BACK

SLUSHFLOWS AS A LANDSCULPTURING AGENT IN MOUNTAIN VALLEYS OF THE KOLA PENINSULA, NORTHWESTERN RUSSIA

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Slushflows – hazardous and potentially dangerous events – are widespread in arctic and subarctic mountainous environments (Fleishman 1978; Nyberg 1989; André 1995; Bozhinsky et al. 2001; Laroque et al. 2001) and represent a specific type of gravitational flow of water-saturated mixture of snow with relatively limited amount of clastic sediment (common < 12%, size up to 1-2 m) occurring in low-order stream channels. They are considered either subtypes of wet snow avalanches, or debris flows, or independent phenomena between the latter two (Perov 1966; Hestnes 1998, Eckerstorfer and Christiansen 2012). Several recent events, some with fatal consequences, reported for Scandinavia (Hestnes and Kristensen. 2010), have increased both the scientific community and public awareness and social demands for reliable risk assessment, prediction and sound protective measures (Relf et al. 2015). All these, however, are still limited by insufficient knowledge of spatial distribution, magnitude and frequency of such hazardous events, especially in the distant past.

Khibinskiye and Lovozerskiye Tundry – compact low mountain massifs located in central part of the Kola Peninsula – are extremely reach in minerals, especially in apatite and nepheline ores, and rare earth elements (Fig 1). Thus, they have been intensely explored since the 1920s and lately became a focus of rapidly growing recreational industry. At the same time, they are an arena of widespread hazardous processes amongst which are snow avalanches, rockfalls and screes, slushflows and debris flows (Belyaev et al. 2015). Ski resorts, tracking mountainous paths and newly established National park combined with complex industrial (quarries, mines, plants, roads etc.) and civil infrastructure stipulate the need to estimate potential risks of those hazards on a basis of thorough understanding of its nature and dynamics.

The largest Kola mountain massif of Khibiny (up to 1201 m ASL) and its smaller neighbor – Lovozerskiye Tundry (1120 m ASL) located 10 km eastward – are both Devonian age plutons of multiphase alkaline intrusions of nepheline syenites (Pozhilenko et al. 2002) partly exposed by denudation. Plateau-shaped summits with relatively steep slopes are dissected by numerous deep (100-500 m) erosional valleys, glacial troughs and cirques, and tectonic lineaments. Debris flows at the Khibiny were thoroughly investigated over the 50 years (Bozhinsky et al. 2001) producing a unique dataset of >200 slushflow-affected mountainous catchments that have been active at least once in centennial. However, those surveys concentrated largely on monitoring the consequences of presently observed events. Other mountainous areas of the Kola Peninsula remain practically unstudied in terms of the hazardous natural processes. Especially there is no reliable published data on localization, dynamics and intensity of slushflows despite the occasionally reported hazardous events such as locomotive thrown down from the railway at the western foothills of Lovorerskiye Tundry in the 1970-s.

