEs, both found at the Cape Bounty Arctic Watershed Observatory, Melville Island, Canada. As explanatory variables, we used the terrain characteristics elevation, slope, distance to water, topographic position index (TPI), potential incoming solar radiation (PISR), normalized difference vegetation index (NDVI; ME model only), and topographic wetness index (TWI). The susceptibility models demonstrate that ALDs are most probable on hill slopes with gradual to steep slopes and relatively low PISR ~~of 1100 MJ·m⁻²~~, whereas MEs are associated with higher elevation areas, lower slope angles and in areas ~~600m~~ from water. Based on these results, this method identifies areas sensitive to high PWP, and helps improve our understanding of geomorphic sensitivity to permafrost degradation.

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1 Introduction

Unusually warm conditions during recent years in the Arctic have led to changes in the thermal, hydrological, and geotechnical properties of the active layer and the uppermost permafrost (Kokelj, 2002; ACIA, 2005; IPCC, 2013). Deepening active layers and thaw of ice-rich permafrost can lead to various forms of degradation, including slope failures referred to as active layer detachments (ALDs), and expulsions of pressurized slurries referred to here as mud ejections (MEs, Holloway et al., 2016) (Figure 1). While these features are morphologically different, the processes causing their formation are similar: i.e., high PWP caused by rainfall events and rapid thawing of ice-lenses at the base of deep active layers (Shilts, 1978; French, 2007; Lewkowicz, 2007). It has been documented in the literature that ALDs can be damaging to infrastructure (Nelson et al., 2002) and increase sediment and solute yields in surface waters (Lamoureux and Lafrenière, 2009). MEs represent a significant gap in the current literature, but are a surface expression of potentially hazardous high PWP.

Water and ice enrichment at the base of the active layer and near-surface permafrost has been well documented (Kokelj and Burn, 2005; Shur et al., 2005; Tarnocai, 2009; French and

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Shur, 2010). The ice-rich layer at the top of the permafrost is called the transient layer, as it undergoes episodic thaw during exceptionally warm years with thick active layer formation (Hinkel et al., 2001; Kokelj and Burn, 2003; Shur et al., 2005). In this way, during warm years with deep thaw the transient layer becomes part of the active layer, but during cold years it remains part of the permafrost. The ice-rich zone develops through ice segregation, or by infiltration of precipitation or melting ground ice in the active layer and subsequent refreezing at the top of the permafrost (Mackay, 1983; Hinkel et al., 2001). When the transient layer thaws during exceptionally warm years the ice melts and creates excess water at the base of the active layer. This addition of moisture from melting of ice-rich soil, as well as infiltration from late season precipitation, results in high pore-water pressures (PWP) at the base of the active layer (Zoltai, 1978; Wang et al., 2005; Yamamoto, 2014). PWP is the pressure that the water in the voids of saturated soil is under, and influences the shear strength of the soil (Mitchell, 1960; Morgenstern and Nixon, 1971; McRoberts, 1978). Similarly, PWP generation at the thawing front and from deep thaw into the transient layer causes slope instability (McRoberts and Morgenstern, 1973; Harris, 1981; Lewkowicz and Clarke, 1998; Andersland and Ladanyi, 2004). Since these pressures can lead to potentially hazardous forms of permafrost degradation and disturbance, it is important to understand how pore-water pressurization occurs across the landscape, particularly in relation to terrain variables. PWP, ALDs, and MEs are caused by either intrinsic variables (slope angle, soil moisture, drainage patterns, solar radiation) or extrinsic variables that act as triggers (major rainfall events and increased temperatures) (Wu and Sidle, 1995; Atkinson and Massari, 1998). Although extrinsic variables are important for the formation of ALDs and MEs, all areas across the landscape experience extrinsic variables like major rainfall events and increased temperatures relatively homogeneously and do not explain sensitivity of the landscape to PWP. It appears that only certain locations which have high PWP, ALDs, and MEs due to specific qualities of the landscape at these locations. Therefore, we are using this modeling approach which identifies the spatial distribution of intrinsic landscape factors contributing to high PWP.

To predict areas at the landscape scale that have the potential for subsurface pressurization, we use susceptibility maps generated using predictive modeling approaches (Rudy et al., 2016a). Susceptibility mapping is based on the assertion that conditions which led to geomorphologic features in the past, will also result in that same feature in the future (or

Deleted: As precipitation or melt water from ground ice percolates downwards through the active layer during the summer months, it is trapped above the impermeable permafrost table. During the fall freeze-back period this water undergoes refreezing, consequently developing an ice-rich transient layer at the base of the active layer (Hinkel et al., 2001; Kokelj and Burn, 2003, Shur et al., 2005). This transient layer undergoes episodic thaw during exceptionally warm years with thick active layer formation (Shur et al., 2005).

