EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Earth`s Cryopshere, 2018, vol. XXII, No. 3, pp. 3–15 **http://earthcryosphere.ru/**

REGIONAL PROBLEMS OF EARTH'S CRYOLOGY

DOI: 10.21782/EC2541-9994-2018-3(3-15)

THE PHENOMENON OF GEOCRYOLOGICAL CONDITIONS IN THE EASTERN PART OF THE OLEKMA-CHARA PLATEAU

S.N. Buldovich, E.N. Ospennikov, V.Z. Khilimonyuk

Lomonosov Moscow State University, Faculty of Geology,
1, Leninskie Gory, Moscow, 119991, Russia; ser_bul@rambler.ru

The paper discusses results of the study of geocryological (permafrost) conditions in the eastern part of the Olekma-Chara Plateau at the watershed divide of the Tokko River and its tributary, the Choruoda River, carried out within the field study of the sites of mineral showings (deposits), whose permafrost conditions are extremely contrasting. The combined impact of hydrogeological factors acting in the middle altitude environment is found to be largely responsible for the unique permafrost conditions in the study area.

Olekma-Chara Plateau, geocryological conditions, hydrological conditions, permafrost, annual average soil temperatures, geocryological processes

INTRODUCTION

The study area, located in the southwest of the Republic of Sakha (Yakutia) and subsumed into the eastern part of the Olekma-Chara Plateau, is underlain by permafrost which had been largely underexplored until the middle of the twentieth century, with the information about it ranging from sketchy (i.e. derived from results of comprehensive geological-geophysical expeditions) to unavailable. The systematic geocryological study began in the 1930s and 1940s and gained traction in the decades to follow. In southern areas of permafrost distribution the studies were conducted by the Aldan permafrost research station (PRS) staff of the Permafrost Institute of the USSR Academy of Sciences (V.M. Ponomarev, S.E. Sukhodolskii, S.M. Fotiev, N.A. Vel'mina, G.N. Filosofov, V.R. Alekseev and others). The 1951–1954 regional survey works as part of permafrost-hydrogeological studies of the Aldan-Timpton interfluve area were conducted by the Yakutia Complex Expedition (A.I. Efimov, P.I. Melnikov, I.D. Belokrylov and others) of the USSR Academy of Sciences Council for the study of Russian natural productive forces. In the 1960s, these endeavors were continued by the Udokan Expedition of the Permafrost Institute of the USSR Academy of Sciences, during which a team of researchers headed by I.A. Nekrasov investigated geocryological conditions of the Udokan Ridge along with the Chara, Verkhne-Kalar and Nizhny Ingamatkit intermountain basins.

More complete data and materials on the formation of permafrost and its regional variability in southern Yakutia were obtained during the works of the 1961–1964 Expedition of the Faculty of Geology of Moscow State University, which conducted a comprehensive permafrost-hydrogeological and permafrost-engineering geological survey within the Aldan-Timpton interfluve area. Later, in 1973–1985, this expedition conducted medium-scale surveys (1:50 000 and 1:200 000) in the areas of coal deposits within the Chulman Plateau, southern Yakutia [*Kudryavtsev, 1975*]. Results of the exogenous geological processes and phenomena surveys (1:200 000 and 1:500 000 scales) in the territory of the Aldan-Timpton interfluve in the late 70s–early 80s of the last century were analyzed and discussed in [*Ospennikov et al., 1980*].

It is noteworthy that the Olekma-Chara Plateau area has been hitherto least studied in southern Yakutia, specifically, its part adjacent to the Tokko river valley [*Ershov, 1989*]. With regard to permafrost aspects, the studies, in themselves, were reduced to the information about ground temperature regime in permafrost zones obtained by M.N. Zheleznyak and others [*Dorofeev et al., 1981; Zheleznyak, 1998, 2005; Semenov and Zheleznyak, 2013*]. Proceeding from these, the average annual temperature of rocks increases in the direction from the watershed divides to the river valley bottoms, where the rocks for the most part remain in the unfrozen state.

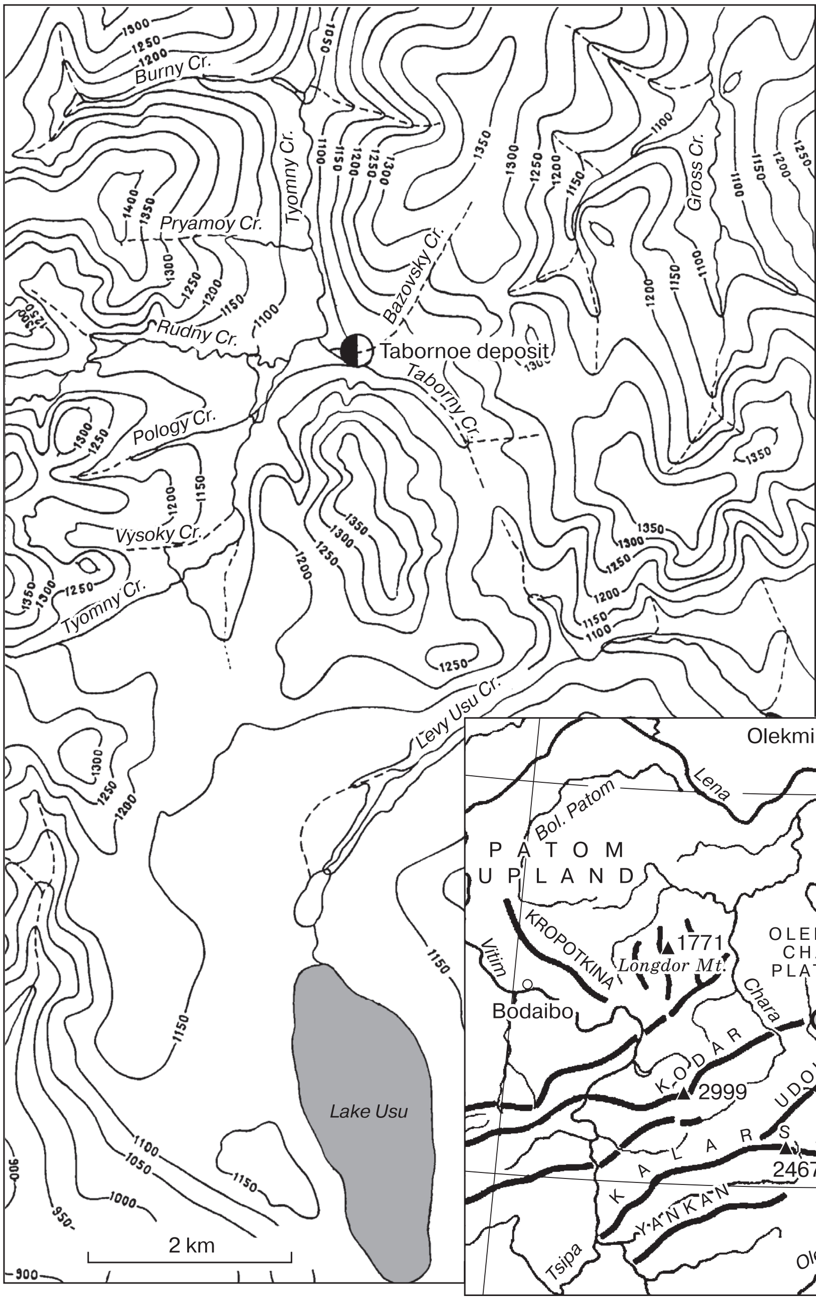
During the 2009 Expedition, the researchers from the Department of Geocryology, Moscow State University conducted geocryological surveys along with the 1:25 000 mapping of one of the sites located within the Verkhe-Tokkin area. The results allowed the first ever comprehensive permafrost characteristics of the study area and provided new insights into its entire geocryological situation.