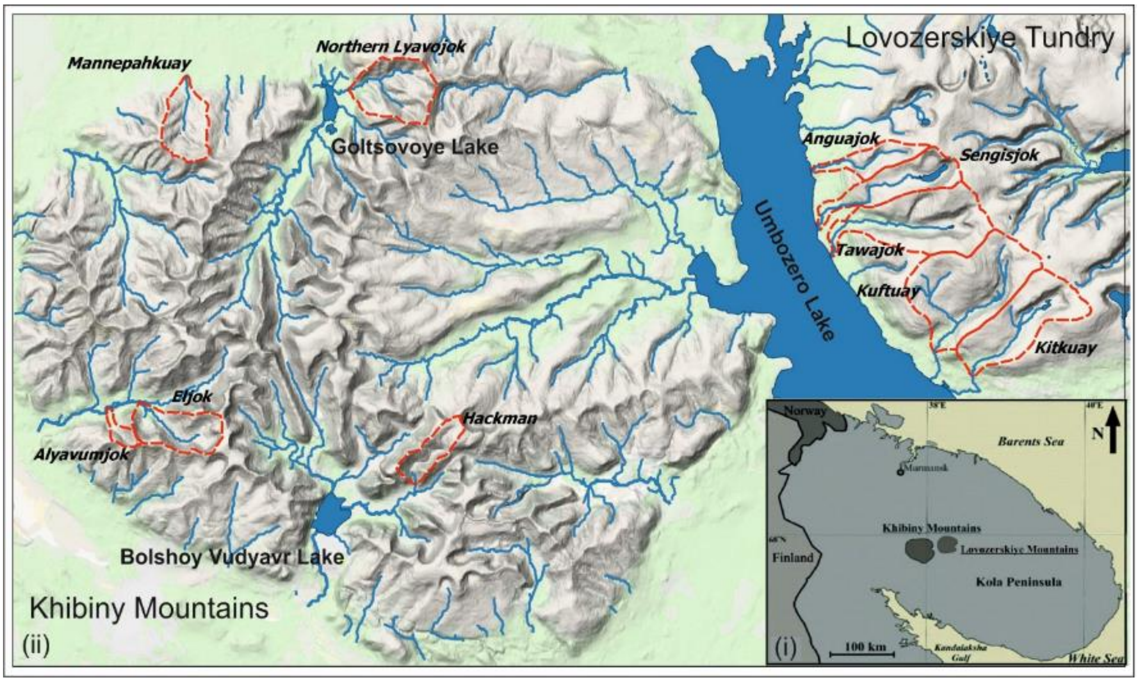

Fig. 1. Location of the Khibinskiye and Lovozerskiye low mountain massifs at the Kola Peninsula, Russia (i) and case study valleys at both massifs (ii) (source: Google global topography, infrustructure and settlements)

Here we report an attempt to reconstruct slushflow activity, evaluate its contribution into sediment budgets and impact on geomorphic structure and fluvial processes in several mountain valleys of the Kola Peninsula by means of detailed study of associated landforms and correlated deposits. Several comprehensive section descriptions and sediment sampling were accomplished through 2015-2017 fieldworks. Grainsize analysis, ^{232}Th radionuclide fingerprinting and ^{14}C dating were applied to reveal the age and common structure of slushflow environments. Geomorphic interpretation of high-resolution aerial and satellite imagery from public services and topographic maps presented widespread geomorphic evidences of debris flow phenomena within the studied massifs. Most of the valleys are regularly affected by modern slushflows and even typical debris flows. For example, specific landforms and deposits distinguishing active slushflow origination, transit and deposition zones were detected and lately directly observed in 22 out of 30 investigated Lovozerskiye Tundry valleys longer than 3 km. More elaborate examination of a number of mountain valleys at the Khibinskiye and Lovozerskiye Tundry (Fig 1) displayed that frequency and thickness of slushflows (and other debris flow phenomena) depend on the morphology, development history and age of the basins.

Debris flow patterns and landforms distribution at places are strongly controlled by the tectonic structure. For example, the Mannepahkuay basin has feather-shaped drainage network pattern caused by the combination of meridional, northeastern and northwestern lineaments inherited by tributary valleys practically perpendicular to each other. Thus, tributary slushflows runout zones are located in the main valley bottom sometimes completely blocking it. Such coarse debris dams provoke the stream to filtrate through deposits and may lead to further debris flow outbursts. All that cause unequal transporting distances of sediment load and specific “wavy” structure of slushflow deposition further downstream into the piedmont forest zone.

Dramatic imprints of extreme events (both slushflow and rockfall) great in clastic volume but transported for relatively short distances were observed in several other basins. At the Northern Khibiny, they are traced in the headwaters of neighboring Northern Lyavojok, Kalijok and Perevalnaya valleys mostly as large debris bodies and fans occupying the foothills of glacial cirques walls and the apertures of short outflows, respectively. At the Western Khibiny, left bank tributaries of the Malaya Belaya river (Eljok-Lednikovaya and Alyavumjok catchments) also show the presence of incompatibly great accumulative landforms either in the upper reaches or in the main valley bottom. Dense lineament structure, poorly sorted large clastic material (more then 1-2 m size) and widespread ongoing rock failures on valley sides suggest unreleased internal tension of the bedrock and a certain relationship of active seismotectonic zones to the distribution and magnitude of those catastrophic events.

The Northern Khibiny valleys are almost devoid of typical glacial deposits and were apparently less affected by the last (Late Pleistocene) continental ice cover (in comparison with southern and western segments of the massif). Nevertheless, widespread thick discontinuous debris bodies (as fans, ridges and elevated fragments of former valley floors) prove the high intensity of debris flows in the past. They were interrupted by several major valley incision cycles (probably due to the local base level subsidence during deglaciation and continuing tectonic uplift). On the other hand, the valleys incising the western slopes of the Lovozerskiye Tundry and Khibiny have significant glacial landforms (Tawajok, Sengisiok, Anguayok, Malaya Belaya, etc.). However, those glacial morphology underwent essential changes by other processes during the Holocene.

