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# Retrogressive Thaw Slumps on Ice-Rich Permafrost Under Degradation: Results From a Large-Scale Laboratory Simulation

François Costard, L. Dupeyrat, A. Séjourné, F. Bouchard, A. Fedorov, B. Saint-bézar

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# 1           **Retrogressive thaw slumps on ice-rich permafrost under degradation:**

## 2           **Results from a large-scale laboratory simulation**

3           **F. Costard<sup>1</sup>, L. Dupeyrat<sup>1</sup>, A. Séjourné<sup>1</sup>, F. Bouchard<sup>1</sup>, A. Fedorov<sup>2</sup>, and B. Saint-**  
4           **Bézar<sup>1</sup>**

5  
6           <sup>1</sup>Géoscience Paris Sud (GEOPS), Université Paris-Saclay, 91405, Orsay, France,

7           <sup>2</sup>Melnikov Permafrost Institute, Russian Academy of Sciences, Yakutsk, Russia

8  
9           Corresponding author: François Costard ([francois.costard@universite-paris-saclay.fr](mailto:francois.costard@universite-paris-saclay.fr))

### 10           **Key Points:**

- 11           •       Retrogressive thaw slumps (RTS) result from the thermal destabilization of ice-  
12 rich permafrost as a consequence of increasing subsurface temperature
- 13           •       Experimental RTS were designed to simulate the thawing of ice-rich permafrost  
14 with vertical and horizontal ice layers
- 15           •       Our laboratory simulations show how ground ice heterogeneities influence RTS  
16 development

17

18           **Abstract**

19           In the ice-rich permafrost of the Arctic regions, thermokarst erosion on slopes induces the  
20 formation of large-scale retrogressive thaw slumps (RTS). They have significant  
21 geomorphological, hydrological and biogeochemical impacts on the landscape. Further research  
22 is thus needed to better understand the respective effect of ice content and permafrost  
23 heterogeneities on the dynamics of these erosional features. Here we present results of a full-scale  
24 physical modelling of RTS development in a cold room. The experimental setup was designed to  
25 simulate and compare two ground-ice settings (ice wedges, icy layers) with the thawing of ice-  
26 poor permafrost (i.e.,reference model). Our results show that the melting of the icy layers induces  
27 a loss of decohesion of the overlapping frozen soil. The heterogeneous frozen soil with ice  
28 wedges needs a longer time until degradation, but undergoes a stronger and faster decohesion of  
29 its structure during the thawing phase.

30

31           **1 Introduction**

32           Over the last few years, various studies have documented significant impacts of recent  
33 global warming across the Arctic since the mid-twentieth century, with a preferential thermal  
34 degradation of ice-rich permafrost and the related release of previously sequestered carbon (e.g.,  
35 Grosse et al., 2011; Romanovsky et al., 2010). These studies indicate a sensitivity of cold Arctic  
36 permafrost to climate-driven thermokarst (thaw) initiation (Olefeldt et al., 2016). The  
37 development of thermokarst results from the thermal destabilization of ice-rich permafrost as a  
38 consequence of the increase in subsurface temperature (Soloviev, 1973; French, 2017). Over the  
39 last decades, this ice-rich permafrost has been highly vulnerable and prone to extensive  
40 degradation within the continuous permafrost zone of Eurasia and North America (Olefeldt et al.,  
41 2016; Lewkowicz and Way, 2019).

42           Retrogressive thaw slumps (RTS) represent a dynamic form of thermokarst. They expand  
43 inland by melting of exposed ground ice in the headwall to form landslide-like U-shaped scars  
44 (Lantuit and Pollard., 2008). In the western Canadian Arctic, widespread permafrost degradation  
45 accompanied by active RTS development is mostly observed in ice-rich formerly glaciated  
46 landscapes (Olefeldt et al. 2016, Rudy et al., 2017; Murton et al., 2017; Kokelj et al., 2017; Nitze  
47 et al., 2018). These ice-rich areas contain buried glacier ice that has been preserved under  
48 permafrost conditions (Rudy et al., 2017). They are present in the form of horizontal massive ice