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present) (Varnes et al., 1984). Thus, areas identified as susceptible will have terrain characteristics similar to those in areas where this feature has already occurred. Recent landslide susceptibility studies in non-permafrost settings have begun to use nonlinear generalized additive models (GAM; Goetz et al., 2011; Niu et al., 2014; Petschko et al., 2014). This research builds upon recent permafrost disturbance susceptibility modelling that used GAMs (Rudy et al., 2016a; Rudy et al., 2016b). For our susceptibility modelling we have used both ALDs and MEs. These latter features represent the surface manifestation of ephemeral high PWPs (Holloway et al., 2016) and are particularly important because MEs may act as an indicator of potentially hazardous pressures that may lead to slope failure. Hence, the objectives of this research are to a) independently identify the modelled susceptibility regions for both ALD and ME features to identify key landscape variables contributing to their occurrence, and b) compare the landscape position of these features to predict areas susceptible to high PWP and landforms caused by them.

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2 Study site

This study was undertaken at the Cape Bounty Arctic Watershed Observatory (CBAWO), on Melville Island, Nunavut, Canada (74°43'N, 109°35'W; Figure 2). CBAWO is a multi-disciplinary research station where monitoring of terrestrial and aquatic ecosystems has been ongoing since 2003. The landscape consists of rolling hills and broad valleys with relief generally <100 m. The study site is underlain by thick continuous permafrost with a seasonally thawed active layer that can reach 0.7-0.9 m by late July (Lewis et al., 2012; Rudy et al., 2013). Permafrost cores taken near an ALD at the site show ice enrichment (>50 % ice) from 60-80 cm below ground surface (Lamhonwah et al., 2017). Similarly, observations in the headwalls of ALDs show ~0.5 m of massive ice starting at ~80 cm. CBAWO is climatically a polar semi-desert, with a mean annual air temperature (based on the nearest long-term weather station at Mould Bay, NWT, 300 km west) of -17.5°C (1971 to 2000) (Environment Canada, 2014). Precipitation primarily occurs as snow, which is extensively redistributed by wind and preferentially deposited on leeward slopes and in low-lying areas. Rainfall is infrequent with total June-July precipitation averaging 33 mm over the 2003-2013 record, but high-magnitude events of 10-35 mm over 24 hours do occur (Favaro and Lamoureux, 2014). Vegetation is composed of graminoid, prostrate dwarf shrub, and forb tundra. Vegetation cover is

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heterogeneous and varies across the landscape reflecting soil moisture and drainage conditions across a mesotopographic gradient (Atkinson and Treitz, 2012).

The site is underlain by sandstone and siltstone bedrock, but outcrops are uncommon (Harrison, 1995). The dominant surficial materials are late Quaternary glacial and marine sediments of unknown thickness and felsenmeer (Hodgson et al., 1984). Stratigraphy of the samples taken from the active layer across the site indicates fine-grained sediments (Holloway et al., 2016).

At CBAWO, ALDs and MEs occurred extensively in late July 2007 when exceptionally high °C and hourly temperatures reaching above 20°C and two major rainfall events on 30 June (9.2 mm) and 22 July (7.2 mm) resulted in deep active layer thaw (~1 m) (Lamoureux and Lafrenière, 2009). Active MEs were also observed in 2011 and 2012, corresponding to years with the highest mean July temperatures of 9°C and 8.8°C respectively since 2003 at CBAWO (Holloway et al., 2016) and since 1948 when measurements began at Mould Bay, NWT (Environment Canada, 2014). ALDs and MEs occur when there is rapid thaw at the base of the active layer resulting in high PWPs, and occur in similar ice-rich soil materials (Harris and Lewkowicz, 1993; Leibman, 1995; Lewkowicz and Harris, 2005; Lamoureux and Lafrenière, 2009). In the case of ALDs, these pressures lead to shear failure and downslope sliding of the active layer over the failure surface (Harris and Lewkowicz, 1993). ALDs are generally shallow, with a steep headwall or scarp and an un-vegetated slump scar often being ~1 m deep (Figure 1) (French, 2007). MEs form when high PWPs eject sediment slurries upward through pre-existing cracks or soil structures. They can occur as active (presently ejecting sediment) or inactive (dry and dormant) stratiform mounds on level terrain, and they naturally elongate downslope when occurring on slopes (Holloway et al., 2016). Previous research completed at CBAWO has found that these features appear to occur in distinct landscape settings: i.e., ALDs are commonly found on vegetated slopes, whereas MEs occur on high-elevation, flat, less vegetated terrain (Holloway et al. 2016).