The Sengisjok (about 7 km long) is an example of major transformation of initially trough-like valley by debris flows. The modern V-shaped valley deeply cuts into the older wide valley bottom partly infilled by glacial, glaciofluvial, glaciolacustrine and debris flow deposits. Within it, there are two terrace-like units, lower of which (up to 20-25 m above the river floor) is undoubtedly formed by repeated high-magnitude debris flows. Its unsorted coarse clastic material (boulders up to 3 m in size) with dense loamy sand matrix cemented by nepheline gels, up to 15-20 m thick, overlies the laminated glacial lake sediments. Such sequences can be correlated with moraine-dammed lakes outbursts during the colder stages of Holocene when smaller glacier still survived in the headwaters cirque. It can also be possibly linked to extreme debris flow discharges and large-scale deposition on the Sengisjok relic fan (area >4 km^2) at the western piedmont. The modern Sengisjok valley morphology reflects later dominant incision trend, mainly associated with continuing debris flow and slushflow activity, though at much smaller scales and transporting capacity of sediment load than in the past.

Obtained results at both Kola mountainous massifs suggest that slushflows and, possibly for some valleys, typical debris flows with lower frequency are a leading mechanism of downstream sediment delivery and valley floor topography formation of the first-order streams. In typical erosion valleys with narrow floor and V-shaped cross-section (Mannepahkuay, Northern Lyavojok, Alyavumjok, Eliok, Hackman, Sengisjok, Anguajok, etc.), fluvial process is almost completely paralyzed by even minor deposition of high-frequency slushflows. A stream is redirected to wash out and re-deposit the finer fractions of debris flow fans and internal deltas (both recent and older ones), forming secondary alluvial features downstream. Small river valleys with typical glacial topography (wide-bottomed troughs with steep slopes) are usually devoid of debris flow sources in the headwaters (Malaya Belaya, Lednikovaya, Tavajok, Kuftuay, Kitkuay, etc.). Only rare extreme slushflow ejections from tributaries producing large superimposed fans in the main valley floor can influence its fluvial cycle. Those lead to major river channel shifts (forced meanders with up to 300-500 m radius of the Malaya Belaya river), 5-10 m deep fresh-looking incisions and au contraire ungraded convex fragments of valley bottom long profiles (e.g. large slushflow deposit body more than 500 m long in the Lednikovaya valley descended from the Eljok inflow).

To evaluate geomorphic effects of hazardous slushflow processes it is important to distinguish both main sediment sources with their relative contribution and zones of debris deposition. Radionuclide fingerprinting approach has been proved to be useful for determination of sediment sources and sinks in wide variety of geomorphic landscapes. Radionuclides can be used for fingerprinting purposes in cases if their chemical properties determine dominant redistribution in fixed conditions with sediment particles (Titaeva, Taskaev 1983). The Hackman valley located in the southern Khibiny is affected by frequent slushflows. Its geological structure is characterized by alternation of plutonic rocks with different content of radionuclides (Zak et al. 1972). In addition, radioactive mine was active in the basin in the 1930-s (Krasotkin et al. 2008). Despite closing, its damps on the right valley side at its middle reach still represent the potential source of radioactive material for the stream and slushflow sediment transport. Gamma-spectrometry analysis of the ^{232}Th radionuclide content in valley bottom deposits and on adjacent colluvial slopes help confirming the role of slushflows in episodic powerful removal and mixing of material along the valley (Garankina and Ivanov, 2016). Contribution of constant water flow within the stream channel is limited to washing out of fine fractions of loose material. The latter, according to the first results of alpha-spectrometry, make the most relevant contribution to the total radioactivity of the samples and, possibly, can cause positive radioactive anomalies in the sedimentation basins (deltas, lakes, artificial ponds) outside the studied catchments.

