Romeyn et al. presents novel and long time series of data on seismic events in a permafrost environment. The data analysis clearly distinguishes two kinds of events, derived from mining activities and natural sources (cryoseisms). The results are very interesting and worth publishing in The Cryosphere. In terms of periglacial geomorphology, however, I would suggest several corrections and clarifications, mainly on the terminology and data interpretation.

Major comments

1. Thermal contraction cracking and frost cracking appear to be confused (e.g., in Section 4.2): Please distinguish between frost cracking (which occurs when ground is 'freezing' and by a mechanism similar to frost heaving) and thermal contraction cracking (which occurs when 'frozen' ground is subjected to rapid cooling. Frost cracking associated with segregated ice tends to produce horizontal cracks which can result in rock fragmentation with repeated freeze-thaw cycles over thousands of years. In contrast, thermal contraction cracking produces vertical cracks with spacing of several meters and may not contribute to rock fragmentation (regolith formation).

This is a fair criticism. We have perhaps allowed the common usage of "frost polygons" to carry across to the description of cracking. We agree it is important that we consistently present that our model is suited to investigating thermal contraction cracking and will make sure this is clear in the revised manuscript. We suggest adding Figure i to more clearly illustrate the hypothesized cracking mechanism we aim to test (which also relates to some of the reviewer's other comments).

