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The ^{232}Th distribution in modern sediments near radioactive lovchorrite mine, the Khibiny Mountains, Kola Peninsula

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ABSTRACT

The ^{232}Th migration in environment is linked to transportation of thorium-bearing mineral particles. In cold climatic conditions of alpine tundra, leaching of ^{232}Th is the least typical process. The spread of ^{232}Th in environment is associated with the transport of thorium-bearing mineral particles. The total content of the ^{232}Th and its distribution between different grain-size fractions, bulk samples of modern sediments from a lovchorrite mine in the Hackman Canyon, in the southern part of Khibiny Mountains (Kola Peninsula, Russia) in 2015–2017 were determined using gamma-ray spectrometry. The most active samples were sequentially extracted and processed via alpha-spectrometry to identify physicochemical forms of radionuclides. It was recognized that ^{232}Th concentrates in fine grain-size fractions of sediments and easily be washed out by temporal or constant water currents. As it was explored during sequential extraction procedure, the genesis of this phenomenon is likely not to be related to leaching and sorption of radionuclides. Hypothetically, uneven redistribution of ^{232}Th emerges during weathering of radioactive rocks. Metamictic thorium-rich accessories with crystal lattice damaged by own radiation destroyed more intensively than more resistant rock-forming minerals. Hence, fine grainsized fractions become enrich with radioactive particles.

1. Introduction

The mining is usually accompanied by providing of wastes (tailings), which are not used in the further production process (Down and Stocks, 1977). However, the concentration of chemical components, including the targeted one, in the wastes may be high enough constituting a serious environmental hazard (Lewin and Macklin, 1986; Moore and Luoma, 1990; Wilkinson and McElroy, 2007; Luís et al., 2009; Candeias et al., 2014), especially concerning the radioactive rocks excavation. If radioactive tailings are not isolated from the natural exogenous impact, it may become a strong source of the environmental contamination (Read and Pickering, 1999; Landa, 2004; Carvalho et al., 2007). The main path of contaminants propagation through the environment is migration with water, which cuts into tailings and transports the eroded material or leaches pollutants (East et al., 1988; Sarin et al., 1990; Alvarado et al., 2014). The radionuclides migration ability in a dissolved state is determined by the complexity of its properties, the composition of rocks, chemical and physical properties of water. The radionuclides transport in mineral form depends on their initial content in rocks and distribution by the granulometric fractions of sediments. The investigated radionuclide – ^{232}Th – is generally included into mineral particles and migrates with sediment yield.

In natural conditions, Th has the only oxidation state +4, which demonstrates ionic and covalent bonds. Thorium has a strong affinity for oxygen and, therefore, occurs in natural oxygen-containing compounds only (Ryabchikov and Golbreih, 1960). In alpine tundra, the Th migration is the least probable in the ionic form. Nonetheless, observed data reveal a growth of the Th content correlated with the increasing share of clay minerals and sesquioxides. Herewith, the Th isotopes leaching cannot be excluded entirely (Titaeva, 2000).

^{232}Th is a natural alpha-emitting radionuclide. This isotope has a very long half-life period of about $1.405 \cdot 10^{10}$ years. The radioactive chain of ^{232}Th contains ten radionuclides and ends with stable ^{208}Pb: $^{232}\text{Th} \rightarrow {}^{228}\text{Ra} \rightarrow {}^{228}\text{Ac} \rightarrow {}^{228}\text{Th} \rightarrow {}^{224}\text{Ra} \rightarrow {}^{220}\text{Rn} \rightarrow {}^{216}\text{Po} \rightarrow {}^{212}\text{Pb} \rightarrow {}^{212}\text{Bi} \rightarrow {}^{208}\text{Tl} \rightarrow {}^{208}\text{Pb}$. The secular equilibrium in this chain can be reached in a comparably short period – less than several decades. Therefore, the content of ^{232}Th can be reliably evaluated on identifying its daughter gamma-emitting radionuclides.

Today the problem of regul oversight of Naturally Occurring Radioactive Materials (NORM) and Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) is discussed worldwide. Different countries and international organizations make great efforts evaluating dozes from natural radioactive materials to draw up a strategy of radiologic safety improvement for the humanity and environment (IAEA, 2011, 2013).

