TRANSFORMATION OF KHIBINY MOUNTAIN VALLEYS BY SLUSHFLOWS, KOLA PENINSULA, NORTHWESTERN RUSSIA

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ABSTRACT

We report an attempt to reconstruct slushflow activity, evaluate its contribution into sediment budgets and impact on geomorphic structure and fluvial processes in the Khibiny Mountains valleys by means of detailed description of associated landforms and correlated deposits analyses (structural, grainsize, radionuclide fingerprinting, ^{14}C dating). Slushflow represent a specific type of gravitational flow of water-saturated mixture of snow with limited amount of clastic material. Available results for the studied basins suggest slushflows as a leading mechanism of downstream sediment delivery and valley floor transformation in Holocene. Recurrence interval of medium-magnitude slushflows does not exceed 10–30 years, though fluvial topography is suppressed or almost nonexistent as streams are unable to rework slushflow deposits. Frequency of extreme events is much lower. Nevertheless, largest-scale bottom features and piedmont fans can be related to much more intense events associated with last deglaciation stages.

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

INTRODUCTION

Slushflow represent a specific type of gravitational flow of water-saturated mixture of snow with relatively limited amount of clastic sediment (< 12%, size up to 1–2 m) occurring in low-order stream channels [3]. Slushflows are considered either subtypes of wet snow avalanches, or debris flows, or independent phenomena between the latter two [11, 5, 4]. Widespread mostly in Arctic and Subarctic mountain environments they cause hazardous and potentially dangerous episodes. Those are common for the Ural, Putarana and Kola Peninsula mountains and Scandes in Eurasia [10, 6], Brooks ridge, Quebec region and Canadian Arctic Archipelago in North America [1, 9] and rarely reported for the lower latitude mountains. They could cause fatal consequences [8] increasing both the scientific community and public awareness and social demands for prediction and sound protective measures [13].

Compact low mountains of Khibiny (up to 1201 m ASL) located in central part of the Kola Peninsula is a Devonian pluton of multiphase alkaline intrusion [12] partly exposed by denudation. Extreme mineral concentrations triggered extensive industrial exploration of the massif for almost a century that yielded in numerous quarries, mines, plants, roads and civil engineering constructions. Lately, rapidly growing touristic flow has focused on Khibiny ski resorts, mountainous tracks and newly established National park. At the same time, being an arena of widespread hazardous processes (snow avalanches, rockfalls and screes, slushflows and debris flows) it requests reliable assessment of potential environmental risks. Debris flows here are thoroughly investigated since 1960s [3] providing a unique dataset of >200 slushflow-affected mountain catchments that have been active at least once in centennial. However, those surveys concentrated largely on monitoring the presently observed episodes whether knowledge of distribution, magnitude and frequency of such hazardous events is still limited by the lack of reliable spatial data and age characteristics on the debris flow deposits and landforms allowing paleogeographic correlatations.

MATERIALS AND METHODS

In order to evaluate slushflows intensity in the Khibiny, its contribution into sediment budgets and influence on geomorphic structure and fluvial processes we accomplished a detailed study of associated landforms and correlated deposits. Geomorphic interpretation of high-resolution aerial and satellite imagery from public services and detailed topographic maps presented widespread evidences of debris flow phenomena within most of them. Through 2015–2017 fieldworks comprehensive section descriptions and sediment sampling for grainsize analysis, ^{232}Th radionuclide fingerprinting and ^{14}C dating were carried out in the six mountain valleys allow revealing the age and common structure of slushflow environments. In addition, reference photo points were established and aerial photography using unmanned aerial vehicle was accomplished for further monitoring of modern slushflow consequences.

RESULTS AND DISCUSSION

Numerous deep (100–500 m) erosional valleys, glacial troughs and cirques, and tectonic lineaments dissect Khibiny plateau-shaped summits and relatively steep slopes. Field inspection of six river basins (Fig 1) revealed both modern and older slushflow landforms: valley floor and stream bank incisions, ridges, levees and hummocks, debris covers, terraces and fans. Surfaces of relatively fresh landforms have no or poor vegetation (fragmentary mosses, lichens, herbs and shrubs) and do not exceed 1 to 2 m in height and 0.02 km^2. Older ones are larger (up to 10 m high and 0.05–0.4 km^2) and mostly well forested or have thick moss-lichen cover in tundra. Deposits vary from large boulders and blocks to sandy silts depending on the geomorphic position above the streambed, the distance from slushflow sources, age and flow energy. Usually up to three levels of debris flow accumulations of different age could be distinguished. Along the middle reaches of 2^{nd}-3^{rd} order streams, they are traced as sequences of superimposed or leaning against each other terraces. At the lower reaches, they appear in cross-sections as series of humic or peat layers buried between coarse debris flow deposits.

