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Evolution of the banks of thermokarst lakes in Central Yakutia (Central Siberia) due to retrogressive thaw slump activity controlled by insolation

A. Séjourné [a,b,*], F. Costard [a], A. Fedorov [c,d], J. Gargani [a], J. Skorve [e], M. Massé [f,b], D. Mège [b]

[a] Univ Paris-Sud, CNRS, Laboratoire GEOPS, UMR8148, 91400 Orsay, France
[b] WROONA Group, Polish Academy of Sciences, Institute of Geological Sciences, Research Centre in Wrocław, Poland
[c] Melnikov Permafrost Institute, Yakutsk, Russian Federation
[d] International Center BEST, North-Eastern Federal University, Yakutsk, Russian Federation
[e] Norwegian Space Centre, Oslo, Norway
[f] Univ Paris-Sud, CNRS, Laboratoire IAS, Orsay, France

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ABSTRACT

As observed in most regions in the Arctic, the thawing of ice-rich permafrost (thermokarst) has been developing in Central Yakutia. However, the relationship between thermokarst development and climate variations is not well understood in this region, in particular the development rate of thaw slumps. The objective of this paper is to understand the current development of thermokarst by studying the evolution of the banks of thermokarst lakes. We studied retrogressive thaw slumps and highly degraded ice-wedge polygons (baydjarakhs), indicative of thermokarst, using high resolution satellite images taken in 2011–2013 and conducting field studies. The retrogressive thaw slump activity results in the formation of thermocirque with a minimum and maximum average headwall retreat of 0.5 and 3.16 $m \cdot yr^{-1}$ respectively. The thermocirques and the baydjarakhs are statistically more concentrated on the south- to southwest-facing banks of thermokarst lakes. Moreover, the rate of headwall retreat of the thermocirques is the most important on the south-facing banks of the lakes. These observations indicate a control of the current permafrost thaw on the banks of thermokarst lakes by insolation. In the context of recent air temperature increase in Central Yakutia, the rate of thermocirque development may increase in the future.

1. Introduction

Permafrost that contains a high ice-content exceeding that of soil pores is referred to as ice-rich (ACIA, 2006; French, 2007). Late-Pleistocene ice-rich permafrost is found in Northern Canada, Alaska, as well as Northern, Central and Eastern Siberia (French and Shur, 2010; Kanevskiy et al., 2011). Ice-rich permafrost is commonly composed of more than 40% volume of ground ice in the form of segregated ice and massive ice-wedges (ACGR, 1988; French and Shur, 2010). Ice-rich permafrost is sensitive to climate change and was extensively thawed during the early Holocene climatic optimum forming numerous thermokarst lakes (Romanovskii et al., 2000; Kaufman et al., 2004; Wanner et al., 2008). The thermokarst denotes the processes and landforms associated with ablation of ground ice and subsequent subsidence of the ground (Popov, 1956; ACGR, 1988; French, 2007).

Recent mean annual air temperature increases in arctic and subarctic regions have been significantly greater than global averages (Serreze et al., 2000; Johannessen et al., 2004; Skachkov, 2010). The frequency and magnitude of terrain disturbances associated with thawing permafrost (thermokarst) are thus increasing in these regions (Osterkamp, 2005; Jorgenson et al., 2006; Lantuit and Pollard, 2008; Lantz and Kokelj, 2008). As climatic simulations predict that the Arctic will experience one of the quickest warming on the planet, thermokarst processes should spread and intensify (ACIA, 2006). Thermokarst is a substantial risk for buildings and infrastructures because of the high volume of ground ice in these regions (Lunardini, 1996; Nelson et al., 2001). Permafrost thaw on lake banks can significantly alter lakes and streams by bringing suspended sediments and solute concentration (Lamoureux and Lafrenière, 2009; Kokelj et al., 2013). A better understanding of the distribution and rate of current thermokarst development is therefore of importance for inferring future changes in the arctic and subarctic regions.

The Central Yakutia, located in Central Siberia, displays an ice-rich permafrost and a strong continental climate favoring thermokarst formation (Fig. 1a) (Soloviev, 1973a; Romanovskii et al., 2000). As the mean annual air temperature at Yakutsk had increased by 3 °C between 1966 and 2009 (Skachkov, 2010) and thermokarst processes seem to develop rapidly at different study sites in Central Yakutia since the early 1990s (Iijima et al., 2010; Fedorov et al., 2014), this ice-rich

* Corresponding author at: Univ Paris-Sud, CNRS, Laboratoire GEOPS, UMR8148, 91400 Orsay, France. Tel.: +33 169 154 929; fax: +33 169 154 882.
E-mail address: antoine.sejourne@u-psud.fr (A. Séjourné).

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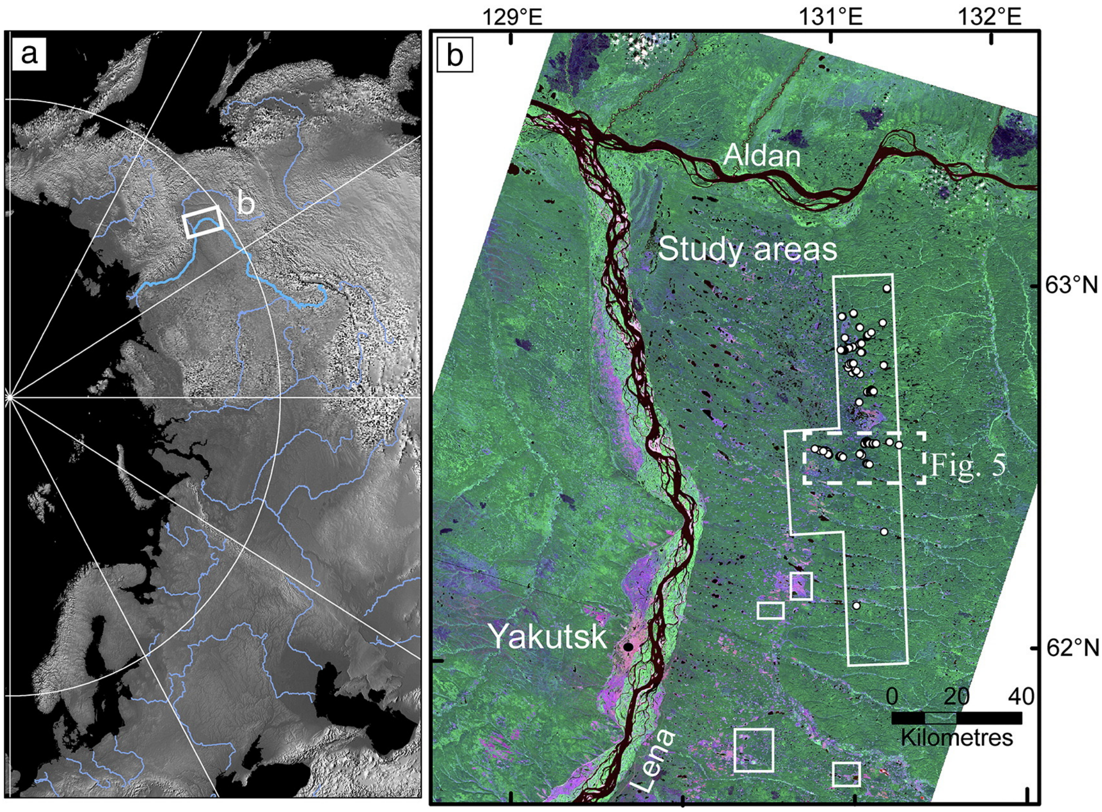

