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Dynamics of landslide slopes and their development on Yamal peninsula

M.O. Leibman & A.I. Kizyakov
Earth Cryosphere Institute SB RAS, Tyumen, Russia

L.D. Sulerzhitsky & N.E. Zaretskaia
Geological Institute RAS, Moscow, Russia

ABSTRACT: A study of the cryogenic (active-layer detachment) slides at Central Yamal peninsula, Russia, is ongoing since 1987. Various methods are used to study the mechanisms of slope instability and the stages of development in connection with landscape features and climate fluctuations. Landslides of various ages are found within one catchment for slopes with different aspects, at the edge or the foot, and for a variety of slope gradients. Dating of each landslide event within one slope system shows the time needed for the slope to exhibit a new active-layer detachment. A case study at a landslide cirque, Central Yamal, allowed six stages of landslide activity to be established, at intervals of 350–500 years.

1 INTRODUCTION

Arctic landscapes are under the influence of subsurface features and relief-forming processes, caused by the existence of permafrost. Permafrost, in turn, is a product of climate–landscape interaction. The most important permafrost features are the depth of thaw, the ice content, and the ground temperature. Climate warming in the Arctic may cause increase of ground temperature, deepening of the active layer, melting of ice, and thus may trigger thermokarst, thermal erosion, active-layer detachments, and other destructive processes.

Specific development of slopes in the permafrost zone is connected with the formation of the transition layer. Ice-rich zones develop during cold periods, thawing occurs during warmer climate cycles. Extra moisture, produced by the thawing of the transition layer, coinciding with periods of high thawing index, cause instability of the active layer on slopes. When there is high atmospheric precipitation at the same time, then hazardous slope instability may occur. Such coincidences happened in 1988–1990 in both the Russian and the North-American Arctic (Lewkowicz 1990, Harris & Lewkowicz 1993, Leibman 1995, Leibman & Egorov 1996).

Geochemical processes triggered by active-layer detachment slides caused growth of abnormally high and dense willow shrubs in Central Yamal (Ukraintseva et al. 2000). As a result, almost all concave slopes in the area are covered with willow "bushes", which leads the authors to assume that all of these slope hollows are actually ancient landslide shearing surfaces. Various degrees of vegetation development, from pioneer sedges to mature moss-lichen shrub communities, indicate several periods of landslide activation. Vegetation and surface morphology give visual indicators of old landslide activity. Shearing surfaces form cascades or a mosaic of shrub-free patches among shrubby tundra of abnormally high willows. At the same time, there are fans at the foot of the slope, which are now covered by willow thickets and are interpreted as ancient landslide bodies or evidence of repeated landslide activity in the same place.

Hundreds of trial pits and boreholes undertaken in the landslide-affected slopes in Central Yamal showed the following. A lithological indicator of an active-layer detachment slide is a sandy landslide body displaced along an icy clayey shearing surface so that it rests (1) with its upper part on the bare surface, and (2) with its lower part on the undisturbed foot of the slope (Leibman 1995). That is why the geological section in the landslide body is comprised of either sand on top of the clayey deposits in the first case, or sandy deposits on top of a buried organic mat, underlain by a sandy-silty layer with clayey deposits further beneath, in the second case.

Various aspects of landslide studies are discussed in numerous publications (e.g. Lewkowicz 1990, French 1996, Harris & Lewkowicz 2000), but the problem of long-term recurrence of the process is not well understood.

The study discussed in this paper was aimed at determining the time intervals between stages of landslide development. This time is required for the slope to accumulate critical strain and to prepare for the next stage of activation. The method used to determine the age of landslides of various generations is by dating soil, turf, humus, wood, buried by the landslide and exposed by trial pits and boreholes.