BRIEF CHARACTERIZATION OF THE GEO-EVIRONMENTAL SETTING

The study area is located in the watershed area of the Tokko River and its tributary, the Charuoda River (Fig. 1).

The area *topography (relief)* is medium-mountain, characterized by 1200–1400 m absolute elevations on the watershed surfaces and deeply embedded (to 200–300 m) bottoms of the river valleys, with the slope steepness reaching 25–30°. The river network of the area, composed by small watercourses, is subsumed into the basins of the Tokko and Charuodo rivers, the tributaries to the Olekma river. All streams are filled with water only during the spring snowmelt and prolonged spells of summer rains. Otherwise, most of the time the stream-beds remain dry. Their thalweg marks range between 1100 and 1180 m.

The *climate* of the area, which is defined as sharply continental, is largely controlled by the mountainous terrain, as well as by the band of air masses transfer shift from western to eastern direction, i.e. to the East Pacific [*Karausheva, 1977*]. This area is characterized by long cold winters and short summers with the average values described as: the mean annual tem-



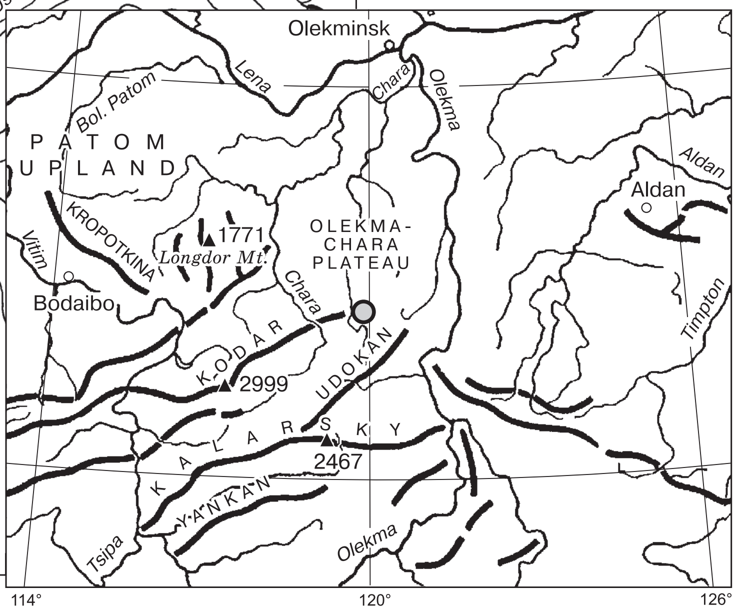


Fig. 1. Location map of the investigated area of the eastern part of the Olekma-Chara Plateau, on the watershed divide of the Tokko Rv. and its tributary Chorouda (Southern Yakutia).

perature is –7.8 °C; the annual amplitude of the mean monthly temperature fluctuations reaches 57 °C; the annual precipitation ranges between 330 and 680 mm, generally increasing with height.

Most of the precipitation falls during the summer season (50–70 %), while only 7–15 % accounts for winter. The snow cover exists from September through May, with its depth reaching 0.7–0.9 m or greater, at the foot of slopes, particularly in their wooded areas. The snow cover density varies from 0.12 to 0.18 g/cm^3, averaging 0.13 g/cm^3. Due to intensive snowdrift transport at the watersheds, the snow cover depth (average density: 0.145 g/cm^3) does not exceed 0.2–0.4 m there.

Soils and vegetation developed in the area belong to the mountain-tundra, mountain-shrub-tundra, mountain-sparse woodland, and mountain-valley types. The area is differentiated by sparse marshy landscapes, observed in some segments of the Levy Usu Creek valley bottom. Judging from the regional vegetation cover pattern, the territory is labeled as the light coniferous taiga province of the middle taiga subzone. The presence of permafrost and seasonally frozen rocks slows down the biochemical reactions flow in the soil horizon during a short vegetative season, along with the formation of soil profile, causing thereby the dominance of thin, primitive and skeletal soils across the area.

Geological structure. In the geological framework of the area, the most ancient structural stage is composed by Archean rocks: crystalline shales, gneisses, amphibolites, quartzites. The upper structural stage is represented by folded and metamorphosed lower Proterozoic sediments, dominated by the metamorphosed terrigenous deposits, mainly sandstones and siltstones. The intrusive Archean, early Proterozoic, late Proterozoic and late Jurassic rocks are made up by amphibolites, gabbroids, pyroxenes, diabases and granitoids. The tectonic setting of the territory is described as the system of thrust-faults, partially compensated by dislocations, extending roughly W–E and in N–E direction.

The unconsolidated (loose) deposits structure is dominated by eluvial, deluvial, colluvial, delluvial-deserption and to a lesser extent by diluvial sediment types, cumulatively composing a continuous cover atop the watershed surface and slopes of river valleys. The glacial and aqueoglacial deposits co-existing with the river-channel and floodplain sediments in the valley bottoms are represented by a strata of poorly sorted indistinctly layered boulder-pebble deposits, which compose the upper part of the section of a through (antecedent) valley of Levy Usu and Tyomny creeks.