Fig. 1. Localization of the study areas in Central Yakutia. (a) Shaded-relief map of Siberia. (b) Distribution of retrogressive thaw slumps along the banks of thermokarst lakes (white dots). White rectangles represent the footprints of the high resolution satellites images used. Landsat ETM+ image as background.

permafrost is highly vulnerable and prone to extensive degradation. Along the banks of thermokarst lakes, the thawing of permafrost forms two different thermokarst landforms: retrogressive thaw slumps and highly degraded ice-wedge polygons (baydjarakhs). Deep permafrost thawing induces retrogressive thaw slumping and the formation of amphitheatrical hollows referred to as "thermocirque" (Fig. 2a) (Czudek and Demek, 1970). While retrogressive thaw slump are intensively studied in some arctic regions, their evolution in Central Yakutia has not been investigated recently (Czudek and Demek, 1970). Moreover, localized melting of ice-wedges forms highly-degraded conical polygons with wide troughs referred to "baydjarakhs" (Fig. 2b) (Popov, 1956; Soloviev, 1973a). While it was assumed that the baydjarakhs only form on south-facing slopes due to insolation (Czudek and Demek, 1970), this assumption has not been demonstrated systematically and statistically.

Here we study the bank degradation of thermokarst lakes in Central Yakutia due to permafrost thaw. The analysis of the evolution of retrogressive thaw slumps and polygonal baydjarakhs provides a better understanding of the current thermokarst dynamic in this region. We used (i) field surveys and (ii) high resolution (50 cm) satellite images taken between 2010 and 2013, with the aim of: (i) characterizing the morphology and geographical distribution of thermokarst lake banks; (ii) estimating the annual rate of thermocirque development; and (iii) understanding the processes and origin of the slump development.

2. Study site

The Central Yakutia (Sakha Republic in the Russian Federation) located within the continuous permafrost zone is the lowland plain stretching along the Lena, Aldan and Vilyuy rivers and the Verkhoyansk Range (Fig. 1a; Bogatova and Bugrimova, 1981). The climate is continental (mean temperature −10 °C), characterized by a distinct seasonal variation (mean temperature +20 °C in July and −40 °C in January) and low precipitation of 250 mm per year, mainly occurring during the warm season (June–August) (Skachkov, 2010). The potential evaporation per year is however up to four times the precipitation in summer, and up to ten times during dry years (Gavrilova, 1973; Fedorov et al., 2014).

The central Yakutian lowlands are covered by Quaternary sediments consisting predominantly of silty clays and sandy silts of fluvial, lacustrine or loessic origin (Soloviev, 1973b; Péwé et al., 1977). Numerous fluvial terraces have developed along the Lena and Aldan rivers and their tributaries during the Pleistocene (Soloviev, 1973b). The permafrost in this region has a thickness of 400 to 700 m, with a maximum of 1500 m observed on the Siberian Plateau in the upstream of the Markha River, associated with an active-layer of 0.5–2 m (Ivanov, 1984; Romanovsky et al., 2007). The mean temperature of the permafrost at 10–20 m deep ranges from −2 °C to −4 °C (Soloviev, 1973b; Ivanov, 1984). In some parts of Central Yakutia, the upper part of the permafrost consists of ice-rich sediments, which are up to 20–30 m thick and called the "Yedoma ice-complex" (Czudek and Demek, 1970; Soloviev, 1973b). They contain ~70–80% of ice by volume and are characterized by massive syngenetic ice-wedges (≥10 m thick), as seen on the headwall of a thermocirque in Fig. 2a (Soloviev, 1959; Ivanov, 1984). This permafrost is syngenetic and made up of Quaternary sediments forming terraces of various origins (Soloviev, 1973b; Péwé et al., 1977). Syngenetic permafrost is defined as permafrost that formed more or less simultaneously with the deposition of the surrounding soil material (ACGR, 1988). The study area intersects the ice-rich Tyungulu and Abalakh terraces of the Lena River that contain ~70–80% of ice by volume (Soloviev, 1959; Dylik, 1964). These terraces can reach 40–60 m in thickness and are made of alluvial sandy loam containing up to 40–50% of ice by volume, and also show massive syngenetic ice-wedges (Katasonov and Ivanov, 1973; Soloviev, 1973b; Ivanov, 1984). A significant part (up to 40%) of the land surface in the

