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RATING OF CRYOGENIC TRANSLATIONAL LANDSLIDING HAZARD IN THE TUNDRA OF CENTRAL YAMAL

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Results of cryogenic landsliding hazard rating in different landscapes of Central Yamal are presented. Authors consider the degree of impact applied to landscape complexes by cryogenic landsliding to be determined by the relative area of the youngest landslide impact. The greater the area affected by modern landslides within the landscape complex, the more sensitive is this landscape complex to possible activation of cryogenic landslides. However, locations disturbed by the latest translational landslides within a landscape unit are considered non-hazardous because, according to our findings, the re-occurrence of landsliding on such locations in coming centuries is unlikely. Analysis of a landscape pattern shows that all modern cryogenic translational landslides are located on concave slopes. Modern landsliding impact differs within the same landscape complexes appearing on different geomorphic levels of Central Yamal. Generally, this impact increases from low to high geomorphic levels. Landscape complexes are associated into 5 groups according to rated cryogenic translational landsliding hazard degree. Expert evaluation of a landslide hazard is based on detection of landscape conditions more or less favorable for cryogenic landsliding and on the latest cryogenic translational landslide impact.

Cryogenic landsliding, cryogenic translational landslides, landscape map, modern landsliding impact, map of the landslide hazard

INTRODUCTION

Among the relief-forming process in permafrost regions, cryogenic landsliding is the most active in the areas of wide distribution of tabular ground ice [*Leibman, 2004*]. Methodology for the study of such processes in the context of specific arctic landscapes of the permafrost zone is discussed in detail in publications by C.R. Burn [*Burn and Lewkowicz, 1990; Burn and Zhang, 2009*], K.A. Ermokhina [*2009*], C. Harris [*Harris and Lewkowicz, 1993*], A.I. Kizyakov [*2005; Kizyakov et al., 2006*], M.O. Leibman [*1995, 1997, 2001, 2005; Leibman and Kizyakov, 2007*], A.G. Lewkowich [*1988*], E.S. Melnikov [*Melnikov et al., 1974, 1983, 2005*], N.G. Moskalenko [*2003, 2006*], O.V. Rebristaya [*Rebristaya et al., 1995*], I.D. Streletskaya [*Streletskaya and Leibman, 2002*], N.G. Ukraintseva [*Ukraintseva et al., 1992, 2000, 2003*], V.D. Vasilevskaya [*Vasilevskaya et al., 2004*].

Cryogenic landslides in the north of the Tyumen region are most common in the Typical Tundra subzone (central parts of the Yamal and Gydan peninsulas), where the area with landscape conditions favorable for cryogenic landsliding is the largest. The main factors contributing to landslide process activity there are: occurrence of tabular ground ice bodies, continuous distribution of permafrost, intense relief dissection associated with wide distribution of both tabular ground ice, and polygonal ice wedges. The patterns of cryogenic landsliding activation driven by technogenic impacts in this area were studied [*Gubarkov, 2009*].

The most hazardous type of instability is associated with formation of cryogenic landsliding in areas with shallow occurrence of tabular ground ice (Earth flows with subsequent formation of thermocirques), since such slopes can be activated even at insignificant increase in the mean summer air temperature and under the least technogenic impact [*Leibman and Kizyakov, 2007; Burn and Zhang, 2009*].

Unlike areas with occurrence of tabular ice, slopes with seasonal ground ice formed at the active layer (AL) base under the forcing of a particular combination of climatic factors persistent during several years are less prone to cryogenic landsliding [*Leibman, 1997*]. At some sites, cryogenic landsliding along this ice (translational landslides) may recur with periodicity once in centuries [*Leibman et al., 2003*].

Cryogenic landslide activation risks can be assessed using both qualitative method [*Kazakov and Gensiorovskii, 2008*], based on the detection of sites with different patterns of cryogenic landsliding, and quantitative method [*Chekhina et al., 2004*], employing rating of probability of landsliding. Engineering protection against cryogenic landsliding is based on assessment of the cryogenic landsliding hazard using qualitative and quantitative methods that include description of geomorphological, geological, geotechnical, and hydro-geological conditions; engineering-geological profiles of landslide bodies; direct land-based and aerial photography-based mapping of cryogenic landslides, field measurements and geophysical survey in the areas affected by cryogenic landsliding [*Postoev et al., 2008*].