The hydrogeological conditions are characterized by the distribution of crevice waters (within crevices of intrusive and metamorphic rocks) and fracture-vein waters confined to the zones of tectonic dislocations. As is the case with watersheds and slopes occupying most of the study area and underlain by permafrost to significant depths, the feeding of groundwaters by infiltration waters is precluded. At this, subsurface waters are recharged dominantly from surface runoff during the warm season. In the bottoms of river valleys, where the groundwater feeding sources are amassed, groundwaters are widely developed in alluvial and fluvioglacial sediments. Judging from the nature of circulation, these are porous phreatic waters, which discharge through the fault zones into the underlying aquifer complex of lower Proterozoic sediments. According to drilling data (depth range: up to 150 m), the rocks are either in the permafrost state to a depth of hundreds of meters, or drained in most of the investigated area. As such, the situation is typical of the interfluve and slope areas and of the valley bottoms. Locally, in eastern part of the study area, the position of water table of the considered aquifer is found to be close to the surface, though.

The deposits' deep drainage within the study area is, undoubtedly, exerted by the proximity of a major regional drain, the Tokko river (~7–8 km to the west from the investigated site) with absolute elevations of the valley tahlweg of about 650 m within the considered intercept along the course of the river. With the spot elevations ranging between 1000 and 1400 m, the investigated site (as part of Tabornoe deposit) represents a topographically elevated area and therefore the sedimentary rocks here are expected to have drained to significant depths. The thickness of the zone of aeration, even beneath the bottoms of the valleys can reach 200–300 m, and significantly deeper in the watershed areas (400–500 m). At this, the fractured solid rock mass is ubiquitously and completely saturated with water below the Tokko river streambed occurrence level.

GEOCRYOLOGICAL CONDITIONS

The field study of permafrost aspects of the area conducted by the authors within the research into its engineering-geocryological conditions, revealed that the geocryological structure of the study area is determined, in addition to regional features of the radiation balance, by the snow and vegetation covers, by absolute elevation and dissection of the terrain, and considering the composition of upper horizons of soils, and the action of surface and ground waters. The authors performed both the numerical and mathematical modeling of the natural setting of the area within the WARM program [*Khrustalev et al., 1994*], as a series of one-dimensional heat problems aiming to measure the impact from natural insulation (snow and vegetative covers) on the thermal conditions of sedimentary rocks. The variations of average annual temperature of rocks throughout the area are largely

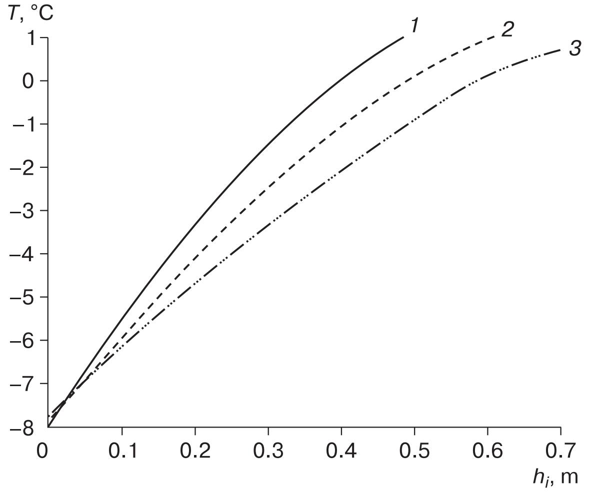


Fig. 2. A relationship between the average rock temperatures *T* and snow cover depth h_i (maximum value for winter) inferred from the mathematical modeling.

1 – h_s = 0; *2* – h_s = 0.1 m; *3* – h_s = 0.2 m.

governed by the combined influence of snow and vegetation.

Figure 2 shows the effect of the interplay of these factors on the average annual temperature of rocks, indicating along with the simulation results, that the contribution from the ground covers, specifically, snow cover is the largest to the temperature field of rocks. Virtually, the entire (fairly wide) range of average annual temperatures of rocks (–5.5...2.0 °C), established by the thermometric measurements in wells within the Tabornoe deposit area, is overlapped by different combinations of the combined impact of the snow and vegetation covers.

The formation of average annual sediment temperature of rocks (°C) is contributed by different natural controls*, such as:

– altitude position ±(0.5–1.5);
– slope exposition and steepness ±(0.5–2.0);
– snow cover +(2.0–10.0);
– vegetation cover –(0.5–3.0);
– bogging –(0.5–3.5);
– moisture infiltration and condensation +(0.2–1.5).

The impact from bogginess, despite the potentially large amount of heat exposure, in fact is inconspicuous due to a very limited distribution of wetlands.

Assumingly significant thermal effect comes from the filtration flow in the river valleys during the summer low-water periods, with completely absent surface runoff in streams in the study area (i.e. streambeds are dry), when cumulative groundwater runoff within the active layer (AL) is directed from the slopes into the drained rocks of the valley taliks, providing additional convective heat input and sediment warming. As such, the absorption of both the surface and near-surface runoff waters by the unfrozen loose sediments in river valleys during summer represents a characteristic feature of the study area, which is associated with a high water-transmissive capacity of alluvial and fluvioglacial sediments serving as the valley infill material, given their relatively big thickness and high longitudinal slopes. The zone of high-fractured underlying rocks also becomes part of the filtration section. The implications are that the river channels in the Tabornoe deposit area are filled with water only during periods of snowmelt and heavy rains, when the water coming from the slopes exceeds the water-transmission capacity of the underflow deposits. It is therefore likely that the additional input of heat convection is remarkably involved in the formation of the *per se* unfrozen, water-permeable rocks in the valley bottoms within the study area.

The interplay of all the considered environmental controls create the complexity of the geocryological situation of the study area.

The average annual sediment temperature at the base of the zero annual amplitude in the South-Ugui gold-bearing area varies from positive to essentially lower negative values (–4...–6 °C and lower) [*Ershov, 1989*; *Zheleznyak, 2005*]. Despite the presence of local deviations, the general trend reflects a decrease in rocks temperature, propagating from the valley bottoms to the watershed zones.

The average annual rock temperature distribution pattern in the specified natural conditions of the studied area has hitherto been largely understudied. Some major features of the formation of geocryological conditions were established during the permafrost survey (scale: 1:25 000) conducted by the authors. The drilling data and results of temperature surveys in wells indicate extremely contrasting distribution of average temperatures of rocks in the area: from –5.0...–5.5 °C on elevated watershed surfaces (1300–1400 m) to 1.0...2.0 °C in the valleys of rivers and creeks (1100–1200 m).

A difference in rock temperatures within one valley side can reach 6–7 °C at a relatively small difference in elevation (~200–300 m). A wide distribution of unfrozen rocks with temperatures from 0...0.3 to 1.0...1.5 °C has been established in the bottoms of river valleys. These are confined to the rudaceous alluvial and glacial deposits, whose areas of distribution can exceed 500–800 m in width. Such a wide extent of unfrozen deposits in the valley bottoms with elevations exceeding 1050 m could hardly be envisaged before the commencement of the research.