The majority of specialists highlights a group of significant factors observed during investigations of natural radioactive material. It includes initial concentration and physicochemical forms of the

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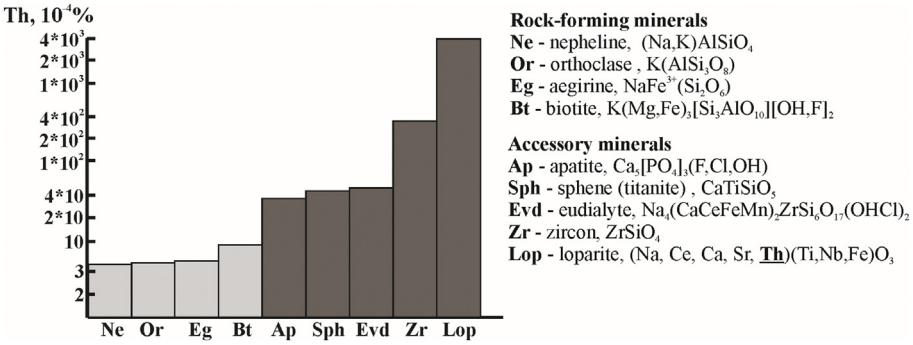

Fig. 1. Th content in rock-forming and accessory minerals of nepheline syenites – Khibiny and Lovozery Mountains (Smyslov, 1974).

radionuclide; different migration types of daughter-radionuclides; properties of applied technology?, which can change physicochemical form of radionuclide; changes in the radionuclide concentration and form, which may occur due to natural processes (radioactive decay, weathering, erosion etc.) (Landa, 2007).

The distribution of natural radionuclides of U and Th decay chains is usually very uneven in bedrocks. There are more than a hundred of known thorium-rich minerals. ^{232}Th has constant isomorphic and paragenetic relation with rare-earth elements (REE), especially with Ce and other lanthanides (Titaeva, 2000). Except its own minerals the main amount of ^{232}Th is concentrated in accessory minerals: zircon, apatite, monazite, titanite, allanite, xenotime and others (Ragland et al., 1967; Ditz et al., 2013) (Fig. 1.). High concentration of Th is much lower than concentration of U and is mostly typical for alkaline plutonic rocks (Balashov, 1963; Smyslov, 1974).

If radionuclides dominantly migrate with mineral particles, being included in their structure or in a sorbed form, the grain size composition of the transported material turns to be a significant factor. Silt and clay particles take the most substantial part in the radionuclide migration because of their high sorption capacity in comparison with sand and an ability to be eroded by water streams (Cho et al., 1996; He and Walling, 1996). It was revealed that the presence of a few particles of high radioactive accessory minerals (mainly zircon and monazite) could significantly change the total ^{232}Th amount in fine grain fractions (De Meijer et al., 1985; Seddeek et al., 2005; Bosia et al., 2016). Correspondingly, high concentrations of ^{232}Th in silt and clay were observed in marine sediments constituted nearby coastline (Marmolejo-Rodríguez et al., 2008; Tripathi et al., 2013). The phenomenon of radioactive beaches called “black sands” where radioactive minerals concentrate is widespread around the world (Greensmith, 1989; Veiga et al., 2006; Kaiser et al., 2014).

The main objective of the proposed investigation was to analyze and to clarify the distribution of ^{232}Th content in modern sediments of the river valley in the Kihibiny Mountains (Kola Peninsula) where thorium-rich rocks were mined in the 1930-s (Lovchorrput mine). The mine wastes were deposited into surface tailings on the valley side.

2. Study area

The field data were collected in the Hackman Canyon near the radioactive lovchorrite mine Lovchorrput. The Hackman Canyon is situated in the southern part of the Khibiny Mountains (Fig. 2A,B) named after a finish geologist Victor Axel Hackman (1869–1941) by A.E. Fersman in 1921 (Koshechkin, 1979).

Khibiny Mountains is a multiphase alkaline pluton with a concentric structure (Pozhilenko et al., 2002). The Hackman Canyon cuts the southern edge of the massif dissecting several geological complexes. The upper reaches of the valley lie within the zone of trachytoid foyaites (Zak et al., 1972; Geologic map …, 2014). Downstream the valley crosses complexes of gneiss-like and massive rischorrites, dikes and veins of gabbroids, bazaltoids, aegirinites and apatite–nepheline ores (Fig. 2C).