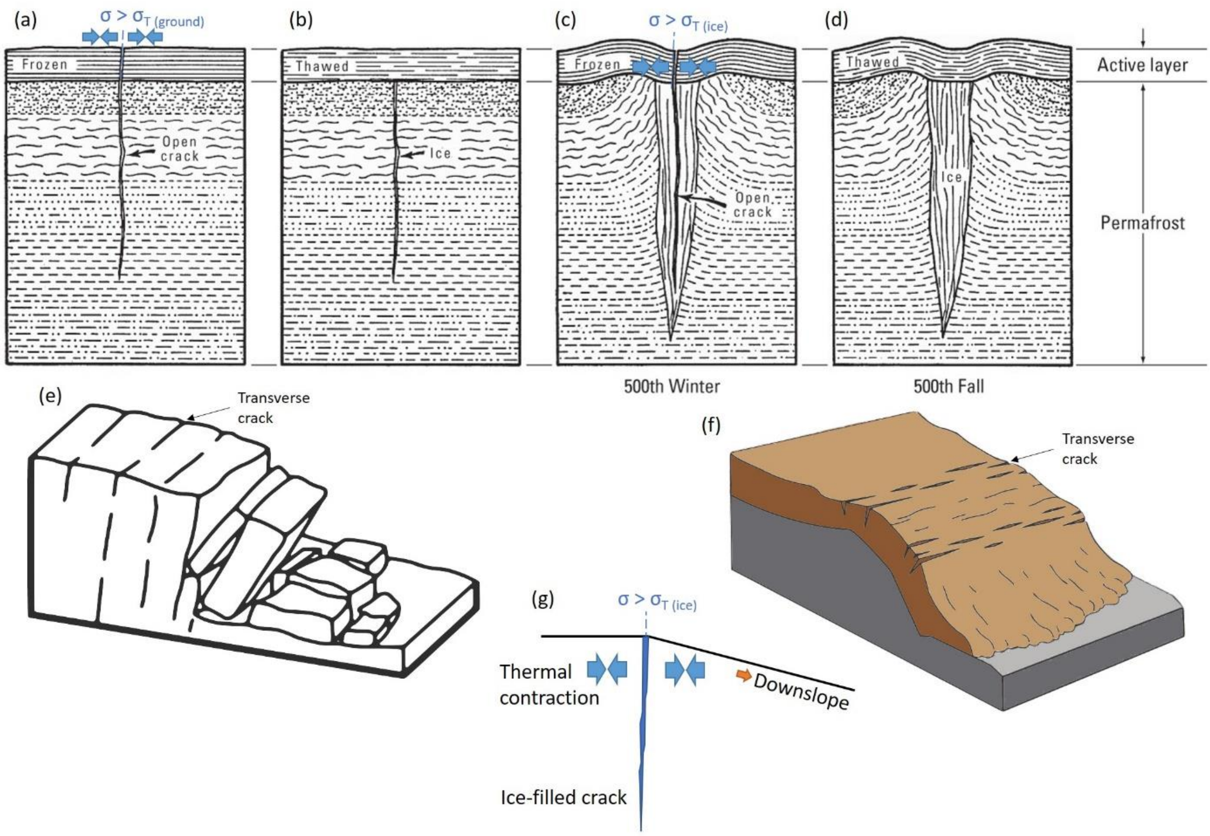

Figure i – (a-d) Lachenbruch (1962) model of ice wedge formation. (a) Thermal contraction of frozen active layer initiates a tensional crack that penetrates into permafrost, (b) meltwater infiltrates and refreezes during the thaw season, (c) ice with lower tensile strength than surrounding ground forms a plane of weakness and cracks repeatedly over many years, (d) the crack-infilling cycle causes ice wedge growth and ground surface deformation that organizes into ice wedge polygons in 2D plan view. Mass movements such as, (e) erosional scarp and (f) frozen debris/solifluction flow initiate transverse cracks/fissures which become infiltrated by water that freezes to ice. (g) Thermal contraction of the surrounding ground and downslope gravitational stress causes the ice to crack under tension.

2. Add more detailed geomorphological information: Boulder-producing scarps (‘rockwalls’ are more popular) and solifluction lobes are regarded as major sources of summer events, but these landforms cannot be identified on the air photographs (Fig. 7b-d). Perhaps on-site photographs or 3D models show more clear features.

Yes, we recognize the need for improvements here. Upon careful revision, we suggest revising to “erosional scarps” since this is most consistent with Tolgensbakk et al. (2000). We think that “rockwall” might overstate the vertical relief of the features in this case. Adding Figure i should help to illustrate these features conceptually (see previous response). In addition, we suggest adding annotation to Figure 7 in the revised manuscript. We can also add the 3D perspective models shown here as Figure ii & Figure iii. Since these figures are quite space consuming, we suggest they might best be included as appendices to the revised manuscript.

Tolgensbakk, J., Sørbel, L., & Høgvard, K. (Cartographer). (2000). Adventdalen, Geomorphological and Quaternary Geological map, Svalbard 1:100,000, Spitsbergen sheet C9Q. Retrieved from https://data.npolar.no/publication/e4188b9f-e773-4435-ab71-259ddaf594df