* The influences from the snow and vegetation covers were estimated by the authors on the basis of numerical-mathematical modeling, while other controls were estimated using method developed by V.A. Kudryavtsev [*Kudryavtsev et al., 2016*].

At this, the presence of permafrost in the areas of the first floodplain terrace with developed moss ground cover was confidently identified in the bottoms of the valleys. Unfrozen deposits can coexist with and sporadic (island) permafrost in the valley bottoms, although relatively small in size in this case, with vertical thickness in the first tens of meters and their average annual temperatures approximating to 0 °C. The thawed zones of the valleys, judging by their large extent in plan view represent through taliks in relation to permafrost thickness.

A comparative analysis with the morphologically identical Aldan-Chulman Upland area has shown that the absolute elevations inherent in the relief of the study area (1000–1400 m) fall into the high-altitude transition zone close to the "ceiling" of the high-altitude air temperature inversion distribution. In this zone, the inversion nature of temperatures distribution (reflecting their rise with height) gives way to a normal decrease in temperatures as the altitude increases, generally showing no pronounced trend in air temperature variations with height (thermopause phenomenon).

Meanwhile, the orographic inversion at the 1300–1600 m altitude interval with a gradient of –0.4...–0.6 °C/100 m is evidenced in the natural settings of the Olekma-Chara Plateau [*Zheleznyak, 2005*]. However, because of a specific relief dissection in the Tabornoe deposit area (~200–300 m), the high-altitude inversion differentiation of the mean annual air temperatures (MAAT) does not account for more than 1.0–1.5 °C.

That large difference in rock temperatures within the study area have been therefore caused by the contributions from the ground covers, primarily, the snow accumulation pattern. The snow-survey as part of the research, has revealed a notable increase in the snow cover depth (from 0.1–0.3 to 0.6–0.8 m or more) with a decrease in spot elevations in the direction from the watershed divides to the valleys, prompting thereby a significant warming effect of the snow and affiliated rise in rocks temperatures. The big picture is superimposed by the vegetation types (shrubs, woody vegetation) largely affecting the patterns of snow accumulation, as well as by the specifics of the radiation and heat balance on the slopes of different exposure and steepness.

Note that the snow cover depth of about 0.4–0.5 m on the exposed surface of sedimentary rocks is considered critical, seeing as any further increase in its depth trigger the rocks temperature transition into a positive domain, which rules out the existence of permafrost here. In the presence of ground vegetation cover, acting as an additional layer of insulation, the warming effect of snow, all other things being equal, becomes markedly reduced. This is associated with a significant decrease in the depth of zero annual amplitude at sites overgrown by vegetation, whereas the warming effect of the snow cover directly depends on the intensity of heat exchange between rocks and the environment and tends to be less with the decreasing contribution from the latter. A moss pillow with a thickness of 0.2 m brings the critical thickness of the snow cover down to 0.6 m.

That big and even greater snow cover depth is reported from the river valley bottoms within the extent of fir-larch woods, where relatively thick moss or lichen ground covers are common. The performed mathematical modeling (Fig. 2) thus allows to explain, in principle, how the interplay of snow and vegetation covers benefits both the wide distribution of thawed rocks in the valleys, and the presence of sporadic permafrost in areas with a developed moss cover.

It is nevertheless possible that the formation of taliks in the bottoms of the valleys composed by coarse alluvial and glacial deposits is largely contributed by the warming effect of convective heat transfer caused by groundwater filtration flows. The hydrological regime of watercourses in this area is unique, inasmuch as the surface runoff transpires here only during the short periods of snowmelt and heavy rains, while the rest of the summer is completely devoid of the runoff process. The coarse sediments of the valley bottoms thus absorb the entire amount of precipitation from the catchment area of the valley and redirect it to the subsurface drainage system (underflow runoff). At this, the high summer temperatures and a measurable mean summer rainfall suggest that the convective heat transfer processes have high thermal energy level.

A continuous permafrost is distributed throughout the entire Tabornoe deposit area, with the exception of the bottoms of streamflow valleys, whereas neither watershed divide – nor hillslope-confined through taliks have been discovered during the research. Given that none of the boreholes have completely penetrated permafrost strata, there is no direct evidence for the permafrost thickness within this area, which therefore has to be inferred from the average annual temperatures of rocks and from the temperature field measurements in the upper part of permafrost.

Using the data on areal distribution of rock temperatures resulting from the permafrost survey and taking into account actual spot elevations, the WARM program [*Khrustalev et al., 1994*] was applied to perform a two-dimensional simulation of the temperature field of rocks measured along a characteristic profile laid through the valley of one of major creeks in the study area and comprising five geothermal wells, with one of them drilled to a depth of 140 m enabling thermometric studies. The difference in elevations within a stretch from the divide to the valley bottom is 200 m (abs. elev. 1320–1120 m); the width (horizontal equivalent) of slope is 500 m, while the valley bottom is 80 m in width. According to the thermometric measurements in wells, the average annual temperature of rocks almost linearly increases down the slope: from –5.5 to 0 °C at its foot and up to 1.5 °C in the valley bottom.

Permafrost thickness. The data from [*Zheleznyak, 2005*] indicate that ancient Proterozoic sandstones composing the main part of the geological section have enhanced thermal conductivity up to 3.7–4.8 W/(m·K). The density of geothermal heat flux from the subsoil is 30–40 mW/m^2 within the study area [*Zheleznyak, 2005, Fig. 4.4*]. We therefore used both the values for thermal conductivity of rocks (4.2 W/(m·K)) and deep heat flux (35 mW/m^2) in the modeling.

The result allowed to obtain the following spatial configuration of the permafrost strata (PS) (Fig. 3): permafrost thickness below the watershed divide measures 450 m; the PS decreases towards the valley, where it completely pinches out at the foot of the slope, which proves the lower limit of permafrost to be almost 200–250 m lower than the valley thaweg.

The obtained spatial configuration of the permafrost distribution is in good agreement with the available thermometric data. The deepest well emplaced along the profile is located in the middle of the slope (about 1220 m in height) and has a depth of 140 m. At this, rocks temperature at the depth of zero annual amplitude (17 m) is –2.8 °C, which tends to increase with depth and equals –1.7 °C at the bottomhole. This temperature coincides with the rocks temperature at the same point of rock massif derived from mathematical modeling of its temperature field (Fig. 3).