Thorium enrichment zone on the right valley side in its middle reach associates with a large fracture zone. Its radioactive mineral lode – Juksporr lovchorrite field – is believed to be the greatest over the entire Khibiny massif. This field consists of pegmatite aegirine-feldspar lovchorrite-rinkolite veins those intrude gneissoid ristschorrites. The main radioactive component is lovchorrite (variety of monsadrite) – a rare mineral found as amorphous yellow and brownish-yellow masses those are not constant in composition. In chemical composition, lovchorrite resembles the rinkolite mineral, $Na_2Ca_4CeTi[Si2O_7]O(F, OH)_3$, and is possibly an amorphous variety of rinkolite. Lovchorrite contains admixtures of such oxides as ZrO_2, Al_2O_3, and ThO_2. It is radioactive and has a cryptocrystalline structure. Lovchorrite forms veins, irregular accumulations, or paramorphs after rinkolite crystals in alkaline pegmatites associated with the nepheline-syenites group. It is an ore for the rare-earth metals and thorium (The Great Soviet Encyclopedia …, 1970–1979). The average ore sample from Juksporr field contained 53.8% of feldspar, 19.4% of pyroxene, aegirine and amphibole, 17.9% of nepheline, 6.5% of lovchorrite and rinkolite; 1.6–2.3% of eudialyte, apatite and titanite, and < 0.5% of sulfides. The content of REE oxides is 11–17%, ThO_2–0.5-1%, $Ta_2O_5 \approx 2\%$, and U_3O_8–0.02-0.25% (Fersman, 1933; Komlev, 1933; Mikhalev, 1937; Krasotkin et al., 2008).

In the first half of the 20th century, lovchorrite was used to produce the incendiary mixture, camera lenses, and in chemical and radio technical industry (generally for military purposes). In 1931, the mining in the Hackman Canyon was launched. Due to severe natural conditions and ore processing difficulties, they conservated the mine in 1939. In 1946, an attempt to resume mining failed, and porduction ceased completely (Krasotkin et al., 2008). Screes, rockfalls, avalanches, slushflows, and debris flows have gradually destroyed Lovchorrput constructions, and only a few ruins still remain (Fig. 2D).

3. Materials and methods

We examined 11 samples of surface sediments collected during 2015–2017 near the Lovchorrput mine in the Hackman Canyon: 2 – from tailings (S-1, S-2); 4 – from natural slopes (valley sides) close to the ^{232}Th enrichment zone (S-3, S-4, S-5, S-6), 3 – from the valley bottom (B-1, B-2, B-3), and 2 – from the stream channel (C-1, C-2) (Fig. 2, E).

Each sample is a clay-silt-sand-gravel mixture (d < 10 mm) collected by 5 points (located in the shape of a square with a central point) within the area of 1–1.5 m^2. Later all samples were dried at a temperature of 105 °C for 8 h. The dry sample mass was adjusted to 100 g. Samples were sieved into fractions of standard particle sizes: < 0.05 mm, 0.05–0.1 mm, 0.1–0.25 mm, 0.25–0.5 mm, 0.5–1 mm, 1–2 mm, 2–5 mm, 5–10 mm. All fractions were ground to powder, and weighted amounts of 1 g were prepared for further gamma-spectrometric analysis.

The most commonly used method for measuring ^{232}Th is gamma-spectrometry based on the equilibrium with its decay products: ^{228}Ac (E