Over the period followed after cryogenic landsliding activation on Yamal in 1989 cryogenic landslides were studied within a specific polygon, with identification of their morphology, areal extent, and association with landscape, geomorphologic and lithological complexes [*Leibman, 1995, 1997, 2004, 2005; Leibman et al., 2003; Leibman and Kizyakov, 2007*]. Peculiarities of soil and vegetation covers related to cryogenic landsliding were investigated and discussed in [*Rebristaya et al., 1995; Leibman, 1997; Leibman and Streletskaya, 1997; Ukraintseva et al., 2003*]. The extent of cryogenic landsliding processes in the area of the Bovanenkovo gas-condensate field was analyzed using GIS-technologies and landscape indication method [*Leibman et al., 1997; Drozdov and Ukraintseva, 2000; Ukraintseva et al., 2005*], with the results subsequently extrapolated for the entire area of typical tundra in the north of West Siberia [*Ukraintseva, 2008*].

N.G. Ukraintseva suggested an express-technique to assess potential cryogenic landsliding hazard within a range of slope processes in the study area [*Ukraintseva et al., 1992*]. It involves the qualitative expert judgement approach to estimation of the landslide hazard based on the analysis of landsliding process manifestation variability within the Bovanenkovo gas field. This expert judgment method was proposed as an alternative to quantitative methods presented in [*Garagulya and Parmuzin, 1980; Grechishchev, 1981; Yershov, 1989*] and requiring specialized long-term stationary observations.

The expert rating technique for estimating activity of geomorphic processes suggested by *L.I. Zotova* [*2010, 2011*] that was applied at central Yamal is capable of taking into account all controls of cryogenic processes, using the "quality points" after *Yu.G. Simonov* [*1997*].

K.A. Ermokhina [*2009; Ermokhina and Myalo, 2013*] assessed probability of cryogenic landsliding activation on the Yamal Peninsula using vegetation as an indicator of the related exogenous processes. This assessment technique is based on differentiation between the degree of vegetation maturity observed at various stages of ecological-dynamic series of plant communities at landslide slopes.

There is a need though in developing a landsliding hazard assessment technique providing a more extensive application of remote sensing data and taking into consideration the revealed patterns of landsliding process activation, and localization of cryogenic landslides within specific geomorphologic and landscape units.

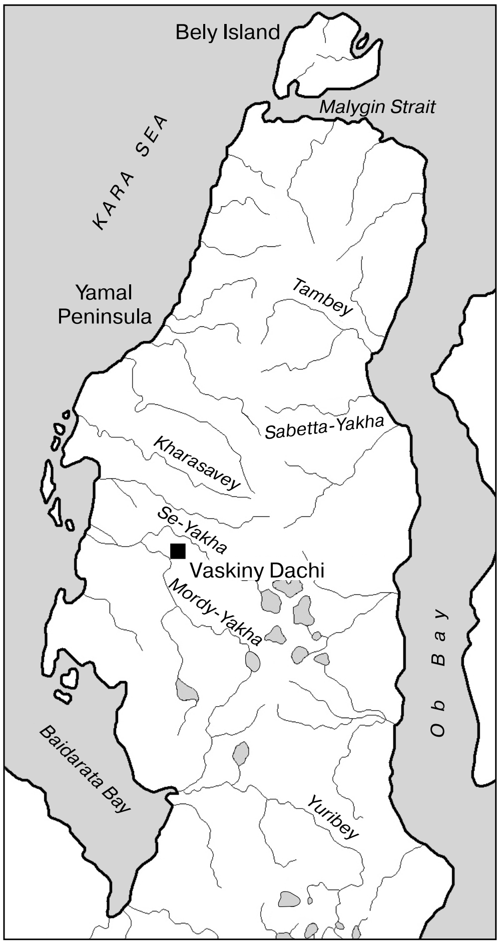

Fig. 1. Location of Vaskiny Dachi key site.

STUDY AREA

Cryogenic landsliding was studied at the Vaskiny Dachi key site located in the watershed of the Se-Yakha and Mordy-Yakha rivers (Fig. 1) in the continuous low-temperature permafrost zone.

The study area is a rolling-hill plain with narrow watersheds and long gentle slopes. The highest elevations (up to 58 m) are found within flat-topped remnants of the Salekhardskaya Marine Plain. The area is intensely dissected by long narrow river and small stream valleys and ravines and drainage hollows, lakes and khasyreys. Given that erosion extent is defined by the relief amplitude, the longest gullies are linked to higher geomorphic levels. The dissection depths of the Kazantsevskaya and Salekhardskaya plains reach 40–50 m. About 60 % of the territory is represented by gentle slopes with gradient less than 7°, slopes with gradient between 7 to 50° occupy ca. 10 % of the area, the rest 30 % being narrow-topped ridges, flood plains and lake depressions [*Leibman et al., 2003*].

