

Review article: Retrogressive thaw slump characteristics and terminology

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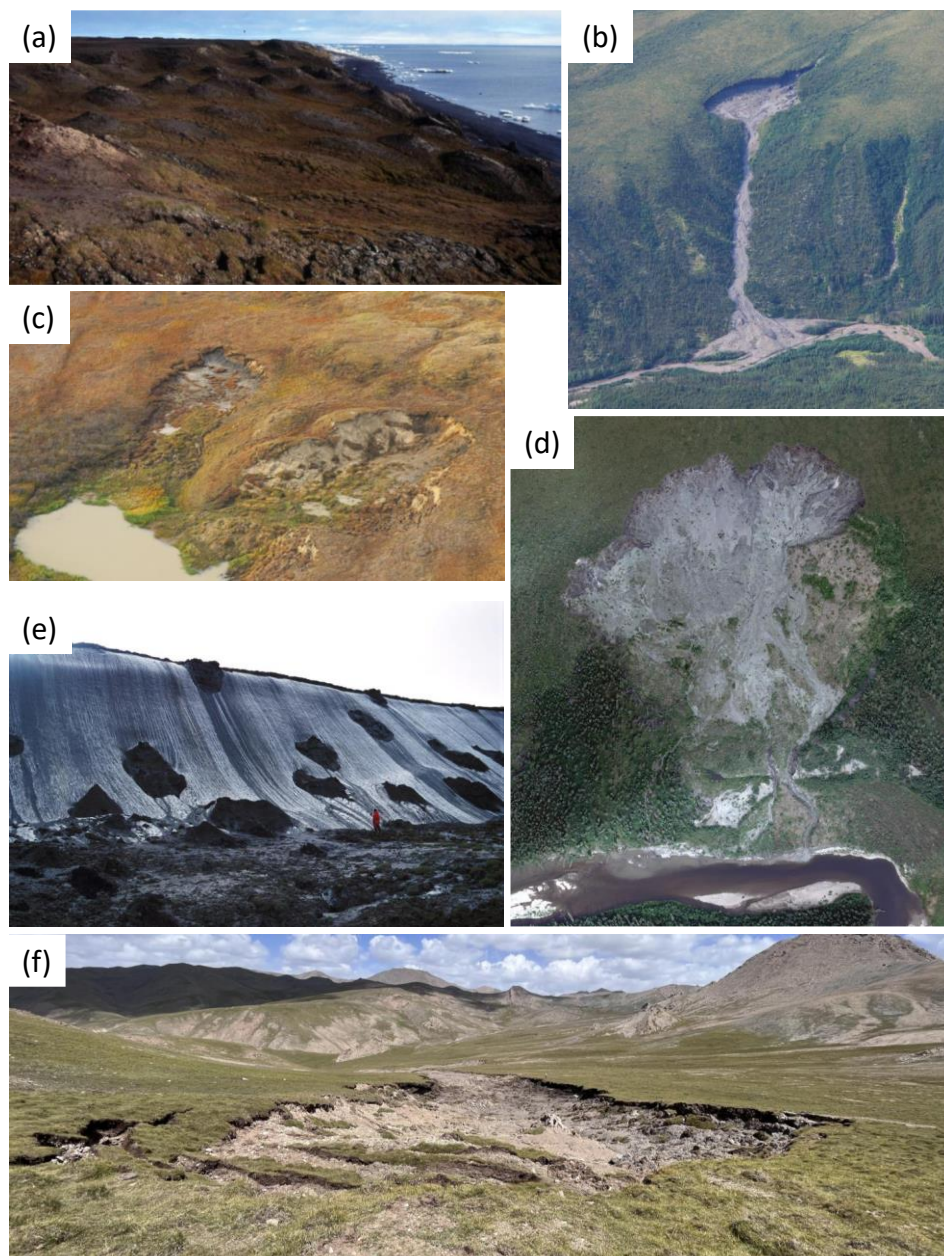
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Abstract. Retrogressive thaw slumps (RTSs in plural and RTS in singular) are spectacular landforms that occur due to the thawing of ice-rich permafrost or melting of massive ground ice often in hillslope terrain. RTSs occur in the Arctic, Subarctic as well as high mountain (Qinghai–Tibetan Plateau) permafrost regions and are observed to expand in size and number due to climate warming. As the observation of RTS is receiving more and more attention due to their important role in permafrost thaw, impacts on topography, mobilization of sediment, carbon, nutrients, and contaminants, and their effects on downstream hydrology and water quality, the thematic breadth of studies increases and scientists from different scientific backgrounds and perspectives contribute to new RTS research. At this point, a wide range of terminologies originating from different scientific schools is being used and we identified the need to provide an overview of variable characteristics of RTS to clarify terminologies and ease the understanding of the literature related to RTS processes, dynamics, and feedbacks. We here review the theoretical geomorphological background of RTS formation and landform characteristics to provide an up-to-date understanding of the current views on terminology and underlying processes. The presented overview can be used not only by the international permafrost community but also by scientists working on ecological, hydrological, and biogeochemical consequences of RTS occurrence as well as remote sensing specialists developing automated methods for mapping RTS dynamics. The review will foster a better understanding of the nature and diversity of RTS phenomena and provide a useful base for experts in the field but also ease the introduction to the topic of RTSs for scientists who are new to it.

1 Introduction

Permafrost in the Arctic is impacted by thawing in step with ongoing pronounced Arctic warming due to climate change (Biskaborn et al., 2019; Smith et al., 2022). Thaw of ice-rich permafrost results in the formation of characteristic landforms due to sometimes rapid terrain subsidence and erosion. One typical and regionally widespread landform formed by the thaw of ice-rich permafrost or melting of massive ground ice is a slope failure termed retrogressive thaw slump (RTS) (Mackay, 1966). These spectacular landforms in the Northern Hemisphere occur throughout the Arctic, Subarctic, and high mountain

33 regions (Qinghai–Tibetan Plateau) with ice-rich permafrost and have a significant environmental impact (Kokelj and
34 Lewkowicz, 1999). Figure 1 shows examples of different RTSs photographed across the Northern Hemisphere. RTSs exhibit
35 regional variations in their appearance and characteristics.



36

37 **Figure 1** Various RTSs across the Northern Hemisphere: (a) stabilized yedoma RTS on Belkovsky Island, NE Siberia, Russia,
38 September 2002, photo: Guido Grosse, (b) RTS in the Peel Plateau, NW Canada, July 2023, photo from the airplane: Guido Grosse,
39 (c) two RTSs in the central Gydan Peninsula, West Siberia, Russia, September 2020, photo from helicopter: Elena Babkina, (d) RTS
40 in Selavik, Alaska, USA, July 2021, aerial camera image, credit: AWI, (e) yedoma RTS in Oyagos Yar, NE Siberia, Russia,
41 September 2002, photo: Guido Grosse, (f) RTS in The Qinghai–Tibet Plateau, China, August 2023, photo: Zhuoxuan Xia.

42 RTS initiation not only alters the topography, hydrology, and vegetation cover but also contributes to substantial sediment,
43 carbon, and nutrient fluxes to downstream environments with impacts on water quality and aquatic ecosystems (Kokelj et al.,
44 2005; Mesquita et al., 2010).

45 Historically, RTS research started with the first mention of exposed ice in a retrogressive thaw slump probably dating back to
46 1881 by Dall in his publication on observations in Alaska (Dall, 1881) The first intensive studies on RTSs were conducted
47 much later in the latter half of the 20th century in Canada (Lamothe and St-Onge, 1961; Mackay, 1966; Kerfoot, 1969) and
48 Siberia (Popov et al., 1966; Czudek and Demek, 1970). These studies on RTSs were field-based and focused on ground ice,
49 morphometry, and dynamics. The publications were written either in English or Russian language with different terms applied
50 to these landforms depending on scientific approaches. Unfortunately, the level of knowledge exchange and reciprocal citation
51 among RTS researchers from Canada and the USSR was relatively low, leading to the establishment of disparate views and
52 terminology for RTS used in the literature.

53 The strong rise in scientific exchange and international collaborations at the end of the 20th century, including joint expeditions
54 within the permafrost community in general and within the topic of RTS in particular (i.e., Vaikmäe et al., 1993; Ingólfsson,
55 and Lokrantz, 2003; Are et al., 2005), as well as the emergence of remote sensing methods substantially broadened the scope
56 of RTS research (Romanenko, 1998; Lantuit and Pollard, 2005; Lantz and Kokelj, 2008; Leibman et al., 2021). Today, a large
57 body of recent literature predominantly focuses on monitoring RTS activity by measuring retreat rates (Kizyakov et al., 2006;
58 Wang et al., 2009; Laccelle et al., 2010) and volume changes (Kizyakov et al., 2006; Clark et al., 2021; Jiao et al., 2022;
59 Bernhard et al., 2022), identifying driving factors (Harris and Lewkowicz, 2000; Laccelle et al., 2010), or more generally
60 mapping of RTSs (Pollard, 2000; Lipovsky and Huscroft, 2006; Khomutov and Leibman, 2008; Swanson, 2012; Segal et al.,
61 2016). Recent publications on RTS mapping notably shifted away from a focus on geological and geomorphological aspects
62 to developing advanced methodologies of RTS detection and classification using spatially and/or temporally high-resolution
63 remote sensing data and digital elevation data, frequently employing artificial intelligence methods (Huang et al., 2020; Nitze
64 et al., 2021; Yang et al., 2023).

65 However, despite the increasing number of studies and strongly rising interest in RTS among the permafrost and remote sensing
66 research communities, there is still no commonly agreed terminology on the RTS phenomenon. Various authors apply different
67 terminology to describe the same morphology and processes or use the same terms for different processes. This leads to several
68 difficulties in communication about RTS within and across research communities. First of all, since the terminology is not
69 always clearly defined or translated in the literature it can lead to potential misunderstandings about what exact features or
70 processes have been investigated in a particular study. The confusion about the object of the study may cause incomparability
71 of the datasets from different RTS studies. Furthermore, different labeling of the same features may result in a completely
72 different image of the phenomena. For example, Nitze et al. (2024, in review) conducted an experiment where 12 domain
73 experts from different countries manually mapped RTSs in Canada and Russia. The results demonstrated a large mismatch of
74 the RTS labeling in Yakutia, Russia, which can be partially explained by different terminology used in the publications
75 describing this region. The confusion in the terminology and labeling of RTSs can also affect the related studies on how RTSs

76 impact hydrology, geochemistry, and ecology or their physical modeling, based on the established terms and concepts in the
77 literature. Moreover, various terms used in the keywords lead to new publications and new data being missed and not included
78 in further reviews.

79 This work aims to clarify the existing terminology of RTS phenomena and ease the understanding of published studies. The
80 paper presents commonly observed RTS characteristics and a neutral review of existing RTS terminology in the literature. Our
81 review considers a broad variety of RTSs in the Northern Hemisphere.

82 **2 Observed characteristics of retrogressive thaw slumps**

83 **2.1. Morphometry and dynamics**

84 RTSs can be of various sizes starting from less than 0.1 ha in area and reaching up to ~80 ha as the Batagay slump, Yakutia,
85 Russia (Kizyakov et al., 2023). Some authors describe RTSs larger than 5 ha (Kokelj et al., 2015) or larger than 20 ha (Lacelle
86 et al., 2015) as megaslumps. Known RTS headwall (in the meaning of the entire steep wall) heights range from a few meters
87 up to 55 m in Batagay slump (Kizyakov et al., 2023). RTS headwall length can exceed 1 km as reported for Yakutia, Russia
88 (Costard et al., 2021).