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3 Methods

3.1 Data sources and processing

High-resolution (0.5m) stereo panchromatic WorldView-2 data were collected on 15 July 2012. Using these data, a high-resolution (1 m vertical resolution) digital elevation model (DEM) was derived using PCI Geomatica 10.3.2 (Collingwood, 2014).

3.2 Model response variables

3.2.1 Active layer detachments

An inventory of ALDs produced by Rudy et al. (2013) was used in this study. The inventory of 131 ALDs was created by field mapping and through visual inspection of the WorldView-2 imagery (Figure 2). To evaluate stable landscapes, an equal number (i.e., 131) of undisturbed points were randomly selected in ArcGIS with constraints defined for distance from a water source (>10 m) and distance to an ALD (>20 m). These constraints were chosen because on average the width of channels at Cape Bounty are less than 10 m, so to ensure that randomized points were not placed in a stream a rule of >10 m was selected. Again, to ensure that randomized points were not placed within the boundary of existing ALDs a minimum distance of 20 m was selected.

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3.2.2 Mud ejections

The dataset used in this study for ME locations was produced by Holloway et al. (2016). Locations were determined by field mapping in June–July, 2012 and July, 2013, and include a total of 228 MEs (Figure 2). Dense clusters of MEs were removed because they resulted in bias in the analysis. Declustering was achieved by creating a 10 m buffer zone around each mapped ME in ArcGIS 10.1 and areas where buffer zones intersected were treated as one large polygon to represent the region of the cluster. One point for every 10 MEs within the polygon were randomly generated within the area as a representative point (i.e., a cluster of 25 MEs would result in 3 points). A total of 6 clusters were removed, leaving a total of 78 MEs. To evaluate control areas where there were no MEs present, 78 sites were randomly generated in ArcGIS 10.1 to correspond to the number of MEs used in the model.

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3.3 Model explanatory variables

Variables tested in the models were elevation, slope, distance to water, topographic position index (TPI), potential incoming solar radiation (PISR), distance to water, normalized difference vegetation index (NDVI; used only for the ME model), and topographic wetness index (TWI). These variables were chosen as they all have the potential to contribute to areas having high PWPs. Elevation (m), slope angle (°), distance to water (m), TPI, and PISR ($\text{MJ}\cdot\text{m}^{-2}$) were derived in ArcGIS 10.1 using the DEM. Elevation is used as a proxy for marine limit in the area, with more frost-susceptible soils and ground ice content being below marine limit (~60–80 m a.s.l) (Barnett et al., 1977). Slope angle is considered an important factor in drainage and in gravitational movements like ALDs, which can occur on low gradient slopes (Niu et al., 2005; van Westen et al., 2008). ~~Distance to downslope water sources (herein called “distance to water”)~~ is an indication of drainage and wetness of the landscape. ~~and water sources have the potential to erode banks and cause ALD initiation (Dai et al., 2001). Distance to water was calculated using the Euclidean Distance Tool in ArcGIS and distances were measured from a ALD or ME to a downslope hydrological vector layer (lake or river; see Figure 4 and 5).~~ TPI compares the elevation of each cell in a DEM to the mean elevation of a specified neighborhood (50 m radius for this study) around that cell, which was used to evaluate drainage conditions for a location (Jenness, 2006; Guisan, 1999). PISR represents differences in intensity of solar radiation, which can control local temperature, evaporation, and snowmelt and therefore soil moisture ~~and active layer depths~~ (van Westen et al., 2008). ~~Total PISR was derived using the Solar Analyst program in ArcMap and calculated for the snow-free period, which is estimated to be 15 July–15 September. Insolation is partitioned into direct-beam and diffuse radiation using the mean cloud cover factor of 0.75 based on the Nav Canada Graphic Area Forecast (Hudson et al., 2001).~~

A normalized difference vegetation index (NDVI) was used as a proxy for vegetation cover, derived from the multispectral Worldview-2 image acquired on 15 July 2012 (see Tucker, 1979). NDVI is a dimensionless radiometric measure that ranges from -1 (non-vegetated surfaces) to +1 (healthy, productive vegetation). NDVI was used only for the ME model, as ME location at the site was shown to be linked to vegetation cover, and vegetation cover determines patterns in soil moisture and ground ice conditions (Holloway et al., 2016). It was not used in the ALD model because original NDVI conditions are changed by ALDs as vegetation is removed (Rudy et al., 2013).