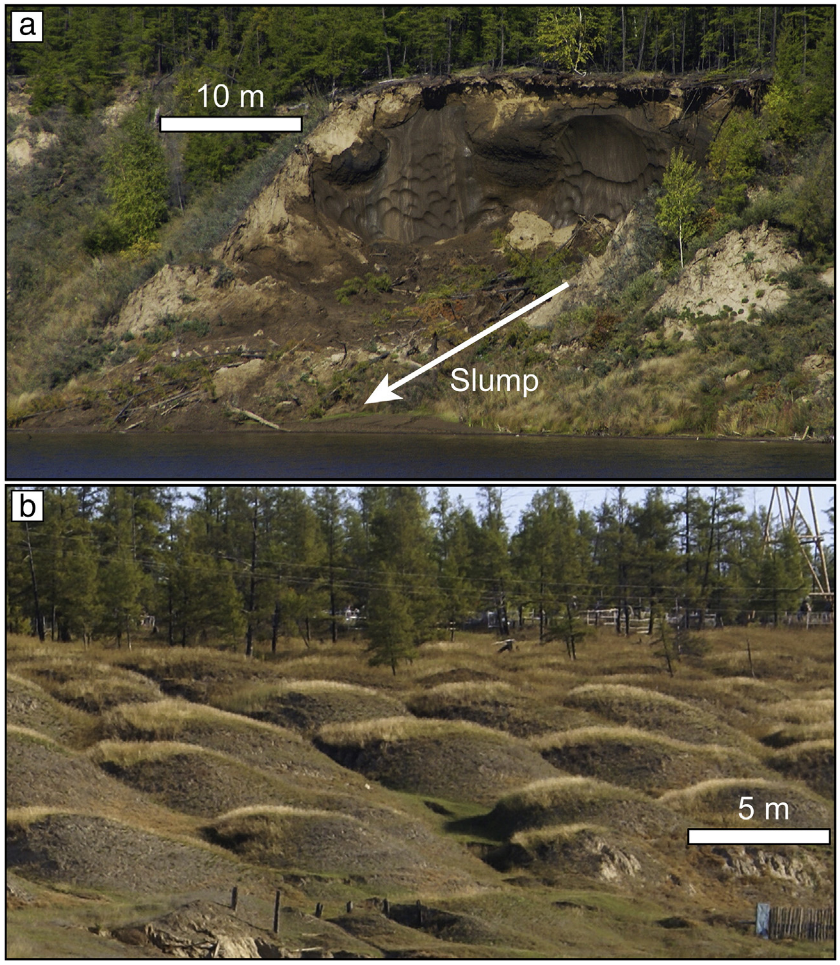

Fig. 2. Thermokarst landforms formed along the banks of thermokarst lakes in Central Yakutia. (a) Thermocirques produced by retrogressive thaw slumping (tree of ~7 m high for scale). (b) Highly-degraded conical ice-wedge polygons with wide troughs referred to as "baydjarakhs".

study area has been modified by thermokarst (Soloviev, 1959; Dylik, 1964; Czudek and Demek, 1970).

3. Methods

The banks of thermokarst lakes were investigated East of the Lena river (61°–63°N and 130°–131°E) using a combination of field works and high resolution satellite image analysis (Fig. 1b). The remote sensing analysis aims to investigate the geographical distribution of thermocirques and baydjarakhs along the banks of thermokarst lakes and alases. According to the model of thermokarst lake evolution of Soloviev (1959), the alases are deep depressions with a residual lake that represent the end stage of thermokarst evolution. We used seven panchromatic GeoEye-1 images and three WorldView-2 images covering a total area of ~2700 km^2, acquired in May 2010, June 2010, July 2010, August 2011, June 2011, September 2012, and September 2013 (Fig. 1b). These high resolution images (50 cm per pixel) enable the observation of thermocirques and baydjarakhs as small as 5 m in diameter. Over the study area, about 2700 thermokarst lakes were examined for the occurrence of thermocirques and more than 710 thermokarst lakes for the occurrence of baydjarakhs (Table 1). In order to understand the distribution and the formation of thermocirques, the distribution of baydjarakhs was also studied. The number of thermokarst lakes investigated for thermocirques are higher in order to obtain a good statistics. A total of 180 thermocirques were identified (Fig. 1b) on the banks of 26 thermokarst lakes, representing 0.96% of the total studied lakes (Table 1). Thermokarst lakes with evidence of anthropogenic influence such as settlements or woodcutting were removed from the analysis.

The orientation of thermokarst lake banks showing thermocirques or baydjarakhs was calculated by using an ArcGIS tool provided by Jenness (2007). We mapped the banks (lines perpendicular to the greater slope in Fig. 3) showing thermocirques and baydjarakhs (Fig. 3). Then we measured the orientation of the banks which

Table 1
Statistical correlation between occurrence of thermokarst lakes and that of thermocirques.

Feature	Population	Percentage of total studied lakes	Percentage of large-sized lakes
Small-sized thermokarst lakes	311	43%	
Large sized thermokarst lakes with baydjarakhs	249	34%	62%
Large sized thermokarst lakes without baydjarakhs	152	23%	38%
Large sized thermokarst lakes without thermocirques	2677	99.04%	
Large sized thermokarst lakes with thermocirques	26	0.96%	

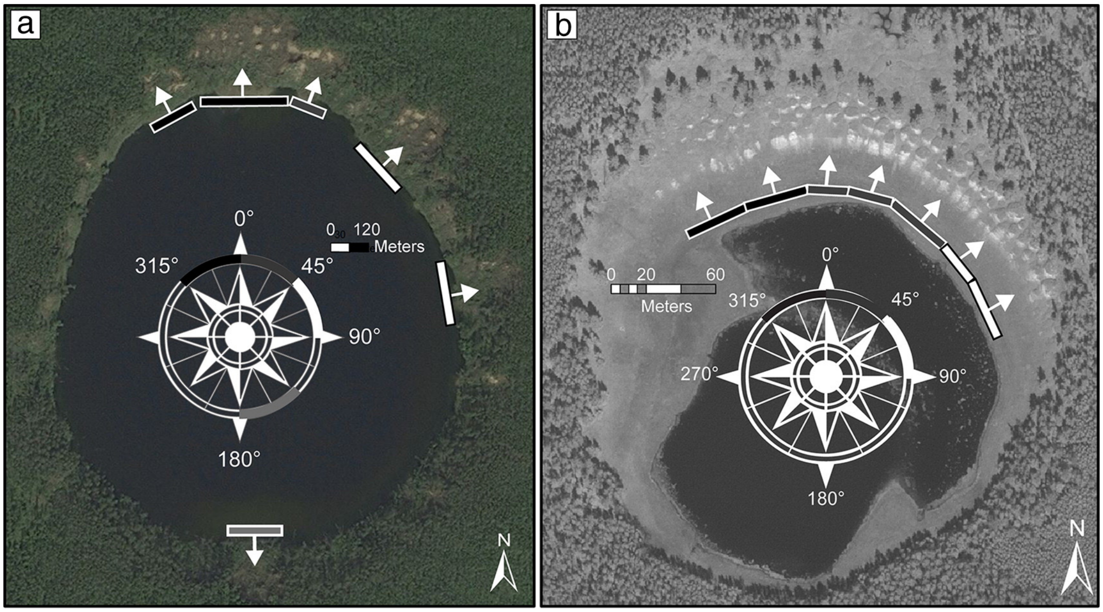

Fig. 3. Orientation of the banks of thermokarst lake showing (a) thermocirques or (b) baydjarakhs. The banks showing thermocirques or baydjarakhs were digitized (lines perpendicular to the greater slope). The orientation of the banks corresponds to the upslope direction (see arrows). This orientation is calculated with respect to the north (azimuth in grayscale).

corresponds to the upslope direction of these banks. This orientation was calculated with respect to the north (azimuth in grayscale in Fig. 3). The thermocirques have their orientation always perpendicular to the greater slope, thus the orientation of the thermocirques corresponds to the orientation of the banks. The data were compiled in a rose diagram representing the orientation of the lake banks showing thermocirques (total number of measurements $N = 190$; Fig. 4a) and baydjarakhs ($N = 2037$; Fig. 4b).