The calculations for different model scenarios revealed one important feature of the PS configuration: within the accepted boundary conditions, specifically, with the linearly increasing average annual temperature of rocks within the hillslopes to zero values at the foot of hills, the valley talik has remained to be a through talik even at a small width of the valley bottom (some first tens of meters). Therefore, through

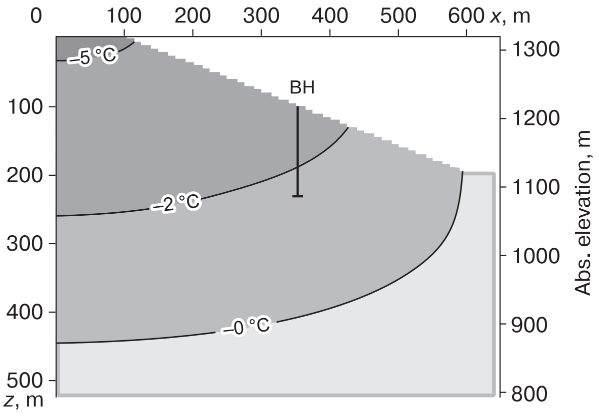


Fig. 3. The configuration of permafrost strata inferred from the mathematical modeling.

taliks of purely conductive origin (i.e. without involvement of convective heat generated by groundwater) have proven to be able to exist even in the valleys of the smallest watercourses in the area. Given that relatively high average annual temperatures of rocks can develop under the influence of only one factor – increased snow accumulation, through taliks of purely thermal origin (snowgenic) are expected to form in the valleys of small watercourses.

Interestingly, the simulation also revealed a specific pattern of subhorizontal redistribution of the deep heat flux in the upper parts of the section, caused by the relief dissection and spatial differentiation of rock temperatures. The latter is considered a major natural control, which determines the complex nature of the geothermal heat flux redistribution. Due to the sharply reduced temperatures of rocks at the watersheds against the backdrop of those in the valleys, the heat flux concentration gravitated to the topmost parts of the watershed divides rather than to the bottoms of the valleys, exactly the way it should occur when affected by the terrain dissection alone. Within the implemented modeling (Fig. 3), which takes into account the linear change in the average annual temperature on the slope surface, the density of heat flux released by the rocks through the watershed surface is 67 mW/m^2; in the center of the slope it is close to a deep-earth value of 35 mW/m^2, while at the valley bottom the heat flux passing through the surface is generally directed downward, into the rock mass, and equals –125 mW/m^2. In the valleys, this additional input of heat flux into the rocks is redistributed towards the cooled watershed divides, contributing to the deep-earth component of geothermal heat. Within depth interval of about 600–800 m from the watershed surface, the impact of surface inhomogeneities of boundary conditions tends to wane, and the density of the ascending heat flux becomes leveled off across the area.

The obtained results also show that the concept of greater stability of frozen rocks in depression zones of the relief in comparison with watershed divides in the territory of southern Yakutia, advocated by D.O. Sergeev and others [*2005*] is just unworkable. It is quite the contrary: given a persistent relationship between the lowest average annual temperatures and high ice content of the upper horizons of the section of rocks, the watersheds, in themselves, appear the most stable in terms of evolution.

The seasonal thaw depth of rocks is basically determined by the following factors: relatively high summer temperatures, ground vegetation, moisture (ice) content and thermophysical properties of sediments. Proceeding from the results obtained, the specificity of seasonal thaw of rocks within the study area is described below.

On the divide surfaces of the upper and middle parts of the slopes affected by seasonal thawing, which, contrary to expectations, was relatively shallow, averaging 1–2 m. Partial thawing of thin cover of drained loose eluvial (sedentary) deposits occurring on mountain rocks, may be accounted for the horizon of altiplain ice identified in the lower part of the active layer (AL). The presence of a significant amount of ice inclusions in the first meters of the section was reported from all wells while drilling. The established by [*Zabolotnik and Zabolotnik, 2014*] pattern of the thaw depth decrease in rocks with a height gradient of 0.85–1.28 m per 1000 m for southern Yakutia was not observed in the considered territory, which may be explained by the specific changes in the composition of rocks. Thus, given an extensive development of corrom covers (stone rivers) on the slopes and stone debris at the divides with similar structure of the AL rocks (blocky-rubbly beds with almost totally missing filler material in-between), the depth of seasonal thaw there also slightly changes with its thickness averaging in the range of 0.8–1.5 m, regardless of the absolute elevations of the terrain. Within the rest of the territory, specifically in the river valley bottoms (on the floodplain and first above-the-floodplain terraces) where moss cover is relatively thick, the thaw depths of rocks range in the 0.3–0.7 m interval. Noteworthy, however, is that at the time of their possible drilling (the beginning of July), the reported active layer thickness (ALT) is still far from its maximum. Besides, the exposed rocks in some cases may be the remnants of a layer of seasonally freezing rocks formed during the winter.

Seasonal refreezing of rocks appears inherent only in river valleys, where unfrozen rocks are fairly extensively developed within the valley bottoms. The greatest depths of seasonal freeze of the AL rocks reach 3.5 m; however, judging from the monitoring results, the thawing of seasonally frozen layer proceeds quite intensively and terminates mainly in the first half of summer. As such, the measurable ALT is primarily caused by low pre-winter moistening of rocks, suggesting a rapid drainage of alluvial and fluvioglacial deposits residing in the river valleys to a considerable depth during the fall.

Cryogenic structure of permafrost underlying the study area is the least studied characteristic. Neither deep drilling, nor examination of the existing outcrops have added to clarity therein. The rocks outcropping in the left side of Rudny Creek, in the gullies along the road to the east of the quarry, as well as in the walls of quarries of building materials, did not expose the ice-rich PS either. Neither inclusions of ice were found in drill cores recovered while drilling wells (thermometric and hydrological). However, ice-rich rocks were discovered along the geological traverse during the test pit excavations in the floodplain sediments and old river bed alluvium, and in biogenic sediments in the southeast of the territory. The obtained characteristics of ice inclusions are fully consistent with the data on the cryogenic structure of the deposits in the areas adjacent to southern Yakutia.

As was shown above, loose permafrost represented by both syngenetically and epigenetically frozen sediments has a relatively limited spatial extent. Syncryogenic permafrost composed by alluvial deposits occupy small areas and is confined to the valleys of large creeks (Rudny, Tyomny) and minor rivers (Maly Usu). These deposits include fine-dispersed sediments of the floodplain and old river bed facies: clay- and sand-loams, often peaty and gleyed, with interlayers and lenses of peat, as well as peat mantles up to 1.0–1.5 m thick. Their cryogenic texture is predominantly layered and layered-reticulate. Total volumetric ice content of these deposits varies between 10–15 % and 40–50 % in mineral soils and up to 90–95 % in peats.