49 layers. In Eastern Siberia, RTS are mostly developed in the Yedoma (Pleistocene-aged) ice  
50 complex area (Opel et al., 2019). In central Yakutia (CY), the upper section of permafrost  
51 contains Pleistocene ice-rich sediments, up to 20–50 m in thickness, containing ~70-80 % of ice  
52 by volume (Soloviev, 1973; Schirrmeister et al., 2020). The Yedoma ice complex is dominated  
53 by huge ice wedges up to a few meters wide and 15-25 meters high within sandy deposits (Opel  
54 et al., 2019; Shepelev et al., 2020). In some places, these large-scale ice wedges can be  
55 continuous and form a massive horizontal ice layer at the base (Opel et al., 2019). In CY, RTS  
56 are smaller than in the High Arctic. Amphitheater-shaped slump hollows are 30-50 m wide and  
57 are characterized by (1) their concave profile of collapsed banks and (2) highly-degraded conical  
58 polygons (Figure 1) with wide troughs referred to as “baydjarakhs” (Soloviev, 1979). This ice-  
59 rich permafrost is characterized by its medium and/or fine sand ( $D_{50}$  200 – 300  $\mu\text{m}$ ) and silty  
60 material ( $D_{50}$  18 – 30  $\mu\text{m}$ ) of Quaternary lacustrine or aeolian (loessic) origin (Schirrmeister et  
61 al., 2020; Soloviev, 1973). These sediments contain ~30–40% of ice by volume, in addition to  
62 large syngenetic ice wedges (Ulrich et al. 2014; Strauss et al., 2017).

63 Several studies estimated the development of RTS in the High Arctic with extended photo  
64 time series (30 years). Headwall retreat rates range from 0.5–1  $\text{m yr}^{-1}$  along thermokarst lakes in  
65 the tundra uplands of the Mackenzie Delta, Canada (Lantz and Kokelj, 2008) to an average up to  
66 0.68  $\text{m}\cdot\text{yr}^{-1}$  and 29.0  $\text{m}^3\cdot\text{m}^{-1}\cdot\text{yr}^{-1}$  on the coast of Herschel Island, Canada, next to the Beaufort Sea  
67 (Lantuit and Pollard, 2008; Obu et al., 2016). Headwall retreat rates of up to 13  $\text{m yr}^{-1}$  were  
68 recently observed in the western coast of Kolguev Island, Russia (Kizyakov et al., 2013). In CY,  
69 the maximal average headwall retreat of these RTS can reach 3.16  $\text{m yr}^{-1}$  for the 2012-2013  
70 period (Séjourné et al., 2015), although maximal values of 30  $\text{m yr}^{-1}$  were recorded at the  
71 Batagay megaslump in Yakutia (Opel et al., 2019). With a length of more than 1000 m, a width  
72 of 800 m and 60 m high headwalls in 2019, this mega-RTS is representative of three typical  
73 cryolithological types of permafrost at a single site. It is characterized by its ice-rich Yedoma  
74 permafrost close to the surface, underlain by ice-poor sands, while at its base a pure ground-ice  
75 layer is present (Shepelev et al., 2020). In close association with the erosion of RTS, small mud-  
76 flows settling on gentle slopes are observed from melted ice wedge network and contribute to the  
77 transport of sediments, dissolved elements and meltwater from the melting of ice wedges (Figure  
78 1a). These RTS liberate both soluble materials and organic carbon accumulated in the  
79 sedimentary deposits that are transported by runoff (Vonk et al. 2015; Shakil et al., 2020). The