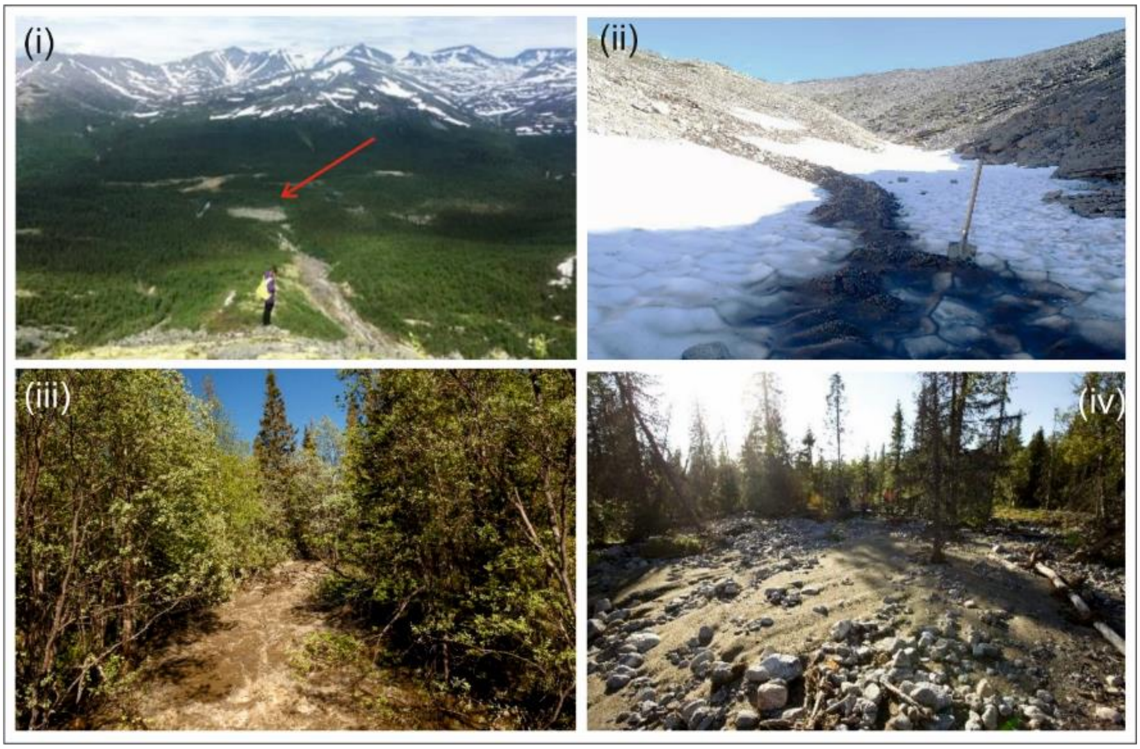

Fig. 2. Slushflow landforms: (i) large fan and (ii) fresh deposits, Alyavumjok valley. (iii) Granular debris flow on June 3 2017 and (iv) its deposits, Sengisjok valley

Recurrence interval of medium-magnitude slushflows in several studied valleys does not exceed 10-30 years, which is in agreement with the published monitoring data. Largest numbers of slushflow events within a single year have been detected at the Khibiny in 1943 and 1946 (presumably), 1950-1952, 1960, 1966, 1969, 1977, 1987 and 1995 (Bozhinsky et al. 2001; Ananiev 1998). At the Sengisjok valley of the Lovozery even higher frequency of debris flows was revealed by repeated fieldwork. Notable slushflow events have reorganized valley floor at least twice since 2009 with the latest one transforming from slushflow at the origin to the granular debris flow occurring on June 3 2017 (Fig 2). Fluvial topography is extremely suppressed or nonexistent under such conditions, as stream channels are unable to rework slushflow deposits and are forced to passively adjust.

Frequency of extreme events is however much lower. For example, large (about 150x300 m) and still non-vegetated slushflow fan of the Alyavumjok superimposed onto the forested floor of the Malaya Belaya valley, acording to historical topographic maps and aerial photographs, is at least 90 years old (Fig 2). Interval between extreme events in the Mannepahkuay valley causing debris fan formation within forested piedmont zone is about 500 years (540±80 (IGRAS-5404) и 1310±70 yrs (IGRAS-5402) according to ^{14}C dating of humic layers separating different slushflow deposit bodies, Fig 3).

Numerous attempts to determine periods of relative landscape stability and activation of catastrophic processes in the more distant past were undertaken (Perov 1971; Sulerzhitskiy et al. 1986; Vashchalova 1987; Bozhinsky et al. 2001; Vladychensky et al. 2007; Kosareva 2007; Romanenko et al. 2011, Romanenko and Shilovtseva, 2016). According to the radiocarbon dating, avalanche-rockfall, slushflow and debris flow activity decreased during 4100-3800 and 2760-2120 BC, 400 BC – 300 AD, 790-1560 AD allowing soil covers to develop on the surface of colluvial and debris flow fans. Oppositely, the highest intensity of avalanches coincides with the Little Ice Age of XIV-XIX centuries. In addition, slope and debris flow processes are assumed to be highly active during the climatic optimum of Holocene (7500-4800 BP). It is partially in coherence with the newly obtained radiocarbon date 4640±70 (LU-8763) for the Sengisjok valley (Fig 3) showing the 5 ka BP age of a peat lens clamped between slushflow deposits underneath and a layer of hyperconcentrated flow sediments. However, low position above the valley floor at upper reaches and particularly well-sorted sediments are somewhat in contradiction with the conditions of high-intensity sedimentation.