89 Reported length-to-width ratios range from below 1 (Lantuit and Pollard, 2008; Ardelean et al., 2020) up to 3 (Niu et al., 2016)
90 and even 5 (Lantuit and Pollard, 2008). Some field studies in Canada suggest that this ratio increases with time due to the
91 headwall retreating faster than the sidewalls, leading to a landform lengthening (Lewkowicz, 1987b). Other studies in Siberia
92 report the widening of RTSs with time due to their merging with neighboring RTSs (Runge et al., 2022; Leibman et al., 2023).
93 RTS dynamics can be estimated by measuring headwall retreat rates. Reported RTS headwall retreat rates vary from several
94 cm per year in Qinghai–Tibetan Plateau, China (Sun et al., 2017) to up to ~66 m per year estimated for Yugorsky Peninsula,
95 Russia (Leibman et al., 2021). Similar extreme headwall retreat rates of ~27 m per year were reported for some RTS in Canada
96 (Lacelle et al., 2015; Jones et al., 2019).

97 **2.2. Position and topography**

98 RTSs form inland or on the coasts. Inland RTS can be found at lake shores, riverbanks, slopes of temporary streams, or valley
99 slopes. As an RTS develops, the thawed material is transferred downstream to valley bottoms or the nearest water body.

100 The extent of RTSs appearing at a particular position varies and is strongly controlled by the topographical and geological
101 characteristics of the area. For example, RTSs in mountain regions mostly occur on slopes unrelated to the waterbodies, as in
102 the Qinghai-Tibetan Plateau, China (Niu et al., 2012; Huang et al., 2018; Hu et al., 2019), or in the Yana Highlands, East
103 Siberia (Kizyakov et al. 2023), while RTSs in the flat terrain of the Yamal and Gydan peninsulas, West Siberia, are generally
104 found next to lake shores (Nesterova et al., 2021). A first analysis across the Arctic has not revealed any correlations between
105 the influence of RTS position in the terrain and its size or activity so far (Bernhard et al., 2022).

106 RTSs were found across a wide range of slopes, including on gentle terrain slopes of $<5^\circ$ (De Krom, 1990; Leibman et al.,
107 2023), medium slopes of 5 to 10° (Niu et al., 2016), as well as on steep slopes $>10^\circ$ (Czudek and Demek, 1970; Barry, 1992;
108 Robinson, 2000). Some studies found that RTSs on steeper slopes tend to have higher headwall retreat rates (see Sect. 3.1.1)
109 than those that occur on less steep slopes (Robinson, 2000).

110 RTSs occur on a great variety of slope aspects. While some studies investigating different regions across the Arctic reported
111 that their observed RTSs tended to have different prevailing slope orientations (Kokelj et al., 2009; Lacelle et al., 2015; Jones
112 et al., 2019; Nesterova et al., 2021; Bernhard et al., 2022), several other studies found that higher RTS ablation rates and
113 headwall retreat (see Sect. 3.1.1) are related to southern aspects (Lewkowicz, 1987a; Grom and Pollard, 2008; Lacelle et al.,
114 2015). However, several other studies did not find any link between the slope aspect and RTS activity (Wang et al., 2009;
115 Nesterova et al., 2021; Bernhard et al., 2022). Bernhard et al. (2022) suggested that differences in the RTS aspect may be
116 explained by regional geological history that defines ice content and ice distribution, which are the main factors of RTS
117 occurrence (Mackay, 1966; Kerfoot, 1969).

118 **2.3. Ground ice**

119 A high excess ground ice content is a prerequisite for RTS occurrence. The shallower the ground ice table the higher the
120 likelihood that seasonal thawing will reach and start melting the ice, potentially triggering the initiation of the RTS. Regions
121 with abundant ground ice presence in Canada feature widespread and ubiquitous slumps (Lamothe and St-Onge, 1961;
122 Mackay, 1966; Kokelj et al., 2017). Similar observations were reported for Central Yamal, Russia (Babkina et al., 2019). RTS
123 in areas with a thinner ground ice-rich layer tend to stabilize faster due to the rapid ice exhaustion (Kizyakov, 2005). The type
124 of ground ice and its local distribution can define some morphologic characteristics of RTS (see Sect. 3.1) and affect retreat
125 rates. For example, RTS forming in syngenetic ice-rich Yedoma deposits with polygonal ice wedges are usually accompanied
126 by the presence of baydzherakhs (conical remnant mounds, for details, see Sect. 3.1.6) on the slump floors. De Krom and
127 Pollard (1989) found that on Herschel Island, Canada, large ice wedges melted slower than the enclosing massive ground ice
128 body. While abundant ground ice is necessary for RTS formation it is not the only control for RTS occurrence.

129 **2.4. Triggers**

130 An RTS forms once very ice-rich permafrost or massive ground ice becomes exposed for any reason and starts melting.
131 Triggers of this exposure can be any anthropogenic or natural permafrost disturbances.

132 Anthropogenic triggers can be any disturbance of the thermal balance of the permafrost due to direct human actions. For
133 example, mining was reported to trigger ice exposure and further formation of RTS in Canada (Fraser and Burn, 1997) and on
134 the Qinghai–Tibetan Plateau, China (Wei et al., 2006; Niu et al., 2012).

135 Natural triggers can be separated into climatic, geomorphological, and wildfires. Wildfire removes vegetation and possibly the
136 upper protective organic soil layer leading to deeper thaw than normal (Harry and MacInnes 1988; Jorgenson and Osterkamp,

137 2005; Lacelle et al., 2010). Climatic triggers are generally associated with a deepening of the active layer and the subsequent
138 thawing of ice-rich deposits or massive ground ice. It can be caused by:

139 • unusually long warm weather periods (Lacelle et al., 2010; Balser et al., 2014; Swanson and Nolan, 2018; Lewkowicz
140 and Way, 2019; Jones et al., 2019), or

141 • heavy precipitation and snowmelt events (Leibman et al., 2003; Lamoureux and Lafreniere, 2009; Balser et al., 2014).

142 Geomorphological triggers slightly differ inland and on the coasts. Coastal triggers reported in the literature include:

143 • thermal erosion (or thermo-erosion) (Burn and Lewkowicz, 1990; Lantuit et al., 2012; Kokelj and Jorgenson, 2013),

144 or

145 • coastal erosion (Burn and Lewkowicz, 1990; Burn, 2000; Dallimore et al., 1996; Lantuit et al., 2012; Kokelj and
146 Jorgenson, 2013; Ramage et al., 2017; Lewkowicz and Way, 2019).

147 RTS formation can also be initiated due to inland geomorphological triggers such as:

148 • development of thermo-erosional gullies downwards (Czudek and Demek, 1970; Jones et al., 2019),

149 • mechanical riverbank and lakeshore erosion (Burn, 2000; Burn and Lewkowicz, 1990; Lewkowicz and Way, 2019;
150 Jones et al., 2019),

151 • thermokarst subsidence (Romanovskii, 1993; Voskresenskii, 2001),

152 • active layer detachment slides (Lewkowicz and Harris, 2005; Lacelle et al., 2010; Swanson, 2021; Jorgenson and
153 Osterkamp, 2005; Lewkowicz, 2007; Lamoureux and Lafreniere, 2009; Lewkowicz and Way, 2019; Jones et al., 2019), or

154 • ice-wedge melt that leads to the degradation of ice-rich slopes (Fraser et al., 2018).

155 Two additional interesting but maybe highly site-specific inland geomorphological triggers were reported to be possible
156 reasons for RTS re-initiation:

157 • the growth of a talik that occurs in ice-rich permafrost can lead to thaw subsidence and stimulate further RTS
158 reoccurrence (Kokelj et al., 2009), or

159 • the growth of a debris tongue (thawed sediments in the shape of a tongue, for details, see Sect. 3.1.8) can eventually
160 obstruct a stream valley and lead to the rise of stream base-level and further thermo-erosion that can erode and expose the
161 ground ice and secondary RTS occurrence (Kokelj et al., 2015).

162 **2.5. Polycyclicality**

163 RTSs can develop in a polycyclic fashion, which means they can be active, then temporarily stabilize, and reactivate again
164 (Mackay, 1966; Kerfoot, 1969; Kokelj et al., 2009). Yet some may end off in one cycle. RTSs can be considered active when
165 there is an ongoing ablation of the exposed ice and thawed material is transferred downslope. Some studies reported continued
166 headwall retreat and thawed sediment fluxes even in slumps where the ice was covered by the sediments (Kokelj et al., 2015;
167 Zwieback et al., 2020). The reasons for these sediment-covered slumps to retain activity were heavy rainfalls and unsuppressed
168 heat flux to the ice.

169 RTSs can stabilize mostly for two reasons: 1) exposed ground ice has completely melted, or 2) the exposed ice is re-buried by
170 sediments and thermally fully insulated from further melting (Burn and Friele, 1989). Once an RTS is stabilized, pioneer
171 vegetation starts to grow in the slump floor. Vegetation in stabilized RTS can go through several stages of succession and for
172 stabilized RTS in Yukon Territory, Canada, it was reported that forest and tundra communities were re-established after 35-
173 50 years (Burn and Friele, 1989). Some researchers found that RTSs can be stabilized for up to several hundred years in West
174 Siberia, Russia, (Leibman et al., 2014). Such long-term stabilized RTS are labeled in some studies as ancient (Nesterova et al.,
175 2023).

176 New active RTS can form within the outline of another stabilized RTS, moreover, neighboring RTSs can grow and coalesce
177 at some point (Lantuit and Pollard, 2008). This leads to the very complex spatial organization of nested and amalgamated
178 RTSs of sometimes different ages. It raises additional challenges when delineating and mapping RTS and their characteristics
179 (van der Sluijs et al., 2023; Leibman et al., 2023).

180 **2.6. Concurrent processes**

181 While triggering processes described in Sect. 3.2 takes place before RTS initiation, concurrent processes start simultaneously
182 or soon after RTS initiation and often are further reinforced by RTS growth. Depending on the terrain, concurrent processes
183 can have different impacts on RTS.

184 If RTS initiation occurs along the ice-wedge polygonal network, it also affects its further development (Fraser and Burn, 1997;
185 Fraser et al., 2018). Ice-wedge degradation can result in the rugged outline of the headwall following the morphology of
186 wedges (Fig.2a, b).