2 STUDY AREA

The study of landslide activity is ongoing at the "Vaskiny Dachi" research station, Central Yamal since

1987. The study area is situated in the mid-west of Yamal on the Se-Yakha–Mordy-Yakha watershed (Fig. 1). It is a deeply dissected marine plain with elevations of 25 to 56 m. The area is represented by low-angled slopes (gradient up to 7°), covering about 60% of the area, and steep slopes (gradient 7° to 50°) covering about 10% of the area, the remaining 30% being narrow tops of ridges, bottoms of ravines and streams, and lake basins. The marine plain is composed of the Middle and Upper Pleistocene regressive series of fine sands, sandy loam, and clay of rather a high salinity (0.1 to 2% of water soluble salts). The lithology of the upper portion of the section involved in a landslide activity is a sandy or silty top layer underlain by clayey deposits. The slope sections depend on the position against the sandy top. The farther from the slope edge (i.e. lower downslope), the more silty/clayey are the slope deposits. As a rule, slope deposits do not exceed 1 m thickness, so that the active-layer depth in many cases reaches the sand (silt)/clay contact, which often serves as an ice-accumulating zone (transition layer), and landslide shearing surface (Leibman 1995, Leibman & Egorov 1996).

It was presumed that specific landforms of the Central Yamal peninsula are landslide cirques formed by series of landslide events happening at different times during the late Holocene. They are represented by concave slopes with a mosaic of more or less mature vegetative cover: patches of high dense willow bushes, alternating with grassy clearings, and heterogeneous mesorelief.

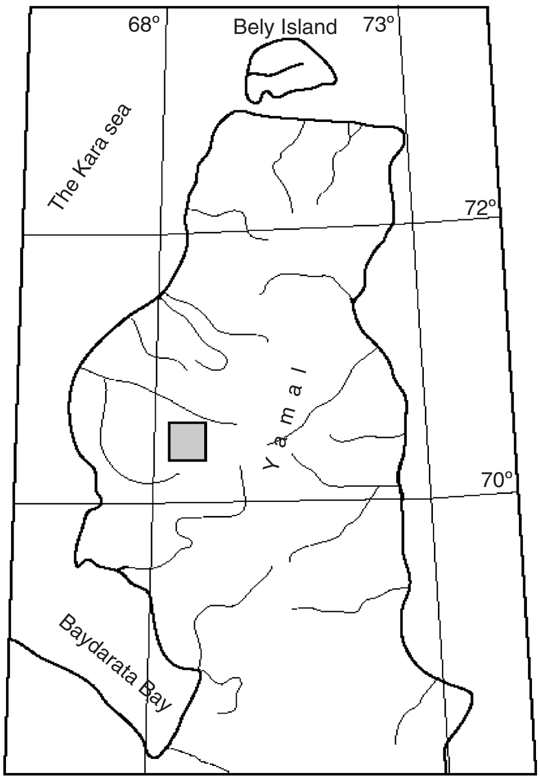

Figure 1. Yamal Peninsula, (the research area in the vicinity of the station "Vaskiny Dachi" is shaded).

Within one catchment, landslides of various ages develop in slopes of different aspects and angles. Sometimes they overlap, with younger landslide bodies resting on top of the older ones.

There are necessary and sufficient conditions, determining the time span between each landslide event: specific climatic situations and period needed for accumulation of strain in the active layer should coincide. Climatic conditions are discussed in detail in a number of publications (Lewkowicz 1990, Harris & Lewkowicz 1993, 2000, Leibman 1995, French 1996, Leibman & Egorov 1996). As to the "preparation" period, it is needed for:

- formation of a transition layer at the active-layer/permafrost interface, at least one cold and wet summer preceding the next colder summer with less seasonal thaw,
- restoration of vegetation and strength of the organic mat, which maintains deposits as a single rigid body, resistant to strain except along the shearing zone,
- leveling of erosion channels formed during the first few years on the shearing surface and providing good drainage, for leading to higher degrees of saturation with potential for high pore pressures.

Dating of each landslide event within one slope system shows the time needed for "preparation" of the slope for the new active-layer detachment, in coincidence with specific climate conditions.

A case study at one of the landslide cirques was aimed at dating a series of landslides from 12 to more than 2000 years old (Fig. 2). It was found that radiocarbon dating of turf and shrubs buried by a landslide body allowed analysis of the timing of the various landslide stages (Leibman et al. 2000).