The youngest slushflow deposits were found almost days and months after their accumulation, respectively, in the valleys of Alyavumjok and Northern Lyavojok and Mannepahkuay. In the latter, they formed small debris covers, individual hummocks up to 1.5 m high and ridges 7–8 m long during the early spring snowmelt 2016 (fresh silty gravel and boulder loads were registered later, in the end of June at the confluence of main headwaters). The successive remote sensing data analysis allowed narrowing the discharge periods of previous slushflows down to spring 2014 and at least once before, in 2012–2013. Larger young landforms were formed by slushflow from the main left tributary in Northern Lyavojok basin. According to the vague vegetative cover of the debris fan protruding the forested area, it happened less than 10–15 years ago. Evidences of relatively young slushflows of extreme volume are observed in the Malaya Belaya river basin. Couple of small catchments (Alyavumjok and Eljok) on the left bank in its middle reaches have large unvegetated debris fans. The valley floor of the former one is almost devoid of loose sediments in its upper part, and the latter has a deep (up to 35 m) V-shaped incision in the middle part. Debris fans with boulder pavings and 200–250 m radius have already been shown on the first historical topographic maps of the Khibiny from the 1930s. Thus, they are at least 90 years old and are superimposed on the older (better vegetated) and even greater in size fans displaying repetitive activity of extreme slushflows in the region.

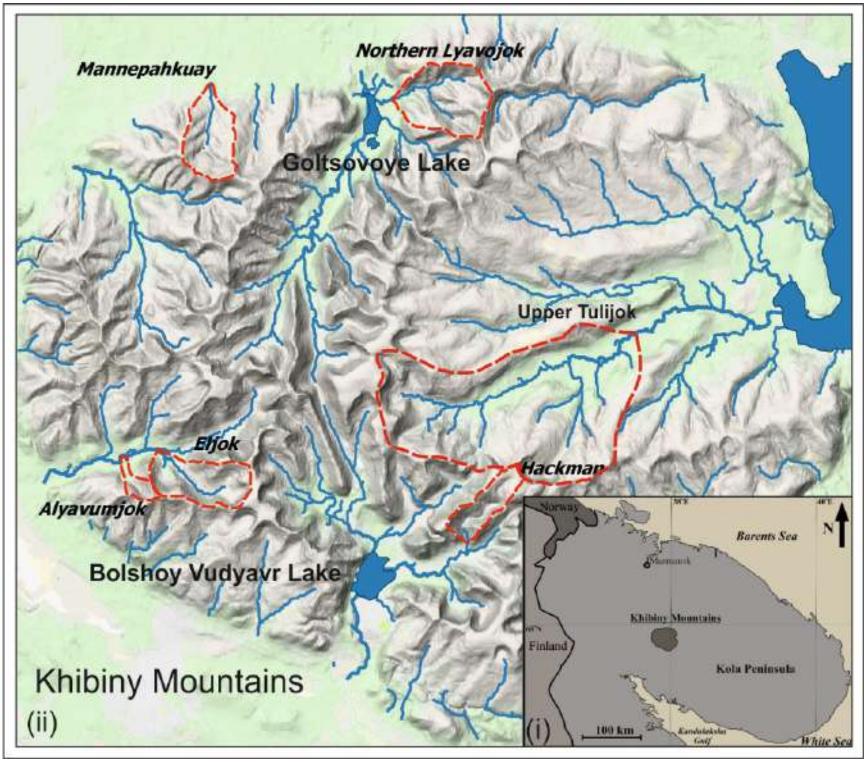

Fig 1 Location of the Khibiny mountain massif at the Kola Peninsula, Russia (i) and case study basins (ii) *(Google global topography, infrustructure and settlements).*