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A topographic wetness index (TWI) (Beven and Kirkby, 1979) was calculated using Whitebox Geospatial Analysis Tools (Lindsay, 2014). TWI, a proxy for soil moisture (Beven and Kirkby, 1979), is used to quantify the factors controlling hydrological processes for a given area using elevation, slope, and the upstream area contributing to any given cell. TWI provides information on where soil moisture is likely to be higher as a result of the drainage of surface and soil water. This is important as an increase in subsurface water content can lead to increased pore-water pressure which is a triggering factor for ALDs and MEs. A FD8 flow algorithm was applied to allow water to flow into multiple neighbouring cells based on the concave or convex nature of the landscape. TWI is an indicator of the likelihood of saturated soil conditions during rain events, and represents hydrologic parameters influenced by slope morphology. Low TWI indicates drier areas, whereas high TWI (15 for our site) indicates wetter locations. While ground ice content is linked to high PWPs, it is not used as an input variable as ground ice maps were unavailable and impractical to attain. However, cores indicate the presence of an ice-rich transient layer at the site (Lamhonwah et al., 2017).

To test for multicollinearity amongst the variables we used variance inflation factors (VIFs) and the Spearman's rank correlation coefficient (ρ_{Sp}). VIFs estimate how much the variance of the regression coefficient is "inflated" because of linear dependence between the variables (Neter et al., 1996). A VIF can be calculated for each variable by deriving a linear regression of that variable on all the other variables. ρ_{Sp} measures the statistical dependence between two ranked variables.

3.4 Generalized additive model

Modelling was performed as a case-control study with points for either ALDs or MEs as cases and randomly selected undisturbed points as controls. An equal number of undisturbed samples were randomly generated in ArcGIS to match the disturbed samples (ALDs or MEs) and resulted in an ALD dataset of 262 samples and a ME dataset of 456 samples (Table 1). The total (combined disturbed and undisturbed samples) dataset was then randomly separated into 70 % calibration and 30 % validation subsets. This resulted in 184 points for calibration of ALDs (92 each disturbed and undisturbed), 78 for validation (39 each disturbed and undisturbed) of ALDs, 320 (160 each disturbed and undisturbed) for calibration of MEs, and 136 (68 each disturbed and undisturbed) for validation of MEs.

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To model the relationship between the response variable (either ALD or ME) and the terrain variables we used a generalized additive model (GAM). GAMs are semi-parametric extensions of generalized linear models (GLMs) and provide the flexibility to represent the response's dependence on the predictor variable as either linear or nonlinear (Hastie and Tibshirani, 1990). This type of model is advantageous as nonlinear effects are known to exist in many geomorphologic studies (Goetz et al., 2011; Rudy et al., 2016a). To account for nonlinear variables, GAMs transform nonlinear predictor variables with a smoothing function. The GAMs in this study were fitted using a spline smoother with 4 degrees of freedom allowing for the detection of complex nonlinear responses. The use of GAMs in susceptibility modelling has shown strong predictive performance and has been used in susceptibility modelling with positive results (Brenning, 2008; Jia et al., 2008; Goetz et al., 2011; Niu et al., 2014; Rudy et al., 2016; Rudy et al., 2016b). The models were developed using R (version 2.15.3, R Core Team, 2013; see Rudy et al., 2016a for details). Model selection was performed using the 'dredge' function of the R-package 'MuMIn' where the GAM was fitted through iterative evaluations of modified combinations of the terms in the global model (Barton, 2011). For both ALDs and MEs, model selection was based on two parameters, Akaike information criterion (AIC) and explained deviance. AIC measures the quality of each model in a set based on goodness-of-fit while penalizing for model complexity (Akaike, 1974). Relative importance of variables was evaluated by the change in explained deviance from the full model as variables were removed individually. If the variable is important for the model it will result in a higher explained deviance. Slope followed by PISR had the greatest explained deviance from the full ALD model, whereas it was elevation for the ME model. Explained deviance was calculated following Eq. (1):

$$\text{Explained Deviance} = \frac{(\text{Null Deviance} - \text{Residual Deviance})}{(\text{Null Deviance})}, \quad (1)$$

where "Null Deviance" is the deviance of the model with only the intercept and "Residual Deviance" is the deviance that remains unexplained after all variables have been included (Leyk and Zimmerman, 2005). Output models were ranked by AIC and all models with $\Delta\text{AIC} \leq 10$ were examined (Burnham and Anderson, 2004). This approach allows us to evaluate a wide range of possible models to ensure that each variable is informative and results in a model with the greatest explained deviance and lowest AIC (Hand, 1997; Hosmer and Lemeshow, 2000; Petschko et al., 2014).