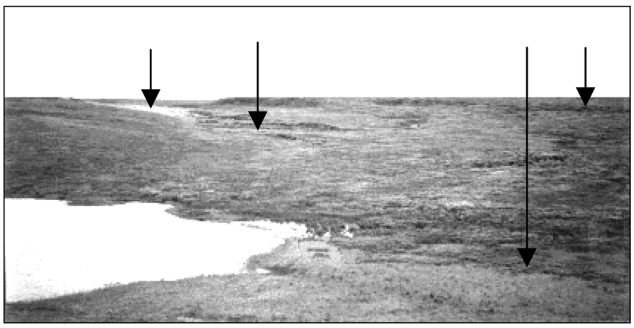

Figure 2. A landslide cirque at the research station Vaskiny Dachi. Arrows from left to right point, respectively, to a young landslide shearing surface, the young landslide body, the foot of the slope with an ancient landslide body covered by willow thickets, and a headwall of a series of ancient landslides.

3 METHODS OF STUDY

Reconstruction of landslide periodicity is based on: (1) interpretation of geological construction of slope deposits in a landslide cirque by revealing buried turf and vegetation, and (2) sampling and dating of organic matter by ^{14}C conventional methods.

Young landslides are clearly visible due to bare or slightly vegetated headwalls and shearing surfaces, flat or folded landslide bodies extending over several tens of centimeters to 1–2 m high above the slope surface. The older the landslides are, the less distinguishable are these features.

A topographic survey was undertaken as a first step to map the landforms and to position the trial pits and boreholes on the cirque surface. Several transects were set up across the landslides (Fig. 3).

As soon as landform signals of ancient landslides are difficult to determine from the landscape, it becomes important to be able to recognize former landslides by the existence of buried soil and vegetative mats in the trial pit or borehole sections. Such buried soil-vegetative layers are often preserved below the new landslide body if they overlap the undisturbed (or re-vegetated) slope surface. In the case of repeated landslide events in the same slope, several horizons of buried soil-vegetative cover should be seen in the section. It is important to distinguish such multi-layer sections formed due to several consequent landslide events from those formed because of landmass deformation. Several organic lenses can result from folding and overlay of turf mats at the front part of the landslide body. This was discovered by trial digging and drilling across the presumed landslide contours.

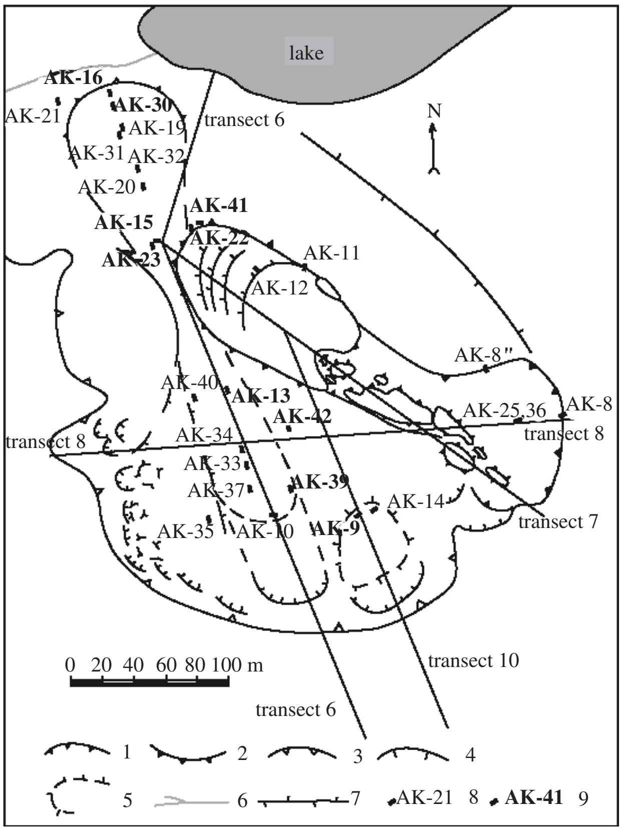

Figure 3. Landslide cirque at research station "Vaskiny Dachi". Key: 1 and 2, 1989th headwall and landslide body contour, 3, landslide cirque contour, 4, ancient landslide headwalls, 5, ancient landslide-body contours, 6, creek, 7, watershed line, 8, point numbers, 9, radiocarbon sampling points.