Active slope processes are typical for the outliers of marine terraces composed of ice-rich deposits with tabular ground ice. Thermocirques are developing on the slopes with its shallow occurrence and transform into landslide cirques as the tabular ground ice is exhausted [*Leibman, 2005*].

According to geobotanical zoning, the Vaskiny Dachi key site is located in moss-lichen (typical)

[*Trofimov, 1975*], or subarctic [*Vorobiev and Belov, 1985*] tundra subzone. The Circumpolar Arctic Vegetation Map (CAVM) [*Walker et al., 2005*] ranks this area as Bioclimate Subzone D.

Watershed areas are commonly overgrown by dwarf birch thickets. Generally drained watershed slopes are occupied by dwarf shrub-moss-lichen tundra. Gentle, poorly drained slopes covered by mosses, shrubs and dwarf shrubs are better developed; dwarf shrub-moss-lichen tundra with spot-medalions is a dominant type on convex hilltops and slopes strongly exposed to wind action [*Trofimov, 1975*]. The river valleys and bottoms of thernocirques and landslide cirques where deep snow cover is formed during winter are characterized by the tundra willow thickets, with their height controlled by the snow cover thickness [*Leibman, 2004; Dvornikov et al., 2015*]. Sedge, sphagnum bogs and peat plateaus are widely distributed on concave watershed and terrace surfaces, on low lake shores, rear parts of the river valleys and other types of depressions.

METHODS AND APPROACHES

The paper is presenting a method for estimation of the potential landslide hazard based on earlier conceptual model of cryogenic landslide process [*Leibman, 2005*] and assigning landscape patterns from interpretations of airborne and space-borne data [*Khomutov, 2010*]. Main attention is given to the latest translational landslides of 1989 providing detailed data on large-scale landsliding events.

Special landscape zoning of the key site suitable for analysis of landslide hazard is undertaken (Table 1). Firstly, geomorphic levels with specific geology and topography are subdivided according to V.V. Baulin and coauthors [*1967*]. Higher geomorphic levels provide greater amplitude, longer slopes and, respectively, higher probability of larger landslides [*Leibman, 2005*]. Then, landforms where cryogenic landsliding activation is probable are assigned. Horizontal surfaces and bottoms are separated where cryogenic landslide formation is impossible, and tops where landslides are improbable. Slopes are considered at the next stage. It is important because it has been shown before that all modern landslides are located on concave slopes [*Ibid.*]. However, new landslides are less probable on concave slopes already affected by modern landsliding than on concave slopes with only ancient landslides. Concave slopes resulting from ancient landsliding, provide conditions necessary for landslide activation, such as thick organic canopy on the surface and well developed icy horizon at the AL base composed of sandy-silty slope sediments.

Landslide hazard is defined as a probability of surface disturbance due to a landslide body displacement (“detachment zone”), formation of a landslide shear surface (“transit zone”), and depositing of a landslide body (“accumulation zone”). Landsliding affects landscape patterns of all the landforms. The watershed edges are in the detachment zone, with edge fissures and suffosion subsidence. The slope surface is exposed in the transit zone, which triggers activation of thermoerosion, and brings to the surface saline deposits affecting vegetation succession. The landslide body is unloaded at the lower part of the slope into the valley, or gully in the accumulation zone. This leads to the change of hydrological regime [*Gubarkov, 2009; Gubarkov and Leibman, 2010*], damming the slope and valley water flow and forming the dammed lakes, which favors thermokarst activation.

The proposed method for assessment of cryogenic landslide hazard involves the analysis of degree of modern landslide impact. The greater is the degree of impact on a landscape complex, the higher is its sensitivity to possible activation of cryogenic landslides. An integrated landscape approach coupled with evaluation of landscape complex sensitivity allows quite accurately identify the landscape complexes with most probable activation of cryogenic landsliding and those where such probability ranges from improbable to impossible. Unlike the earlier considered method for landslide hazard estimation [*Leibman, 1995*], based on rating of slopes depending on their steepness, length, and lithology of the profile, the new approach takes into account a full range of landscape factors directly or indirectly affecting the probability of cryogenic landsliding activation.