Most of the alluvial and fluvioglacial deposits, composed by boulder-pebble, pebble, pebble-gravel, sandy, and sandy loam varieties were subjected to epigenetic freezing, while presently, most of them remain in the unfrozen state. In southeastern part of the study area, though, north of the heads of Levy Gross and Pravy Gross creeks, they are frozen and their textural characteristics are largely dominated by ice-cement and crusts, as well as by basal cryotectures (at relative humidity close to 100 % moisture-holding capacity).

The most complex cryogenic structure is associated with the epigenetically frozen lacustrine-boggy sediments (mainly biogenic), forming covers in the river valley bottoms. The frozen peat is dominated by porphyry, lenticular-layered, lenticular- reticulate, banded, plicate, ataxite, cortical and massive cryogenic textures. Given different cryogenic textures are involved, ice content changes in relatively narrow range in peat layers, and usually does not exceed 10–20 % (from 72 to 93 %), whereas it is 2–2.5 times higher in mineral dispersed soils.

Epigenetically frozen diluvial and diluvial-solifluction deposits in the perennially frozen state are characterized by massive, rarely lenticular-layered, cryogenic textures. Volumetric ice content appears higher in rubbly horizons from this group (40–50 % of the total rock volume), while it is lower (25–40 %) in syngenetically frozen solifluction-affected loamy sediments, which usually have lenticular-layered cryostructure.

Massive, crust-forming and rarely thin lenticular-layered cryogenic textures are typical of eluvial and deluvial deposits. In areas abounding with rock caldrons and polygons which are usually characterized by complete water saturation of clastic rocks, basal cryogenic texture is dominant.

Diluvium-deserption deposits of corroms noted for altiplain ice (the underlying ice band acting as transporting medium for rock debris), are partially distended and characteristically exhibit high ice content (10–30 % of total rock volume), as is the case with altiplain ice, which is also typical of eluvial-deluvial deposits at high-altitude (1200–1350 m) watershed divides and is encountered at a depth of 1.5–2.0 m from the surface, where it is overlain by crushed-block eluvial-deluvial beds.

Exogenous geological processes and phenomena observed in the study area are divided into three groups: cryogenic geological processes (frost weathering, frost cracking, frost heaving of the rocks, icing), gravitational processes (rock sloughing and cryodeserption, formation of avalanches, mud flows, and corroms) and thermohydrogenic process (thermoerosion) and the affiliated phenomena.

Unlike the formation of corroms, **gravitational processes** having a relatively limited area of distribution, develop on steep (>25–30°) slopes, and are commonly represented by *screes*, a product of stream current washing away weathered and broken bedrock material, which is emplaced along the rivers' banks and at the base of the near-divide steep slopes.

The scree-prone slopes are also inherent to ancient corrie (cirque) glaciers, localized in the upper reaches of Levy Gross Creek, in the near-divide part of the Pravy Gross and Small Usu creeks intefluve, etc. The corrie glacier tends to be open here in the N–E and N–W directions, with the slope steepness reaching 35–40°. The unstable parts of the slopes are associated with the locations of snowfields, implying their significant role in the slope deposits weathering (Fig. 4, *a*).

Snow avalanches and mudflows, in themselves, represent paragenetic processes developing at different time at the same sites of the study area: in ancient cirques, steeply dipping heads of the streams and narrow valleys. They give rise either to snow avalanches (in winter), or to mudflows (in summer), when a large amount of precipitation has been received. Traces of these processes are commonly observed in almost all parts of the study area (Fig. 4, *b*). At the present stage, mudflow activity is showing some signs of mitigation. Features of the structure of one of the mudflow cones (in the tributary to Taborny Creek) and the revegetation pattern indicate that in the past 20–30 years, the descents of mudflows and debris have ceased, while the mudflow cone have become eroded by temporary watercourse formed in the ancient glacial cirque located up the slope.

Corrom-forming processes are developing ubiquitously on the slopes. The corrom-overlain area measures many tens of square kilometers. By their in-plan outlines, they are divided into stone fields and stone streams.

Stone fields are the debris of blocks of hard-rock, occupying an area whose length across and along the slope is approximately equal. Alternatively, the length across the slope may be bigger than the latter (Fig. 4, *c*). In the study area, stone fields on the slopes tend to form a mosaic system, where they alternate with wooded zones, in chessboard order.

Stone streams as linear forms of the stone debris on the slopes with the length to width ratio of more than 1:2, are commonly confined to the bottoms of small ravine and shallow gullies on the slopes.

The microrelief of rock glaciers is often complicated by gullies, cirque depressions, terrace-like bluffs and benches. Their surface is composed of small and medium-sized platy blocks of sandstones. Characteristically, a significant part of the blocks have their main axis vertically oriented, while the rest bear indications of "ridging", when the blocks located up the hill, creep over those underlying.

The structure of the corrom section is differentiated by clastic material decreasing in size from top to bottom, while the content of dispersed infill material (usually sand- and clay-loams) increases. Thus, in the pit, located on the west-facing slope of the slope of Tyomny Creek (steepness: 30–40°), the following sequences are exposed from its top down (Fig. 4, *d*):

0–0.5 m – blocks of sandstone, platy in shape, subvertically oriented, with dimensions up to 0.6–0.8 m with thickness of 8 cm. The surface of blocks is covered with crustose lichen, light green and black in color. The infill material is absent. Dusting of vegetable detritus as partially decomposed remains of lichens and pine needles is observed between the blocks;

0.5–1.0 m – blocks of sandstone without infill material, averaging 0.2–0.4 m in size in plan view, and 3–6 cm in thickness. In the left-hand part of the walls of the pit the blocks are in vertical position. The right-hand part is dominated by low-tilted boulders (<15° to the center of the wall). Interlayers of fine landwaste are observed between the blocks, characterized by weak and medium degree of abrasion;

1.0–1.6 m – small boulders and rubble of sandstone, with platy shape. The location of debris is disordered. Fine landwaste is found in the right-hand part of the wall, along with ruble with inclusions of small blocks (up to 20 %). The debris is exceedingly wet from the surface side. A layer of boulders and rubble in the left-hand part of the front wall of the pit is filled with dark brown plant detritus exhibiting a high degree of decomposition;

1.6–1.7 m – small blocks of sandstone with light grayish or light brown sandy loam with fine landwaste as infill material, which is very wet.