As the landslide activity was most likely to be triggered by the Holocene climatic warming, the landslide age for ancient landslides marked by mature vegetation communities would not exceed several thousands of years. Primary analyses of aerial photos of the area (Leibman et al. 1997) showed that old landslides, i.e. those differing from the young ones by restored vegetation mats, which were none the less still immature vegetation communities, could not be younger than 40 years old. This conclusion is based on the fact that landslides noticed on the aerial images of 1960-s were not fully re-vegetated by 2001. In some cases, such landslides can be dated by tree-rings (Leibman et al. 2000). The landslides exhibiting well developed organic mats and rather mature vegetation communities are considered older than hundreds of years and thus are suitable for accurate radiocarbon dating (Zaretskaia 2001).

As the soil-turf cover, thick enough to provide conditions for the next landslide event, may form during over hundreds of years, the data obtained by radiocarbon dating from the samples comprising the mixture of organic materials of various ages, shows an average date, which can be 100–200 years older than the landslide event (Zaretskaia 2001). Dating of willow branches should give a narrower time span (Zaretskaia et al. 2001) for landslide event age, compared with turf, because the usual life span of willows in the study area is less than 100 years (Leibman et al. 2000).

4 RESULTS

The area of the landslide cirque under study is $320 \times 370\,m^2$, the height of the slope from edge to foot is 22 m. The youngest landslide happened on August 15, 1989, and was 10–12 years old at the time of the field study (1999–2001). The shearing surface was still more than 50% bare after 10–12 years of natural restoration, with no lichen-moss mats, and only patches of sedges in vegetative cover.

Hundreds of landslides near the research station had more or less the same appearance. The sedge coverage was higher at the wetter sites, and less at dryer sites, but the dominating vegetation communities were the same. Landforms were easily interpreted, such as the headwall, lateral compression ridges, and the frontal scarp. The landslide body was 80–90 cm thick, and, in

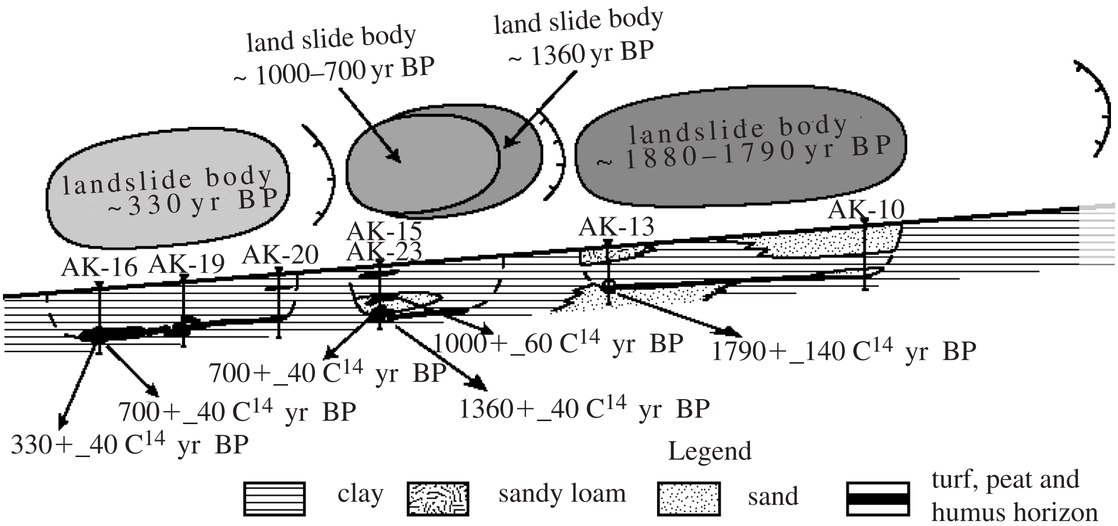

Figure 4. Sketch plan and geological section along transect 6 (see also Figure 3).

Table 1. Results of radiocarbon dating by GIN RAS.