To analyze modern landsliding impact, 19 landscape complexes (Table 1; Fig. 2) were allocated within different landforms, with the related combination of surface character and plant associations. The area and number of the latest landslides were calculated within each landscape complex.

All landslides fall into three groups depending on their area (km^2): less than 0.002; 0.002–0.01; more than 0.01. The related landscape complex was defined in the following way. A landslide is considered to be linked to the landscape complex, from which it was detached beginning from the upper point of the back scarp, even if the outlines of this landscape complex directly contact only the landslide shear surface, while the landslide body unloads within the limits of the adjacent landscape complex.

RESULTS

Degree of modern landsliding impact. At the Vaskiny Dachi key site, most of the largest landslides with area more than 0.01 km^2 (up to 0.08 km^2) are found on lengthy gentle and concave ancient landslide-affected slopes, as well as on slightly slopping portions of well-drained subhorizontal watershed surfaces.

Landslides with area 0.002–0.01 km^2 are generally found in all landscape complexes, however, they are linked more often to ancient landslide-affected

Table 1. **Landscape pattern of the Vaskiny Dachi key site**

Landscape complex index	Landscape complex (LC)	Area of LC, % / landslides of 1989 impact, % of the LC				
		Geomorphic levels				
		V	IV	III	II	F
	Rather drained LCs					
1	Rolling hills (convex hilltops and their slopes) with polygonal dwarf shrub-herb-lichen tundra with wind-blown sands on sandy and silty soils, alternate with herb-shrub-moss tundra on silty and clayey soils	4.1/3.6	6.0/2.9	1.4/6.2	–	–
2	Flat subhorizontal watershed surfaces with hummocky herb-dwarf shrub-moss-lichen and tussocky shrub-herb-moss tundra on silty and clayey soils (locally with wind-blown sands)	0.4/0.0	2.3/0.2	0.9/1.5	–	–
3	Flat subhorizontal watershed surfaces with herb-shrub-moss tundra on silty and clayey soils, with patches of polygonal herb-shrub-lichen-moss tundra on sandy and silty soils	1.8/8.0	10.1/0.6	1.2/0.0	–	–
4	Flat subhorizontal watershed surfaces with hummocky-tussocky shrub-herb-moss tundra on silty and clayey soils	5.9/7.4	1.3/0.6	0.4/0.0	0.2/0.0	–
5	Edges of flat subhorizontal surfaces with hummocky polygonal herb-dwarf shrub-moss-lichen tundra on silty soils (locally with wind-blown sands)	–	–	–	0.1/0.0	–
6	Polygonal subhorizontal watershed surfaces with cloudberry-sedge-lichen-sphagnum peat plateaus on peaty silty, clayey and peat soils	–	0.1/0.0	0.1/0.0	–	–
	Poorly drained LCs					
7	Flat slightly slopping surfaces with herb-moss-shrub tundra on silty and clayey soils	–	1.4/0.0	0.7/0.0	0.6/0.0	–
8	Flat gentle slopes with tussocky forb-grass-moss willow thickets (dwarf birch presented) on clayey soils	0.4/0.0	9.3/0.0	0.6/0.0	0.5/0.0	–
9	Flat gentle slopes with tussocky shrub-sedge-sphagnum communities on silty and clayey soils	0.5/20.5	7.1/1.2	–	–	–
10	Concave gentle slopes with ancient landslide shear surfaces, with forb-grass willow thickets on clayey and saline clay soils	4.3/15.9	9.0/0.7	1.3/4.1	–	–
	Wet LCs					
11	Concave subhorizontal surfaces with dwarf shrub-sedge-sphagnum and herb-moss bogs with patches of polygonal peat plateaus on peaty silty and clayey soils	–	0.6/0.0	0.4/0.0	3.0/0.0	–
12	Flat subhorizontal surfaces with herb-moss bogs on silty and clayey soils	–	0.1/0.0	–	1.9/0.0	–
	Periodically wet LCs					
13	Flat and concave bottoms of khasyreys with mostly dwarf shrub-lichen communities on more drained sites (with peaty silty and peat soils), with cottongrass-sedge-moss willow thickets and dwarf shrub-sedge-sphagnum bogs on wetter sites (with peaty clayey and peat soils)	–	2.5/0.0	0.6/0.0	0.2/0.0	–
14	Flat and concave surfaces of low lake terraces with tussocky sedge-moss communities on peaty silty and clayey soils	–	1.1/0.0	0.1/0.0	–	–
15	Flat rare zone of flood plain with tussocky sedge-moss and sedge-cowberry-moss communities on clayey soils	–	–	–	–	0.2/0.0
16	Small stream valleys with forb-moss willow thickets on clayey soils	1.6/2.3				
17	Drainage hollows with cottongrass-sedge-moss communities on clayey soils	0.3/6.7	2.2/0.1	0.2/0.0	0.4/0.2	–
18	Ravines and gullies with flat wet herb-moss bottom and steep hummocky-tussocky slopes with herb-moss willow thickets and dwarf birch on clayey soils	4.3/0.9				
19	Lake beaches with fragmentary of cottongrass-arctophila communities on sands	0.1/0.0				
lake	Lakes	8.0/–				
	Cryogenic translational landslides of 1989 overgrown to a various degree: landslide shear surfaces mostly with pioneer grass groups on saline clay, landslide bodies with partly degraded typical vegetation on silty and clayey soils	2.2/100.0				
Quarry	Anthropogenic-affected surface – abandoned sand quarry	0.2/–				