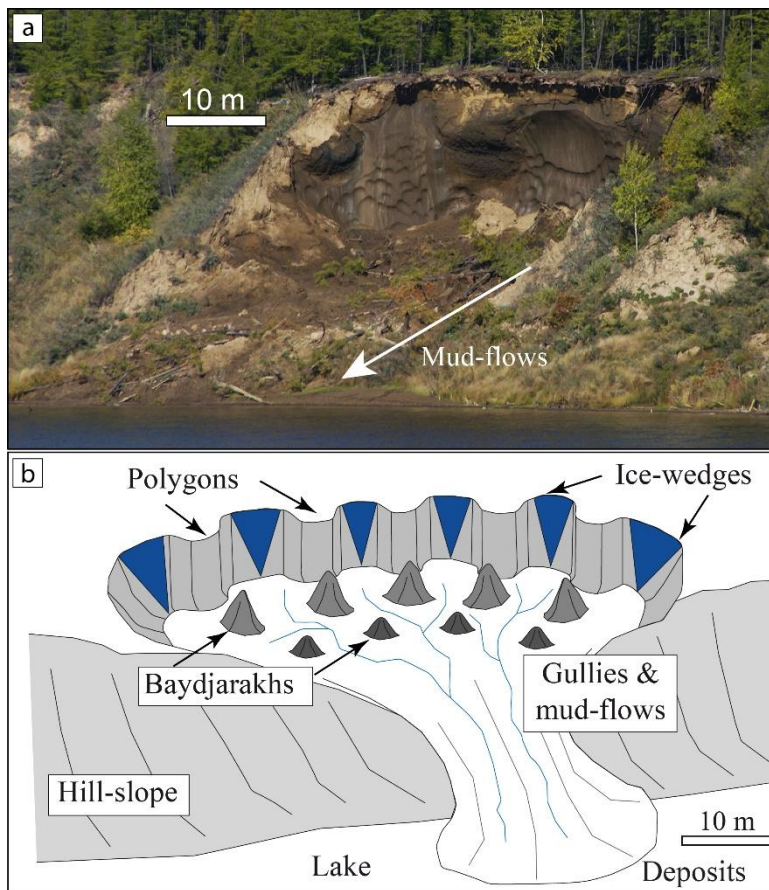
80 abrupt thawing of ice-rich permafrost is thus a major issue because of the positive feedback on  
81 global climate (Schuur et al., 2008; Turetsky et al., 2020).

82         The possible causes of present-day initiation of thermokarst are numerous but their  
83 interrelations are not well understood. According to Ward Jones et al. (2019), record summer  
84 warmth in 2011 and 2012 in the Canadian Arctic promoted thermokarst initialization in  
85 previously unaffected terrain. Permafrost degradation is always initiated by deepening of the  
86 active-layer as a consequence of an increase in subsurface temperature (Fedorov et al., 2014;  
87 Fedorov and Konstantinov, 2009). Retrogressive thaw slumps are initiated by a variety of  
88 mechanisms that expose ice-rich sediments, including mechanical erosion by fluvial processes,  
89 wave action, thermally driven subsidence along the banks, and mass-wasting (Burn and  
90 Lewkowitz 1990; Wolfe et al., 2001; Lantuit and Pollard, 2008; Kokelj et al., 2017; Lacelle et  
91 al., 2010). According to Segal et al. (2016), climate change, in conjunction with increases in air  
92 temperature and precipitation, induces an acceleration of RTS activity. According to Séjourné et  
93 al. (2015), RTS in CY mainly occur along the south- to southwest-facing banks of thermokarst  
94 lakes due to solar insolation and increased air temperature. However, the timing of this recent  
95 increase over the last few decades and its links to climate have not been fully established (Lantuit  
96 and Pollard, 2005; Lantz and Kokelj, 2008; Wolfe et al., 2001). Local differences in recent  
97 erosion rates across the circumpolar Arctic may be due to a difference in local climate, headwall  
98 height, and ice content (Kokelj and Jorgenson, 2013). Other authors suggest that the presence of  
99 massive ground ice (ice wedges, massive segregated ice, buried glacier ice) is a precondition for  
100 RTS development. (Leibman et al., 2008; Lantuit et al., 2012). While it was observed that RTS in  
101 CY develop in Yedoma ice complex terrain with huge syngenetic ice wedges (Figure 1b), the  
102 heterogeneous structure of ice-rich permafrost and its subsequent influence on thermokarst  
103 degradation has not been analyzed. The relative importance of the main parameters affecting RTS  
104 are, however, difficult to assess in the field. Numerous factors work simultaneously, and their  
105 interdependence makes their separate analysis difficult. Physical modelling provides a unique  
106 tool for a more detailed monitoring compared to field observations.