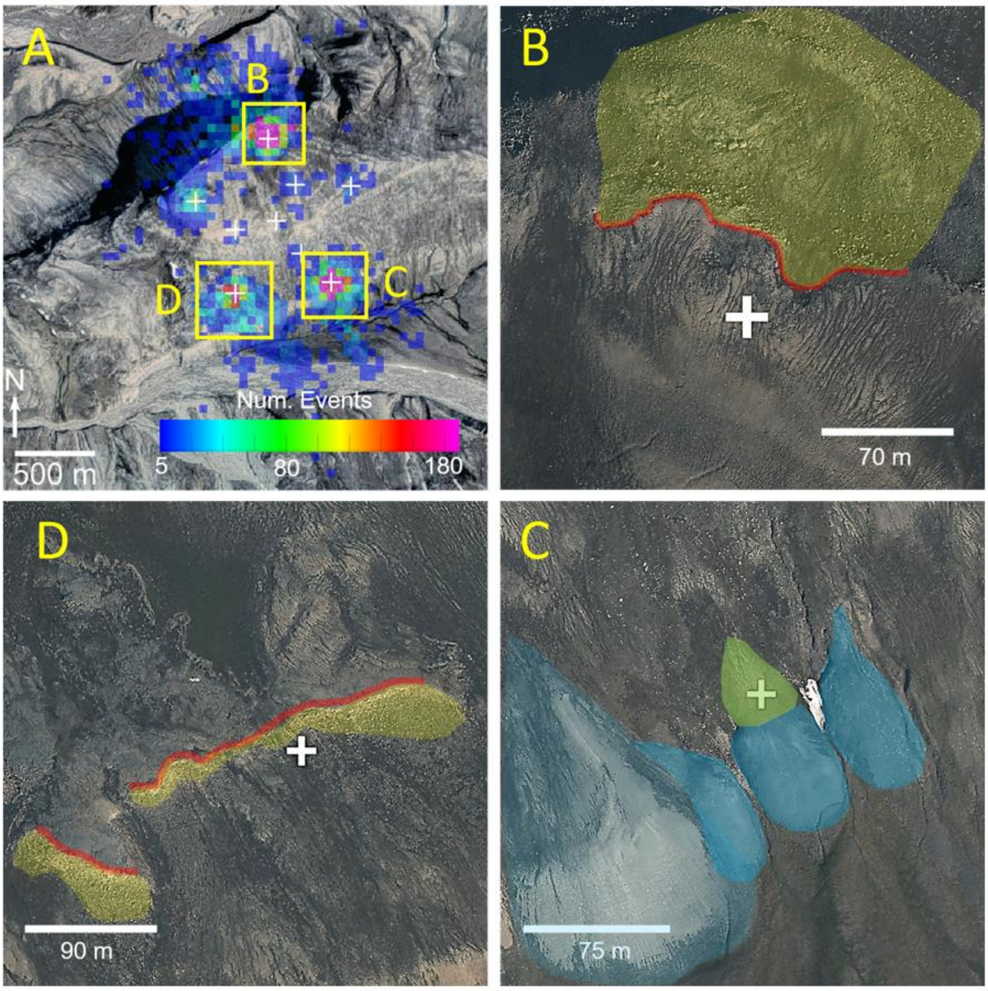

Figure 7 – (a) Dec-Feb events as plotted in Figure 6 with orthophotograph details illustrating the geomorphologic features associated with the most seismically active areas. Erosional scarps (b), (d) are annotated in red and associated boulder fields in yellow, and frozen debris/solifluction lobes (c) are annotated in blue. A faintly visible area of polygonal patterned ground is annotated in green in (c). Orthophoto © Norwegian Polar Institute (npolar.no).

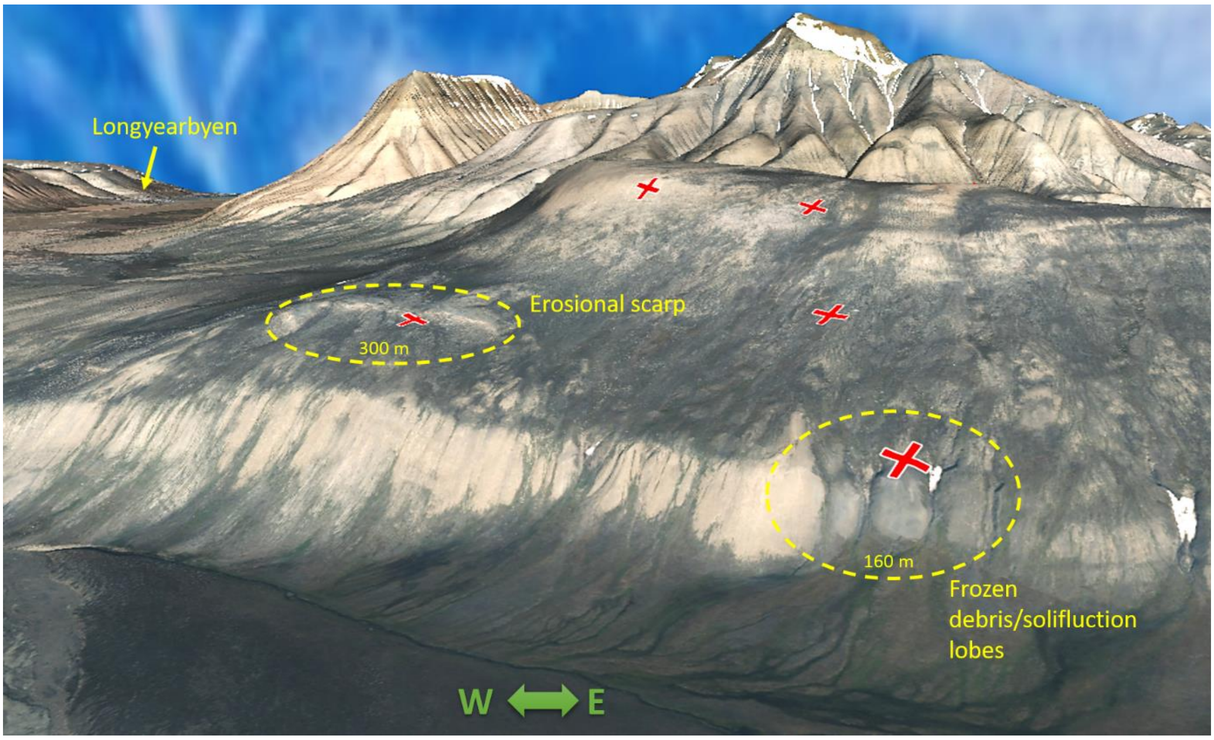

Figure ii – 3D perspective view of the southern flank of Janssonhaugen highlighting two of the three areas associated with anomalous seismicity. The 3D model was constructed by draping an orthophoto on top of a 1.5x vertically exaggerated DEM. Red crosses mark locations of SPITS seismometer stations. Orthophoto/DEM © Norwegian Polar Institute (npolar.no).