Note. V – Vth Marine (Salekhardskaya) plain; IV – IVth Coastal-marine (Kazantsevskaya) plain; III – IIIrd Alluvial-marine plain; II – IInd river terrace; F – Mordy-Yakha river flood plain. For designations on the map (Fig. 2) and in Table 2 we use letters: a – V, b – IV, c – III, d – II, f – F; CTL – cryogenic translational landslides.

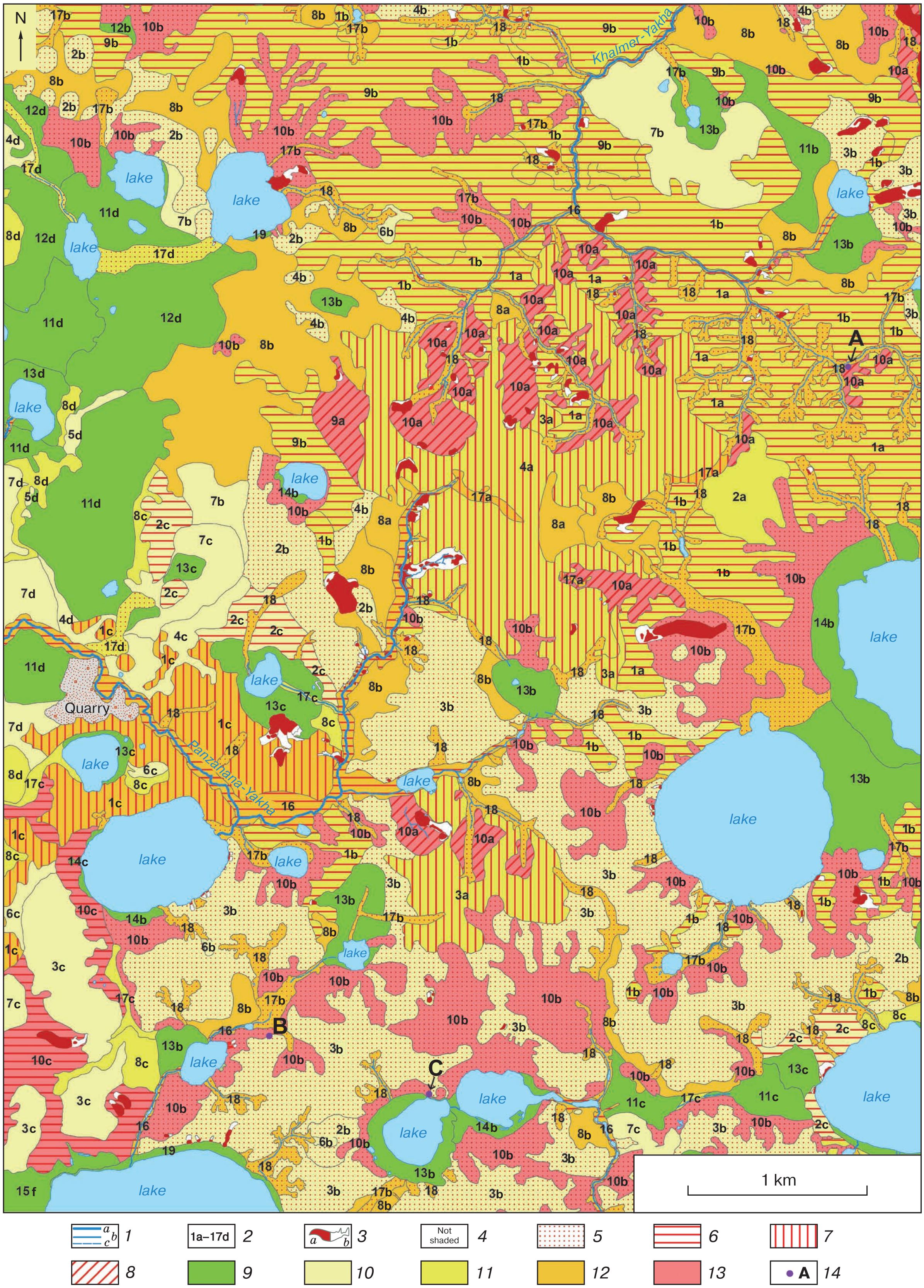

Fig. 2. Map of landscape pattern based on the degree of recent landslide impact (landscape complex sensitivity) and landslide hazard at the Vaskiny Dachi key site.

1 – hydrographic network: *a* – small rivers, *b* – small streams, *c* – temporal streams; *2* – indices for landscape complexes (cf. Table 1); *3* – cryogenic translational landslides of 1989: *a* – landslide body, *b* – landslide shear surface; *degree of modern landslide impact*: *4* – not affected (0 %), *5* – low (0–1 %), *6* – moderate (1–5 %), *7* – high (5–10 %), *8* – the highest (10 % and more); degree of *cryogenic landsliding hazard*: *9* – impossible, *10* – minimal, *11* – average, *12* – serious, *13* – maximal; *14* – objects of cryogenic landsliding occurrence in 2012–2013 (A, B, C).

Table 2. **Groups of landscape complexes (LC) by the degree of modern cryogenic landsliding impact (LC sensitivity) and cryogenic landslide hazard on the Vaskiny Dachi key site**

Sensitivity	Landslide hazard				
	Impossible	Minimal	Average	Serious	Maximal
Not affected (0 %)	11bcd, 12bd, 13bcd, 14bc, 15f, 19	3c, 4cd, 5d, 6bc, 7bcd	2a, 8cd, 17c	8ab	–
Low (0–1 %)	–	2b–4b	17d	17b, 18	10b