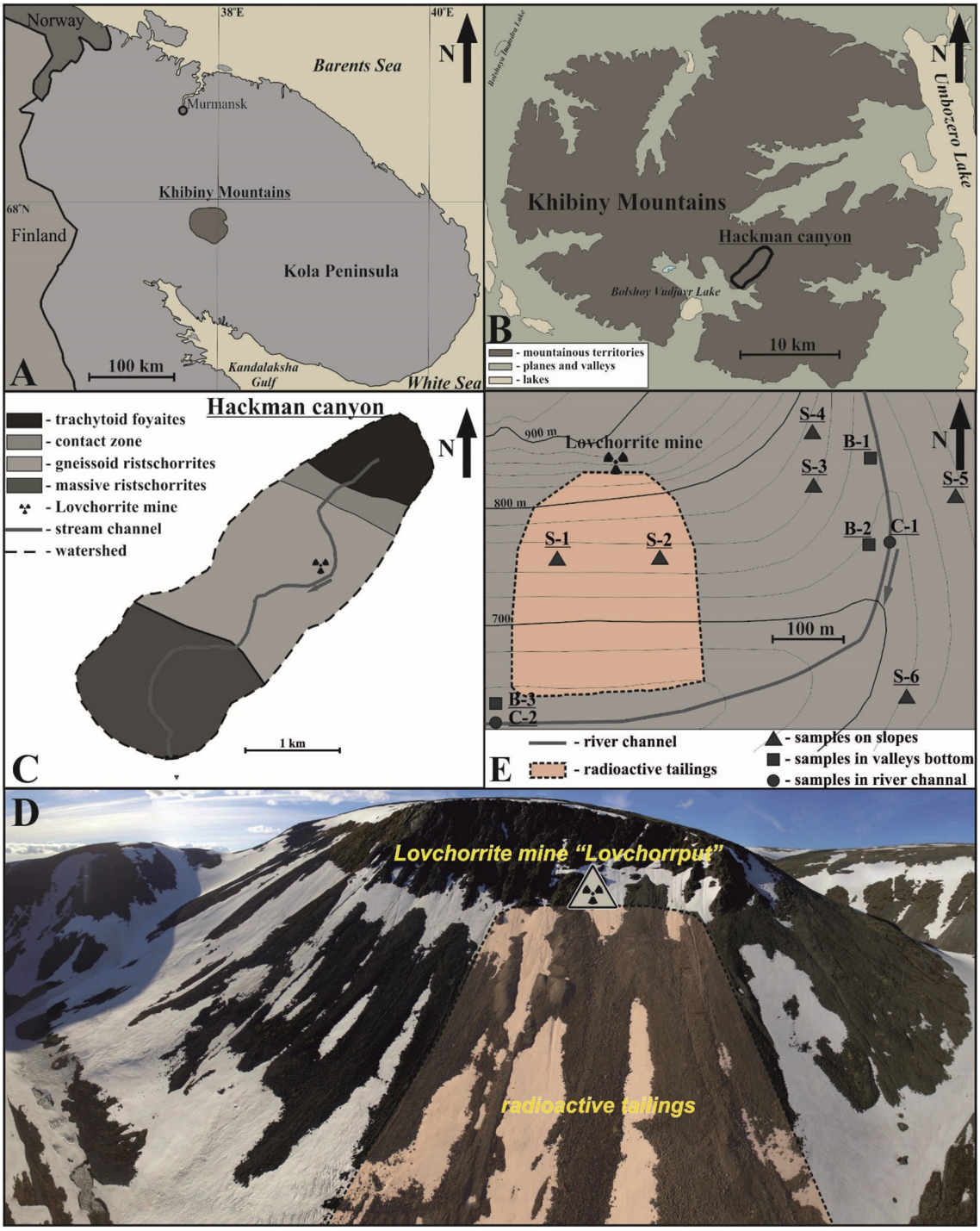

Fig. 2. A – a location of Khibiny Mountains; B – a location of Hackman Canyon; C – a geologic scheme of Hackan Canyon and a location of lovchorrite mine (base on Geologic map …, 2014); D – a panorama of Lovchorrput mine and radioactive tailing on the right slope of Hackman Canyon; E – a location of sampling site near lovchorrite mine.

– 911.2 keV, p – 0.26; E – 338.3, p – 0.11), ^{212}Pb (E – 238.6 keV, p – 0.43), ^{208}Tl (E – 583.2 keV, p – 0.84) (Antovic and Svrkota, 2009). It was found that two peaks of ^{228}Ac can be adopted as the "reference" peaks in all spectral corrections, and they can even be reliably suggested as "analytical peaks" for ^{232}Th activity analysis in almost all measurement conditions (Yucel et al., 2011). The activities of ^{226}Ra (609 keV, p – 0.448) and ^{40}K (1460 keV, p – 0.11) were additionally examined. Is was revealed that the concentration of ^{228}Ac has a very strong positive correlation with ^{226}Ra (R^2 = 0.63), but the values of the later turn to be more than three times lower. Therefore, redistribution of uranium daughter radionuclides do not constitute high interest. The concentrations of ^{228}Ac and ^{40}K have a very weak negative correlation, thus, it was also excluded from observation. Our measurements were conducted with the gamma-spectrometer ORTEC GEM-C5060P4-B with HPGe detector (relative efficiency 20%), the average deviation between the obtained absolute values of different decay products of ^{232}Th < 8%.