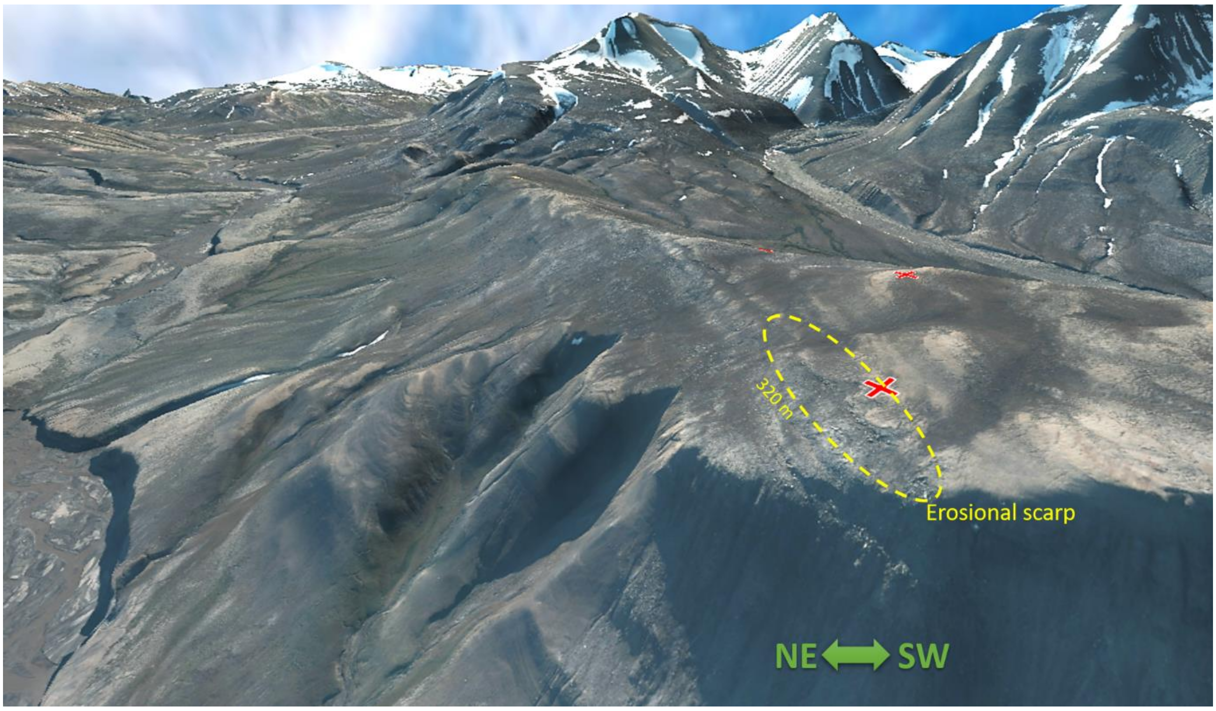

Figure iii - 3D perspective view of the northeastern flank of Janssonhaugen highlighting the third area associated with anomalous seismicity. The 3D model was constructed by draping an orthophoto on top of a 1.5x vertically exaggerated DEM. Red crosses mark locations of SPITS seismometer stations. Orthophoto/DEM © Norwegian Polar Institute (npolar.no).

3. Natural seismic events apart from thermal contraction cracking: Solifluction lobes are considered one of the possible sources of seismic events both in Abstract and Conclusion, but how does solifluction (slow soil deformation) produce seismic events? Landslides (active-layer detachment slides) may also be a possible source of summer events? Note that observations at nearby sites within Adventdalen shows that seasonal frost heave is most active in September or October and thaw subsidence in June (Harris et al., 2011; Watanabe et al., 2012), which seems to coincide with some peaks of the summer seismic events.