Point #	Depth (cm)	Material	^{14}C Age (years BP)	Laboratory code
AK-9	82–88	peat	1060 ± 70	GIN-10314
AK-13	40–45	peat	1790 ± 140	GIN-10315
AK-15	57–67	peat	1360 ± 40	GIN-10316
AK-16	42–51	peat	700 ± 40	GIN-10317
AK-16	42–51	wood	330 ± 40	GIN-11298
AK-22	45–64	humus	1880 ± 120	GIN-11299
AK-22	78–81	humus	2250 ± 100	GIN-11300
AK-23	48–54	humus	1000 ± 60	GIN-11301
AK-23	63–65	humus	700 ± 40	GIN-11302

the folded portions, was up to 2 m high above the shearing surface. This landslide has also overlapped older ones, which makes it complicated to delineate the boundaries between them, although study of the geological sections is helpful. One of the transects is schematically shown in Figure 4. Older landslides can be seen, both on the plan and in the profile, to have been overlapped by younger slips.

Radiocarbon dates were also determined from buried turf, humus, and willow branches, which were collected from several pits. Some tests were duplicated in order to test the reliability of the detection methods. Results of ^{14}C tests performed at the isotope geochemistry and geochronology laboratory of Geological Institute of the Russian Academy of Sciences (GIN RAS), Moscow (sample code: GIN), are presented in Table 1. Sampling points are shown on Figures 3, 4 and defined by a pair of letters and numbers.

5 DISCUSSION

One of the possible patterns of the studied landslide cirque development is suggested (in Figure 5).

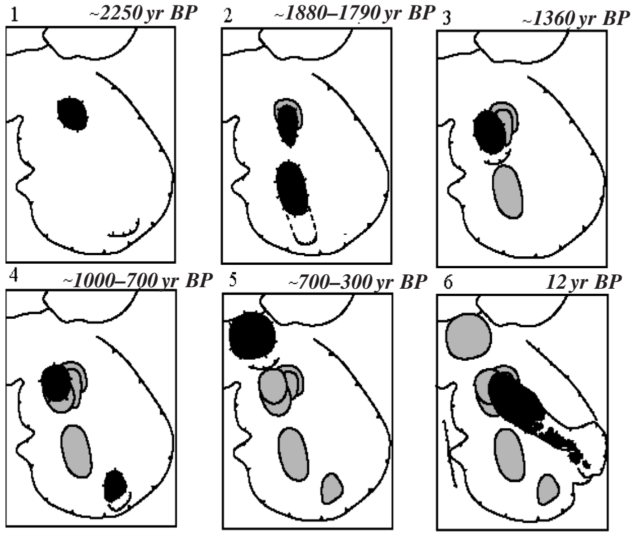

Figure 5. Six stages of the landslide cirque development at the research station “Vaskiny Dachi”. The landslide of the current generation is shown at each stage in black.

Turf collected at the point AK-22 from a depth of 78–81 cm has a ^{14}C age of 2250 ± 100 yr BP (GIN-11300, Table 1). It is the most ancient date obtained at the landslide cirque discussed. The landslide body of the first (the oldest) generation, which has buried this turf, is found at the foot of the slope. At the same point, at 45–64 cm depth, the second horizon of buried soil showed an average ^{14}C age of 1880 ± 120 yr BP (GIN-11299, Table 1). Proximity of the age of this soil to the date obtained at the point AK-13 (1790 ± 140 yr BP, GIN-10315, Table 1) suggests that a single soil unit was buried by a landslide of the second generation.

During the third stage of the landslide cirque development, the landslide, defined by buried turf discovered at point AK-15 at the depth 60 cm, happened at 1360 ± 40 yr BP (GIN-10316, Table 1). Point AK-23 is a duplication of point AK-15 and two dates were

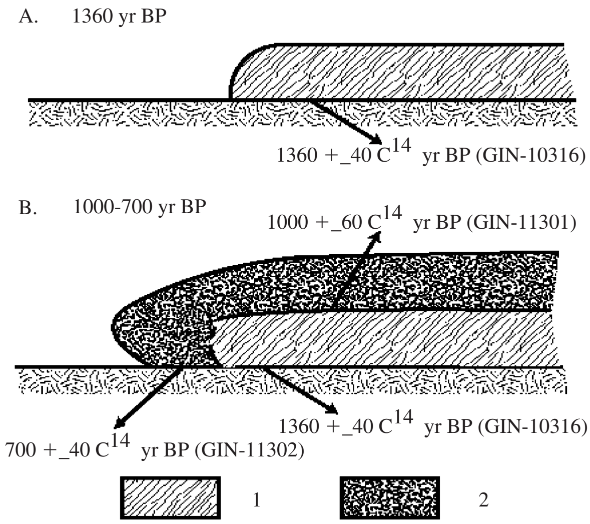

Figure 6. Stages 3 and 4 of landslide formation based on dates obtained at points AK-15 and AK-23. A landslide body: 1, 1360 years old; 2, 1000–700 years old.