For the examination of physicochemical forms of ^{232}Th in the most active samples, we applied a procedure of sequential extraction. Sequential extraction was accomplished according to Schultz et al. (1998) – modified scheme of Tessier et al. (1979), and consisted of five

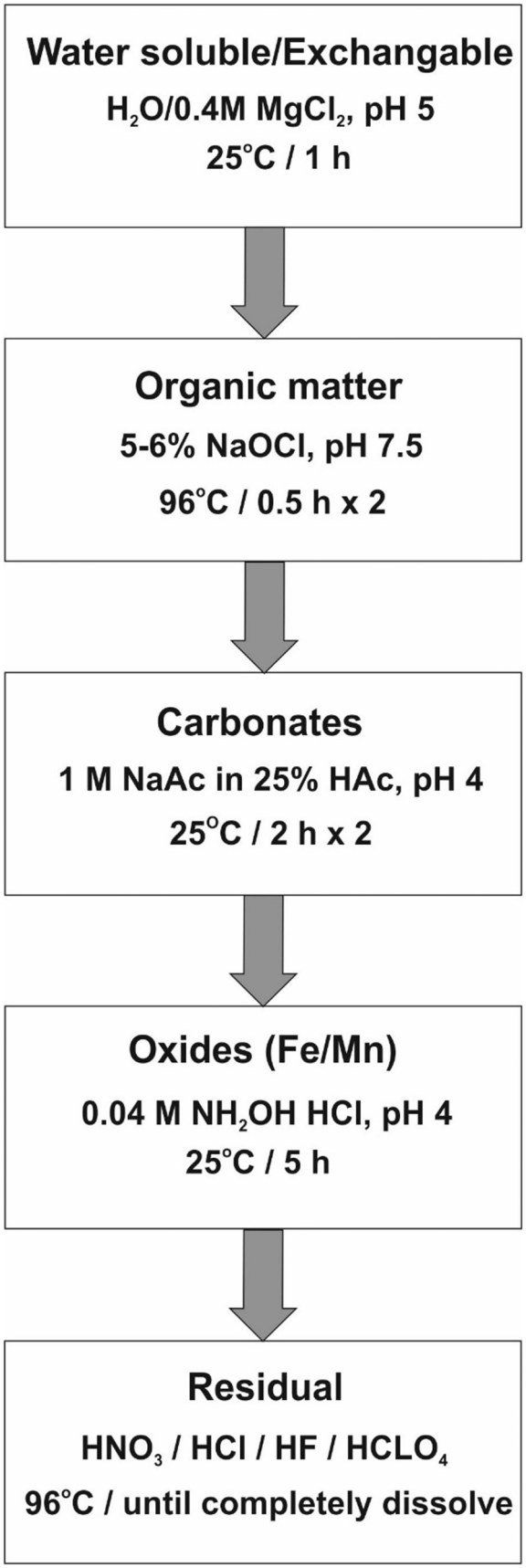

Fig. 3. Procedure of sequential extraction by Schultz's method.

stages (Fig. 3). The ratio of sample to reagent was 1:15. After each phase liquids were separated by centrifugating (3500 g, 45 min).

After sequential extraction samples were evaporated and dissolved in 3 M HNO_3 for purification with TEVA resin (a quaternary ammonium salt) produced by TrisKem International and planted into the cartridge with a volume of 2 ml. Th was coprecipitated with CeF_3 on Resolve filters (d = 0.1 μm). The alpha-activities of Th isotopes ($^{228,\ 232}$Th) were measured with the spectrometer ORTEC Alpha-Ensemble-2 with detector ENS-U900 type UL-TRA-AS. The yield during purification procedure was controlled with gamma-active spot – ^{234}Th (E – 63.9 keV, 92.4–92.8 kEv; p – 0.048, 0.056; efficiency 17%).

Additionally, a series of samples were collected from the stream and ground waters and snow to examine mineralization via liquid chromatography method and pH-values.

4. Results and discussion

Gamma-spectrometric examination of samples revealed that variability of ^{232}Th activity in sediments within the investigated area has a systemic pattern expressed in the following (Fig. 4). The first trend is a sharp contrast between activity (63 ± 4 Bq/kg) of slope sediments in the area of gneissoid ristschorrites (S-4) and high values (175 ± 14–807 ± 50 Bq/kg) found in the thorium enrichment area and mine tailings (S-1, S-2, S-3, S-5). The major part of radioactive lode represents on the right valley side. On the left side, high value at the S-5 point (175 ± 4 Bq/kg) turns to the level observed upstream the enrichment zone – 51 ± 8 Bq/kg – at S-6. High resistance of the thorium-rich geologic body to erosion can probably explain this. After incising its narrowest part (between points S-3 andS-6), the stream inherited the most fractured zone not filled with hydrothermal ores and cut around the radioactive lode leaving the most active bedrocks on the right valley side.