This is a good point. In the submitted manuscript we presented the spatial correspondence of areas of enhanced seismicity without elaborating the mechanism of cracking. For clarity, we suggest that mass movement processes associated with erosional scarps and frozen debris/solifluction lobes may initiate transverse cracks/fissures that are open at the surface. These fissures are infiltrated by water that subsequently freezes. This infiltration ice is then subject to thermal contraction cracking in a manner analogous to the ice-wedge thermal contraction model of Lachenbruch (1962), as illustrated in Figure i. We suggest adding the following explanation in the revised manuscript when describing the high seismicity areas:

> Polygonally patterned ground indicative of cryoturbation of the active layer and/or ice wedges in the underlying permafrost are observed extensively across Janssonhaugen, except where downslope mass movements destroy or interrupt the formation of polygonal networks (Sørbel and Tolgensbakk, 2002). In this study, we observed anomalously high cryoseismicity associated with erosional scarps and a frozen debris/solifluction lobe, which are all associated with downslope mass wasting. We suggest that these downslope mass movements initiate or precondition transverse cracks or fissures to open (e.g. Darrow et al., 2016, Price, 1974). Water from rain or snowmelt infiltrates these fissures and freezes when temperatures drop below freezing (e.g. Darrow et al., 2016). Rapidly falling ground temperatures during winter then cause the surrounding ground to thermally contract. This causes the vein-ice filling the frozen fissures to crack under tension, since the tensile strength of ice is lower than the surrounding ground and therefore constitutes a plane of weakness. Cracking relieves the accumulated thermal stress.
>
> This mechanism is analogous to the Lachenbruch (1962) model of thermal contraction cracking of ice wedges in permafrost. However, the cracking may occur more frequently or under milder surface cooling because 1) the frozen fissures may be pre-stressed by downslope gravitational forces making them more prone to failure and 2) the fissures extend to the ground surface where thermal stresses are largest. For the case of ice wedges, the ice wedge is located below the permafrost table (Figure i-c). There may be vein ice extending through the active layer only if the previous seasons thermal contraction crack has remained open through the summer thaw season. If the crack has closed so that vein ice is not formed during the early freezing season, initiation of thermal contraction cracking of the ice wedge would require accumulation of thermal contraction stress at the level of the permafrost table, requiring a longer or more extreme surface cooling episode. Tensile cracks could also form in the active layer where ice veins/ice wedges are absent (as in Figure i-a), but this would require thermal contraction stresses exceeding the tensile strength of frozen ground, which is greater than that of polycrystalline ice and may therefore occur less frequently.

We can also revise the interpretation of summer events to include mass wasting processes more generally, although the steep rock wall (shadowed area at the bottom right of Figure iii) seems most suggestive of rockfall/rockslide. Mass wasting processes producing long duration ground motions are less likely to be detected by our STA/LTA detector, unless they have high amplitude peaks of shorter duration. This is something that we can't rule out so it is correct that we should list additional processes as possible.

Price, L. W. (1974). The developmental cycle of solifluction lobes. Annals of the Association of American Geographers, 64(3), 430-438.

Darrow, M. M., Gyswyt, N. L., Simpson, J. M., Daanen, R. P., & Hubbard, T. D. (2016). Frozen debris lobe morphology and movement: an overview of eight dynamic features, southern Brooks Range, Alaska. The Cryosphere, 10(3), 977-993.

Specific comments

Line 43: Polygonal arrangement is primary represented by 'troughs' between a pair of ridges. Separated by troughs, ridges do not show polygonal array.

We suggest slightly re-phrasing to "forcing the displaced ground upwards and resulting in a series of troughs/ridges in a polygonal arrangement that are one of the most recognizable landforms in permafrost environments". We agree with the point, but conceptually the ridges are also important since ice is emplaced in the ground which must be displaced upwards to accommodate it. We suggest adding a reference to Plug & Werner (2002), which nicely illustrates how ridges formed by ground deformation due to ice wedging organise into polygonal networks.

Plug, L. J., & Werner, B. T. (2002). Nonlinear dynamics of ice-wedge networks and resulting sensitivity to severe cooling events. Nature, 417(6892), 929-933.

Line 54: Solifluction results from frost 'heaving' and creep.

Thanks for catching this, we will replace "cracking" with "heaving".

Line 57: 'asymmetrical trajectory of soil' rather than asymmetry between the heaving forces?

We agree that the phrasing here could be improved. We suggest the revised formulation:

"Solifluction is broadly defined as the slow mass wasting resulting from freeze-thaw action in fine-textured soils (French, 2017; Matsuoka, 2001) and occurs due to the asymmetry between frost heaving perpendicular with the sloped ground surface and vertical subsidence upon thawing under the force of gravity."

Line 111: 'indicating the presence of sand/ice wedges': If the polygons are small (e.g., <3 m in diameter), they could be produced by desiccation cracking or cryoturbation within the active layer and sand/ice-wedges may be absent.

Good point, we suggest the following reformulation:

"The surface topography is generally flat but loose surface material is sorted into polygons (Isaksen et al., 2001, Tolgensbakk et al. 2000), due to active layer cryoturbation and/or ice wedge formation."