During field investigations, 63 active retrogressive thaw slumps located on the banks of six thermokarst lakes were studied (Fig. 5). The field studies took place during two different periods: in August 2009 and 2010 when the thawing was active, and in October 2012 after the thawing reached its maximum and was inactive. The inner topography of thermocirques was studied by performing topographic surveys with a theodolite (Fig. 6). The active-layer thickness was estimated by using a metal rod to probe the depth to frozen layer table along longitudinal transects parallel to the topographic profile of Fig. 6. The depth was not measured close to the headwall of thermocirque because the thaw slumps were still relatively active. The depth measurements were made at the end of August, which corresponds to the maximum of thawing and therefore close to the active layer thickness.

We combined field observations and high resolution satellite image time series to estimate the headwall retreat of thermocirques due to thaw slump on the banks of six thermokarst lakes for 2011–2013 (Fig. 5 and Table 2). During fieldwork in 2010 and 2012, we estimated their development by visual inference using different benchmarks in the field (marked trees or rods). Several satellite images were captured at the time when field surveys were undertaken (2011 and 2012). We examined consistency between the evolution of thermocirques based on the images and fieldwork. Using ArcGIS, the satellites images were manually re-georeferenced and re-aligned to match ground control points defined during field studies. The cliff of thermocirques was digitized manually on both images in order to underline the potential change (Fig. 7). Based on the 50 cm$\cdot$pixel^{-1} image resolution, the uncertainty on cliff mapping is estimated to be 1 m. Finally, the annual rate of headwall retreat (development of thermocirque) is obtained by dividing the change in longitudinal length by the number of years. We

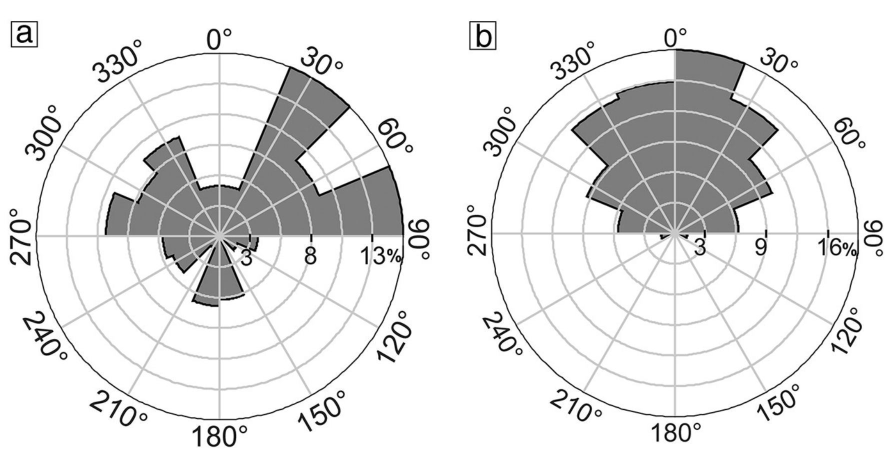

Fig. 4. Rose plot of the orientation and the frequency (%) of thermokarst lake banks showing thermocirques or baydjarakhs. The orientation values are grouped into 22.5° sectors. (a) Orientation of the banks of 26 thermokarst lakes showing 180 thermocirques ($N = 190$). (b) Orientation of the banks of 710 thermokarst lakes showing baydjarakhs ($N = 2037$).

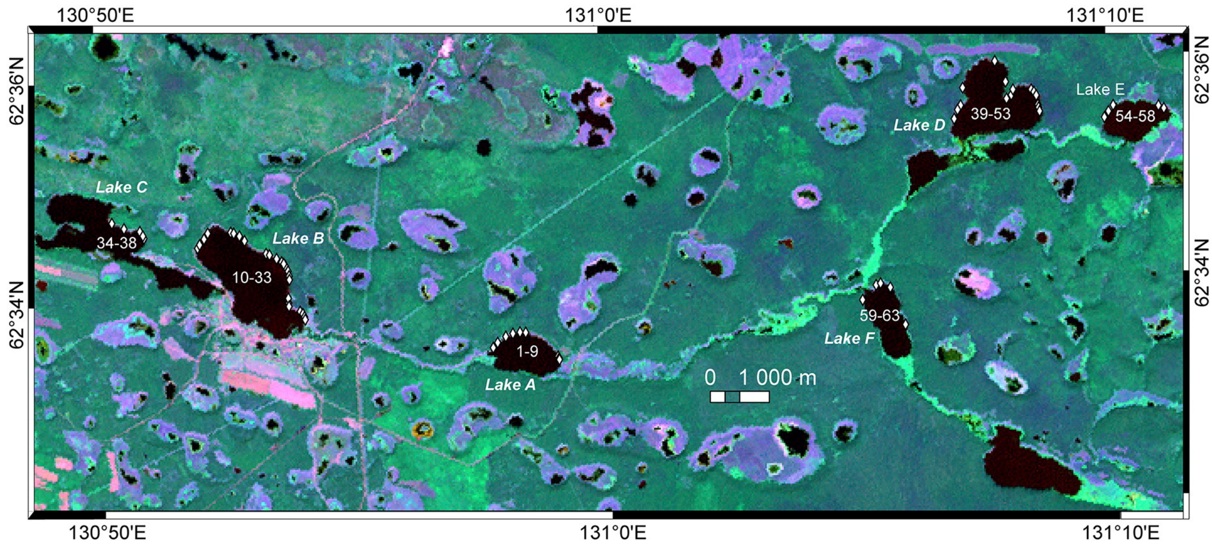

Fig. 5. Distribution of estimated headwall retreat for 63 thermocirques for years 2011–2013 (white diamonds; see Table 2). The thermocirque number is determined in clockwise order. Landsat ETM+ image as background.

decided to differentiate the minimum and maximum headwall retreat amounts in order to highlight that some parts of thermocirque change faster than others (Table 2). Given the uncertainty on the measured distances (1 m) and the image time series (two years), the uncertainty on the development rate is 0.5 m·yr^{-1}. According to the image overlap as well as the sun and camera azimuth similarities for each image, the headwall retreat was estimated for 63 thermocirques over the period 2011–2013 (Table 2). The slope aspect of each thermocirque is reported in Table 2.

We analyzed hourly wind direction and speed data set (eight measurements per day at 10–12 m high) from the Yakutsk meteorological station (station #24959 http://meteo.ru) between 2005 and 2010. Data from May to September representing the warm season with mean daily temperature >0 °C were extracted from the record for 2005–2010 ($N = 614$) (Fig. 8b).