107         Here, we present results of a full-scale physical modelling of RTS development in a cold  
108 room. For this purpose, the experimental RTS were designed to simulate the thawing of ice-rich  
109 permafrost with various heterogeneities (ice wedges, icy layers) that were supposed to be  
110 representative of RTS development in CY. In a first experimental set-up, we simulated artificial

111 ice wedges (vertical ice layers), which are common in large parts of continuous permafrost across  
 112 the Northern Hemisphere (i.e., polygonal landscapes and Yedoma ice complex). In a second set-  
 113 up, horizontal ice layers mimic a second type of ice-rich permafrost that might find its natural  
 114 expression in formerly glaciated Arctic landscapes with soft sediments and large masses of  
 115 segregated ice or buried glacier ice. Each experimental set-up was compared to reference frozen  
 116 ground with no excess ice. Therefore, this study is representative of three typical cryolithological  
 117 types of permafrost in unconsolidated material, which cover several hundreds of thousands of  
 118 km<sup>2</sup> in the Arctic.

119



120  
 121 Figure 1: (a) Headwall of retrogressive thaw slumps (RTS) along a thermokarst lake in central  
 122 Yakutia (Eastern Siberia). Permafrost with alluvial sandy loam containing up to 40-50% of ice by volume  
 123 and syngenetic ice-wedges of ~7 m in thickness. (b) The localized melting of ice wedges along the banks  
 124 of thermokarst lakes forms highly-degraded conical polygons with wide troughs (baydjarakhs). These  
 125 typical structures are indicative of heterogenous ice-rich permafrost with a preferential erosion along ice  
 126 wedges.

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## 2 Experimental setup

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Physical modelling of RTS was undertaken using large-scale frozen soils in a temperature-controlled chamber. The major purpose of the experiment was to examine the respective effects of different ground-ice content and type affecting the ground thermal regime and vulnerability to subsidence. We used the cold-room at the GEOPS laboratory (University Paris Saclay, France) dedicated to the physical modelling in periglacial geomorphology. The specificity of our experiments was to simulate the thawing of ice-rich permafrost, compared to the thawing of ice-poor permafrost (i.e., reference conditions). In a first experimental setup (experiment n°1), we worked with artificial ice wedges (vertical ice layers, see SI1), which are common in large parts of continuous permafrost across the Northern Hemisphere (i.e., polygonal landscapes). In a second setup (experiment n°2), we worked with horizontal ice layers mostly typical of formerly glaciated Arctic landscapes with soft sediments and large masses of segregated ice or buried glacier ice (see SI2). Our experiment is composed of a rectangular box of 2.5 m x 2.5 m wide and 0.5 m deep in which fine sand ( $D_{50} = 200 \mu\text{m}$ ) was saturated with water (Figure 2). Here, we used the grain size distribution of Bayeux sand as an analog to sands from the banks of most RTS in CY. The basal slope was  $5^\circ$  for the release of meltwater overflow during the thawing phase. A foam rubber was placed all around the experiment to ensure thermal insulation. For each experiment, the sediment structure was homogeneous and had a water content of 20% by volume. A well-proven technique was used to create a homogeneous porous medium of more than one ton of saturated soil (Costard et al., 2003). To obtain the optimal porosity at water saturation, we first mixed the sand with water to a wet density of  $1.81 \text{ g.cm}^{-3}$  corresponding to the “Proctor compaction” technique (Costard et al., 2003). We manually compacted layers of 10 cm each and then put them on top of each other until 0.5 m thickness was reached. Such technique allows a parametric control on a homogeneous block of about 1 ton of already saturated material with a volumetric water content of 20 %. There might be some small interfaces (thin unconformities), but they remain insignificant. In order to evaluate the effect of permafrost heterogeneities on the development of RTS, we artificially built vertical and horizontal ice layers to respectively mimic ice wedges and icy beds (volumetric ice content of 100 %). Before the freezing phase, each icy block was installed within the right side of the experiment (see Figures SI1 and SI2). Finally, all the material was frozen in the cold room at -