3.5 Performance assessment

Two methods were used to assess model performance - the area under the receiver operating characteristic (AUROC) curve and a confusion matrix. The receiver operating characteristic (ROC) curve plots all possible combinations of sensitivities (i.e., percentage of correctly classified disturbance points) against the corresponding specificities (i.e., percentage of correctly classified undisturbed points) that can be achieved with a given classifier and is independent of the spatial density of disturbance (Goetz et al., 2011). Overall model performance is then determined by calculating the AUROC curve where the curve ranges from 0–1. A model that has an AUROC of 0.5 or less does not predict the occurrence of disturbance any better than chance, whereas a model with an AUROC of 1 represents a model with perfect prediction of the two classes. The quantitative-qualitative relationship between AUROC and prediction accuracy can be classified as follows: 0.9–1, excellent; 0.8–0.9, very good; 0.7–0.8, good; 0.6–0.7, average; and 0.5–0.6, poor (Yesilnacar, 2005). To assess the performance of a presence/absence classifier the agreement between predictions and actual observations can be examined using a confusion matrix. For a disturbance to be predicted as present or absent, the predicted probability will be higher or lower than a pre-assigned probability threshold. For this study, a threshold of 0.50 was selected to maximize the sensitivity to specificity ratio.

3.6 Permafrost disturbance susceptibility maps

For each GAM model, the results were interpolated (and extrapolated) with R packages “raster” and “rgdal” to produce a probability map that was classified into a permafrost disturbance susceptibility map. For this study, we classified our map into susceptibility zones, using the 50th, 75th, 90th, and 95th percentiles, representing: Very Low (<50); Low (50–75); Moderate (75–90); High (90–95); and Very High (>95) susceptibility to future disturbance. This is the classification used in the current literature for susceptibility modelling, but is based on expert opinion and is not statistically tested (Dai and Lee, 2002; Ohlmacher and Davis, 2003).

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4 Results

4.1 Model fit and predictive power

ALDs and MEs were accurately modeled in terms of susceptibility to future disturbance across the study area (Table 1). Terrain variables included in the final ALD model were slope, elevation, PISR, TPI, distance to water, and TWI resulting in an explained deviance of 45 %. In the ME model distance to water, NDVI, elevation, PISR, TPI and TWI were included in the highest performing model with an explained deviance of 57 %. The ALD model calibrated with a sensitivity and specificity of 84 % and 81 %, respectively, while the ME model had a sensitivity and specificity of 91 % and 88 % (Table 1). These predictive metrics indicate that both GAM models are consistently identifying both disturbed ALDs and MEs and undisturbed points. AUROC values were consistently high for both: 0.91 for ALDs and 0.95 for MEs (Table 1).

4.2 Importance of predictor variables

AUROC was used to assess the discriminatory power of individual variables outside a statistical model using single variable models (Table 2). The strongest predictors for ALDs were slope and PISR (AUROC > 70 %), followed by elevation, TPI, and distance to water (AUROC > 60 %). Although TWI was weakly related to ALD occurrence (AUROC < 60 %), its interactions with the other model variables led to an increase in the performance of the full model. For MEs, all variables with the exception of slope and TWI had AUROCs > 70. Differences in values between undisturbed and disturbed ALD points were checked for significance using a Wilcoxon rank sum test (for continuous variables). In the ALD model, all continuous variables with the exception of TWI and distance to water are statistically significant at the 99.9 % level whereas in the ME model all continuous variables with the exception of TWI and PISR are statistically significant at the 99.9 % level.

VIFs and pSp were used to examine correlations between predictor variables in both models. For the ALD model, slope and PISR had the strongest correlation with pSp equal to -0.52, all other variables had weaker correlations with $|pSp| < 0.5$. All variables in the ALD model had VIFs below two. For the ME model, elevation and distance to water had the strongest correlation with pSp equal to 0.54, all other variables had weaker correlations with $|pSp| < 0.5$. All variables in the ME model had VIFs below two.