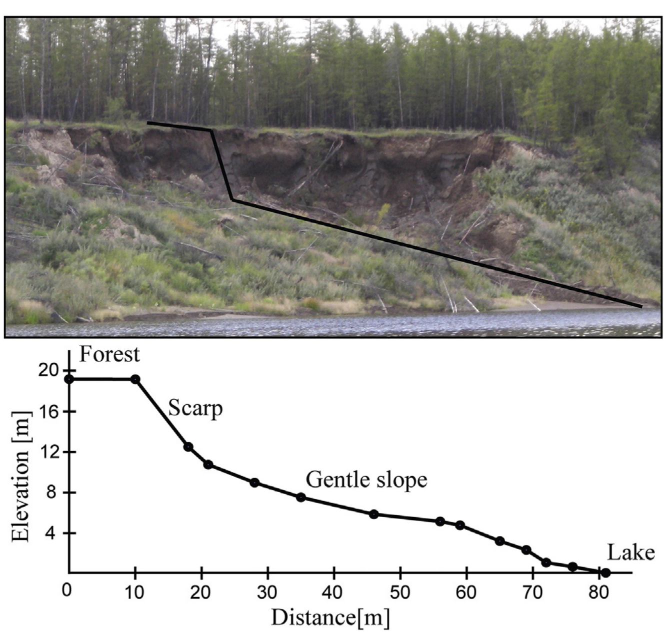

Fig. 6. Topographical profile of a thermocirque based on a topographic survey with a laser theodolite. The height of the headwall is 7.8 m. The length of the headwall is 11 m. The total height and height of the thermocirque is 15.5 and 66 m, respectively.

4. Results

4.1. Thermocirque morphology and distribution

Along the banks of thermokarst lakes, thermocirques are elliptical hollows with serrated edges ranging from 10 to 60 m in diameter (Figs. 6 and 7). Some large thermocirques are 100 m in diameter and present evidence of coalescence. The thermocirques have a concave longitudinal profile composed of a 5–9 m high headwall and a 20–60 m long gentle slope (Fig. 6). Permafrost thaw triggers retrogressive thaw slumps taking the form of collapses and small mud-flows that settle on the gentle slope and form subaerial fan deposit extending into the lake (Fig. 9a). A slope value for the gentle slope of 8–10% is typical for mud deposits (Philipponnat and Hubert, 2000). On the headwall and within the thermocirques, relatively small baydjarakhs are observed and their diameter and height decreases away from the headwall scarp, reflecting their progressive thaw (approximate width change from 5 to 3 m and height change from 4 to 2 m; Fig. 9b). Inside the thermocirques, some gullies eroding these deposits provide a natural cross-section that provides a deposit minimum thickness estimate of 1–2 m (Fig. 9b). The banks of the thermokarst lakes and the upper surface around the thermocirques are forested (Fig. 6). Our survey of active-layer thickness through a thermocirque (parallel to the profile of Fig. 6) in August 2010 demonstrates that the active layer thickness is 1.0–1.2 m on the upper forested surface around thermocirques and ranges from 1.5 to 2 m on the gentle slope close to the lake shore. In Central Yakutia, the forest plays a key role in keeping permafrost temperatures low: for example the active layer is about 1.2–1.5 m thick in forested areas but 1.8–1.9 m thick in open areas (Brouchkov et al., 2004). In some places around thermocirques, the vegetation cover is disturbed and collapsed areas reflect the underlying partially melted ice-wedge network.

After identifying the key characteristics of thermocirques in the field (heart-shaped hollow, baydjarakhs, and retrogressive thaw slumps), we mapped their distribution on the banks of thermokarst lakes. The 26 thermokarst lakes and alases that show thermocirques have a diameter ranging from 500 m to 8 km (Figs. 1b and 3a). According to the model of thermokarst lake evolution of Soloviev (1959), these large-sized thermokarst lakes and alases with flat floors and relatively steep slopes represent developed thermokarst features (5–15 m in depth). The large-sized thermokarst lakes show commonly thermocirques and baydjarakhs on their banks. From our mapping, the thermocirques are

Table 2
Summary statistics of headwall retreat of thermocirques shown in Fig. 5 due to retrogressive thaw slumps along the banks of thermokarst lakes for years 2011–2013.

Thermokarst lake	Thermocirque number	Longitude (°)	Latitude (°)	Min headwall retreat ($m \cdot yr^{-1}$)	Max headwall retreat ($m \cdot yr^{-1}$)	Slope aspect (°)
A	1	130.960	62.533	0	1.56	118.6
A	2	130.961	62.534	0.85	6	137.8
A	3	130.964	62.535	0	4.34	149.9
A	4	130.966	62.535	0.65	4.62	164.4
A	5	130.969	62.535	0	5.39	174.5
A	6	130.970	62.535	0.4	3.27	192.88
A	7	130.981	62.532	0.3	2.65	238.48
A	8	130.981	62.531	0	2.71	259
A	9	130.981	62.531	0	2.94	259
B	10	130.863	62.550	0.55	4.1	127.6
B	11	130.864	62.551	0.6	3.55	127.6
B	12	130.866	62.551	1.43	3.21	125.6
B	13	130.867	62.552	1	6.03	116
B	14	130.874	62.552	1.75	5.1	202.1
B	15	130.876	62.552	1.34	4	198.1
B	16	130.877	62.552	1.01	5.31	208.3
B	17	130.879	62.551	2.45	3.68	236.65
B	18	130.886	62.549	2.55	5.1	200.7
B	19	130.887	62.549	0	5.95	206.5
B	20	130.889	62.548	0	6.1	209
B	21	130.891	62.548	0	2.55	221
B	22	130.892	62.547	0	2.35	229.7
B	23	130.892	62.547	0	2.2	235
B	24	130.893	62.546	0	1.15	254.1
B	25	130.893	62.546	0	0.85	264.8
B	26	130.893	62.545	0	1.1	262.3
B	27	130.893	62.542	0.4	0.75	264.3
B	28	130.893	62.541	0	0.6	265.7
B	29	130.893	62.541	0.4	2.05	264
B	30	130.897	62.540	0.52	2.25	219.2
B	31	130.898	62.540	0.54	2.25	230.3
B	32	130.898	62.539	0.25	3.81	253.9
B	33	130.898	62.539	0.55	4.78	266.3
C	34	130.836	62.554	1.9	4.5	214.06
C	35	130.840	62.553	1.63	5.8	210.25
C	36	130.845	62.553	1.85	3.79	220
C	37	130.846	62.552	1	3.11	251
C	38	130.846	62.552	0.45	3.85	254.4
D	39	131.113	62.566	0.4	2.61	107
D	40	131.115	62.568	0	0.9	108
D	41	131.116	62.568	0	1.85	140
D	42	131.117	62.571	0	0.85	98.2
D	43	131.127	62.575	0.4	2.26	180
D	44	131.131	62.572	0.87	2.19	277.9
D	45	131.131	62.569	0	4.25	184.8
D	46	131.132	62.570	0	4.3	103.7
D	47	131.133	62.570	1.55	5.65	113.4
D	48	131.139	62.570	0.5	4.45	221
D	49	131.140	62.570	0.44	2.6	228.9
D	50	131.141	62.569	0	2.19	234.1
D	51	131.141	62.568	0	3.27	260
D	52	131.141	62.568	0	2.88	256.2
D	53	131.142	62.567	0.3	3.09	268.2
E	54	131.163	62.566	0	1.61	125.3
E	55	131.164	62.567	0.3	3.77	122
E	56	131.166	62.568	0	1.15	135
E	57	131.181	62.567	0.55	2.9	203.6
E	58	131.182	62.567	0.55	2.18	208.22
F	59	131.081	62.539	0	0.35	82.9
F	60	131.086	62.541	0.4	1.25	142.6
F	61	131.088	62.542	0.48	6.75	172.2
F	62	131.091	62.541	0.52	1.73	230.1
F	63	131.095	62.535	0	0.98	263.6