It should be emphasized that the corrom material gradually reduces in size to become small rubble and gravel in the lower part of the section of clastic rocks. The fragments receive sufficiently perfect roundness due to their friction against each other in the course of repeated freezing and thawing in the context of excessive moisture. As such, the structure of the corrom section significantly reduces internal friction between the fragments, and, accordingly, the stability of the entire corrom cover during undercutting of slopes by seismic shocks.

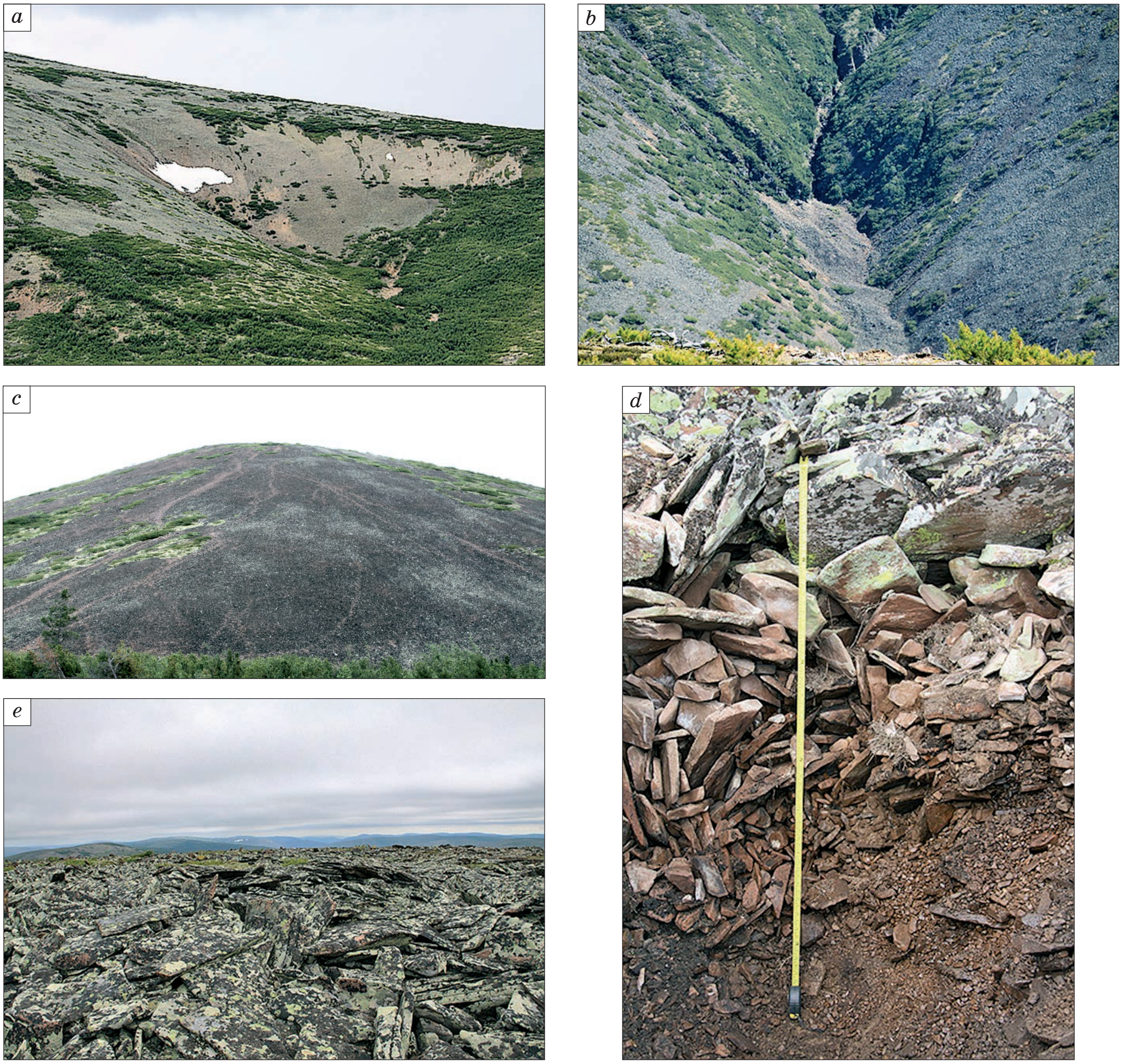


Fig. 4. Gravitational exogenous processes and phenomena:

a – talus slopes of ancient corrie glaciers (heads of Vysoky Cr.); *b* – avalanche chute and debris cone (left side of the unnamed right tributary to the Tokko Rv.); *c* – corroms-field on the slope of the altiplain ice in the upper reaches of Rudny Cr.,; *d* – vertical section of the corrom on the valley slope of Tyomny Cr.; *e* – rock debris (felsenmeers) at the watershed divide (Olekma-Chara Plateau, the Tokko Rv. basin). Photograph by E.N. Ospennikov.

A distinctive feature of the corrom structure is the altiplain ice that fills all the voids between the fragments below the AL base. Altiplain ice shows obvious signs of freezing from the surface of the surrounding fragments (chains of air bubbles are drawn normal to the surface of blocks and are amassed in the central parts of ice inclusions as they are displaced thereto by the suprapermafrost waters freezing in the corrom body). The distribution of corroms in the study area is primarily governed by the composition of rocks and their resistance to weathering. Corroms readily develop in places of the outcropping Archean igneous and metamorphic rocks (granites, granite-gneisses). They also form on slopes of different steepness and exposure, occupying more than 40–50 % of their area. In respect with rocks less resistant to weathering (sandstones, siltstones), corroms tend to develop on the slopes with steepness more than 10–15° and occupy much smaller areas.

Stone fields are the product of cryo-elluvial processing of the AL rocks on watershed surfaces. They are morphologically divided into stone polygons and felsenmeers (Fig. 4, *e*).

The study area is dominated by stone polygons and their variety – stone caldrons, with the rock material mobilized either in relatively narrow bands (up to 2–5 m), forming polygons of irregular shape, or in caldrons, located at the intersection of their sides. The structure of stone polygons in many ways replicates both the main structural features of corroms, and the material composing stone polygons, which shows close affinity with the composition of parent rocks. The structure of the section is differentiated by stratification, which is inverse relative to the normal eluvium structure, as the debris material decrease in size from top downwards.

The structure of stone polygons often includes relatively well-rounded fragments resulting from the processing of fragments near the permafrost table through thermal and cryogenic heaving, aggravated by processes of repeated freeze/thaw of water. The variability of particle size distribution of the debris material are consistent with the patterns established for corroms. The stone polygons distribution across the study area is determined primarily by the bedrocks composition and their resistance to weathering. These are most common in areas of developed crystalline Archean rocks. In the segments composed by Proterozoic sandstones, their extent is to some extent lowered, and so is the predominant particle size of the material composing the stone bands.