Line 199: Lachenbruch (1962) first proposed the visco-elastic behavior of ice-wedge polygons, so it should be cited here.

We will add a reference to Lachenbruch (1962).

Line 262 (also Table 1): Why tensile strength of polycrystalline ice is used? Strength may be larger in frozen soil and at lower temperature (e.g., 2-7 MPa: Haynes & Karalius, 1977) and even more in frozen bedrock.

That ice-wedges or veins of ice form planes of weakness in the ground that are prone to repeat fracturing is a fundamental part of the Lachenbruch (1962) model. The reduced tensile strength of polycrystalline ice forming ice wedges, compared to frozen soil is a necessary condition to explain the formation of ice-wedge polygonal networks (e.g. Plug & Werner, 2002). We will revise the text so this point is conveyed more clearly.

Plug, L. J., & Werner, B. T. (2002). Nonlinear dynamics of ice-wedge networks and resulting sensitivity to severe cooling events. Nature, 417(6892), 929-933.

Figure 4: Improve the complicated units of distance. The northing distance is given by 10^6 m, but the easting by 10^5 m. I suggest both axes are given by a clearer unit like km.

Good point. We had chosen to use UTM coordinates, but agree that readability will be improved by using a local coordinate system with km units.

Line 318: 'lowest during summer': but still high at Location 9?

Based on suggestions of other reviewers we will add the numbers of events for each subfigure to make comparison easier. Comparing between seasons, much fewer events are recorded in summer. Locally this area around the northernmost seismometer is still quite active, likely due to mass movements such as rockfalls/rockslides as we mention in the text.

Line 321: Landslides (active-layer detachment slides) can be added as a trigger?

Yes, this is plausible and we can add active-layer detachment slides/debris flows as possible seismic sources. Speculatively, we would expect these processes to produce signals of longer duration than our event detector is tuned to trigger on. This is common for mass movement related seismic events, simply because the source process is longer than crack formation. On the other hand, short lived peaks in amplitude remain a possibility, so we can't rule out these processes completely and it does make sense to list them as possibilities. It would also be interesting to investigate if it is feasible for active-layer detachment slides to occur frequently enough to explain the observed seismicity. Perhaps a future study focussing more specifically on the summer seismicity could elaborate further on these issues.

Line 330: Boulder-producing scarps ('rockwalls' are a more popular term) and solifluction lobes: See the major comment 2.

Upon careful revision, we suggest revising to “erosional scarps” since this is most consistent with Tolgensbakk et al. (2000). We think that “rockwall” might overstate the vertical relief of the features in this case.

> *Tolgensbakk, J., Sørbel, L., & Høgvard, K. (Cartographer). (2000). Adventdalen, Geomorphological and Quaternary Geological map, Svalbard 1:100,000, Spitsbergen sheet C9Q. Retrieved from https://data.npolar.no/publication/e4188b9f-e773-4435-ab71-259ddaf594df*

Line 348: See the major comment 1.

Yes, we recognise the need to revise the phrasing here. In line with the reviewer’s comment on Line 111, which we see as relevant and helpful also in this section, we suggest the following revision:

“…it corresponds with the 20-30cm thick regolith layer at Janssonhaugen (Isaksen et al., 2001), suggesting that cryoturbation within the active layer may have weathered the bedrock over time to produce the surficial layer.”

Line 366: ‘Thermal contraction cracking of segregated ice bodies’: I cannot understand why segregated ice body is required for cryoseisms.

Good point. We had referred to segregated ice in an attempt to differentiate from distributed pore-ice without accounting for the fact that this terminology is connected with the specific occurrence of ice lenses formed by capillary action. In line with our responses to major comments 1 & 3, we suggest re-phrasing to:

“Thermal contraction cracking of ice wedges and crack filling vein-ice”

Line 368: ‘most likely rockfalls’: How about solifluction or landslides? (see major comment 3)

Yes, we could be more general here and suggest rephrasing to:

“The clusters of events recorded June-August, when thermal stress is low (see Figure 6 and Figure 10), are most likely mass movements associated with steep terrain (e.g., rockfalls, active layer detachment slides, debris flows etc.), possibly initiated by melting of fracture-filling ice leading to loss of strength or joint lubrication (Matsuoka, 2019; Weber et al., 2017).”

Line 373 (Figure 10b): ‘modelled number of frost quakes’: Are they counted when thermal stress exceeds 1.0 MPa?