The uncertainty on the headwall retreat rate is 0.5 $m \cdot yr^{-1}$.

preferentially localized (78% of them) on the northern sides of the lakes (azimuth from 270° to 90°N; Fig. 4a). More specifically, the majority of the thermocirques (40% of them) is concentrated on the slopes facing SE to ESE (Fig. 4a). The distribution of the retrogressive thaw slumps over the study area occurs in both ice-rich terraces of the Lena River (Tyungulu and Abalakh terraces). The morphology and distribution of the thaw slumps do not differ from one terrace to the other. The headwall of thermocirques in Fig. 9 shows an exposure of the Tyungulu terrace (1 m thick active layer) in which the polygons are 5–7 m wide (see letter p in Fig. 9b) and the syngenetic ice-wedges are at least 7 m thick and 1 m wide at the top (see letter w in Fig. 9b). This terrace is made up of alluvial sandy loam containing up to 40–50% volume of ice (Katasonov and Ivanov, 1973; Soloviev, 1973b).

During field works, the analyzed thermocirques showed evidence of active retrogressive thaw slumping every year (Figs. 5 and 10). Based on the satellite image time series from 2011 to 2013, the minimum and

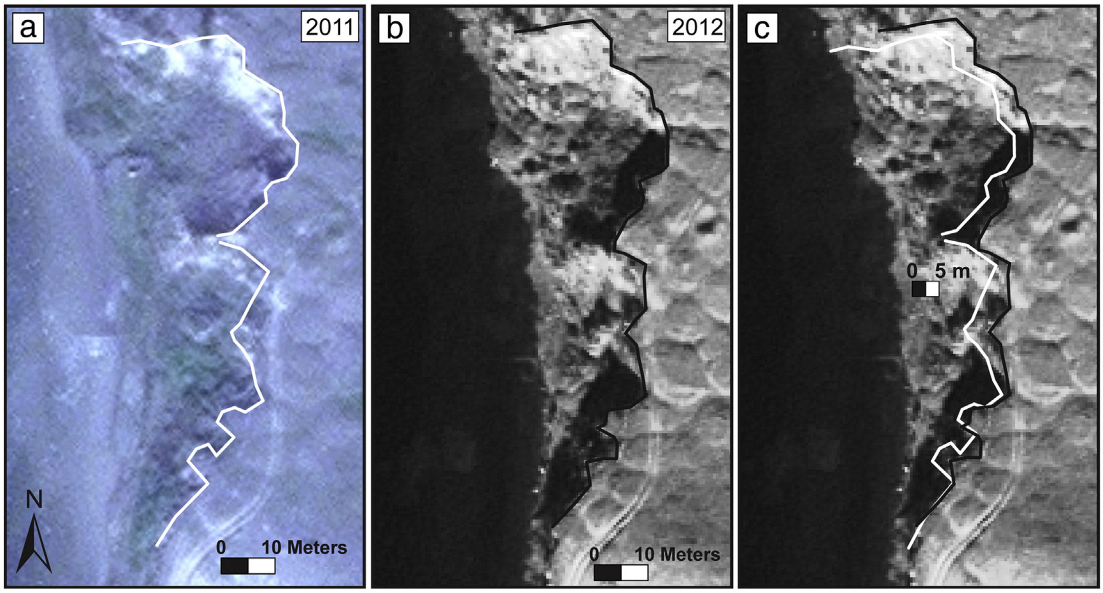

Fig. 7. Estimation of headwall retreat of thermocirques for years 2011–2013. The cliff of each thermocirque was mapped manually using high resolution satellite images. Panel (c) shows an example of the comparison between 2011 (a) and 2012 (b) and the annual development rate for the thermocirques number 32 and 33 in Table 2.

maximum average headwall retreat of thermocirques is 0.5 and 3.16 $m \cdot yr^{-1}$ respectively (Fig. 7 and Table 2). For most thermocirques, the headwall retreat is not homogenous along the cliff; it can be minor (<1 $m \cdot yr^{-1}$) or significant (5–6 $m \cdot yr^{-1}$; Fig. 7). Thermocirque coalescence can occur through their retrogressive development (Figs. 7c and 10). The development of thermocirques is also not constant through time. For example, the retreat rate shown in Fig. 7 ranges from 0 to 5 $m \cdot yr^{-1}$ for the period 2011–2012, but 0.25 to 4.78 $m \cdot yr^{-1}$ for the period 2011–2013 (thermocirque numbers 32 and 33 in Table 2). The melting of ground ice, and development of thermocirques, were more important during the year 2011 than 2012. The results also indicate a higher rate of headwall retreat on the northern banks of thermokarst lakes (azimuth from 300° to 30°N; Fig. 8a).

4.2. Baydjarakh distribution

In areas where thermocirques are observed, they are commonly surrounded by large baydjarakhs of 10 to 30 m in diameter on the banks of thermokarst lakes (Fig. 3a). The baydjarakhs are only observed on the banks of large thermokarst lakes and alases (150–8000 m in diameter; Fig. 3b). According to our study, 62% of large thermokarst lakes and alases show baydjarakhs on their slopes, representing 34% of total studied lakes in Table 1. Baydjarakhs are invariably observed on the northern sides of the lakes (azimuth from 270° to 90°N) with 64% of them concentrated between 0° and 45°N of azimuth (Fig. 4b). This asymmetric distribution is also observed for alas valleys that formed by coalescence of several lakes.