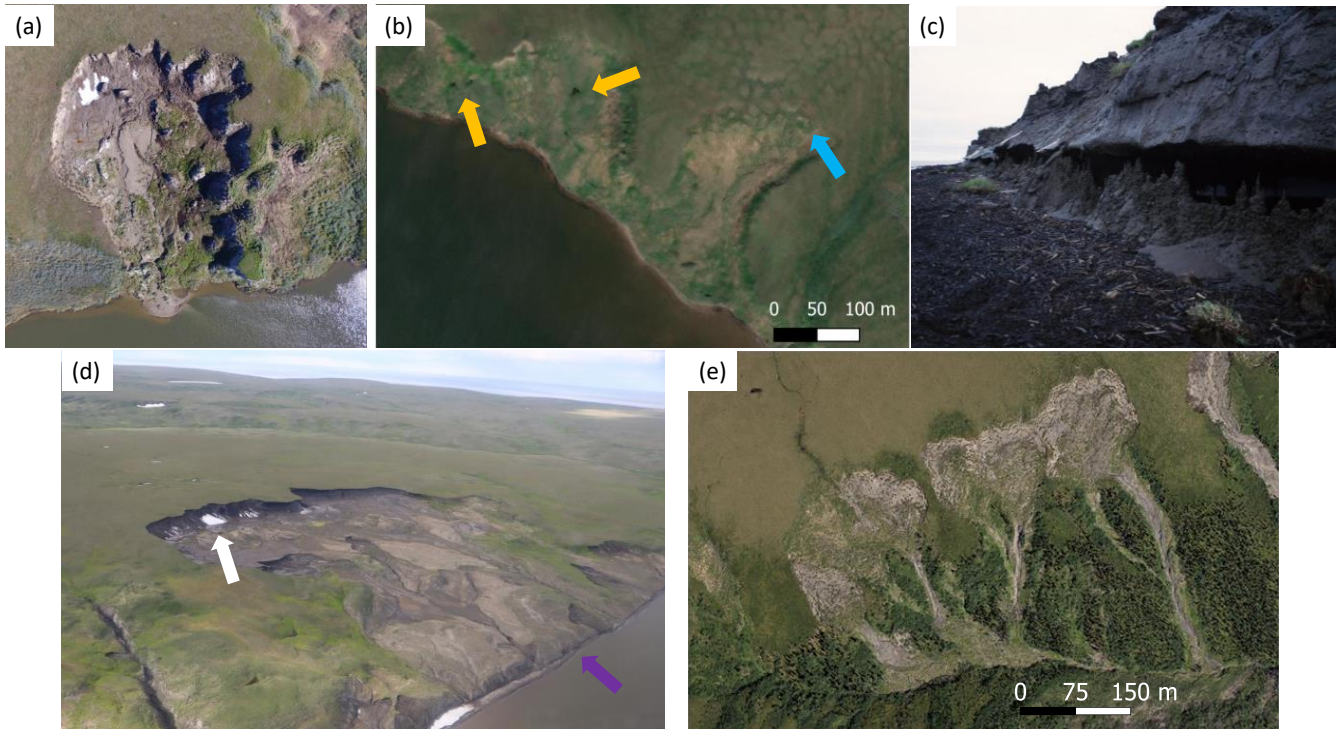
187 RTSs at the sea coast or any large water bodies (lakes, rivers) where wave action takes place are affected by coastal erosion at
188 the bluff base. This process manifests itself in washing away the debris tongue of RTS thus promoting further RTS growth by
189 removing debris blockages (Burn and Friele, 1989; Are, 1998), steepening the erosional base by coastal retreat, and in some
190 cases also undercutting the coast and niche-formation adding to further collapse of steep shore bluffs (Fig.2e).

191 As mentioned above, RTSs can form due to massive ground ice exposure in thermo-erosional gullies. Usually in such RTSs
192 lateral thermo-erosion continues to act simultaneously with ice ablation and thaw-related mass wasting. Sometimes lateral
193 thermo-erosion can appear in already existing RTS (Kerfoot, 1969; Lantuit and Pollard, 2005; Gubarkov et al., 2009). In both
194 cases, the RTS has or develops a specific gully-like shape (Fig.2c).

195 Due to specific RTS geometries and climatic conditions, thick snow packs accumulating from wind drift of snow in the winter
196 can remain within some RTS over summer (Fig.2d). This can affect RTS development by thermal insulation (Zwieback et al.,
197 2018). It was reported that snow packs prevented fast headwall retreat rates compared to the headwalls not covered by snow
198 (Lacelle et al., 2015).

199 Thermokarst subsidence and ponding can also occur within a slump floor (Fig.2b). This happens if the ground ice lies deeper
200 than the level of the slump floor, and there are conditions for water to accumulate in local concavities (Leibman and Kizyakov,

201 2007). It also can happen that meltwater streams can go into ice wedge tunnels, disappear in sinkholes on the slump floor, and
202 reappear further down at the slump floor.



203

204 **Figure 2** Concurrent processes affecting RTS: (a) ice-wedge degradation in an RTS on Yamal Peninsula, West Siberia, Russia, July
205 2018, UAV photo: Artem Khomutov, (b) Thermokarst subsidence indicated by yellow arrows and ice-wedge degradation indicated
206 by a light-blue arrow in a stabilized RTS on Gydan Peninsula, West Siberia, Russia, July 2019, ESRI Basemap, GeoEye-1 satellite
207 image, (c) Erosional niche formed due to the coastal erosion affecting RTS, Oyagos Yar, NE Siberia, Russia, September 2002, photo:
208 Guido Grosse, (d) white arrow indicates snow packs staying over summer, the purple arrow indicates an area where coastal erosion
209 undercuts the coast and washes away debris tongue of an RTS on Herschel Island, Northern Canada, July 2022, photo from
210 helicopter: Saskia Eppinger, (e) active thermal erosion in RTSs that occurred within gullies near Willow River, NW Canada, July
211 2023, aerial camera image, credit: AWI. ESRI basemap used in (b) has the following credits: Esri, DigitalGlobe, GeoEye, i-cubed,
212 USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

213 3 Terminologies used in the literature

214 3.1. Morphologic parts

215 RTS have various morphologic parts, of which some are characteristic of all RTS but some may be present only in certain RTS
216 types and depend on local geological conditions (Figure 3). Moreover, some of these RTS features can still be visible even
217 after the RTS stabilized. Some studies use various terms to describe the same parts of RTS, which then are synonymous terms,
218 while other studies use the same terms but actually describe partially or fully different parts of the RTS with them. This can
219 cause confusion when comparing RTS characteristics across different studies (Table 1).

Table 1 Morphologic parts of RTS and different terminologies used to describe them. The last column represents the presence “+” or the absence “-” of the morphologic part in stabilized RTS.

Most common term	Other related terms	Description	Presence in stabilized RTS
Present in all RTS (essential)			
1. <i>Headwall</i> (Kerfoot, 1969; Egginton, 1976; Burn and Friele, 1989; Burn and Lewkowicz, 1990; Barry, 1992)	<ul style="list-style-type: none"> • <i>Backwall</i> (Lamothe and St-Onge, 1961; Worsley, 1999; Leibman et al., 2021) • <i>Headscarp</i> (De Krom, 1990; Lewkowicz, 1987b; Lantuit and Pollard, 2005) • <i>Slump face</i> (Huang et al., 2022) • <i>Ice face</i> (Kerfoot, 1969; Lewkowicz, 1987b) • <i>Scarp</i> (Mackay, 1966; Kerfoot, 1969; Egginton, 1976; Fortier et al., 2007; Wang et al., 2009; Nicu et al., 2021) • <i>Escarpment</i> (Swanson and Nolan, 2018; Swanson, 2021) 	A steep retreating wall consisting of ablating ice and frozen sediments at the back of RTS	-
2. <i>Slump floor</i> (Mackay, 1966; Lewkowicz, 1987a; Burn and Friele, 1989; De Krom, 1990; Barry, 1992; Lantuit and Pollard, 2005; Lacelle et al., 2010) or <i>Scar</i> (De Krom, 1990; Barry, 1992; Kokelj et al., 2002; Kokelj et al., 2009)	-	The low-angle to horizontal area of the hollow’s bottom	+

3. <i>Mudflow</i> (Lamothe and St-Onge, 1961; Egginton, 1976; Lewkowicz, 1987a)	<ul style="list-style-type: none"> • <i>Earth / Mud flow</i> (Leibman et al., 2014) • <i>Debris flow</i> (Murton, 2001; Lipovsky and Huscroft, 2006) 	The meltwater stream that carries thawed viscous sediment material downslope across and out of the slump floor	-
4. <i>Edge</i> (Cassidy et al., 2017; Leibman et al., 2021; Leibman et al., 2023; van der Sluijs et al., 2023; Kizyakov et al., 2023)	<ul style="list-style-type: none"> • <i>Outline</i> (Burn, 2000; Yang et al., 2023) 	The boundary line of the headwall or entire landform	+
Present in some RTS depending on various local characteristics (optional)			
5. <i>Mudpool</i> (De Krom and Pollard, 1989; Lantuit and Pollard, 2005)	-	The area of the first accumulation of thawed liquid material, generally at the base of the headwall	-
6. <i>Evacuation channel</i> (Lacelle et al., 2004; Lacelle et al., 2010; Delaney, 2015)	-	Channel the thawed sediments and meltwater (debris) pass through when leaving the slump floor	+
7. <i>Debris tongue</i> (Worsley, 1999; Kokelj et al., 2015; Segal et al., 2016)	<ul style="list-style-type: none"> • <i>Slump lobe</i> (Lantuit and Pollard, 2005) • <i>Mud lobe</i> (Lantuit and Pollard, 2005) 	Thawed sediments and meltwater (debris) in the shape of a tongue that slid downslope from the slump floor	+
8. <i>Slump block(s)</i> (Swanson, 2012; Kokelj et al., 2015)	<ul style="list-style-type: none"> • <i>Remnant island</i> (Burn and Friele, 1989; Bartleman et al., 2001) 	Pieces of soil and vegetation that slid or fell from the headwall and are located within a slump floor	-
9. <i>Baydzherakh(s)</i> (Czudek and Demek 1970; Zhigarev, 1975; Pizhankova, 2011; Séjourné et al., 2015)	-	Conical hills within a slump floor remnant after thawing of large ice-wedges	+
10. <i>Mud levees</i> (Kerfoot, 1969; Lantuit and Pollard, 2005)	-	“Dams” of dried stagnated thawed sediments within a slump floor	-

11. <i>Mud gullies</i> (Lantuit and Pollard, 2005)	-	Erosional channels within thawed sediments formed by meltwater flow within a slump floor	-
12. <i>Dropwall</i> (Leibman et al., 2021)	-	A cliff between the edge of the hanging RTS floor and the shore	+
13. <i>Side-wall</i> (Lewkowicz, 1987b)	-	A steep retreating wall consisting of ablating ice at the side of RTS	-

222 **3.1.1. Headwall and Side-walls**

223 The term *headwall* is used in the literature in two ways: 1) as a broad general term for the steep wall of RTSs, where the ice is
224 exposed (Kerfoot, 1969; Egginton, 1976; Burn and Friele, 1989; Burn and Lewkowicz, 1990; Barry, 1992) and 2) as a term
225 for only the upper vertical part of the wall that consists of the active layer and ice-poor organic or mineral sediments (Lantuit
226 and Pollard, 2005; Lewkowicz and Way, 2019). The second lower part of the RTS wall according to these authors is a steep
227 (20°-50°) *headscarp* that consists of exposed ice-rich sediment or massive ground ice. Exposed ice is not only called a
228 *headscarp* in the literature but sometimes also an *ice face* and in such cases, the *ice face* is a part of the headwall that represents
229 the whole RTS wall in a general way (Kerfoot, 1969; De Krom, 1990; Burn and Lewkowicz, 1990; Barry, 1992).

230 There are several terms in the literature that are used to describe the whole RTS wall (*headwall* in a general way): for example,
231 *slump face* (Huang et al., 2022), *scarp* (Mackay, 1966; Kerfoot, 1969; Egginton, 1976; Fortier et al., 2007; Wang et al., 2009;
232 Nicu et al., 2021) and *escarpment* (Swanson and Nolan, 2018; Swanson, 2021). Another similar term is a *backwall* and it is
233 used to describe the whole RTS wall but separate it by its location on the back of the RTS (Lamothe and St-Onge, 1961;
234 Worsley, 1999; Leibman et al., 2008). Those RTS walls that are located at the sides are sometimes called *side-walls*
235 (Lewkowicz, 1987b). Side-walls can be called an optional morphologic part since they mostly occur only in bowl-shape
236 morphologies.

237 Since a *headwall* is a wall with exposed ablating ice and frozen sediments, it can only be found in an active RTS. The remnants
238 of the headwall in stabilized RTSs are sometimes called *stable headwall* (Kokelj et al., 2009) or *old headscarp* (Zwieback et
239 al., 2018).