Bivariate plots were constructed to view the relationship between the probabilities of an ALD or a ME occurring and the terrain variables that had the largest influence on the models

(Figure 3). When the slope is low the probability of an ALD occurring is also low, but as the slope increases to $\sim 12^\circ$ the probability peaks and then starts to decline slightly as the slope increases. The opposite is the case for MEs, where the probability is highest at low slopes and decreases with steeper slopes. For PISR, the probability of ALDs is highest when PISR of $1100 \text{ MJ}\cdot\text{m}^{-2}$ and decreases in a logistic pattern as PISR increases. For MEs, the probability is low when PISR $\sim 1150\text{--}1200 \text{ MJ}\cdot\text{m}^{-2}$ and then peaks at $1250 \text{ MJ}\cdot\text{m}^{-2}$. For distance to water, the probability of ALDs is highest when the distance to water is small, and decreases as the distance to water becomes greater (although slightly increasing again at 500m). For MEs, the probability is lower with smaller distances to water and peaks at 600m, after which is steadily decreases as the distances get higher. For TPI, the probability of ALDs is highest with a TPI of -2.5, while for MEs is highest at a TPI of 1, indicating the ALDs occur in landscape concavities and MEs occurring in areas that are more convex to flat. For elevation, both ALDs and MEs have low probability at low elevations, albeit the probability of ALDs is higher than that of MEs. The probability of ALDs peaks at about 50m, where it decreases as elevation increases. For MEs, the probability is highest at 80m and decreases as the elevation increases. When considering TWI, the probability of ALDs is high when TWI is low, and decreases as TWI increases. The probability of MEs is low when TWI is low, peaks between 5 and 10, and then declines again. For NDVI, the probability of MEs peaks at -0.1 and declines as NDVI increases.

4.3 Permafrost disturbance susceptibility maps

The spatial predictions of the GAM for ALDs and MEs (Figure 4) indicate that ALDs have a high probability of occurring on moderate to steep slopes with relatively low PISR, whereas MEs are more likely to occur at high elevations with low slope angles and far from water sources (i.e., drier). For ALDs, the areas of high susceptibility on the landscape are found along river channels and on steeper upland slopes. Areas of low susceptibility are found on plateaus, far from water sources with relatively higher PISR. Although high susceptibility zones account for a small portion of the landscape, there is a greater density of disturbance at these locations (Table 3). By contrast, the areas of high ME susceptibility are found on dry, barren, uplands and plateaus.

4.4 Validation of ALD and ME susceptibility maps

Probability values were extracted from the independent validation datasets to validate the susceptibility maps. A threshold of 0.5 was selected to maximize the sensitivity and specificity and was used to distinguish between disturbed and undisturbed points where values > 0.50 indicate disturbance and values < 0.5 indicate undisturbed points. Again, based on the validation, the ALD and ME models performed well (Table 1). Additionally, the models were validated without a user-defined threshold resulting in an AUROC of 0.86 and 0.92 for ALDs and MEs respectively, indicating good discrimination between disturbed and undisturbed points.

4.5 Spatial extent of susceptibility zones

The spatial extent of moderate to high susceptibility zones was compared between the two models to identify key terrain attributes responsible for high PWPs (Figure 5, Table 4). Very little overlap exists between the models ($< 1\%$ of the study area, Table 3). Terrain characteristics are similar between the features in low susceptibility zones, but differ in the modelled high susceptibility zones (Table 2, Table 4). ALDs are commonly found on sloped terrain while MEs tend to occur on plateaus. Slope is the main variable driving ALD initiation, while distance to water is the most important variable explaining ME formation.

5 Discussion

5.1 Landscape distribution and terrain controls over features formed by pore-water pressurization

This analysis demonstrates that the distribution of ALDs and MEs that have developed since 2007 at CBAWO are largely distinct in terms of their spatial occurrence. The terrain associated with high susceptibility to MEs include 60m elevation sites, frequently on plateau or interfluve locations with moderate to low slope angles (Table 2). For the ME model very high susceptibility zones were far from water and had a negative NDVI value indicating more barren surfaces. High elevation sites correspond with dry, mostly barren plateau environments at the study site, which undergo deeper seasonal thaw than wetter vegetated settings (Smith et al., 2009; Woo, 2012). These areas also correspond with landscape convexities that experience wind scour of snow which results in relatively deeper active layers (French, 2007; Woo, 2012). In warm years, this deep thaw can liberate water as ice melts from the transient layer and increase

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PWP. Flat or low sloping environments result in minimized hydraulic gradients and poor drainage, resulting in the accumulation of water and potentially increased PWP. TPI was a less important variable in the ME model, but the susceptibility is highest as TPI approaches 1, indicating flat areas, supporting the statements above. PISR and TWI were not significant variables in the ME model.