5. Discussion

Our estimate of the headwall retreat of thermocirques (average from 0.5 to 3.16 $m \cdot yr^{-1}$) represents a first step in assessing their development in Central Yakutia. In comparison, Are et al. (1974) reported thermoerosion in 1971 along the side of thermokarst lakes with ice wedges in Central Yakutia to be 4.7–7.7 $m \cdot yr^{-1}$ on a cliff and 2 $m \cdot yr^{-1}$ on gentle slopes. While there is no mention of the presence of thermocirques in their study, this rate is similar to our study. Furthermore, several studies estimated the development of retrogressive thaw slump in the high Arctic with long photo time series (30 years). The rate ranges from 0.5 to 1 $m \cdot yr^{-1}$ along thermokarst lakes in the tundra

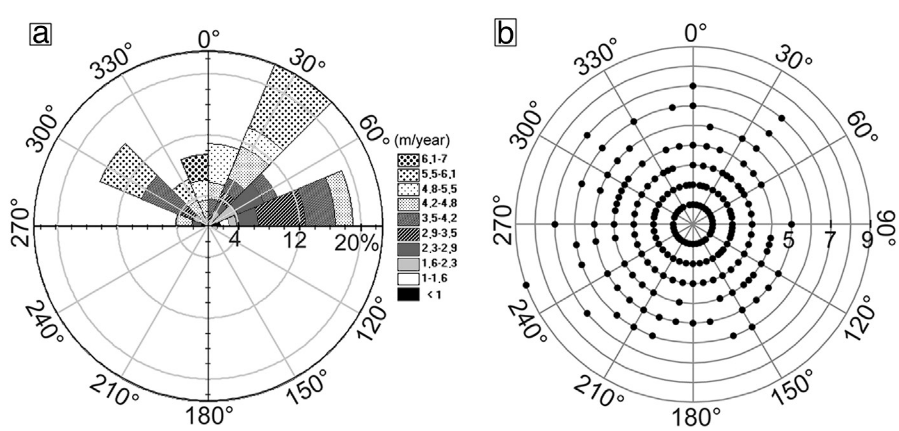

Fig. 8. Comparison between the maximum headwall retreat rate of thermocirques and wind direction. (a) Rose plot of the maximum headwall retreat for years 2011–2013. Data are from Table 2. The rates are classed and the frequency of rate values is plotted in percentage. The orientation values are grouped 22.5° sectors. (b) Rose plot of the hourly wind direction and speed in Yakutsk during the warm season (May–September) for years 2005–2010.

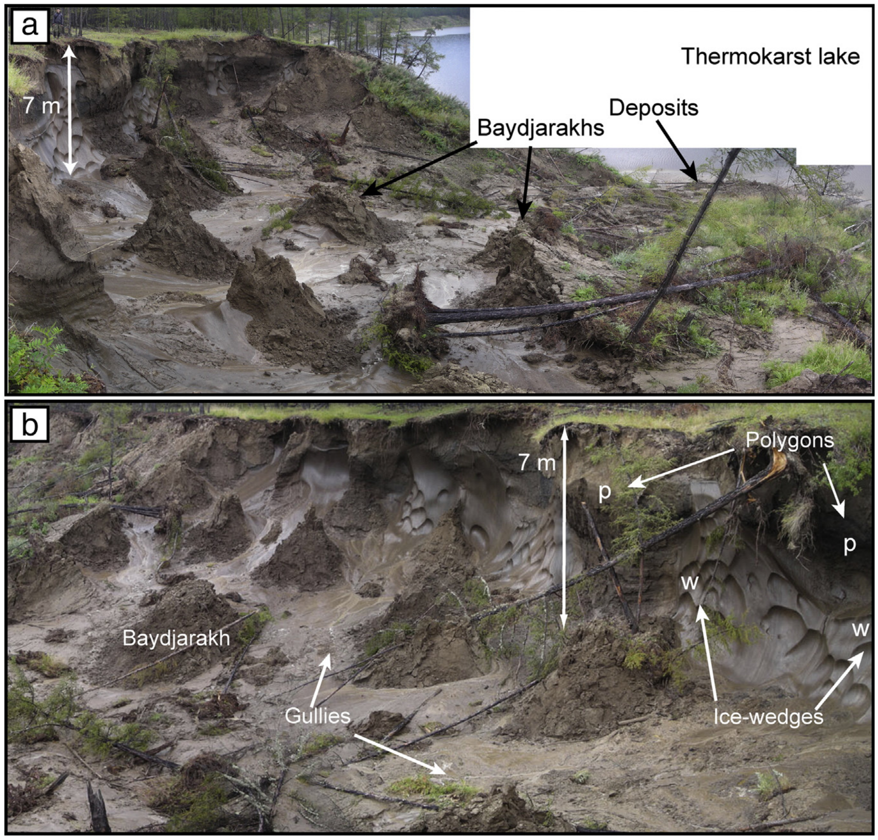

Fig. 9. Panorama of a thermocirque. (a) Longitudinal view of the headwall retreating by collapses and small mud-flows settling on the gentle slope. (b) Headwall of thermocirque showing ice-rich terraces composed of sandy loam containing up to 40–50% of ice by volume (p), and syngenetic ice-wedges of 7 m in thickness (w).

upland on the Mackenzie Delta, Canada (Lantz and Kokelj, 2008) to an average up to 9.6 m·yr^{-1} on the coast of Herschel Island, Canada, next to the Beaufort Sea (Lantuit and Pollard, 2005). Although it could be challenging to directly compare rates obtained in different studies due to possible differences in the acquisition or presentation of data (averaged values and the range of values), our headwall retreat rates appear to be lower than those generally reported in the high Arctic (Wolfe et al., 2001; Lantuit and Pollard, 2005; Lantz and Kokelj, 2008). This difference may be due to a difference in local climate, headwall height, ice content (Kokelj and Jorgenson, 2013), as well as period of photo time series.