240 **3.1.2. Slump floor or Scar**

241 As a *headwall* retreats it leaves a low-angle surface that can also be described as the bottom of the RTS hollow. This surface
242 is termed *slump floor* (Mackay, 1966; Lewkowicz, 1987a; Burn and Friele, 1989; De Krom, 1990; Barry, 1992; Lantuit and
243 Pollard, 2005; Lacelle et al., 2010), highlighting its flatness or sometimes with the term *scar* (De Krom, 1990; Barry, 1992;

244 Kokelj et al., 2002; Kokelj et al., 2009) that originates from landslide terminology and means the bare surface that is left after
245 the removal of the mobilized sediments by mass movement. Both of the terms are equally popular in the literature and
246 sometimes are used simultaneously in the same study as an interchangeable term (De Krom, 1990; Barry, 1992). A *slump floor*
247 or *scar* can be found in active as well as stabilized RTSs.

248 **3.1.3. Mudpool and Mudflows**

249 The area of the mud in the *slump floor* right next to the headwall is often (but not always) the place where meltwater
250 accumulates. Some authors call this area of the RTS slump floor a *mudpool* (De Krom and Pollard, 1989; Lantuit and Pollard,
251 2005). Thawed sediments after their first accumulation in the *mudpool* are transported downslope by the streams of meltwater.
252 These flows of meltwater-saturated mud depending on the amount of water are generally called *mudflows* (Lamothe and St-
253 Onge, 1961; Egginton, 1976; Lewkowicz, 1987a), *earth/mud flows* (Leibman et al., 2014) and *debris flows* (Murton, 2001;
254 Lipovsky and Huscroft, 2006).

255 **3.1.4. Mud gullies and levees**

256 Meltwater streams can lead to the formation of *mud gullies* within a *slump floor* – erosional channels that are carved by
257 meltwater streams into debris (Lantuit and Pollard, 2005). If transported debris stagnates and dries out it may form *mud levees*
258 bordering *mudflows* (Kerfoot, 1969; Lantuit and Pollard, 2005).

259 **3.1.5. Slump block**

260 The pieces of ice-poor, often organic-rich peaty soil covered with vegetation that slide down the headwall into the slump floor
261 and stay rigid when moving downslope with mudflows are called *slump blocks* in some studies (Swanson, 2012; Kokelj et al.,
262 2015). If these features consist of active layer soil, they generally preserve the initial undisturbed tundra vegetation. Some
263 authors called these blocks also *remnant islands* (Burn and Friele, 1989; Bartleman et al., 2001).

264 **3.1.6. Baydzhherakh(s)**

265 *Baydzhherakhs* (from the Yakutian language, but now a more commonly accepted term) are conical mounds in the *slump floor*
266 of RTSs representing largely still frozen remnants of ice-wedge polygon centers where the surrounding polygonal large ice
267 wedges have thawed substantially already. They are typical for RTSs located on upland slopes with ice-rich deposits and large
268 polygonal ice wedges up to 50 m thick (i.e., Yedoma Ice Complex) (Tikhomirov, 1958; Czudek and Demek, 1970; Zhigarev,
269 1975; Pizhankova, 2011; Séjourné et al., 2015). *Baydzhherakhs* can reach significant sizes: up to 11 m in height, 15 m in width,
270 and 20 m in length (Tikhomirov, 1958). Thus, they can be found not only in active but also in stabilized RTSs. As a typical
271 feature of Yedoma upland slopes *baydzhherakhs* are widely distributed in the Yedoma Ice Complex regions of Eastern and
272 North-Eastern Siberia, Alaska, and North-Western Canada (Strauss et al., 2021) as well as in other areas formed by ice-rich

273 deposits with large polygonal ice wedges. *Baydzhherakhs* will therefore not form in areas where RTSs are formed in deposits
274 with thick ice layers.

275 **3.1.7. Evacuation channel**

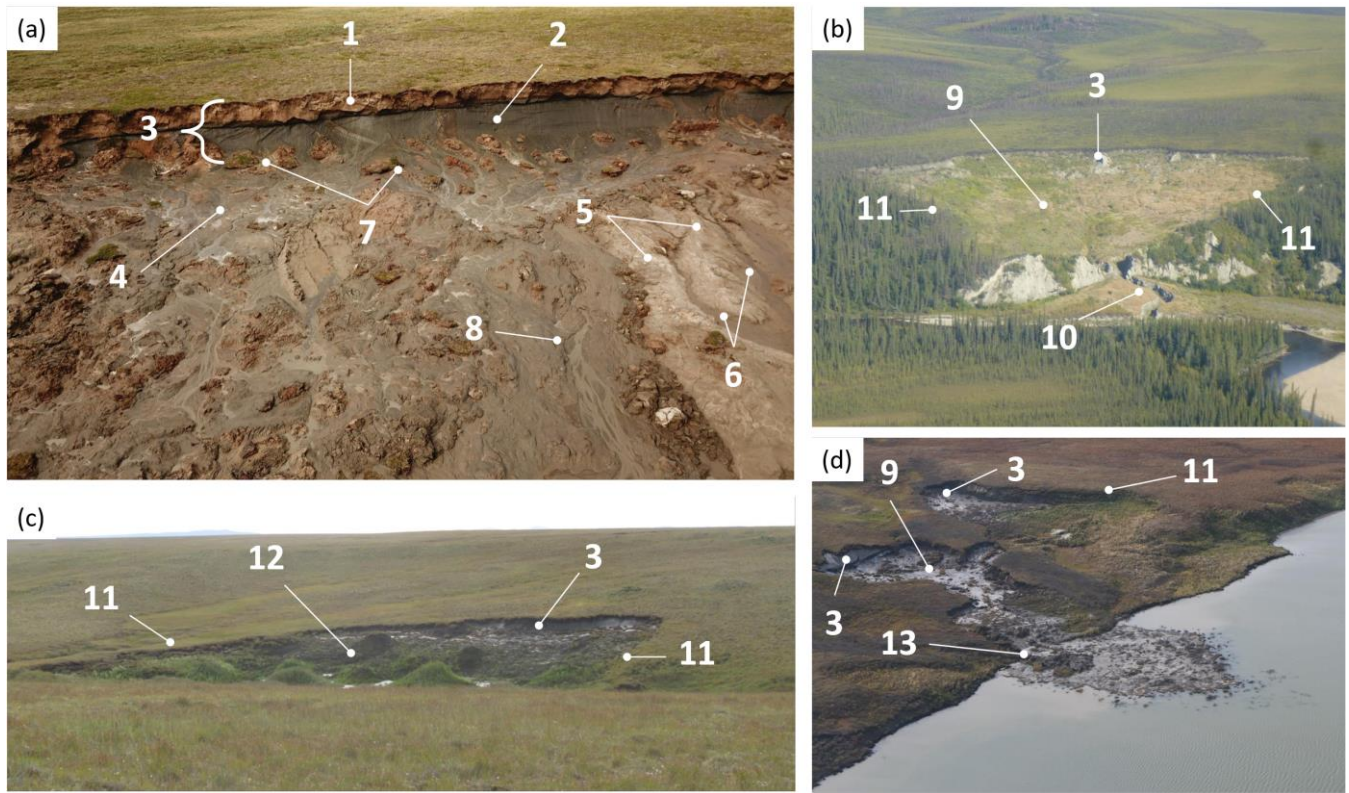
276 Depending on the morphology of an RTS, thawed sediments and meltwater (debris) can leave the *slump floor* through the
277 trench connecting the *slump floor* and the base level. This optional morphologic part of RTSs is termed an *evacuation channel*
278 (Lacelle et al., 2004; Lacelle et al., 2010; Delaney, 2015).

279 **3.1.8. Debris tongue**

280 Thawed sediments and meltwater (debris) moving downslope can eventually escape from the *slump floor* directly or via an
281 *evacuation channel*. Once this happens, thawed sediments accumulate in the shape of a “tongue” on any surface where an RTS
282 outflow ends. Such features are generally called *debris tongues* (Worsley, 1999; Kokelj et al., 2015; Segal et al., 2016), but
283 are sometimes referred to as *mud* or *slump lobes* (Lantuit and Pollard, 2005).

284 **3.1.9. Edge and dropwall**

285 The term *edge* of RTS is used in the literature to indicate: 1) the outline of the whole feature (van der Sluijs et al., 2023) and
286 2) the boundary line of active retreat (Cassidy et al., 2017; Leibman et al., 2021; Leibman et al., 2023; Kizyakov et al., 2023).
287 There is also the term *outline* itself that is used to describe the whole area of the RTS landform (Burn, 2000) or only the
288 polygon that is considered to be the RTS detected by automated mapping methods (Yang et al., 2023). Furthermore, the *edge*
289 of RTS is also sometimes classified into upper edge meaning the boundary line of active retreat of the *headwall* (Kizyakov et
290 al., 2023), and *lower edge* meaning the boundary line of the cliff retreat for RTSs on the sea coasts (Leibman et al., 2008;
291 Leibman et al., 2021). The face (cliff) from the *lower edge* of coastal RTS to the beach level has been called a *dropwall*
292 (Leibman et al., 2021) to differentiate this morphologic part of the RTS from the rest of the coastal cliff.



293

294 **Figure 3 Morphologic parts of active RTSs in (a) Yamal Peninsula, West Siberia, Russia, July 2019, unmanned aerial vehicle (UAV)**
 295 **photo: Nina Nesterova, (b) Alaska, USA, August 2016, photo from the airplane: Ingmar Nitze, (c) Bykovsky Peninsula, NE Siberia,**
 296 **Russia, August 2015, field photo: Alexandra Veremeeva, (d) Gydan Peninsula, West Siberia, Russia, 2020, photo from helicopter:**
 297 **Elena Babkina. The numbers on the photos stand for the following morphologic parts: 1 – headwall, i.e. the upper vertical part of**
 298 **the wall only; 2 – headscarp; 3 – headwall (or a backwall), more generally describing the entire steep wall; 4 – mudpool; 5 – mud**
 299 **levees; 6 – mud gullies; 7 – slump block; 8 – mudflow; 9 – slump floor or scar; 10 – evacuation channel; 11 – side-wall; 12 –**
 300 **baydzherakhs; 13 – debris tongue.**

301 3.2. Landforms

302 3.2.1. Retrogressive thaw slump (RTS)