Moderate (1–5 %)	–	2c	1ab, 9b	16	10c
High (5–10 %)	–	–	3a, 4a	1c, 17a	–
The highest (>10 %)	–	–	–	–	9a, 10a

shrubby slopes. A few landslides of this type occur on the upper portions of rather drained subhorizontal surfaces with hummocky and tussocky tundra, drainage hollows, ravine, and small stream valley slopes.

Small-scale landslides with area less than 0.002 km^2 are widely distributed on steep slopes of ravine and stream systems and frequently are linked to boundaries between these landscape complexes and edges of flat and rolling hills dissected by ravines and stream valleys. Such landslides may often be linked to generally drained edges of subhorizontal surfaces, adjacent to lake depressions.

Modern landsliding impact differs within the same landscape complexes, appearing on different geomorphic level: Vth Marine plain, IVth Coastal-marine plain, IIIrd Alluvial-marine plain, IInd river terrace, Mordy-Yakha river flood plain. Landscape complexes are associated in five groups according to per cent of modern landsliding impact (only landslides of 1989) (Table 2; Fig. 2, Notations: *4–8*). Generally, impact of recent landsliding (landscape sensitivity) increases from lower (II–III) to higher (IV–V) geomorphic levels.

The highest landsliding impact occur on concave/gentle landslide-affected slopes (10*) and flat gentle slopes with tussocky shrub-sedge-sphagnum communities (9) on Vth Marine plain. These landscape complexes have the largest area of coverage by cryogenic landslides of 1989: 16 and 20 %, respectively.