Concurrently with the growth of activity on the slopes, activity in the valley bottom also increase from 92 ± 5 Bq/kg (B-1) to 150 ± 9 Bq/kg (B-2) remaining through the thorium enrichment zone (B-3). However, activity in the bottom sediments is times lower than on the slopes due to avalanches and slushflows periodically collecting the material upstream in the less active zones of the valley, mixing it and transporting downstream along the bottom. Therefore, a contribution of local sources from the slopes constitutes not the major part of observed sediments in the bottom, but it appears to be enough to increase the level of ^{232}Th content almost two times.

In samples taken from streambed (C-1 and C-2), the activity turned out to be almost two times lower than on the adjacent slopes and in the bottom,: 150 ± 9 Bq/kg (B-2) against 75 ± 5 Bq/kg (C-1) and 141 ± 7 (B-3) against67 ± 5 (C-2). It looks like the water stream offsets the contribution of highly radioactive material from the thorium enrichment zone and radioactive tailings. Keeping in mind the very low probability of Th leaching, it was fair to suggest that its content would correlate with the share of the finest and, though, most easily washed out particles. Moreover, chemical analysis of water and snow showed its composition to be very close to distilled water. The water has mineralization ranged from 2.5 to 24.7 mg/l and weak alkali pH (6.5–9.1).

As we learned from gamma-spectrometric analysis of different grain size fractions for the group of samples, the distribution of ^{232}Th activity is very uneven. There is an apparent negative correlation between grain size and activity of the particles of < 1–2 mm size. For the particles of a larger size, the correlation is absent. This pattern expresses most sharply in samples from the tailings (S-1 and S-2) and slopes with the high total activity of Th isotopes (S-3) (Table 1). Obtained data demonstrates that the fine radioactive fractions may substantially contribute to the total activity of the sample with a meager mass share.

Hence, the three finest and most active fractions (< 0.05 mm) were selected from the samples S-1, S-2 and S-3 to figure out the origin of such high Th isotopes concentration in fine material by sequential extraction and alpha-spectrometry procedure. Concurrently alpha-

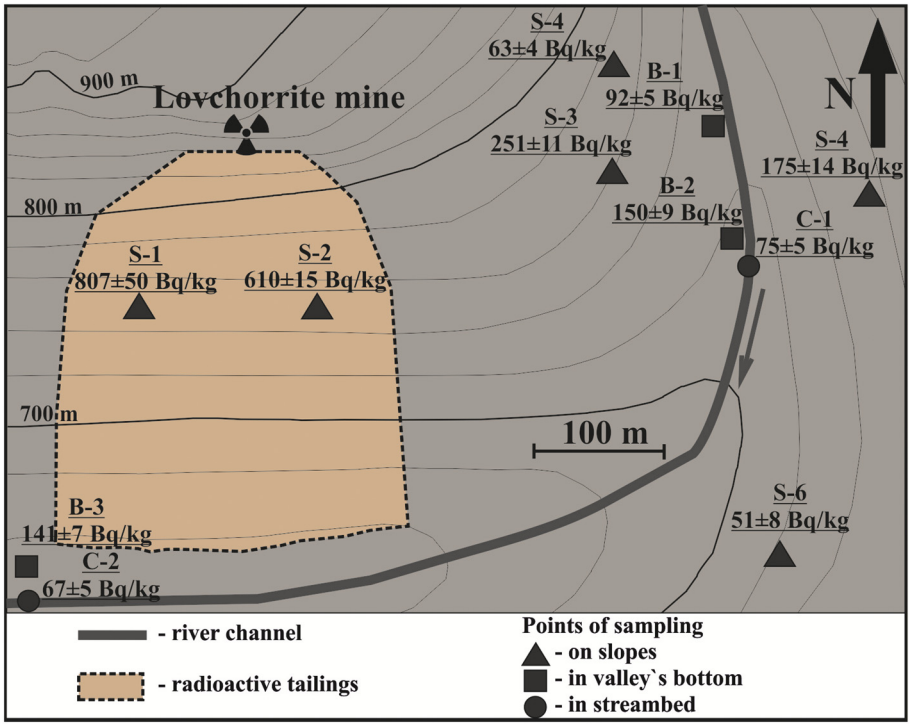

Fig. 4. The distribution of ^{232}Th activity in sampling points within explored area.

spectrometry provided an opportunity to verify different methods of ^{232}Th detection. The obtained results show a very good overlap of evaluations achieved by independent methods (Table 2). The losses controlled by ^{234}Th did not exceed 30%.