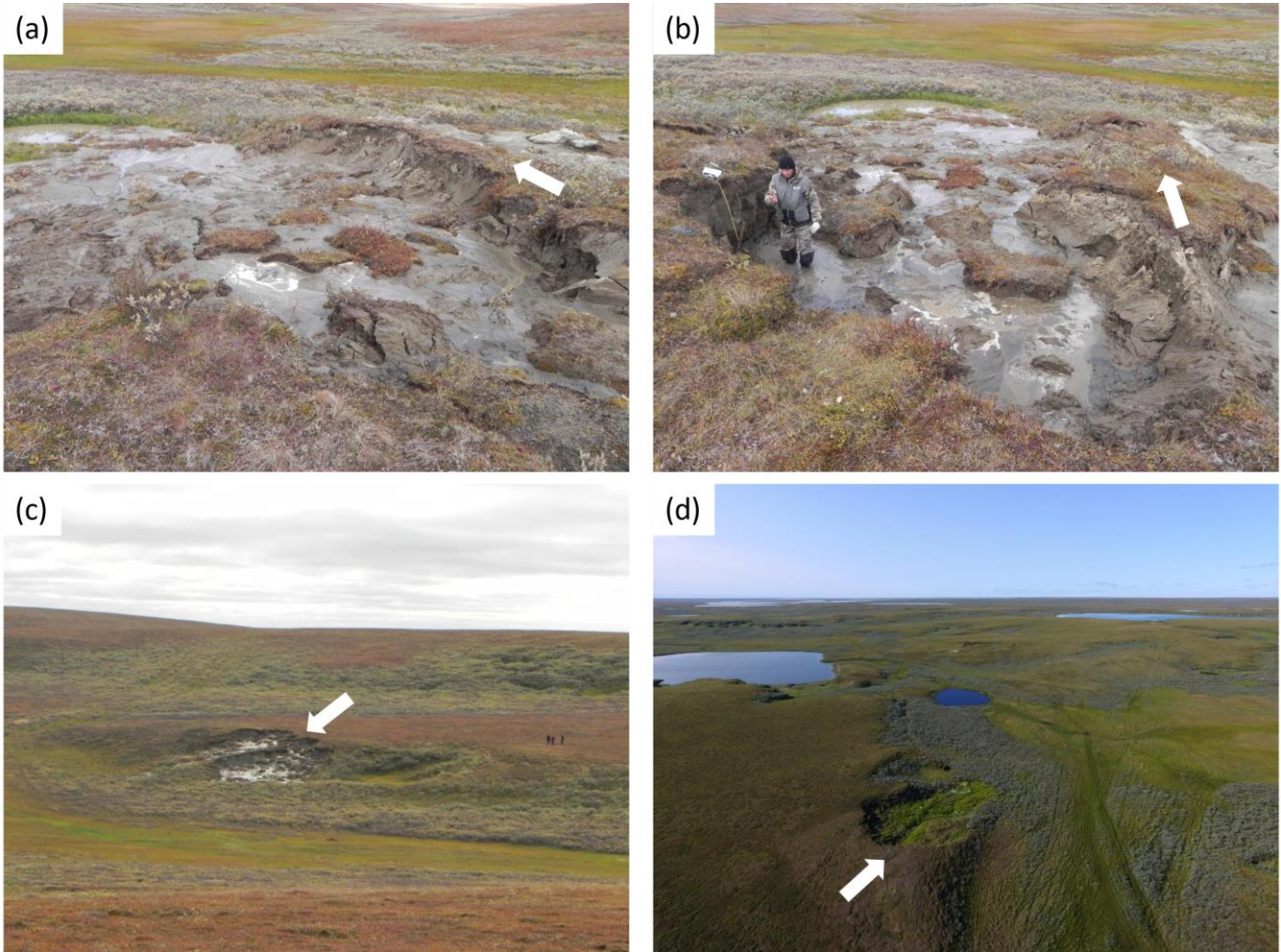
303 According to the International Permafrost Association Multi-Language Glossary of Permafrost and Related Ground-Ice Terms
 304 (van Everdingen, 2005), an RTS is defined as: “A slope failure resulting from thawing of ice-rich permafrost. Retrogressive
 305 thaw slumps consist of a steep headwall that retreats in a retrogressive fashion due to thawing and a debris flow formed by the
 306 mixture of thawed sediment and meltwater that slides down the face of the headwall and flows away. Such slumps are common
 307 in ice-rich glaciolacustrine sediments and fine-grained diamictons.”
 308

309

310 **3.2.2. Cryogenic earthflow**

311 In Russian literature, the word *cryogenic* is usually used to describe the periglacial nature of the processes. It refers to
312 thermophysical, physicochemical, and physicommechanical processes occurring in freezing, frozen, and thawing deposits (van
313 Everdingen, 2005). This term is usually omitted in the literature in English (Poppe and Brown, 1976).

314 The term *cryogenic earthflow* was introduced by Leibman (1997, in Russian) meaning a viscous or viscoelastic flow of water-
315 saturated soil of the active layer sliding on the surface of massive ground ice bodies or the table of ice-rich permafrost. The
316 examples of cryogenic earthflows in Central Yamal are demonstrated in Fig.4.



317
318 **Figure 4** The examples of two cryogenic earthflows next to each other being active on (a), (b) and (c) photos in Central Yamal, West
319 Siberia, Russia made on a photo camera in 2012 and stabilized on (d) the photo made by UAV in 2017. The arrow indicates the
320 direction of flow. Photos: Artem Khomutov.

321 **3.2.3. Thermocirque**

322 The term *thermocirque* was first mentioned by Czudek and Demek (1970, in English) to describe “amphitheatrical hollows”
323 that occur after ice wedge melt in the gullies at the river banks in Yakutia (Russia). Thermocirques according to the authors
324 had “a vertical and overhanging slope at the head and an uneven floor”. In Russian-language literature, the term thermocirque
325 was sometimes called by interchangeable term “*thermokar*” when describing a round or cirque-like hollow at the river banks
326 or the lake shores composed of icy permafrost (Grigoriev and Karpov, 1982, in Russian; Voskresenskii, 2001, in Russian).
327 Following the development of theoretical concepts of cryogenic landsliding (Sect. 3.2.3 and 3.2.4) the term thermocirque was
328 defined as an extensive landform resulting from a series of multi-aged cryogenic earthflows (Leibman, 2005, in Russian;
329 Leibman et al., 2014). The scheme visualizing thermocirque formation and the example of the thermocirque in Central Yamal,
330 Russia are demonstrated in Fig.5.



331
332 **Figure 5 (a) Scheme of Thermocirque formation, the black arrow indicates the direction of mass movement of thawed material, and**
333 **the red dashed line stands for the cross-section of the headwall and the slump floor (see Sect. 3.5). Note that the scheme demonstrates**
334 **the particular ice morphology of a layer of tabular massive ground ice (adapted from Kizyakov, 2005), but may also consist of other**
335 **forms of ice-rich ground. Example of a thermocirque in Central Yamal, West Siberia, Russia show on (b) in a UAV photo in August**
336 **2019 (photo: Artem Khomutov) and (c) in a WorldView-2 satellite image from July 2018 (Source: ESRI satellite basemap). ESRI**
337 **basemap used in (c) has the following credits: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid,**
338 **IGN, IGP, swisstopo, and the GIS User Community.**

339

340 **3.2.4. Thermoterrace**

341 The term *thermoterrace* was first mentioned by Ermolaev (1932, in Russian) to describe “picturesque outcrops of ice falling
342 vertically onto a narrow, 1-2 m wide space located along the seashore along the edge of the ice wall that can reach 30-35 m”.
343 The local term to describe these icy cliffs was muus kygams - муус кьхам in Yakutian language (Ermolaev, 1932). The more

344 precise definition of thermoterrace was given by Zenkovich and Popov (1980) as a terrace-like area in the upper part of the icy
345 cliff at the seashore that results from the cliff retreat due to the thermal influence of warm air and solar radiation.
346 Thermoterraces were reported to reach up to a few km in length along the coast and more than 200 m in width (Are et al.,
347 2005). A scheme visualizing thermoterrace formation based on Kizyakov (2005) and an example of a thermoterrace on the
348 Bykovsky Peninsula, Yakutia, Russia are shown in Fig.6.



349
350 **Figure 6 (a) Scheme of thermoterrace formation, the black arrow indicates the direction of mass movement of thawed material; note**
351 **that the scheme demonstrates the particular ground ice morphology of a layer with large ice-wedges (adapted from Kizyakov, 2005),**
352 **but may also consist of other ground ice morphologies. Example of Thermoterraces in Bykovsky Peninsula, NE Siberia, Russia**
353 **shown (b) on the ground in August 2016 (photo: Alexander Kizyakov) and (c) in a WorldView-2 satellite image from August 2020**
354 **(ESRI satellite basemap). ESRI basemap used in (c) has the following credits: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA,**
355 **USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.**

356 3.2.5. Active layer detachment slide

357 Another closely related slope landform linked to RTS formation (see Sect. 3.2) is an active layer detachment slide or failure
358 (ALD). The term ALD is prevalent in recent publications (Blais-Stevens et al., 2015; Balsler, 2015), yet, unlike RTS, there is
359 no universally endorsed term to describe ALD phenomena in the Glossary (van Everdingen, 2005):

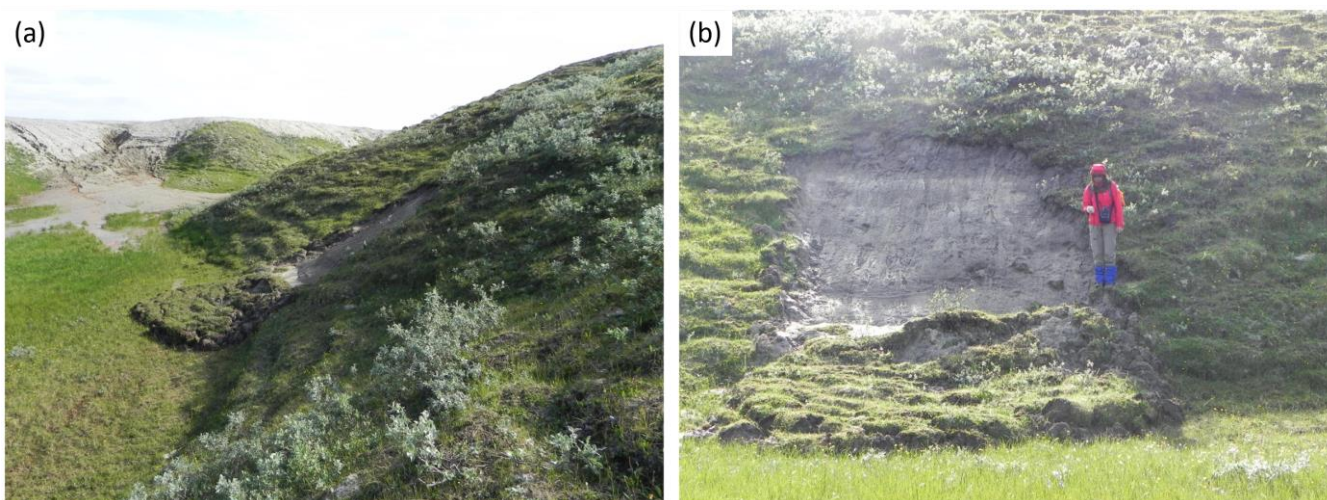
- 360 • active layer failure - “A general term referring to several forms of slope failures or failure mechanisms commonly
361 occurring in the active layer overlying permafrost” (not recommended synonym: skinflow)
- 362 • detachment failure - “A slope failure in which the thawed or thawing portion of the active layer detaches from the
363 underlying frozen material” (not recommended synonyms: skin flow, active layer glide)

364 French (2018) defines active layer detachment slides as rapid slope failures restricted to the active layer that generally occur
365 at the middle or upper slopes. In one of several classical works on ALD, Lewkowicz (1990) defines ALD as being a rapid

366 mass movement on permafrost slopes without strict limitation to the active layer: “Failure involves the unfrozen mass detaching
367 from the underlying substrate and sliding downslope over a thawing ice-rich zone within the active layer or the upper part of
368 the permafrost.” Examples of mass movements that seem deeper than the active layer and are nevertheless termed ALD are
369 shown by Rudy et al. (2016).

370 3.2.6. Cryogenic translational landslide

371 The term *cryogenic translational landslide* (CTL) was suggested by Kaplina (1965, in Russian), and the definition was later
372 elaborated in further publications based on observations in Central Yamal, Russia (Leibman and Egorov, 1996; Leibman,
373 1997; Leibman et al., 2014). The definition of CTL summarized from the abovementioned publications can be phrased as
374 single-time lateral displacement of thawed soil block sliding on the surface of the seasonal ice formed at the active layer base.
375 This type of seasonal ice is formed due to the active layer's upward freezing, ice aggradation at the base of the active layer,
376 and later melting (Leibman et al., 2014; Lewkowicz, 1990). Examples of CTL in Central Yamal are shown in Fig.7.