In contrast, ALDs are found at downslope landscape positions on low to moderate slope angles, often in areas of convergent slope drainage and topographic concavity. This pattern has been observed elsewhere (Lewkowicz and Harris, 2005; Rudy et al., 2016a; Rudy et al., 2016b). On shallow slopes water movement is decreased resulting in an overall increase in PWPs (McRoberts and Morgenstern, 1974; Leibman et al., 2014). ALDs are associated with mean elevations of 50 m, which is below the local marine limit of 60-80 m. The frost susceptibility of marine clays tend to be more ice-rich, form segregated ice-lenses, and have low liquid limits which contributes to slope instability (Kokelj and Burn, 2005). The probability of ALDs increases with as PISR approaches $1100 \text{ MJ} \cdot \text{m}^{-2}$. The median value for PISR at the site is $1238 \text{ MJ} \cdot \text{m}^{-2}$, indicating that ALDs are more probable in areas that have generally lower PISR (Rudy et al., 2016b). Low PISR is commonly associated with north-facing slopes. These areas have shallower active layers with more near surface ground ice, and longer persistence of snow which leads to increased soil moisture. Saturated soil which freezes can lead to ice aggradation and increased PWP the following summer (McRoberts and Morgenstern, 1974). TWI and distance to water were not significant in the ALD model.

While surficial materials are broadly similar across CBAWO, the landscape zonation of these two features appears to follow a slope continuum, with MEs on upslope convex areas and ALDs on mid-slope concave areas. The toposequence at our site includes: dry, exposed plateaus at c. 80m elevation, with polar-desert vegetation or bare rock; intermediate hillslopes from 40-70 m elevation, with mesic vegetation and moderate drainage; and, low hillslope areas with wet sedge meadows and river valleys from 20-40 m. It has been shown at this site that the polar-desert plateau has deeper active layers and warmer ground temperatures than mesic tundra sites, which corresponds to the presence of MEs (Holloway et al., 2016). Mesic tundra sites have colder ground temperatures due to the presence of vegetation, shallower active layers with more near surface ground ice, conditions which can lead to formation of ALDs. This toposequence

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corresponds with Subzone B of the Circumpolar Arctic Vegetation Map and is comparable to other sites within this zone (Walker et al., 2002).

As stated, high PWPs can lead to various forms of slope instability including ALDs

(Harris and Lewkowicz, 1993; Lewkowicz and Harris, 2005). Similarly, MEs have been documented in settings in proximity to ALDs and the occurrence of MEs is associated with deep active layer thaw and potentially with summer rainfall (Edlund, 1989; Lewkowicz, 2007; Holloway et al., 2016). While soil PWP measurements are not available to confirm pressurization in these instances, the inferred mechanism of ME formation is diapirisation of sediment slurries from the base of the active layer caused by pore-water pressurization due to ice thaw (Holloway et al., 2016; Lewkowicz, 2007). Similar climatic conditions and active layer processes are attributed to both ALD and ME formation (Holloway et al., 2016; Lamoureux and Lafrenière, 2009). However, when reaching some threshold of PWP, the landscape response varies depending on localized terrain characteristics shown in this study, and high PWPs are expressed at the surface as ALDs or MEs.

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Deleted: Temperature and rainfall were not included in our model, but will be mentioned below because they are important triggers for both MEs and ALDs. The precise relationships between pressurization events in warm years and feature development remain speculative but provide explanation for the distinct distribution of relationship between ALDs and MEs. In 2007, the year with the highest mean July temperature/warmest year since regional records began in 1949, deep active layer development of ~1 m and late July rainfall of 7.2 mm triggered widespread ALD formation (Lamoureux and Lafrenière, 2009). At the time of ALD initiation, adjacent slopes were characterized by numerous MEs in soil that was minimally disturbed (Figure 6), indicating both the presence of pressurized fluids in the disturbance, and the formation of MEs in areas with limited or no slope failure. Similar conditions were observed with MEs associated with terminated active layer fractures in 2012 further suggesting the presence of fluid slurries in situations approaching those that generate ALDs (Figures 1 and 6). These observations suggest that MEs, while clearly reflecting evidence for subsurface soil water pressurization (i.e., Lewkowicz, 2007), also likely play a stabilization role through pressure release to the surface (Urciuoli and Pirone, 2013). Holloway et al. (2016) noted that MEs were primarily located in areas where surface soil was relatively dry and bare, and inferred these soil conditions may contribute to desiccation cracking and soil ped formation soil structure conducive to allow mud ejection/slurry diapir formation and PWP release.

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5.2 Susceptibility modelling and landscape implications

Modelling results provide a means to evaluate spatial patterns of features formed by high PWPs across the entire landscape. The independently generated models show strong mutual exclusivity of the locations where ALD and ME susceptibility is high, representing ~1% of the study area (Figures 4 and 5). Although at the landscape scale this overlap appears minimal, these areas are of particular interest since this is indicative of where we expect a transition in soil stability and hence, areas of key potential insight into fine-scale landscape controls over disturbance. Figure 6 shows a photo of one of these areas where both feature types are present on the west central part of the study area (Figure 2). These locations will be monitored in the future to determine PWP compared to areas where models suggest low susceptibility to ALD and ME, and thus lower PWP.