The frequency of such disastrous events can be estimated by the ^{14}C dating of buried soils within the forested piedmont area of the Mannepahkuay valley. Here, the ages of organic-rich paleosol layers overlaid by slushflow deposits under well-developed spruce forest are 540±80 (IGRAS-5404) and 1310±70 (IGRAS-5402) ^{14}C yrs. in two successive slushflow accumulation zones 0.5 km apart. Therefore, we can expect high-magnitude slushflows to release at least twice per millennia in the basin and probably much more often. Such extreme episodes could cause radical changes for the mountain valley and piedmont environments. Besides essential adjustments in surface conditions of large areas (eliminating primary sediments, soil and plant cover), they lead to great alterations in topography and landscape dynamics. Large tributary slushflow fans overlap receiving valley floor and induce the main river channel to intensely erode or even significantly shift its position. Thus, large forced meander up to 350 m in radius occurred in the Malaya Belaya river valley due to the Alyavumjok fan. Dramatic imprints of both slushflows and rockfalls great in clastic volume but transported for relatively short distances were observed at the Northern Khibiny. Here, in the neighboring headwaters of Northern Lyavojok, Kalijok and Perevalnaya, large debris bodies and debris fans appear at the foothills of glacial cirques walls and apertures of short brooks. Multiple signs of faulting and widespread ongoing rock failures on valley sides suggest still unreleased tectonic tension in the bedrock at the described areas. Poorly sorted clastic material (blocks >1–3 m size) and common distribution of such landforms in the closely located valleys indicate definite relationship between active seismotectonic zones and the discharge and magnitude of those catastrophic slushflows.

The magnitude of slushflows can also be affected by the specific geomorphic structure of a basin. For example, feather-shaped drainage network pattern induce slushflow runout zones from steeply inclined tributaries to allocate in the flattened bottom of main valley sometimes completely blocking it. Such coarse debris dams provoke the stream to filtrate through deposits and may lead to further outbursts and even typical granular debris flows downstream. All that cause unequal transporting distances of sediment load and specific "wavy" structure of slushflow deposition in the lower reaches spreading into piedmont forest zone. Consequently, in the higher order river basins, it is often hard to recognize zones of dominant slushflow origination, transport and accumulation whether simple arranged catchments (mostly streams of the 1st order) usually present distinctively confined morphodynamic zones of slushflows.

A little is known about hydrological mode of slushflow-affected streams. Registered discharges in the lower reaches of the Tulijok River (the biggest watercourse of the Khibiny) rise from 4.5 m^3/sec during the low water periods up to 80 m^3/sec in the high waters. Occasionally, slushflows exceed the latter value. At the same time, main river channel is almost devoid of modern debris flow phenomena with an exception of local outbursts when riverbed snow dams in upper reaches are being destroyed. Those small slushflow events generally of the wet avalanche type intensely erode floodplains and terraces riverbanks leaving channel extensions, hummocky and ridge shoals and accumulative coarsegrained levees along the floodplain edges. Floodplain here has two levels almost non-differentiated by height above the riverbed. However, the younger step has distinct ridges of debris flow and alluvial genesis along the upper valley part whether the older and slightly higher one is almost flat and does not show any signs of recent accumulation. Slushflow traces of various ages were observed in numerous tributaries of the Tulijok dissecting slopes of adjacent plateaus, but modern slushflow accumulation terminates inside their catchments not reaching the main valley floor.

Erosional potential of slushflows could be estimated based on the geomorphic evidences. Deep V-shaped incisions in the upper reaches of the 1st-order streams and brooks almost dry during most of the warm season attest to its origination by agent other than fluvial. In places, they dissect even bedrocks showing great intensity of the eroding flow. Usually, catchment basins above them (cirques, niches, etc.) provide abundant snow and water supply and serve as slushflow sources. Downstream major valley, several incisive cycles are imprinted into the bottom topography of the basins of higher orders. According to the relatively low discharge rates and no geomorphic indication of active erosion by fluvial processes, those should also be correlated with slushflow episodes probably caused by climatic fluctuations, or sometimes, local base level declines.

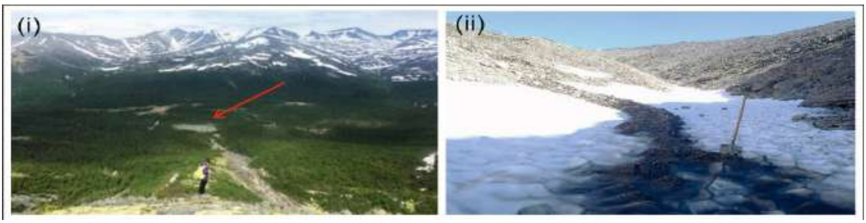

Fig 2 Slushflow landforms: (i) large fan and (ii) fresh deposits, Alyavumjok valley .