377
378 **Figure 7 Example of a cryogenic translational landslide (CTL) in 2019 in Central Yamal, West Siberia, Russia (photo: Artem**
379 **Khomutov), (a) view from the side and (b) view from the front.**

380 3.3. Formation process

381 The process of RTS formation in the recent literature is termed in two different ways: as *thermocarst* and as *thermodenudation*.

382 3.3.1. Thermocarst

383 The term *thermocarst* was first suggested by Ermolaev (1932) to describe the surface subsidence due to the melting of ground
384 ice as a similarity to the *karst* process by dissolution. However, in the context of RTS formation processes the term *thermocarst*
385 is mostly referred to in the North American literature as a set of processes that lead to the occurrence of specific landforms
386 due to the thawing of ice-rich permafrost or melting of massive ground ice (Kokelj and Jorgenson, 2013).

387 3.3.2. Thermodenudation

388 The term *thermodenudation* originally was suggested by Panov (1936), defining “the influence of the sun in a direct or
389 transformed form through soil or water on the sediments containing a certain amount of ice cement or ice masses, as well as
390 on bedrock with negative temperature <...> that leads to mass-wasting as well as some forms of thermo-erosion or
391 thermokarst”. In the context of RTS formation, this term has been used referring to ground ice thaw and slope mass waste
392 (Leibman et al., 2021) as well as the retreat of upper bluff edges along coastal RTS (Guenther et al., 2012).

393 4 Discussion

394 4.1 Divergent terminologies

395 The terminology used to describe the RTS formation processes and related landforms in 21st-century publications has historical
396 roots in the distinct scientific approaches developed in the USSR and North America (both Canada and the USA) during the
397 20th century.

398 The process of RTS formation following the initiation by various triggers and the further development into the landform has
399 neither been named nor specifically classified in classical works on RTS and exposed ground ice (Mackay, 1966; Mackay,
400 1970; Rampton and Mackay, 1971; Lewkowicz, 1987a; Burn and Friele, 1989).

401 In the literature of the 20th century, this process was often termed *solifluction*, *thermokarst*, and *thermodenudation*. Initially,
402 none of these three terms took the more specific formation of RTS into account in their definitions. At some point, however,
403 the definitions of these three terms were expanded to include RTS formation. The process of RTS formation was also
404 previously very broadly referred to as the process of *erosion* (Lamothe and St-Onge, 1961), but this term was later no longer
405 used in publications in this context.

406 The general chronology of usage of these three terms which differ in definitions in the 20th century is shown in Fig.8. While
407 this chronology graph has some limitations due to the a) ambiguity of some definitions, b) definition reformulation by some
408 authors through their later publications, and c) usage of several terms for the same process etc., it helps understanding how the
409 RTS terminology evolved in the scientific literature and how different schools of thought influenced its development.

410 The term *solifluction* was first introduced by Andersson (1906) and describes the process of slow downslope movement of
411 saturated unfrozen materials (van Everdingen, 2005). In non-Russian language literature, this term has always been used for
412 very slow movements up to several centimeters per year (Smith, 1988) and never for the rapid mass-wasting that can lead to
413 RTS. Meanwhile, Russian-language authors have included the process of slumping into the *solifluction* calling it *rapid*
414 *solifluction*. Probably the most remarkable publication with such a statement was issued by Kaplina (1965). The concept of
415 rapid solifluction was later criticized by Dylík (1967) and Leibman (1997) for summarizing processes that have process rates
416 differing by several orders of magnitude under one term. Nevertheless, this approach of referring to the RTS formation process

417 as *rapid solifluction* was frequently used in the literature until the end of the 20th century. The last publication in which *rapid*
418 *solifluction* was mentioned in connection with the formation of RTS was by Yershov (1998).

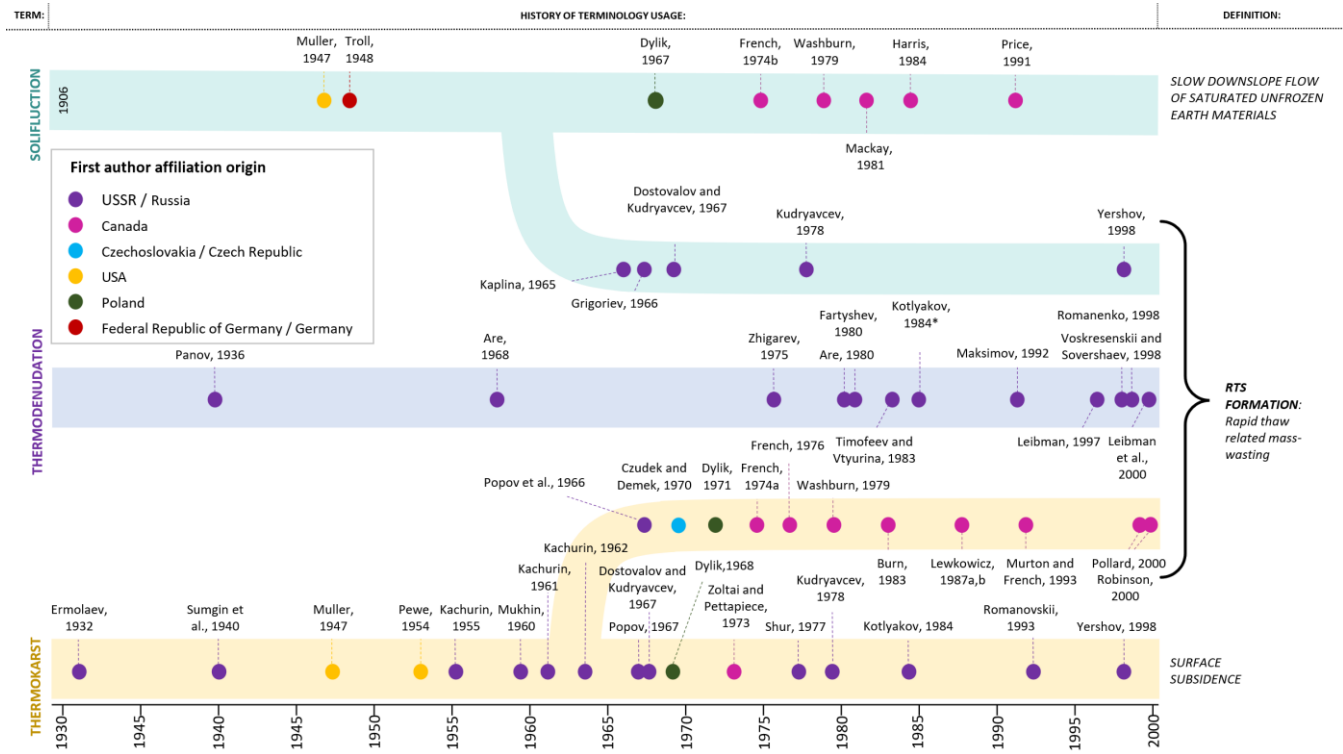
419 In general, the term *thermokarst* has mostly been used by Russian-language researchers for describing the subsidence of the
420 land surface (Sumgin et al., 1940; Kachurin, 1955; Mukhin, 1960; Dostovalov and Kudryavcev, 1967; Shur, 1977;
421 Romanovskii, 1993; and many more later). Some exceptions can be found in two publications of Popov: one in English (Popov
422 et al., 1966), where he included the slumping process in *thermokarst*, and another one in French (Popov, 1956), where his
423 definition of *thermokarst* was not purely limited to the process of subsidence. Meanwhile, a different approach was suggested
424 by Czudek and Demek (1970), who put the RTS formation process under the umbrella of the thermokarst term. They proposed
425 two types of *thermokarst*: down-wearing which included only subsidence and back-wearing which included the RTS
426 formation. This approach found support from French (1976), who extended this term by adding *thermal erosion* to it. French's
427 (1976) definition of *thermal erosion* as "a dynamic process 'wearing away' by thermal means, i.e. melting of ice" differs from
428 the one in the Glossary, where the main erosional agent is moving water: "The erosion of ice-rich permafrost by the combined
429 thermal and mechanical action of moving water." This is the reason why the RTS formation process is sometimes called
430 *thermal erosion*. For example, Burn (1983) relates the process of RTS formation to *thermal erosion*, which he in turn describes
431 as part of the *thermokarst* process.

432 Since French (1976) expanded the definition of thermokarst processes to encompass slope processes and in particular thaw
433 slumping, the RTS formation process has consistently been perceived as a thermokarst process in the North American literature
434 (Washburn, 1979; Burn, 1983) or sometimes specified as hillslope thermokarst (Gooseff et al., 2009). There was no agreement
435 among scholars on the terminology of the RTSs itself. RTSs were termed in the literature as tundra mudflows (Lamothe and
436 St-Onge, 1961), ground-ice slumps (Mackay, 1966; French, 1976), retrogressive-thaw flow slides (Hughes, 1972), bi-modal
437 flows (McRoberts and Morgenstern, 1974), or just thaw slumps (Washburn, 1979). The 1998 Glossary (van Everdingen, 2005)
438 initially recommended using the term "retrogressive thaw slump", though alternative terms persist in later literature, such as
439 "retrogressive thaw flowslides (thawslides)" (Wolfe et al., 2001) or "retrogressive thaw flows" (Highland and Bobrowsky,
440 2008).

441 Unlike RTS, the process of ALD was not always classified as thermokarst in the North American literature (Lewkowicz, 1990;
442 Lewkowicz and Harris, 2005, etc.). For example, French (1976; 2018) describes ALD under the section of "Rapid mass
443 movements", but not "Thermokarst" in all of the editions of his textbook "The Periglacial Environment". ALDs are included
444 in the list of thermokarst processes described for Alaska by Jorgenson et al. (2008) and classified as hillslope thermokarst by
445 Gooseff et al. (2009). Recent publications tend to include the process of ALD under the concept of thermokarst (Kokelj and
446 Jorgenson, 2013; Ramage et al., 2019; Kokelj et al., 2023).