Yes. The fracture model is described in section 3.3.1, but we agree it would be beneficial to include a cross reference in the figure caption to help the reader understand this quantity.

Line 382: ‘including the inherently stochastic nature of seismicity’: Spatial variability of thermal conditions may be the primary factor of the deviation, since the modelled frost quakes are derived from temperature data at only one location?

We cover this point in more detail in the response to the comment on Line 386. The connection to observations by Matsuoka et al. (2018) that the reviewer highlighted allows us to interpret the spikes in seismicity much more precisely than in the initial manuscript. We will therefore re-write the section from line 379-390 and eliminate these somewhat vague speculations. We thank the reviewer for highlighting this connection to us, which allows us to significantly improve upon the submitted manuscript.

Line 386: ‘the periods 17-26 Feb 2010 and 7-16 Feb, 2012’: Note that thermal contraction cracking was very active at down-valley sites during these two periods (see Matsuoka et al., 2018: Fig. 12).

We are very appreciative that the reviewer highlighted this connection, which we had overlooked despite being familiar with the Matsuoka et al., (2018) study. The cracking episode we recorded around 17-26 Feb 2010 does appear to correspond to the C10 cracking episode identified by Matsuoka et al., (2018) and is likely driven by similar processes. Matsuoka et al., (2018) observed that this cracking episode was preceded by a highly unusual period of mild weather, accompanied by rain, positive air temperatures, significant snowmelt and surface water pooling. This surficial water subsequently froze when air temperatures dropped and an extensive series of fresh cracks were observed in the surficial ice by Matsuoka et al., during a field visit on 28 Feb 2010. These cracks can be interpreted as thermal contraction cracks of the surficial ice and this explains why they were not accurately predicted by the subsurface thermal stress model (since they occur in response to air temperature rather than ground temperature).

Following this line of reasoning, we were able to connect all of the large, anomalous spikes in seismicity that were not predicted by our model with rare, heavy-rainfall events reported on by Dobler et al. (2019). These unusual winter rainfall events are driven by strong south-southwesterly atmospheric flows with advection of water vapor from warmer areas and are often linked to “atmospheric river” features in the precipitable water anomaly field (Serreze et al., 2015). We further illustrate the correspondence between mild weather/rain events and cracking related seismicity in Figure iv using meteorological observations at Svalbard airport which is located ~21 km from our study site at Janssonhaugen. Thermal contraction cracking of newly formed surface ice is therefore a plausible explanation for the anomalous spikes in seismicity we observed at the SPITS array.

We can specifically annotate the anomalous spikes in seismicity in Figure 12 and include the additional Figure iv either in the main body or as an appendix to the revised manuscript.

Dobler, A., Førland, E. J., & Isaksen, K. (2019). Present and future heavy rainfall statistics for Svalbard—Background-report for Climate in Svalbard 2100. NCCS Rep, 3, 29.

Serreze, M. C., & Stroeve, J. (2015). Arctic sea ice trends, variability and implications for seasonal ice forecasting. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 373(2045), 20140159.