158 25°C and then progressively reheated at -10°C (Figures SI3 and SI4). This technique allowed us  
 159 to prepare homogeneous samples with reproducible densities and without ice segregation  
 160 (Costard et al., 2003). Figures 2, SI1 and SI2 show the homogeneous model S1 (or reference  
 161 model) on the left, and the heterogeneous model S2, which corresponds to a ice rich permafrost  
 162 with a total of 30 % ice by volume, on the right. The size, geometry and spacing of these icy  
 163 blocks within the frozen soil represent a simplification of the natural setting, but the main  
 164 objective here was to understand the influence of heterogeneities on permafrost degradation from  
 165 a strictly thermal point of view.



166  
 167 Figure 2: RTS experiment n°1 (with ice wedges) of 2.5 m x 2.5 wide and 0.5 m height showing on  
 168 the left side a homogeneous frozen soil and on the right side the same frozen soil (saturated fine sand)  
 169 with additional artificial ice wedges. The thick vertical brown line on the top of each photo separates left  
 170 from right part. Active erosion due to the presence of ice wedges is observed on the right side of the  
 171 experiment. White cables correspond to temperature sensors.

172  
 173 Figure 2 presents the case of RTS development in an ice-wedge setting with pure ice  
 174 blocks of 5 cm thick. In experiment n°2, we added horizontal heterogeneities (pure icy layers)  
 175 instead of ice-wedges (Figure SI2). In that experiment, we artificially built icy layers of 10 cm in  
 176 thickness and set them up in the right part of the experiment in the cold room (Figure SI2). We  
 177 used the same protocol as for the experiment n°1 for preparing the frozen soil. The left side of the  
 178 experiment corresponds to the reference model with saturated and homogeneous frozen ground.



179 All the models were instrumented using ten temperature sensors (platinum resistance  
180 thermometers Pt100 with  $\pm 0.1^\circ\text{C}$  accuracy) to survey the freezing and thawing front vs. time. A  
181 first series of 5 sensors, spaced every 5 cm, was placed in the homogeneous frozen soil at a depth  
182 of 20 cm. A similar series of sensors was placed in the frozen soil with ice heterogeneities  
183 (Figures SI1 and SI2). During each simulation, we also analyzed the development of associated  
184 degradation landforms using time-lapse photography with a video camera (Figures SI5 and SI6).  
185 This allows later analysis of the repeated observation of permafrost degradation. For each  
186 experiment, we compared ice-rich permafrost degradation (with a total of 30 % ice by volume)  
187 with a reference model (homogeneous permafrost with 20% ice by volume). In these  
188 experiments, we assumed that the scale effect was not a limiting factor. Here, we restricted our  
189 approach to the relative importance of the heterogeneities (ice wedges, icy layers) and their  
190 thermal influence on permafrost degradation.

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### 192 **3 Results and discussion**