447 Additional definitions of thaw-related slope processes in the North American literature worthy of mention can be found in
448 "The Landslide Handbook — A Guide to Understanding Landslides" of the United States Geological Survey by Highland and
449 Bobrovsky (2008). In the section "Flows in permafrost", the authors define ALD as the "rapid flow of shallow layer of saturated

450 soil and vegetation” that moves over but on the underlying permafrost. Retrogressive thaw flows (as an analog term for RTS)
 451 are described as the features resulting from the thawing of exposed buried ice lenses (Highland and Bobrowsky, 2008).
 452

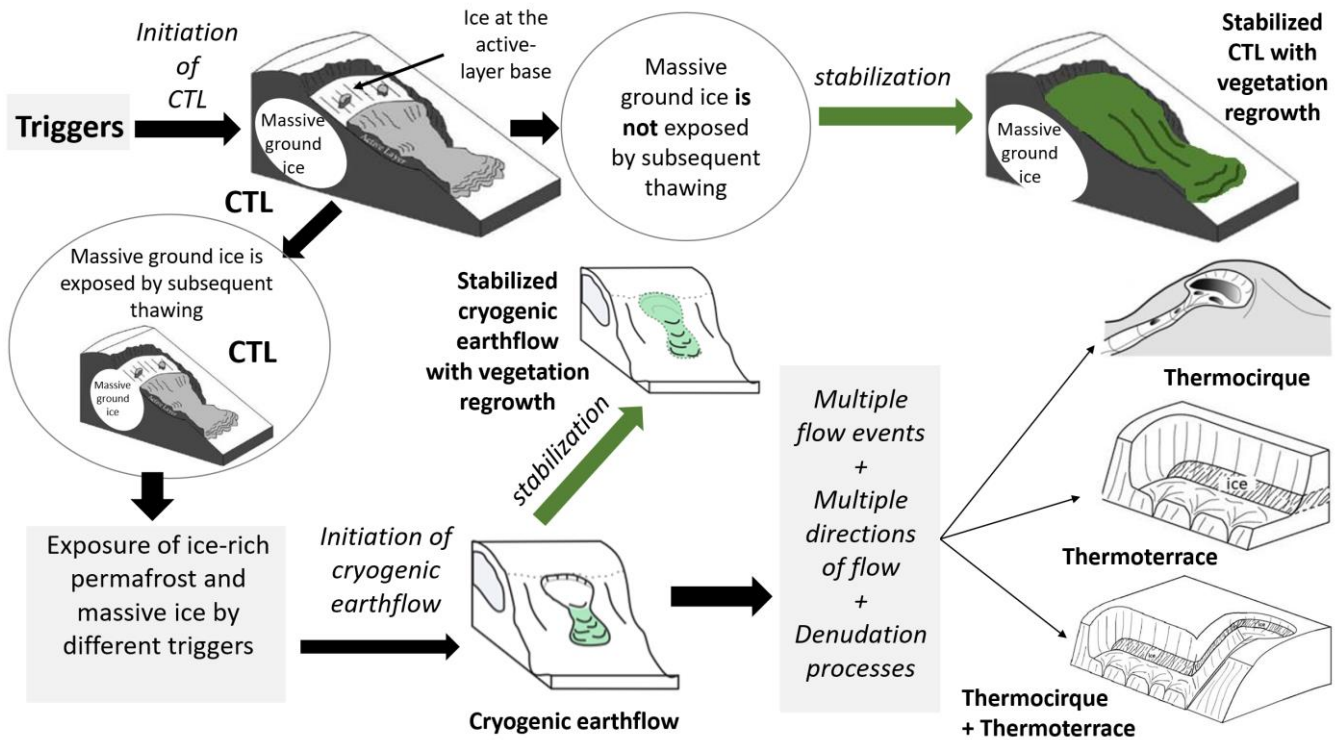


453
 454 **Figure 8 Chronology of the usage of different RTS-related terms by selected most cited authors in the 20th century. Three color-**
 455 **coded wide lines represent the term on the left side and the main process by definition on the right side. The dots represent**
 456 **publications and are color-coded based on the first author affiliation origin.**

457 The term *thermodenudation* (sometimes also spelled as *thermal denudation*) has never been properly introduced in English-
 458 language literature, however, it is widely used in Russian-language permafrost literature with two types of definitions: narrow
 459 and wide. For the initial (narrow) definition see Sect. 3.3.2. Are (1968) used this term to describe the thermal effect of solar
 460 radiation and sensible heat affecting the retreating ice-rich coastal cliffs. Zhigarev (1975) highlighted the importance of the
 461 slope in his definition of *thermodenudation* as “a complex of gravitational and erosive processes that develop on slopes during
 462 thawing of ice-rich deposits of various genesis”. The only wide definition of *thermodenudation* was introduced in the Glossary
 463 of Glaciology (Kotlyakov, 1984) as: “a set of cryogenic destructive processes and the transfer of the products of destruction
 464 downwards. *Thermodenudation* includes cryogenic weathering, nivation, cryogenic slope processes (mass movements),
 465 thermal erosion, thermal coastal erosion, thermokarst, and thermal suffosion”. This wide definition by Kotlyakov (1984) of a
 466 thaw-related process is quite similar to the expanded version of the thermokarst term by French (1976).
 467 In the context of RTS formation, the term *thermodenudation* was widely applied in its narrow definition as a set of slope
 468 processes associated with thawing of ice-rich deposits and leading to the occurrence of mass movements and concavities of

469 different shapes (Fartyshev, 1980; Romanenko, 1998; Leibman et al., 2021; and many more). These mass movements were
470 classified by Leibman (1997) into two types depending on the sliding surface: cryogenic translational landslides on the seasonal
471 ice in the base of the active layer (for detailed definition see Sect. 3.2.3) and cryogenic earthflows on the massive ice or icy
472 permafrost (for detailed definition see Sect. 3.2.4).

473 Figure 9 demonstrates a conceptual scheme that explains the interrelation of different processes and lists the landforms
474 resulting from *thermodenudation* (in narrow definition) in the Russian literature. When the cryogenic translational landslides
475 do not lead to the exposure of ice-rich permafrost or massive ground ice, the surface of exposed bare soil gets revegetated
476 (Khomutov and Leibman, 2016). Otherwise, if the icy deposits or the massive ice body are exposed because of this disturbance,
477 a *cryogenic earthflow* can occur. Such features can also stabilize if the accumulation of drying sediments insulates the exposed
478 ice. Once further thawing is suspended, the surfaces of these landforms get revegetated (Fig. 9) (Leibman, 2005). In contrast,
479 the continued expansion of the flow and mass movements in several directions involving additional cryogenic processes lead
480 to the formation of mature landforms defined in the literature as *thermocirque* (for detailed definition see Sect. 3.2.5) and
481 *thermoterrace* (for detailed definition see Sect. 3.2.6). *Thermocirques* are reported in the literature to exhibit amphitheater-
482 like shapes (Leibman et al., 2014), while thermoterraces are described as landforms elongated along the coast or the shore with
483 coastal erosion contributing to the cut of its lower part (Are et al., 2005). The combinations of these two landforms are also
484 observed in some regions (Leibman et al., 2023) (Fig. 10). This is usually found in two settings: one or more *thermocirques*
485 form and grow in a former but now stabilized *thermoterrace* (Fig.10a), or when an originally separate *thermocirque* and
486 *thermoterrace* merge at the coast into one outline (Fig.10b).



487

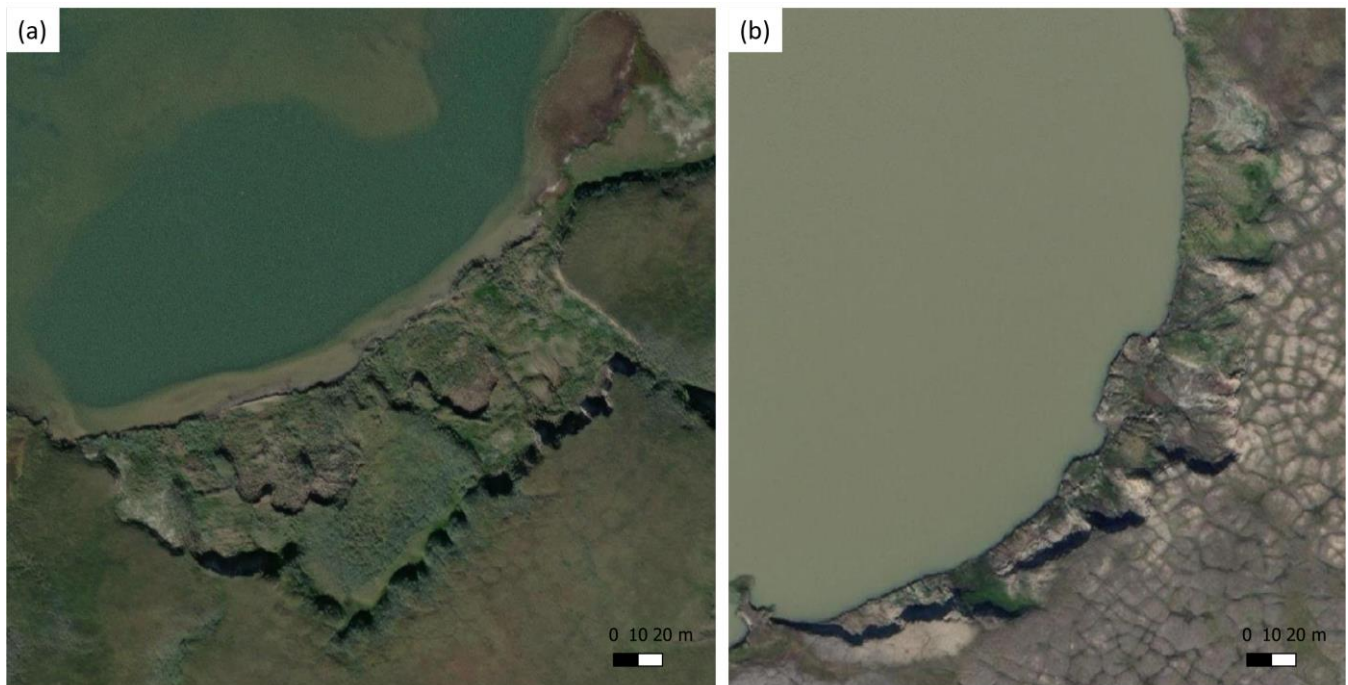
488

489

490

491

Figure 9 Conceptual diagram of the interrelation of different terms in the Russian literature used to describe the RTS formation process and the resulting landforms. CTL stands for cryogenic translational landslide. Note that what is shown as massive ground ice in the diagram may have different characteristics in different regions and could include buried glacial ice, thick ice layers, or large syngenetic ice wedges.



492

493 **Figure 10** Examples of combined RTS morphologies with thermoterraces and thermocirques. (a) Thermocirque(s) growing into a
 494 stabilized thermoterrace in Central Yamal, West Siberia, Russia as seen in a WorldView-3 satellite image from August 2018 (ESRI
 495 satellite basemap). (b) Thermocirque and thermoterrace merging at the coast into one outline in Western Yamal, West Siberia,
 496 Russia as seen in a WorldView-3 satellite image from August 2018 (ESRI satellite basemap). ESRI basemap has the following credits:
 497 Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User
 498 Community.

499 **4.2. Overlap in terminologies**

500 The terms described above refer to similar phenomena of the RTS formation process and resulting landforms, leading to
 501 inevitable similarities and overlaps but also differences (Table 2).

502 *Cryogenic translational landslide* corresponds to shallow active layer detachment slide in North American literature that is
 503 triggered by high pore-water pressure and low effective strength (Lewkowicz, 2007). *Cryogenic earthflow* corresponds to a
 504 deep ALD in the North American literature and is the very early stage of RTS formation. *Thermocirque* and *thermoterrace*
 505 signify the mature stage of RTS of different morphology.

506 The process of RTS formation can generally be described as a mass-wasting (landsliding) process resulting from the melting
 507 of massive ground ice exposed due to various triggers. Regardless of which terminology is used (*thermodenudation* in Russian
 508 literature or *thermokarst* in North American literature), it can be seen as a sequence of physical events (Fig.11): trigger, massive
 509 ground ice exposure, ice ablation, thaw-related mass movement, and landform formation. The first two physical events (trigger
 510 + massive ground ice exposure) are usually considered the RTS initiation stage. Triggers of massive ice exposure lead to mass-
 511 wasting and RTS landform occurrence.