The results of sequential extraction revealed that the majority of Th isotopes (^{228,232}Th) is concentrated in minerals (residual form), which was anticipated according to discussed chemical Th properties (Table 3).

In non-residual fractions, Th isotopes were redistributed in the following order: carbonates > oxides > exchangeable > organic. There is still some minor inventory of Th, which is not included in minerals and can be leached: ^{228}Th – 19.3%, ^{232}Th – 7.5%. Therefore, the observed concentration of ^{232}Th in the fine grain fraction is not related to leaching and sorption of Th isotopes. The leaching of Th and concentration in clay fraction may be typical for the extremely acid and humid ecosystems (Braun et al., 1998) or linked to the abundance of organic acids in a more temperate climate (Leirós et al., 2000). In observed case, cold climatic conditions and chemical composition of natural water do not provide any opportunity for leaching.

Table 2
The results of gamma- and alpha-analysis of ^{228,232}Th activity for the grain-size fractionation of < 0.05 taken from the radioactive tailings and natural slope.

Location	Radioactive tailings		Slope
Sample	S-1	S-2	S-3
^{232}Th activity assessed by gamma-analysis, Bq/kg	2452 ± 196	1268 ± 101	695 ± 55
^{232}Th activity assessed by alfa-analysis, Bq/kg	2391 ± 61	1695 ± 53	548 ± 25
^{228}Th activity assessed by alfa-analysis, Bq/kg	3253 ± 60	1652 ± 55	440 ± 48

The concentration of Th-rich minerals in silt and clay fractions of beach sediments was previously discussed, and this phenomenon was explained as a result of the sedimentary process, predominantly of minerals with a high specific density (De Meijer et al., 1985). However,

Table 1
The Redistribution of ^{232}Th activity (Bq/kg) and share of mass between different grain-size fractions in different types of sediments.

Grain size, mm	S-1	S-2	S-3	B-1	B-2	C-1
< 0.05	2452 ± 196	1268 ± 101	695 ± 55	461 ± 37	240 ± 29	695 ± 55
	7.9%	2.3%	8.7%	3.0%	3.5%	0.3%
0.05–0.1	912 ± 73	690 ± 55	287 ± 29	148 ± 27	117 ± 22	287 ± 29
	3.6%	9.2%	4.4%	1.6%	3.0%	0.3%
0.1–0.25	569 ± 45	359 ± 29	174 ± 26	198 ± 34	77 ± 20	174 ± 26
	10.8%	15.9%	7.5%	4.8%	7.8%	2.7%
0.25–0.5	327 ± 33	168 ± 18	109 ± 19	164 ± 28	38 ± 12	100 ± 19
	9.0%	9.9%	6.5%	6.0%	9.5%	6.0%
0.5–1	389 ± 31	236 ± 26	101 ± 20	52 ± 8	95 ± 21	101 ± 20
	11.3%	11.0%	0.3%	10.5%	12.7%	10.9%
1–2	141 ± 11	130 ± 17	2 ± 0.5	50 ± 28	4 ± 1.8	9 ± 22.3
	16.0%	12.2%	17.0%	16.8%	17.7%	16.5%
2–5	270 ± 21	604 ± 48	92 ± 28	65 ± 23	139 ± 10/31.3%	92 ± 28
	28.3%	18.8%	6.2%	34.6%		34.2%
5–10	23 ± 8	30 ± 16	6 ± 4.4	23 ± 8	3 ± 1.5	2 ± 0.7
	13.1%	10.6%	9.4%	22.7%	14.1%	29.0%

Table 3
The redistribution of ^{228,232}Th between residual and non-residual physico-chemical forms for the grain-size fractionation of < 0.05 taken from the radioactive tailings and natural slope.

Location		Radioactive tailings		Slopes
Sample		S-1	S-2	S-3
^{232}Th	Residual	98.9 %	92.5 %	98.2 %
	Non-residual	1.1 %	7.5 %	1.8 %
^{228}Th	Residual	92.5 %	80.7 %	89.4 %
	Non-residual	7.5%	19.3 %	10.6 %

in the investigated case the concentration emerges at the beginning of deposition – on the slopes, almost immediately after the constitution of eluvium and its transportation down the slope or after excavation and redeposition, in case of mining. Another explanation for such uneven redistribution in slope sediments appears to be metamictization – a damaging of crystal lattice in radioactive minerals and transforming into amorphous form caused by radiation of radionuclides included into minerals (Vegard, 1916; Robinson et al., 1971; Vance and Anderson, 1972; Woodhead et al., 1991; Jolliff et al., 1995; Ewing, 1994; Ewing et al., 2003; Cao et al., 2015). If metamictization causes changes in physical and chemical properties of minerals, their resistance to weathering and fractalitization of a solid bedrock into separate particles may decrease. Hence, such metamictic minerals as lovchorrite may enrich fine fractions of eluvium with radionuclides.