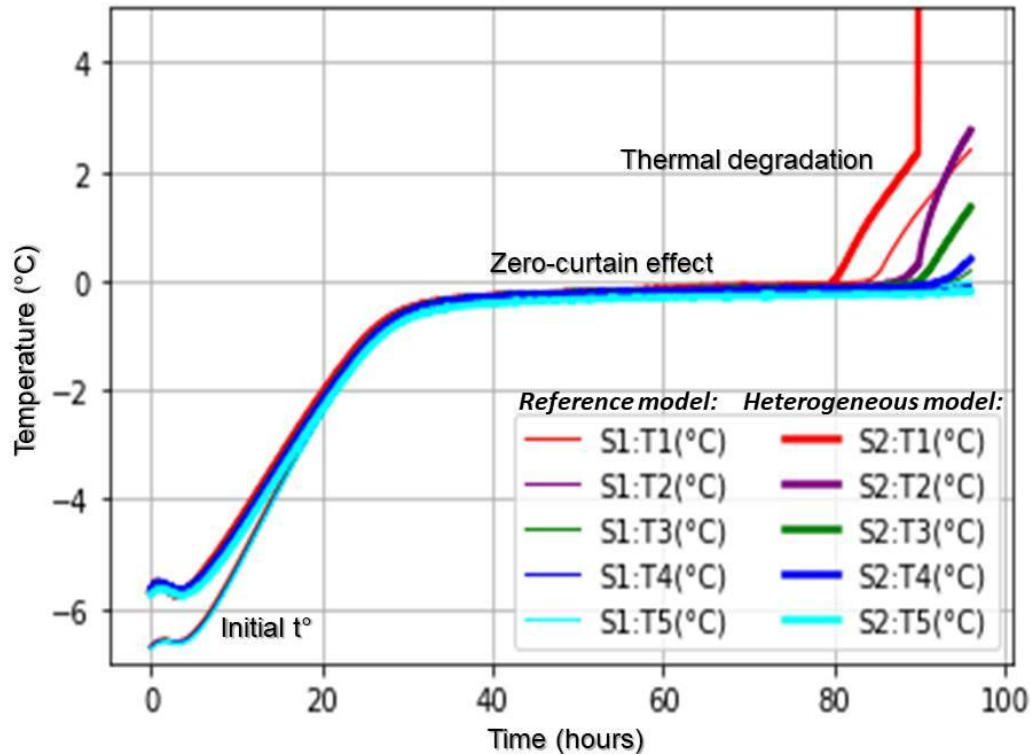
193 Our objective was to test different scenarios (different types of heterogeneities), but also  
194 different environments. Therefore, we tested permafrost thawing with different initial  
195 temperatures ( $-6^\circ\text{C}$  and  $-10^\circ\text{C}$ ) and different warming conditions (slight and severe). Figure  
196 3 shows the typical case of a slight warming, whereas Figure 4 presents a more severe scenario  
197 (i.e. with a steeper warming phase).

198 For experiments n°1 and n°2, we started to analyze the data recording when all  
199 temperatures in the frozen ground were stabilized at around  $-6^\circ\text{C}$  and  $-10^\circ\text{C}$  respectively. We  
200 performed a systematic measurement of the thermal wave propagation from the ten Pt100 sensors  
201 during the warming phase (Datasets SI3 and SI4). Three main stages within that warming phase  
202 were recorded (Figures 3 and 4): (i) The first stage corresponds to a rapid increase in the  
203 temperature monitored for all sensors, within approximately 24 hours, with all sensors reaching  
204  $0^\circ\text{C}$ . (ii) The second stage corresponds to a period of relatively stable temperatures around  $0^\circ\text{C}$   
205 due to the zero-curtain effect (latent heat release). A considerable amount of heat has to warm the  
206 ground up to the melting point before ablation can proceed, in agreement with recent  
207 investigations on temperature-dependent RTS development (Zwieback et al., 2018). (iii) The  
208 third stage starts when sensors record positive temperatures.

209 In experiment n°1, the reference model (left side of the experiment on Figure 2) showed a  
210 relatively slow rise of temperatures (Figure 3). On the contrary, the heterogeneous frozen soil  
211 (right side of the experiment on Figure 2) showed a rapid increase of soil temperature, notably  
212 faster than the reference model (Figure 3). From a morphological point of view (Figures 2 and  
213 SI5), the homogeneous block (reference model) remains stable (without any deformation, even  
214 after thawing during the warming phase), while the heterogeneous one shows dramatic evolutions  
215 (slumping, subsidence). In experiment n°2 with horizontal heterogeneities (icy layers), again the  
216 reference model (homogenous frozen soil) remained mechanically stable without subsidence,  
217 even after complete thawing (Figure SI6). On the contrary, the heterogeneous frozen soil with icy  
218 layers showed a clear subsidence due to the melting of the excess ice. From a thermal point of  
219 view, we can observe a relatively faster warming of the heterogeneous frozen soil and a relatively  
220 colder temperature for the reference model (Figure 4). The analysis of the time-lapse  
221 photography (Figure SI5) clearly shows the evolution of the individual blocks of permafrost in  
222 between ice wedges (i.e., modeled polygon centers) towards a hummocky morphology similar to  
223 the development of high-centered polygons (i.e., baydjarakhs). Our experiments clearly show the  
224 detachment and vertical subsidence of individual blocks along ice wedges and the subsequent  
225 formation of ‘mud’ flow at the basal slope due to the basal concentration of oversaturated  
226 sediments (Figure SI5), in agreement with previous laboratory work focused on rainfall-induced  
227 slope failures (Tohari et al., 2007).