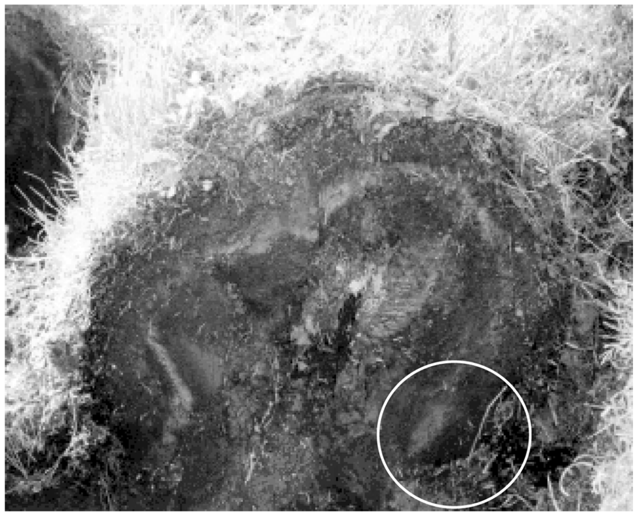

Figure 7. A folded landslide body at the frontal scarp. The zone in the circle (which is about 20 cm in diameter) is where older soil is resting on top of younger turf.

obtained here. The age of the buried humus lenses at a depth of 48–54 cm is 1000 ± 60 yr BP (GIN-11301, Table 1), and the age of the discontinuous turf horizon at a depth of 63–65 cm is 700 ± 40 yr BP (GIN-11302, Table 1). Inversion of dates has been observed at this point, younger organic materials have been buried by older ones. In the immediate proximity at the depth of about 60 cm, there are soils with dates of 1360 ± 40 and 700 ± 40 yr BP. One of the possible explanations for these facts is as follows. At points AK-15, and AK-23 the older of the pair of landslides buried turf with an age of 1360 ± 40 yr BP. The next landslide buried the frontal zone of the older landslide in front of which the age of the younger soil was 700 ± 40 yr BP, and age of soil from the covering, more mature surface was 1000 ± 60 yr BP (Fig. 6). It is also possible, that at a frontal scarp of a landslide, the younger organic horizon was tucked under the older one by a "caterpillar" effect at the frontal scarp of a landslide (Fig. 7, near the point AK-41, see Fig. 3).

At the foot of the slope, close to the lake (Fig. 3), the age of the buried turf was determined to be 700 ± 40 yr BP at point AK-16 (GIN-10317, Table 1). Buried willow branches were collected from the same horizon at the same location, and their age was found to be 330 ± 40 yr BP (GIN-11298, Table 1).

The dating which has been carried out on wood gives a more precise time frame than the average age of turf, because the maximum age of willows in this landslide cirque does not exceed 80 years (Leibman et al. 2000), and thickness of the selected fragments allows their age to be estimated accurately to within 40–50 years. The conclusion would be that 330 years would characterize the age of the fifth landslide generation most accurately.

This experiment showing the difference in soil-turf and wood dates from the same depth at point AK-16 (Table 1) proves the suggestion that it takes at least 330 years for organic mat to form in the climatic and landscape conditions of the study area (700 years of average turf age minus 330 years of branches age, and minus maximum 40 years of the willow life span). The area of this landslide was contoured due to discovery of buried organics at points AK-19, AK-20, AK-21, AK-30, AK-31, and AK-32 (Fig. 3). Finally, the last stage of landslide activity is represented by the landslide of the sixth generation, which happened in 1989, and is dated by direct observation. Probably, we should include a small landslide which is older than 1989, but is not vegetated enough to be dated by radiocarbon methods, in this generation. Only about 80% of its surface is vegetated, and early stages of moss-lichen development are observed. Estimation based on field experience and analyses of the aerial photos leads to suggestions that the landslide event in this concave area developed about 30–50 years ago.