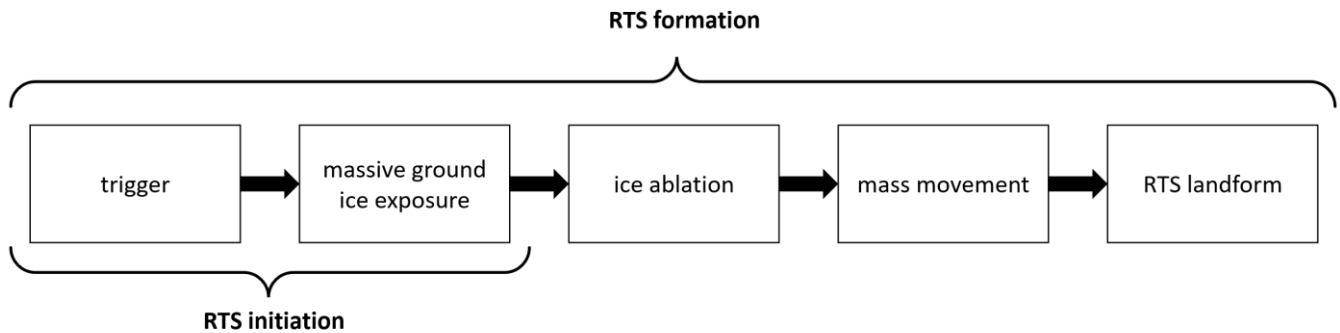
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Table 2 Correspondence of the process, landform, and terminology in the different approaches currently used

Main physical process	Process term		Resulting landform			
	North American literature	Russian literature	North American literature		Russian literature	
			term	comment	term	comment
<p>Mass-wasting on seasonal ice at the base of the active layer (within the active layer)</p> <p>Mass-wasting on massive ground ice (upper part of the permafrost)</p> <p>Mass-wasting due to the exposure and further thawing of ice-rich permafrost or melting massive ground ice plus other denudational processes resulting in concave hollows</p>	<i>Thermokarst (in wide definition)</i>	<i>Thermodenudation (in narrow definition)</i>	Active layer detachment slide (ALD)	shallow, relatively dry	Cryogenic translational landslide	Can trigger massive ground ice exposure
Retrogressive thaw slump (RTS)			deep, saturated	Cryogenic earthflow	The initial stage of retrogressive thaw slump formation	
				-	Thermocirque	The mature stage of retrogressive thaw slump development. Morphology: mostly horseshoe shape
					Thermoterrace	The mature stage of retrogressive thaw slump development. This landform is initiated on coastal bluffs or large lakes with coastal erosion playing a role. Morphology: mostly elongated

517



518
519 **Figure 11 Broadly accepted sequence of physical events of RTS formation.**

520 **4.3. Limitations of divergent terminology**

521 All the terms used to explain RTS formation both in North American and Russian literature have their limitations. The usage
522 of a single term Thermokarst for a wide variety of processes leads to confusion about the direction of the physical process
523 happening: whether it is the vertical lowering of the surface in the case of thermokarst lakes or lateral mass movement in the
524 case of RTS occurrence. Since the term Thermokarst in this case incorporates both directions of the process, it is crucial to
525 clearly state that RTS formation implies back-wearing thermokarst (or hillslope thermokarst). Another confusion can appear
526 when talking about mass movements that are deeper than the active layer and slide on the surface of massive ground ice. In
527 the North American literature, such landslides can still be called active layer detachment slides. However, since these mass
528 movements expose massive ground ice, the retrogression can already start, which means that it is already an early-stage RTS.
529 Such mass movements on the surface of massive ground ice are called cryogenic earthflows and are considered early-stage
530 RTS in Russian literature. However, it is difficult to distinguish an early-stage RTS (cryogenic earthflow) from a mature-stage
531 RTS (thermocirque) since mature RTS can also be of small sizes. Clear separation of these two categories is almost impossible
532 with remote sensing data and is quite demanding in the field since it requires thorough knowledge of the environment and the
533 dynamics of each RTS.

534 The definitions of *thermocirque* and *thermoterrace* present in the literature are based on the morphology of the features.
535 Considering morphology as a distinguishing factor can be subjective since no established curvature values exist in the literature
536 to differentiate them. In some cases, a thermoterrace can appear more curved, rather resembling a thermocirque. In contrast, a
537 thermocirque can further elongate in width following the initial shape of massive ground ice (e.g., Fig.1 in Swanson and Nolan,
538 2018), while its mudflow can reach the neighboring water body base level.

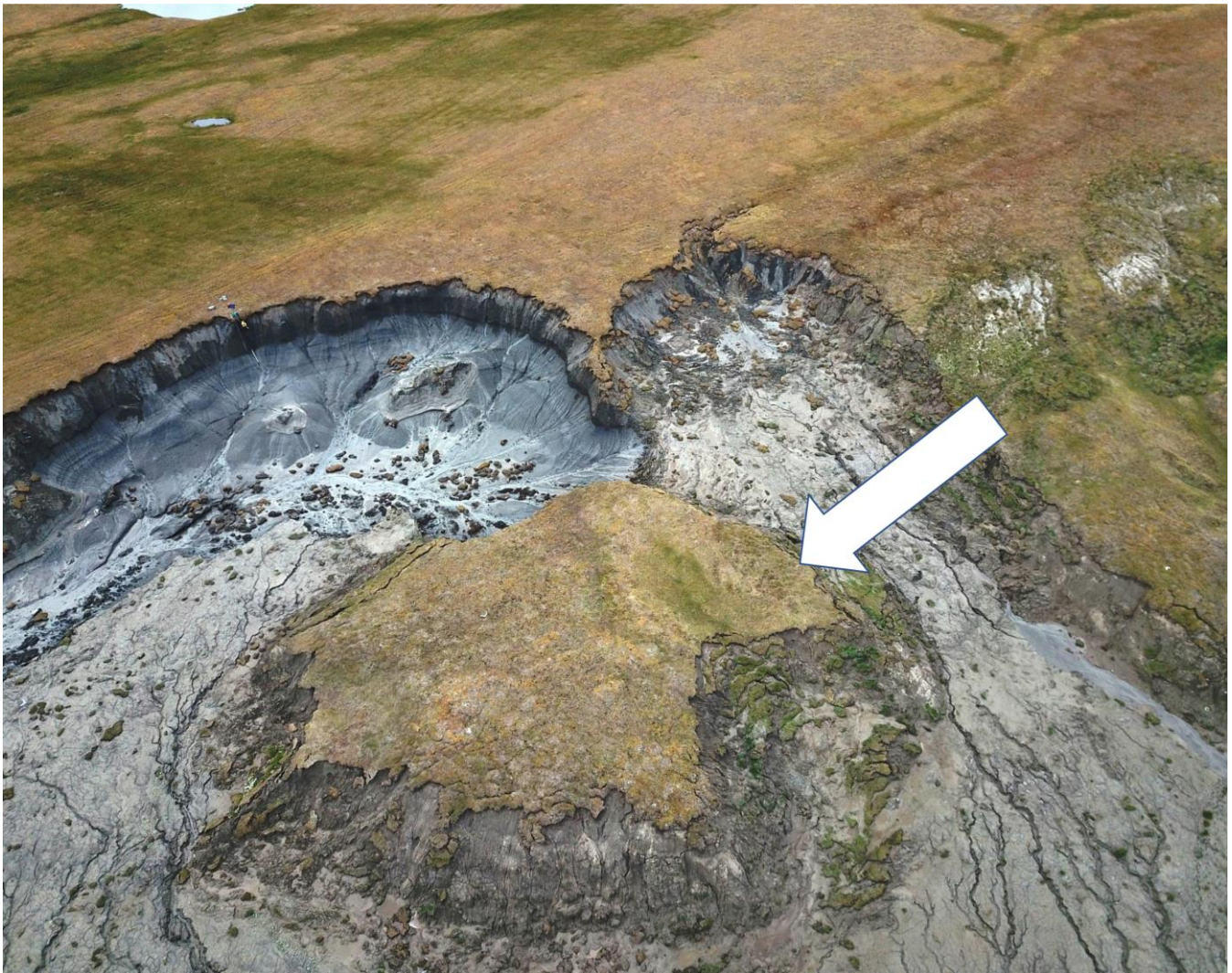
539 **4.4. RTS definition in the Glossary**

540 With a large number of recent RTS mapping studies in different permafrost regions, it has become clear that RTS
541 characteristics and morphologies vary widely, that RTS can occur in a range of different permafrost and ground ice settings,
542 and feature processes important for understanding their dynamics and environmental impacts. However, these aspects are not

543 yet covered by the current definition of a “retrogressive thaw slump” in the International Permafrost Association Multi-
544 Language Glossary of Permafrost and Related Ground-Ice Terms (van Everdingen, 2005) (see Sect. 3.2.1). This definition is
545 rather short and describes a portion of RTS characteristics, it is limited in its scope and does not capture the full breadth of
546 RTS variability emerging from the many studies. In particular, the definition only focuses on the active stage of RTS, while
547 the polycyclic nature of many RTS also includes the stages of stabilization without activity. Moreover, this definition does not
548 reflect the variety of possible morphologies as horseshoe-like (thermocirques) or elongated along the coast (thermoterrace)
549 and different stages of the landform evolution. Furthermore, some other settings also feature slump-like landforms that exhibit
550 a similar headwall backwasting but were not covered in this review. Such slumps for example occur on recent dead-ice
551 moraines that experience retrogressive rotational sliding or back slumping of the ice-cored slopes (Kjær and Krüger, 2001).
552 Thus, a clear distinction should be drawn in the definition. We recommend considering these points when preparing the next
553 International Permafrost Association Multi-Language Glossary of Permafrost and Related Ground-Ice Terms.

554 **4.5. Missing terminology**

555 Our review of morphologic elements of RTS (see Sect. 3.1) showed that there is no term to describe unthawed permafrost
556 remnants within a slump floor. The term *slump block*, in our opinion, fits the best to explain pieces of soil with vegetation that
557 move downwards while the term *remnant island* sounds rather confusing because it does not assume the moving nature of
558 such a feature. We rather suggest using the term *remnant island* to describe unthawed permafrost remnants within a slump
559 floor. These remnant islands are generally larger than slump blocks and do not move since they still have unthawed cores. An
560 example of such a remnant island is shown in Fig.12.



561

562 **Figure 12** Example of an unthawed remnant island (indicated with white arrow) within a slump floor of RTS in Yugorsky Peninsula,
563 **European Arctic, Russia, September 2019. UAV photo: Nina Nesterova.**

564 **5 Conclusions**

565 Retrogressive thaw slumps are complex permafrost region landforms that despite recent wide scientific interest are still studied
566 very differently in terms of terminology. Based on our review of the literature and terminologies we draw the following
567 conclusions:

- 568 • The RTS formation process is currently explained with two different terms (thermokarst and thermodenudation) in
569 the North American and Russian literature based on different theoretical views that were formed in the 20th century.

- 570 • RTS is a general umbrella term applied to different stages of landform activity and also a variety of mass-wasting
571 landforms on slopes with ice-rich permafrost (thermocirque/thermoterrace).
- 572 • RTSs can differ in shape, triggers, ground ice types, position in the relief, activity, concurrent processes, and spatial
573 aggregation.
- 574 • For active RTS we identified four essential morphologic parts (headwall, slump floor, mudflow, edge), while nine
575 additional parts may or may not be present in an RTS.

576 The study of RTS formation and accompanying processes is important to better understand how rapid mass wasting on
577 permafrost slopes can mobilize sediment, meltwater, carbon, and nutrients, how biogeochemical dynamics are influenced by
578 specific processes during the RTS formation and growth, and how RTS may pose hazards to infrastructure. More clarity on
579 used terminology and scientific views will foster this understanding and can guide new research.

580 **Author contribution**

581 NN: Conceptualization, Resources (literature sources), Investigation, Writing – original draft preparation. ML:
582 Conceptualization, Supervision, Writing – review & editing. AK: Supervision, Writing – review & editing. HL:
583 Conceptualization, Supervision, Writing – review & editing. IT: Resources (literature sources), Writing – review & editing.
584 IN: Writing – review & editing. AV: Writing – review & editing. GG: Conceptualization, Supervision, Writing – review &
585 editing.

586 **Competing interests**

587 The authors declare that they have no conflict of interest.

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