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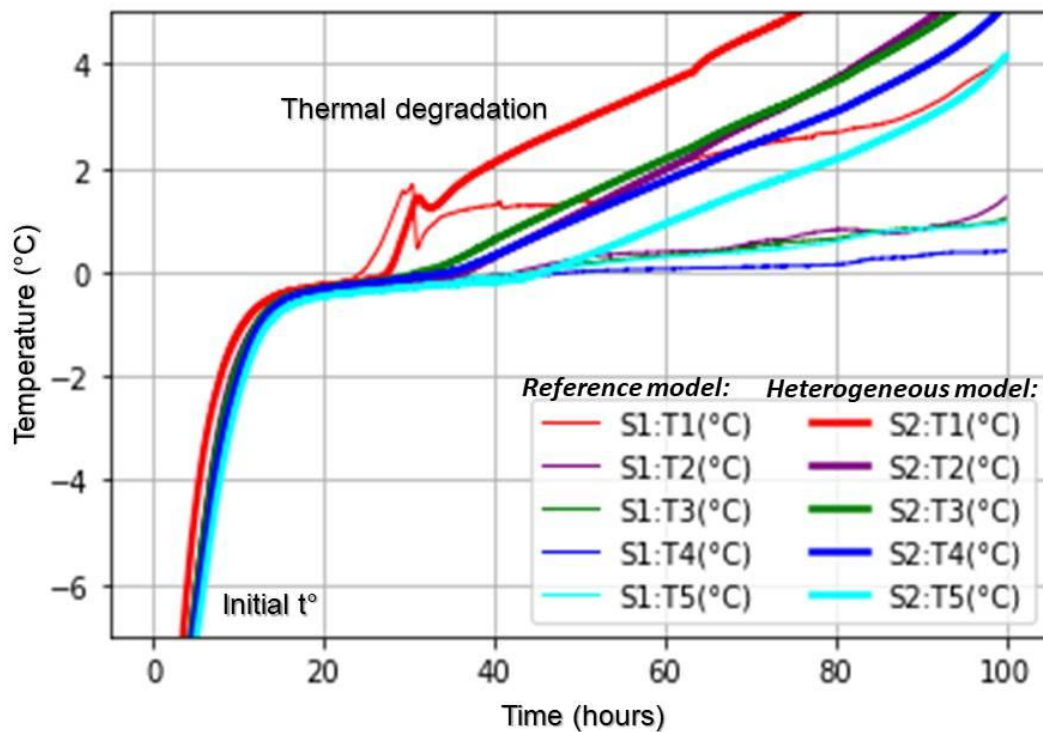
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230  
 231 Figure 3: Experimental setup n°1: Evolution of temperature in homogeneous frozen soil (thin  
 232 lines: S1) and heterogeneous frozen soil with artificial ice wedges (bold lines: S2). A first series of 5  
 233 sensors (S1:T1 to S1:T5), spaced every 5 cm, was placed in the homogeneous frozen soil at a depth of 20  
 234 cm. A similar series of sensors was placed in permafrost with ice heterogeneities (S2:T1 to S2:T5). In both  
 235 blocks, the temperature is similar in the first heating stage and in the following zero-curtain effect stage.  
 236 After melting, greater temperatures are observed in the heterogeneous permafrost compared to the  
 237 homogeneous one.