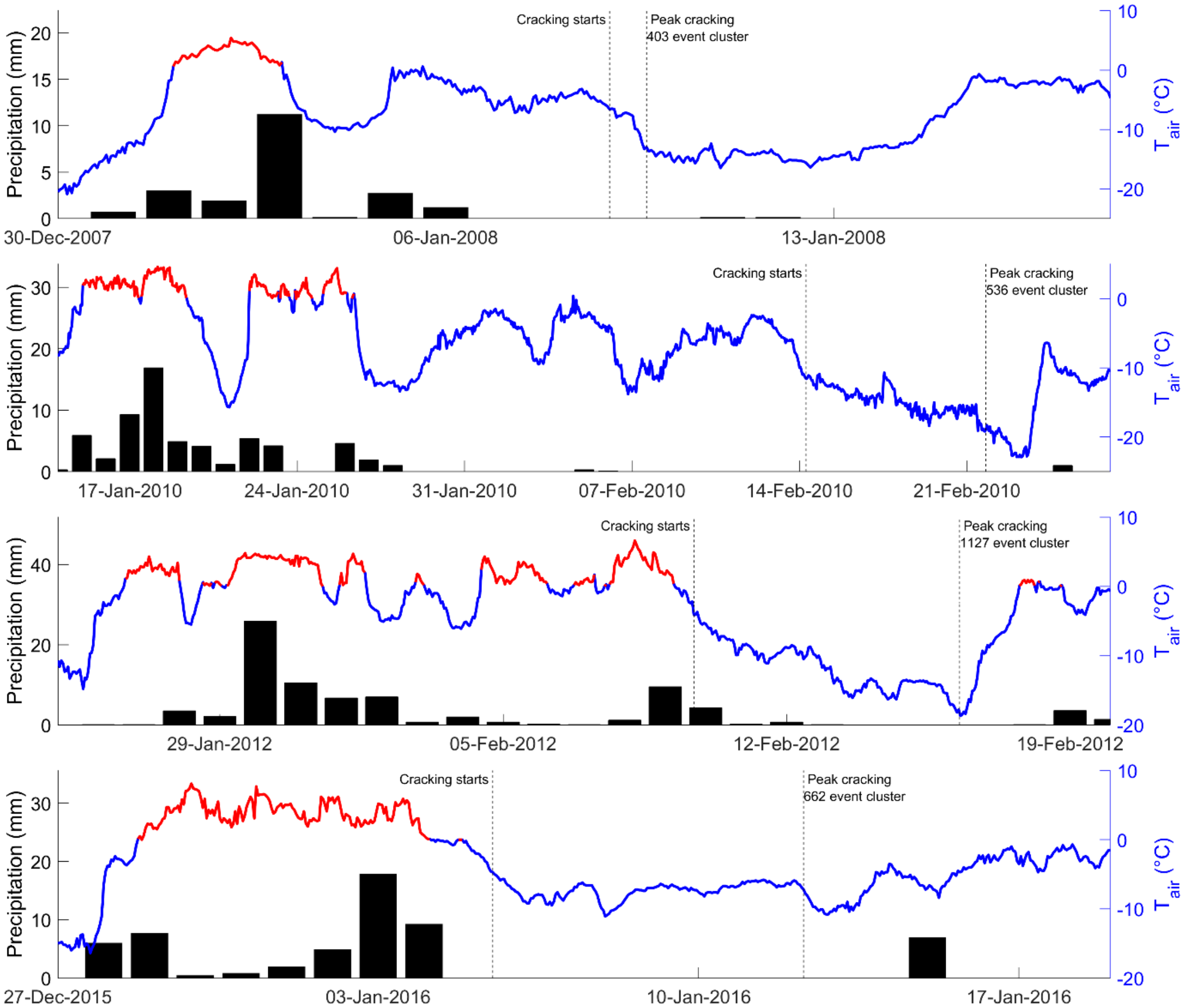

Figure iv – Svalbard airport air temperature (line) and precipitation (bar) records (met.no) illustrate that anomalous spikes in cracking related seismicity were preceded by unseasonably mild temperatures >0 °C (red line) and rain, presumably leading to snow melt, water pooling and surface ice formation as observed in the field at Adventdalen by Matsuoka et al. (2018) in Feb 2010.

Line 418: How does solifluction produce seismic events? See major comment 3.

See previous response to major comment 3. We hypothesise that this is a secondary effect. The downslope movement of frozen debris/solifluction lobes can produce open cracks transverse to the slope. This occurs at the head of the lobe where there is a transition in slope, i.e., convex terrain (e.g. Darrow et al., 2016, Price, 1974). These cracks or fissures can then become filled with ice (referred to as infiltration ice by Darrow et al., 2016). The ice, being weaker under tension than the surrounding ground, is then preferentially cracked when the ground contracts during rapid cooling episodes.

These were helpful comments, because we fully agree that this aspect of the dynamics was not fully elaborated in the submitted manuscript.

Price, L. W. (1974). The developmental cycle of solifluction lobes. Annals of the Association of American Geographers, 64(3), 430-438.

Darrow, M. M., Gyswyt, N. L., Simpson, J. M., Daanen, R. P., & Hubbard, T. D. (2016). Frozen debris lobe morphology and movement: an overview of eight dynamic features, southern Brooks Range, Alaska. The Cryosphere, 10(3), 977-993.

References

Lachenbruch, A. H.: Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost, Geological Society of America, 1962.

Sørbel, L. and Tolgensbakk, J.: Ice-wedge polygons and solifluction in the Adventdalen area, Spitsbergen, Svalbard, Norsk Geografisk Tidsskrift-Norwegian Journal of Geography, 56, 62-66, 2002.

Tolgensbakk, J., Sørbel, L., and Høgvard, K.: Adventdalen, Geomorphological and Quaternary Geological map, Svalbard 1:100,000, Spitsbergen sheet C9Q. , Norwegian Polar Institute, 2000.