Nevertheless, extensive occurrence of distinctive large relic landforms and thick bottom deposits without any detectable organic material indicates substantially higher magnitude debris flows activity in the past. Most likely they functioned in colder environments during the last deglaciation stages , particularly those associated with moraine-dammed lakes outbursts. Reliable chronology of those stages is yet to be obtained and represents the most challenging problem for future research in the area.

The study was funded by the RFBR project №17-05-00630 and GM AAAA-A16-11632810089-5.

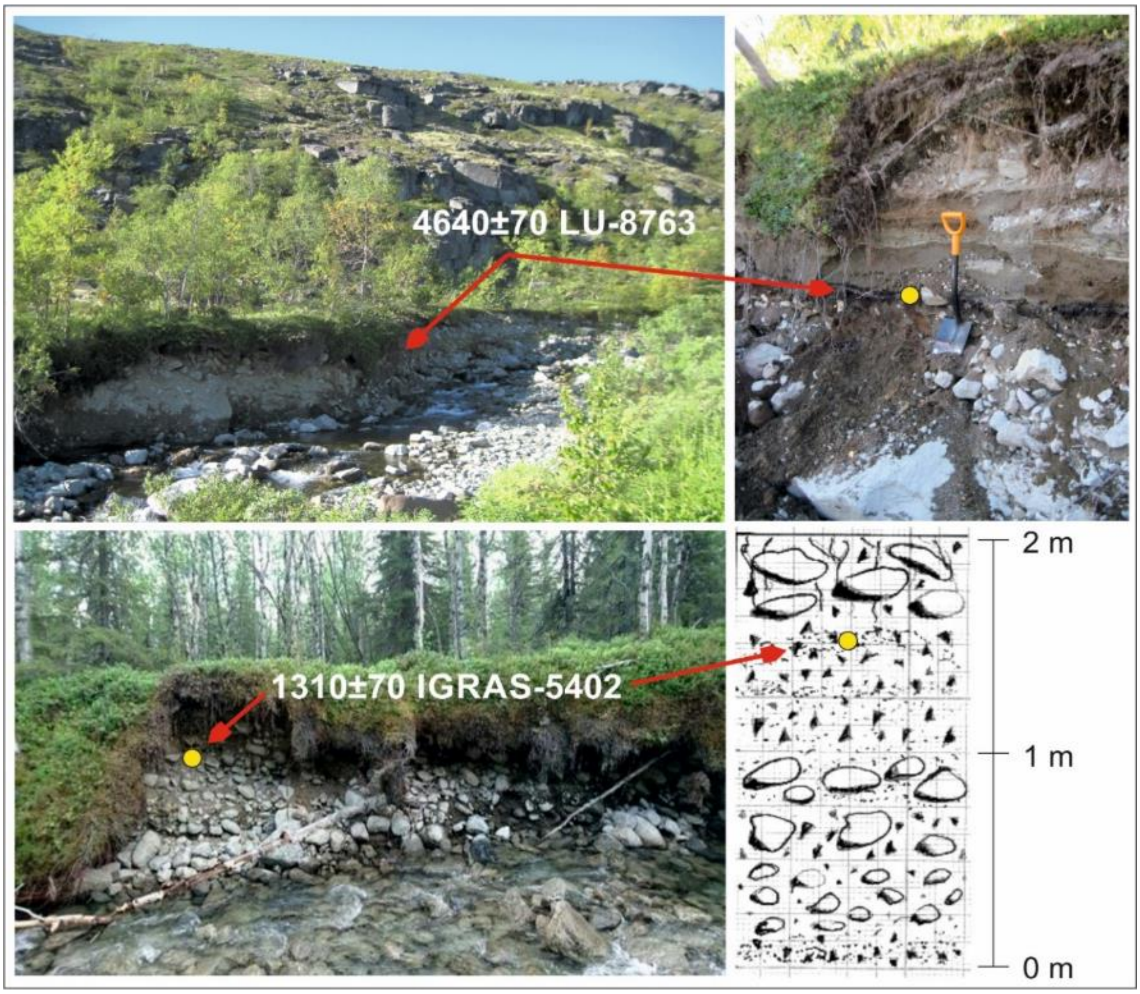

Fig. 3. Radiocarbon dates of burried organic layers in cross-sections of slushflow terraces at the upper Sengisjok valleys (i) and at the fan of the Mannepahkuay valley (ii)

Keywords: slushflow, debris flow, mountain, valley, subarctic.

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