238  
 239 In experiment n°1, the efficient warming in heterogeneous soil can be related to the  
 240 melting of ice wedges (Figure 2) and the formation of associated voids along the ice wedges that  
 241 allow for a better heat diffusion within the thawing soil. In fact, during the thawing phase, the  
 242 progressive melting of ice wedges (excess ice) induces a larger heat capacity of liquid water that  
 243 enhances temperature increase of the soil. All the experiments showed that ice wedges increase  
 244 the preferential erosion during the warming phase and supply meltwater to the thawing frozen  
 245 interface, which accelerates basal slumping. These observations are in agreement with field  
 246 observations of RTS from Lantuit et al. (2012) and Séjourné et al. (2015). For experiment n°2,  
 247 the melting of the icy layers induces a loss of cohesion of the overlapping frozen soil (Figure SI6:

248 video material) and a better warm air circulation within the soil. These results indicate that  
 249 discontinuities (ice wedges, icy layers) in frozen soils are much more prone to intense thermal  
 250 degradation (warming and thermokarst development) compared to homogeneous and ice-poor  
 251 permafrost. Our laboratory results are in agreement with recent investigations along the Batagay  
 252 thaw slump in Yakutia, where the presence of a basal horizontal ice layer of merged ice wedges  
 253 is the precondition for its deep incision, while the continuous presence of large ice wedges close  
 254 to the surface seems to be decisive for its large areal extend and exponential growth (Opel et al.,  
 255 2019).  
 256



257  
 258 Figure 4: Experimental setup n°2: Evolution of temperatures of modelled heterogeneous  
 259 permafrost (bold lines: S2) with horizontal heterogeneities (icy layers). Thin lines (S1) correspond to the  
 260 homogeneous frozen soil (reference model).  
 261  
 262

## 263           **4       Conclusions**

264           The underpinning question of our study was to evaluate the main controlling factors of the  
265 formation of retrogressive thaw slumps. Cryogeological (granulometry, ice-content and type) and  
266 climatological conditions differ greatly across regions where RTS can be observed. We simulated  
267 two major ground-ice settings (ice wedges and buried massive ice) compared to a reference  
268 model (low ice content). Therefore, this study is representative of three typical cryolithological  
269 types of permafrost, which can be found at one site together (Batagay megaslump in Central  
270 Yakutia). Our study allows a normalized view on RTS development assuming equal thermal,  
271 volumetric ground-ice and grain size conditions and contributes to a better understanding of the  
272 relative contribution of heterogeneities, during permafrost degradation processes. Our laboratory  
273 simulations attest the efficiency of heterogeneities that control thermokarst and RTS development  
274 by two main mechanisms: (i) the strong decohesion of its structure during the thawing phase and  
275 an easier circulation of warm air (Figures 3 and 4), and (ii) the excess of water from the  
276 preferential melting in ice-rich permafrost, which increases the slumping effect (Figures SI5 and  
277 SI6).

278           We calculated the onset of degradation for each experimental setup using the duration of the  
279 zero-curtain effect. The moderate initial temperature and the slight warming phase of model 1  
280 (ice wedges, Figure 3) induce a longer onset of degradation than the one for model 2 (icy layers  
281 under a severe warming condition, Figure 4). The ice-wedge type needs more time before  
282 degradation, but then this degradation occurs more rapidly compared to model 2 (icy layers). Our  
283 experimental approach suggests that the ice-wedge setting strongly increases the efficiency of  
284 RTS development.

285           This study provides a better understanding of how ground-ice heterogeneities influence  
286 RTS development, hence serving as a point of reference for future in situ studies of periglacial  
287 geomorphic processes and their impacts on the carbon cycle in the Arctic.

288

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300

### 301 **Authors contributions:**

302 F.C. conceived, designed and carried out the cold-room experiment. A.S. and F.B.  
303 developed the hypothesis and its implications. L.D. created and performed calculations of the  
304 thermal database, and B.S.B. and A.F. guided the research effort and discussions. The manuscript  
305 was collectively written by F.C., A.S. and F.B. All authors provided input on the manuscript and  
306 the broader implications of this work.

307

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