Considerably more of the landscape is highly susceptible (in the high and very high zones) to disturbance in terms of ALDs rather than MEs (Table 3). Terrain does not vary as much

between MEs and ALDs in the low/moderate susceptibility zones, whereas it varies substantially in the very high susceptibility zone (Table 2). This landscape zonation of ME and ALD activity is consistent with field observations at CBAWO, and constitutes the first recognition of a broader landscape pattern of soil pore-water pressurization landforms. While results indicate that many areas of the CBAWO landscape appear to be less susceptible to excess pressurization processes as expressed by MEs and ALDs, we can interpret these results to reflect controls over how pressurization affects landscapes and the locations and terrain types most susceptible. Further, the mutual exclusivity of these modelled high susceptibility areas over space suggests differential responses to pressurization across different terrain factors.

The distinct zonation of ME in upland areas with low slopes indicates that soil water pressurization results in artesian fluid release at the surface in years exhibiting warm conditions and deep active layer thaw (Holloway et al., 2016). MEs also occur coincident with conditions that result in ALD formation (Figure 6) and have been observed in cases where ALD formation was initiated but ultimately stabilized (i.e. soil cracking at surface where the active layer was failing but stabilized, with mud ejections surrounding the area). These observations suggest that MEs, while clearly reflecting evidence for subsurface soil water pressurization (i.e., Lewkowicz, 2007), also likely play a stabilization role through pressure release to the surface (Urciuoli and Pirone, 2013). Collectively, these observations strongly suggest that MEs result from soil water depressurization where active layer failure and movement is not possible or necessary. By contrast, ALDs are associated with sufficient pressurization to induce slope fracturing and downslope movement. MEs appear to be caused by fluid release to the surface that reduced subsurface pressures, essentially acting as a fluid pressure release mechanism. While this process is observed in permafrost settings where manual drainage stabilizes slopes (Andersland and Ladanyi, 2004), and in other geotechnical settings where drainage stabilization is used for landslide mitigation (Urciuoli and Pirone, 2013), it is not clear if the presence of a ME will stabilize the soil surface and prevent soil fracturing or any slope movement. Given that that ME zones occur where ALDs are not generally observed, we interpret the ME susceptibility zone to represent areas conducive to pore-water pressurization but where slope disturbance is inhibited, primarily by low slope angles. However, at this time it is unclear the extent to which MEs represent a soil stabilization mechanism.

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The combined extent of modelled high susceptibility areas provides a key set of terrain conditions that appear to be associated with soil water pressurization during warm summers at CBAWO. ALDs appear in many permafrost landscapes (French, 2007; Lewkowicz, 2007; Harris, 2005; McRoberts and Morgenstern, 1974; Rutter et al., 1973; Morgenstern and Nixon, 1971), while MEs have had less attention. The literature and our observations indicate that MEs occur on Ellesmere (Lewkowicz, 2007), Banks and Melville Islands in the Canadian High Arctic, and further south in Nunavut and the Northwest Territories in very different vegetation and terrain conditions (Shilts, 1978). Despite these observations, the broader distribution of MEs remains poorly understood, and the terrain conditions that are associated with their occurrence at CBAWO may not apply to other settings. Hence, while MEs are indicative of subsurface fluid pressurization in permafrost settings, the function they play in dissipating potential slope instability requires further investigation, particularly with field observations to determine the localized processes of water accumulation within the subsurface.

6 Conclusion

Independent GAM models accurately captured the terrain controls that appear to affect the distribution of ALDs and MEs on the landscape. The susceptibility models demonstrate that ALDs are most probable on hillslopes with gradual to steep concave slopes and relatively low PISR, whereas MEs are associated with higher elevation areas, low angled convex slopes, and in areas relatively far from water (drier). Both features are thought to be formed when high soil PWPs are generated and dissipated, resulting in slope failure or liquefied sediment ejecting to the soil surface. This analysis reveals that these features are found in proximity, but in largely discrete areas at CBAWO. Hence, the joint zones of susceptibility appear to be sensitive to development of high PWPs and point to a possible larger scale landscape pattern to active layer response to climate warming. While further research and field measurements is necessary to elucidate these patterns, these results provide new information on landforms related to high soil PWP and improves our understanding of geomorphic sensitivity to permafrost degradation and related geohazards in Arctic landscapes.

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