The retrogressive thaw slumps have a seasonal activity from July to August; ice ablation induces retrogressive headwall retreat and active thermocirque development (Figs. 9a and 10). According to our field studies, the stabilization of the slump activity in August occurs when the ice-rich headwall is covered by sediments (Fig. 10b). This period of inactivity of thermocirque development is characterized by the absence of melting of ground ice and minor modification of the scarp by falls. Retrogressive thaw slumps are initiated by a variety of mechanisms that expose ice-rich sediments, including mechanical erosion by fluvial processes, wave action, thermally driven subsidence along the banks, and mass-wasting (Burn and Lewkowicz, 1990; Wolfe et al., 2001; Lantuit and Pollard, 2008; Kokelj et al., 2009; Lacelle et al., 2010). Based on our field observations, we infer that thaw slumps can be initiated in July by: (i) thickening of the active-layer due to an increase in insolation or air temperature, causing melting then removal of the insulating layer; or (ii) removal of the insulating layer by active-layer detachment, channelized flow along ice-wedge or mechanical and thermal erosion by waves, then melting of the exposed ground ice. From our observations within the thermocirques, the beginning of melting on the headwall and the presence of fan deposit in the lake indicate that the wave erosion at the base of the cliff is not a significant process exposing ground ice (Fig. 10a). Moreover, the water level of the lakes does not change significantly during the warm season as most of the lakes are connected with creeks that would regulate a potential increase of water discharge in the lake. The wind can also be responsible for an enhanced directional degradation on the slopes through thermal erosion by waves. However, the absence of prevailing direction of dominant wind during the warm season (Fig. 8b) and the absence of thermo-erosional niches near the slump scar disprove wave erosion in enhancing the melting. There is no evidence of active-layer detachments around thermocirques or thermoerosion gullies marking the preferential flow of water along the polygonized network (Fig. 10a). Moreover, the snowmelt water does not seem to affect the development of the thaw slumps because at the time slump activity initiates (July), melted snow has already been evacuated. We showed instead that the occurrence and rate of thermocirque headwall retreat are the most important on the south to southwest-facing banks of thermokarst lakes (Figs. 4a and 8a). The statistical results confirm enhanced thermokarst degradation on these banks subject to insolation, as suggested by Czudek and Demek (1970). The south- to southwest-facing slopes receive the highest energy in the afternoon, while insolation and air temperature are the highest. The insolation can generate favorable conditions for the initiation of thaw slumps (deepening of active-layer, formation of baydjarakhs and steeper slopes). Other studies in the high Arctic showed the role of solar radiation and sensible heat flux in controlling retrogressive thaw-slump activity along coastal bluffs and thermokarst lake banks (Lewkovicz, 1986; Grom and Pollard, 2008; Ulrich et al., 2010).

The observation of thermocirques and baydjarakhs only along the banks of large-sized thermokarst lakes may underline a threshold in the depth/diameter of these thermokarst depressions. For the thermocirques, the diameter of lakes are larger than about 500 m,

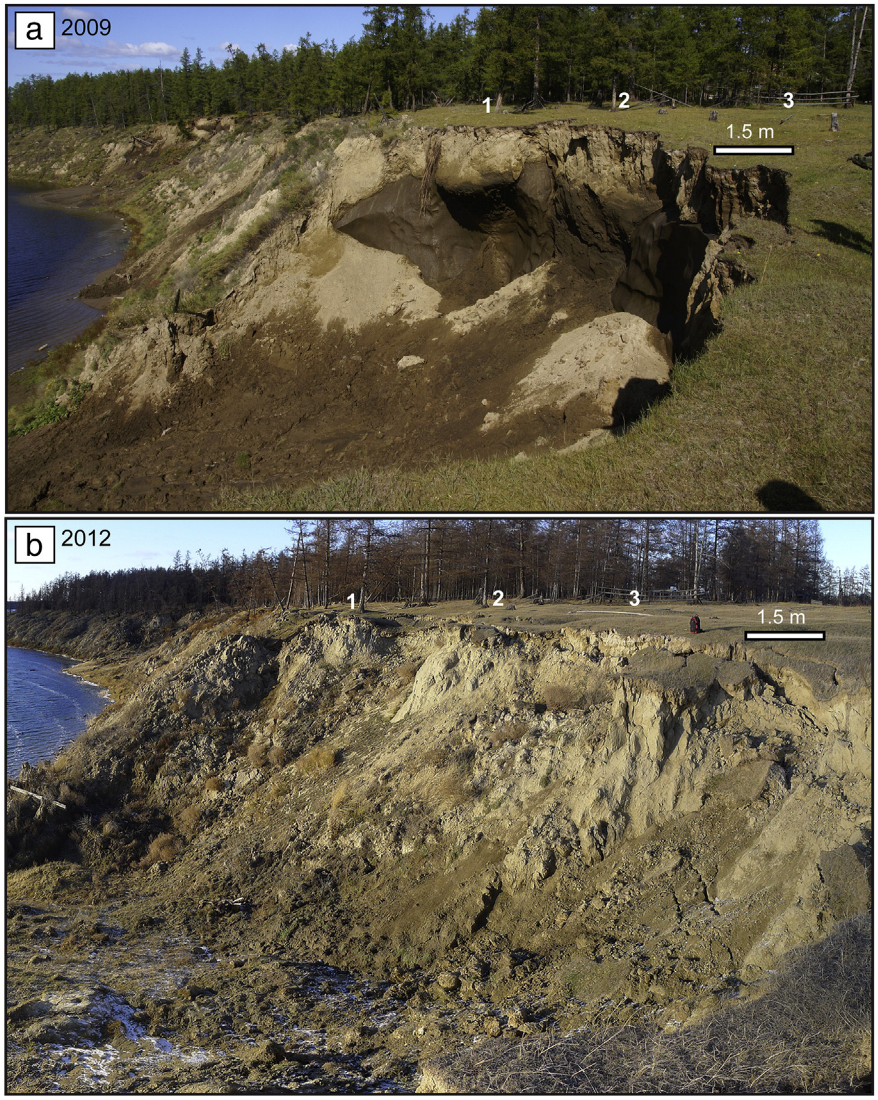

Fig. 10. Development of a thermocirque from 2009 to 2012. (a) Initiation of thaw slumping at the base of the headwall (July 2009). (b) Inactive thermocirque where the ice-rich headwall is covered with sediments (October 2012). Numbers show benchmarks.

whereas for the baydjarakhs the threshold is about 150 m. According to the model of thermokarst lake evolution of Soloviev (1959), slope steepness increases with the increase in lake size and depth. Therefore, the deep thawing of permafrost and following formation of thaw slumps and baydjarakhs requires relatively steep slopes. The location of the thaw slumps does not depend on the characteristics of the near-surface ice-rich permafrost because there is no correlation with a particular ice-rich terrace at the west of the Lena River. Soloviev (1973b) pointed out elongation of some thermokarst depressions in northern and eastern directions due to more intense warming and erosion of slopes exposed to the south and west. However, we did not observe a clear correlation between the occurrence of the thaw slumps and the elongation of the thermokarst lakes in the study area.

6. Conclusion

In Central Yakutia, the thawing of ice-rich permafrost on the south-facing slopes of thermokarst lakes leads to retrogressive thaw slumping that forms thermocirques. The ablation of ice results in active thermocirque development with a minimum and maximum average headwall retreat of 0.5 and 3.16 $m \cdot yr^{-1}$. The development and statistical distribution of thermocirques as well as degraded polygonal baydjarakhs support the view that current thermokarst development is mainly controlled by insolation on the banks of thermokarst lakes.

A future study will aim at constraining the period of activity of thermocirques and correlate it with meteorological data including solar radiation, precipitation, and air temperature, collected in the field. In the context of recent air temperature increase in Central Yakutia, the rate of thermocirque development may also increase in the future.

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