If ^{232}Th in rocks is concentrated in a group of radioactive minerals than their relative share in sediments might dramatically change total radionuclides content. We could indirectly prove this speculation by following. It is probable for fine particles to have homogeneous mineral composition. It may also be interpreted as a higher probability for the larger particles to consist of several crystals of different minerals, and for one or more of them to be radioactive. According to the learnt ^{232}Th redistribution between grain size fractions, the negative correlation disappears in the majority of cases for the particles with size 2–5 mm; it is most evident for the samples from the slopes and tailings (S-1, S-2, S-3) (Table 1).

In valley bottom sediments the pattern of ^{232}Th distribution is close but smoother due to the decrease in the most active fractions amounts: < 0.05 mm, 0.05–0.1 mm, and 0.1–0.25 mm. Alongside with the decrease of activity, the share of these fractions becomes lower as well: from 20.6 to 27.4% (on slopes) to 9.4–14.3% (in the bottom). The rise of the total activity downstream the northern boundary of the thorium enrichment zone – 150 ± 9 Bq/kg (B-2) against 92 ± 5 Bq/kg (B-1) upstream – is accompanied by the growth of activity in almost all grain size fractions (Table 1). This illustrates that the material from slopes migrates to the bottom generally by rockfalls and screes, without significant sorting of particles, and enriches all grain size fractions of sediments with Th isotopes.

In the streambed sample (C-1) no correlation between grain size composition and ^{232}Th activity distribution by fractions was detected. However, some large and heavy radioactive particles remain in the streambed, and the share of fine fractions becomes negligible due to washing out. ~~The migration of the most radioactive fractions with sediment yield may be an issue for different angles.~~ The intensity of radionuclides migration with sediment yield in the case of mining is an essential factor of environmental safety. If radionuclides concentrate in the finest and most mobile fractions, the potential impact may occur not only nearby the mining but also in distant regions, especially in the zones of sediment redeposition: lakes, floodplains, natural and anthropogenic sinks etc. Moreover, the supply of high-radioactive solid material may be used for fingerprinting in basins where the source of radionuclides is detected.

5. Conclusion

This study brought up a group of results those could be concluded in following points:

1. Observed variability of ^{232}Th content in the Hackman Canyon has systematic character and is controlled by two factors. The first one is the initial radionuclides content, and the second – modern exogenous processes those destroy, redistribute, mix and sort material at valley slopes, bottom and streambed. The role of the second factor gradually increases along the pathway of the sediments from the sources down the valley.
2. It turns out that ^{232}Th content observed in sediments samples correlates with the grain size. The highest concentration of ^{232}Th is discovered in the finest grain size fractions. Even with the relatively low mass share, these fractions may significantly alter the total content of ^{232}Th in sediments.
3. Conducted sequential extraction procedure revealed that the major portions of Th isotopes in three most radioactive samples of fine fractions (< 0.05 mm) occur in minerals (residual fraction). Therefore, the concentration of ^{232}Th in this grain size fraction is most likely not due to leaching and further sorption, but some other mechanisms. The most drastic contrast of ^{232}Th redistribution between particles of different sizes occurs on the slopes and mine tailings where fractioning during deposition is supposed to be weak. Apparently, there have to be another process resulting in the correlation between ^{232}Th content and mechanical composition of sediments almost after eluviation. Hypothetically, the reason for such redistribution could be the low resistance of radioactive minerals to fracturing during weathering caused by metamictization. This enquiry has justified a comprehensive study in the future.
4. The concentration of Th isotopes in fine fractions those could easily be washed out proposes that these particles may concentrate in zones where sediment yield is deposited. Hence, this process has a substantial impact on sediment yield and environment even on the distance from the NORM source. In addition, changes of ^{232}Th content in sediments linked to the supply of fine radioactive particles can be used in fingerprinting studies for detecting sediment sources in river catchments where radioactive thorium-rich rocks are eroded.

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