A high degree of landsliding impact is observed on flat watersheds with shrub-moss tundra (3), with hummocky-tussocky tundra (4) and in drainage hollows (14) on the Vth Marine plain, as well as on low rolling hills (1) of IIIrd Alluvial-marine plain. The degree of modern cryogenic landslide impact is rated moderate on rolling hills (1) on Vth Marine and IVth Coastal-marine plains, and on subhorizintal watersheds with hummocky-tussocky tundra (2) on IIIrd Alluvial-marine plain due to landslides located on the boundaries of these landscape complexes with gullies, small stream valleys and deep lake depressions. Despite small-scale landslides being numerous on stream valleys (16), as well as concave landslide-affected slopes (10) on IIIrd Alluvial-marine plain and gentle slopes (9) on IVth Coastal-marine plain, these landscape complexes are characterized by moderate landsliding impact. The drainage network that includes bottoms and steep slopes (18) is characterized by low modern landsliding impact, because the area of small landslides located on steep ravine slopes is insignificant. On IInd river terrace only drainage hollows (17) are characterized by a low recent landslide impact due to a single landslide unloaded into the lake basin as a result of the surface cutting by vehicle track. All other landscape complexes on all levels are not affected by recent landsliding.

None of the allocated 19 landscape complexes are affected by the recent landsliding by more than 20 %. Therefore, surfaces free of modern landslides and thus sensitive to future landsliding range from 80 to 100 % of each landscape complex area. Activation of cryogenic landsliding of translational type is of low probability in the coming 300 years [*Leibman and Kizyakov, 2007*]. This is determined by insufficient time for the formation of transient, i.e. very ice-rich, horizon [*Shur, 1988*] at the AL base within recent landslide shear surfaces. Moreover, specific mechanical properties of AL deposits affected by bi-directional freezing have not been formed [*Lewkowicz, 1988*], whereas active thermal erosion promotes drainage of excessive moisture required for detachment of a landslide [*Leibman and Kizyakov, 2007*].

Cryogenic landslide hazard rating. Landscape complexes affected by the latest landslides are considered more sensitive to landsliding activation to the extent their area is disturbed by translational landslides (the greater is the affected area the more the landscape complex is sensitive to landsliding). The most hazardous areas in terms of possible activation of landsliding is associated with the sites on sensitive landscapes without modern landslides. According to this principle, and based on the analysis of cryogenic translational landslides of 1989 coverage within different landscape complexes and geomorphic levels, landscape complexes are merged into five groups of hazard degree (Table 2; Fig. 2, Notations: *9–13*): impossible, minimal, average, serious and maximal, based on estimation of geomorphic features, slope steep-

* Here and further in the text, indices for landscape complexes are assigned in parentheses, according to Table 1.

ness, drainage, microrelief, vegetation associations and former landslide activity.

Maximal hazard of cryogenic landsliding persists on concave shrubby slopes (10) at all geomorphic levels. Hazard of large landslides on gentle shrubby/partly shrubby slopes (8, 9) increases from lower to higher geomorphic levels. Hazard of small landslide formation on subhorizontal surfaces (1–4) increases if deeply dissected by drainage network and small stream valleys without noticeable relation to their geomorphic level.

DISCUSSION

Methods existing for Central Yamal landslide risk assessment are qualitative or semi-quantitative in nature. *N.G. Ukraintseva et al.* [*1992*] allocates types of regions and sites (in the range of "landscape unit" and "locality") on the map and describes processes (including cryogenic landsliding) developing within these units, based on field measurements and expert judgement and using analyses of landscape structure and engineering-geocryological conditions. The resulting 1:100 000 maps comprise the surfaces of IIIrd Alluvial-marine plain and river terraces. Prediction of potential activation of slope processes is based on distribution of recent processes: the more uniformly and wider is the extent of the processes, the more hazardous is the area. This method, however, does not take into account our results and findings, which bear a strong evidence of possibility for cryogenic landslides to re-occur at the same site no sooner than in a few hundred years, except for the areas with shallow occurrence of tabular ground ice. Method authored by N.G. Ukraintseva was developed for and tested in the area of the Bovanenkovo gas-condensate field, providing good results due to lower geomorphic levels predominant in the area (from IIIrd Alluvial-marine plain to the Se-Yakha river flood plain) and weakly dissected relief.

The estimations after *L.I. Zotova* [*2010, 2011*] based on cryogenic process hazard rating, which included analysis of all factors affecting activation of cryogenic processes, however, does not work for assessing hazard of one specific process. As a result, high probability of cryogenic process activation is determined for all surfaces even those with already 60 % of impact. This can be true for assessment of complex destruction of tabular ground ice, rather than for translational cryogenic landslides.