To evaluate geomorphic effects of hazardous slushflows and its interactions with other exogenous 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 useful determining sediment sources and sinks in wide variety of geomorphic landscapes. Radionuclides can serve as tracers in cases if their chemical properties display dominant redistribution in fixed conditions with sediment particles. Two valleys — Hackman and Northern Lyavojok — with confirmed Thorium-232 radionuclide sources have been chosen for fingerprinting studies. Both basins in the Southern and Western Khibiny are located in the highly contrast geological conditions characterized by alternation of alkaline plutonic rocks with different content of radionuclides. At the first one, strong ^{232}Th signal is confined to the lovchorrit vein and associated radioactive mine damps on the right valley side. In opposite, radionuclide sources in the second valley are scattered along the catchment and do not show any proven bedrock concentration. Frequently affected by slushflows, valleys are an arena of potential sediment transport and redistribution of naturally radioactive deposits.

Gamma-spectrometry analysis of the ^{232}Th radionuclide content revealed definite concentrations in accumulative deposits in valley bottoms compared with adjacent colluvial slopes, on one hand, and alluvium in streambeds, on the other. This allows confirming episodic powerful removal and mixing of material along the Hackman valley by slushflows [7]. 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. Thus, secondary re-deposition of the ^{232}Th contaminated thin material is possible downstream the receiving Uksporrjok valley, right into the Bolshoy Vudyavr lake.

At the same time, increased ^{232}Th values in the bottom of Northern Lyavojok valley, as well as in the bottom sediments of the receiving reservoir, Goltsovoye Lake, with respect to the potential scattered sources require further investigation. Probably, in the latter case, the granulometric differentiation of sediments takes place. Further analysis of the ^{232}Th content fluctuations in the lake sedimentary column provided with several ^{14}C dates and palaeogeographic reconstructions [15] may clarify the dynamics of slushflow activity (indirectly by the amplified release of silts with higher radioisotope content with the hyperconcentrated floods anticipated by slushflows in the upper reaches).

CONCLUSION

The frequency and magnitude of slushflows and debris flows at the regularly affected river basins display definite relationship with the morphology, history and age of basins. Obtained results suggest that slushflows and, possibly for some valleys, even typical debris flows with lower frequency are a leading mechanism of downstream sediment delivery and valley floor transformation of the 1st-order streams. Fluvial topography here is extremely suppressed or nonexistent under such conditions, as stream channels are unable to rework slushflow deposits and are forced to passively adjust. In typical erosion valleys of the 2nd order with narrow floor and V-shaped cross-section (Mannepahkuay, Northern Lyavojok, Alyavumjok, Eliok, Hackman, etc.), fluvial processes are also 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 slushflow fans and internal deltas (both recent and older ones), forming secondary alluvial features downstream. Small river valleys of the 3rd and higher orders with typical glacial topography (wide-bottomed troughs with steep slopes) are usually devoid of major slushflows (Malaya Belaya, Lednikovaya, Tulijok etc.) except particularly low-magnitude events generally of the wet avalanche type in the riverbed. 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, deep fresh-looking incisions and ungraded convex fragments of valley bottom long profiles.

Recurrence interval of medium-magnitude slushflows in studied valleys does not exceed 10–30 years that is in agreement with the published monitoring data. Thus, the 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 [3]. Frequency of extreme events is, however, much lower. It was estimated to be at least twice per millennia in several valleys, according to ^{14}C dating of humic layers separating different slushflow deposit bodies, analysis of archive topographic maps and aerial photography. Nevertheless, extensive occurrence of distinctive large relic landforms and thick bottom deposits without any detectable organic material indicates substantially higher magnitude of debris flows activity in the distant past. Most likely, they functioned in colder environments during the last deglaciation stages, particularly associated with moraine-dammed lake outbursts. Reliable chronology of those stages is yet to be obtained by the means of comparative analysis of grainsize, radionuclide and organic content of the correlated deposits (slushflow fans, deltaic and lacustrine sediments) and ^{14}C dating. Such reconstruction of slushflow dynamics represents the most challenging problem for future research and may provide reliable basis for further risk assessment in the area.

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