6 CONCLUSIONS

Specific landforms of the Central Yamal peninsula included concave slopes with mosaic vegetative cover represented by various pioneer to mature vegetative communities, patches of high willow bushes, and heterogeneous mesorelief. These were shown to be landslide cirques formed by a series of landslide events, which happened at different times during the late Holocene.

Buried organic material appears as a mixture of soil, humus, turf, and plant remnants buried by a landslide body. One to several interbeddings of organic materials are found in the geological section at the depths of 20 to 90 cm. The state of organic material discovered closer to the surface did not allow a definite statement to be made about its origin. Uppermost organics in some cases could be buried by folding of creep-susceptible slope deposits with the turf of older or the same age.

Field mapping of landforms, mesorelief, vegetative zones of various maturity, along with topographic surveys and digging, revealed contours of landslides of various generations within the landslide cirque. This reflected the various stages of the complex landslide development. Six stages of landslide activity are shown on Figure 4, and supported by radiocarbon dates from Table 1. The series happened approximately at (1) 2250, (2) 1880–1790, (3) 1360, (4) 1000–700, (5) 330 and (6) 50–12 years ago.

The time span separating landslide events ranges from 350 to 500 years. This time is needed for a slope to prepare for the next landslide event: to restore the vegetative cover, fill in and flatten the thermo-erosion gullies, and form an icy transitional layer at the active-layer base. Climatic situations of extreme precipitation and air temperature provide suitable conditions for the onset of the next period of landslide activation on a slope in a state of incipient failure.

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REFERENCES

French, H.M. 1996. *The Periglacial Environment.* London: Longman.

Harris, C. & Lewkowicz, A. 2000. An analysis of the stability of thawing slopes, Ellesmere Island, Nunavut, Canada. *Canadian Geotechnical Journal* 37(2): 449–462.

Harris, C. & Lewkowicz, A.G. 1993. Form and internal structure of active-layer detachment slides, Fosheim Peninsula, Elsmere Island, Northwest Territories, Canada. *Canadian Journal of Earth Sciences* 30(8): 1708–1714.

Leibman, M.O., Archegova, I.B., Gorlanova, L.A. & Kizyakov, A.I. 2000. Stages of cryogenic landslides on Yugorsky and Yamal Peninsulas. *Earth Cryosphere* 4(4): 67–75 (In Russian).

Leibman, M.O. 1995. Preliminary results of cryogenic landslides study on Yamal Peninsula, Russia. *Permafrost and Periglacial Processes* 6(3): 259–264.

Leibman, M.O. & Egorov, I.P. 1996. Climatic and environmental controls of cryogenic landslides, Yamal, Russia. In *Landslides:* 1941–1946. Rotterdam: Balkema.

Leibman, M.O., Streletskaya, I.D. & Konyakhin, M.A. 1997. Assessment of surface dynamics at Bovanenkovo gas field (Central Yamal Peninsula) during the period 1949 to 1990. *Geomorphology* 2: 45–48 (In Russian).

Lewkowicz, A. 1990. Morphology, frequency and magnitude of active-layer detachment slides, Fosheim peninsula Ellesmere Island, N.W.T. *Permafrost-Canada. Proc. of the Fifth Canadian Permafrost Conference*. Quebec: Collection Nordicana 54.

Sulerzhitsky, L.D. 1998. Microbial pollution of organic matter from permafrost (radiocarbon dating case study). *Earth Cryosphere* 2(2): 76–80 (in Russian).

Ukraintseva, N.G., Leibman, M.O. & Streletskaya, I.D. 2000. Peculiarities of landslide process in saline frozen deposits of central Yamal, Russia. In E. Bromhead, N. Dixon and L.-L. Ibsen (eds), *Landslides. Proc. VIII International Symposium on Landslides* 3, London: Thomas Telford.

Zaretskaia, N.E. 2001. *Radiocarbon research of peat bogs and the chronology of the Holocene events of South Kamchatka and Upper Volga.* Candidate of science thesis. Moscow: GIN RAS (in Russian).

Zaretskaia, N.E., Ponomareva, V.V., Sulerzhitsky, L.D. & Dirksen, O.V. 2001. Radiocarbon dating of the Kurile Lake caldera eruption (South Kamchatka, Russia). *Geochronometria* 20: 95–102.