K.A. Ermokhina [*2009*] assessed probability of reoccurrence of landsliding event from the degree of revegetation on the slopes of marine terraces, sub-

Fig. 3. Objects of cryogenic landsliding occurrence in 2012–2013.

a – cryogenic translational landslide on ravine slope (A, cf. Fig. 2), 2012; *b* – earth flow at the boundary between watershed and concave slope (B), 2012; *c* – thermocirque formed in 2012 (C), 2013. Photo by A.V. Khomutov.

jected to multiple landsliding. Her methods are relevant to this type of slopes alone, though, and cannot be applied to other landforms.

South of Bovanenkovo gas field, at the Vaskiny Dachi key site, where the relief is more complicated and geomorphic levels are higher, tabular ground ice sits deeper, and anthropogenic impact is less pronounced. Therefore, a different method is required for estimation of cryogenic landslide hazard, which is proposed herewith. Besides the account of factors commonly associated with activation of cryogenic landsliding, we include quantitative analysis of landslide distribution over the territory, which is enabled by long-term field studies of the areal extent of cryogenic landslides and various mechanisms of their formation [*Leibman, 1995; Leibman et al., 2003; Khomutov and Leibman, 2010*].

The map of landscape complexes sensitivity (Fig. 2) shows landscape units affected by modern landsliding in shading. The authors suggest that a higher impact accounts for higher landscape sensitivity, which applies only to areas free from the latest landslides. Comparison of our landsliding hazard map (Fig. 2) and landslide prediction maps after N.G. Ukraintseva [*Ukraintseva et al., 1992*] and K.A. Ermokhina [*2009*] revealed that the areas of potentially hazardous sites do not differ much. However, the mapped territory was differentiated in more detail in relation landslide activation hazard, which was enabled by combining results of longer-term field studies with high spatial resolution remote sensing data. The results of 2012 field campaign included descriptions of: translational cryogenic landslide (Fig. 3, *a*), earth flow (Fig. 3, *b*), and thermocirque (Fig. 3, *c*), which, the authors believe, initially were formed by translational cryogenic landslides. Cryogenic landslide A (Fig. 2) formed on a steep slope of a gully (18), while the upper part of landslide shear surface was related to concave landslide slope. Cryogenic landslide B (Fig. 2) initiated at flat subhorizontal watershed surface (3) near the boundary with concave slope covered by willow thickets (10). Thermocirque C (Fig. 2) also activated within the concave shrubby slope (10), and in 2013 it inserted into subhorizontal watershed surface (3). Therefore, all the objects described in 2012 formed within landscape complexes associated into the maximal hazard group, which justified application of the proposed method.

CONCLUSIONS

Cryogenic landslide hazard rating method is based on quantitative analysis and expert judgment of modern cryogenic landslides distribution and their parameters within different landscape complexes.

The degree of landslide impact on landscape complexes determines their sensitivity to possible activation of landsliding depending on the area occupied by surfaces affected by youngest landslides. Landscape complexes with high sensitivity to landsliding activation are considered hazardous only in their portions free of the latest landslides.

The landscape complexes affected by recent landslides- are not rated hazardous in terms of re-occurrence of landsliding in the near future due to the absence of a basic prerequisite for initiation of cryogenic translational landslides: an icy transient layer, as it takes rather a long time for it to form at the active-layer base.

The results of application of the suggested method for cryogenic landsliding hazard rating showed that:

– cryogenic landslide activation hazard is very high on concave shrubby slopes at all geomorphic levels, except for IInd river terrace and Mordy-Yakha river flood plain;

– large-landslide hazard increases from lower to higher geomorphic levels on gentle horizontal/concave, shrubby or partly shrubby slopes. Small-landslide hazard on subhorizontal surfaces increases in landscape complexes deeply dissected by drainage network and small stream valleys independent of their geomorphic level.

The studied landscape complexes are characteristic of the entire Typical Tundra subzone of Central Yamal. The results therefore can be applied in other regions (including those under active development) with wide distribution of tabular ground ice and shrubby tundra (indicators of the continuous since Late Holocene development of hazardous slope processes) to the north of the Yuribey river.

The application of cryogenic landsliding hazard that involves analysis of the degree of impact on landscape complexes by modern cryogenic landsliding, based on landscape differentiation approach is considered quite effective and low time-consuming. Given that high-resolution satellite images are available for the area of interest, the method described here can be readily applied in combination with limited field studies required to a great extent to clarify interpretation of local features of relief and vegetation to compile landscape maps basic for research. Using this landscape method coupled with the phyto-indication technique suggested by *K.A. Ermokhina* [*2009*] will definitely result in more accurate prediction of landsliding processes, which requies however more detailed ground survey data.

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