Another factor affecting the pattern of distribution of stone fields is the height of watershed divides.

Fig. 5. Cryogenic and thermos-hydrogenic exogenous processes and phenomena:

a – thermoerosion washout on the motor-and-tractor road in the upper reaches of Rydny Cr.; *b* – solifluction tongue in the upper part of the slope of the right side of the Pravy Gross Cr. valley; *c* – solifluction splash in the slope bottom of the tributary to Taborny Cr. (Olekma-Chara Plateau, the Tokko Rv. basin). Photograph by E.N. Ospennikov.

The processes of frost sorting tend to be intensified with increasing altitude, while the processes of soil formation become suppressed. As a result, the extents of stone fields distribution also increase. At this, the felsenmeers representing continuous covers of block material are steadily gaining ground. Stone scattering in the watershed divides (felsenmeers and stone polygons), and corroms on the slopes have a common genetic nature, specifically, because of the leading process of their formation is the clastic material expulsion onto the surface under the action of thermal and cryogenic heaving. As a result of the transition from watershed surfaces to slopes, stone polygons and felsenmeers grade into corroms, forming a single system of stone covers.

Thermal erosion (as the only **thermo-hydrogenic process**) in the study area practically does not occur under natural conditions. Despite the orographic (dissected terrain with slopes of more than 5°) and climatic (relatively large amount of summer precipitation) conditions, favorable for the emergence of this process, the planar and linear erosion of rocks is precluded by thin loose cover, its coarse material composition, as well as a relatively well-developed vegetation cover.

Consequently, both erosion and thermal erosion processes have developed mainly in the form of small washouts in areas of vegetation disturbed by tracked vehicles and along roads. The size of erosion forms depends primarily on the composition and thickness of loose sediments. Therefore, erosion develops for most part in the bottoms of the creek valleys, composed by sandy and sand-loam sediments, as well as on gentle slopes and slopes with medium steepness (Fig. 5, *a*).

Cryogenic geological processes proper

Processes of cryogenic weathering prepare the conditions for the development of many phenomena, such as landslides, screes, corroms, etc., whereas the harsh continental climate and the deep penetration of freezing and thawing of rocks determines physical aspects of the intensive development of frost (cryogenic) weathering. The nature of weathering and the composition of products of disintegration are largely controlled by the composition, texture and structure of the bedrock. Thus, depending on the mineralogical and structural varieties, some rocks form large-boulder streams (granite-gneisses, granites), others yield small blocks, rubble and landwaste (siltstone) during the weathering. Nepheline syenites erode even more readily, seeing as nepheline has low resistance to weathering, which is not the case with afanite diabases (Torsky complex of late-Riphean intrusions) particularly resistant to weathering (the affected depth does not exceed a few meters from the surface).

The dependence of rocks disintegration on their composition and structural features is best manifested by the weathering of sedimentary terrigenous deposits. Thus, massive varieties of Proterozoic sandstones of the Olonnokon Formation often form a thick-platy structures up to 1.5–2.0 m in size, whereas schistose sandstones produce smaller ones. Siltstones, when experiencing weathering, form small platy blocks up to 0.4–0.6 m in size and platy rubble up to 10–15 cm in diameter with sandy-loamy aggregates. These petrographic types are characterized by the thickness of weathering zone increasing on average to 8–10 m, within which the rocks are intensely ferruginous and often pierced by closely-spaced fine cracks. The actual thickness of cryo-eluvial bodies on watersheds usually does not exceed 1.5–3.0 m.

The intensity of rocks weathering varies significantly depending on the surface exposure. On the slopes of the southern exposure, the products of weathering have for the most part greater thickness, and their sediment composition is the most dispersed. On the contrary, a coarser cover of Pleistocene–Holocene material is developed on the north-facing slopes with shallow seasonal thaw depth, where the weathering is described as less intense.

Frost cracking plays a significant role in origination of a number of other cryogenic geological phenomena – corroms, stone fields, stone polygons and caldrons, as well as fine polygonal forms of the relief. Frost cracking in surface sediments and associated polygonal relief are most pronounced in areas underlain by relatively low-temperature (less than −2...−3 °C) permafrost with a thick layer of dispersed deposits (primarily in bottoms of gentle slopes), and are most remarkably expressed as stone polygons on the surface of gently convex watershed divides.

In these environments, the polygons vary on average from 5 × 5 to 10 × 10 m in size; while cracks with a length ranging from 20 to 40 m and a visible depth of penetration of 2–3 m, do not exceed a few centimeters in width. The penetration depth of cracks is determined by the thickness of loose deposits (eluvial-diluvial). Low variability of the main parameters of polygonal network developed in the area is explained by the annual temperature amplitudes on the soil surface, being a major control of the size of polygons, vary within small limits due to the relatively uniform distribution of the snow cover. The exceptions are the watershed divides where the snow is either blown off or subjected to compaction. Ice wedges typical of southern Yakutia and localizing in the bottoms of river valleys, do not develop within the study area mainly due to the unfrozen state of rocks composing them and because of a lack of organogenic rocks prone to shattering.

Frost heave of rocks within the investigated area represents one of the most common cryogenic geological processes, resulting in the formation of heave mounds, spot-medallions, stone caldrons and polygons and other exogenous phenomena in different geocryological environments. The process of heaving is accompanied by intensive restructuring of the surface microrelief. The most common are the water migration induced frost heave mounds.

Frost-heaved peat mounds are found on the ancient sites of the first floodplain terrace, in the swampy upper reaches of creeks and rivers in eastern part of the territory, the most remote from the Tokko river valley. The size of frost-heaved mounds is not big, seeing as their height rarely exceeds 0.3–0.5 m, while the area at the base is sized from 1.5 × 2 to 3 × 5 m. All heaved mounds within the study area emerge seasonally and are reported completely thawed by the end of the summer period. One of the forms of the frost heaving process is the expulsion of stone material, resulting in frost sorting of the material of loose formations and deposits in the active layer.

Despite the fact that no *hydrolaccoliths* have been found during the fieldwork in the area, their seasonal small-size replicas can probably be formed in winter in the completely freezing-through creeks and rivers, specifically, in the lower parts of slopes. The absence of perennial heaved mounds is accounted for the failure of multi-year freezing of the talik areas, whereas rocks in the existing taliks are usually drained during their freezing in winter. The study area has been practically unaffected by thermokarst development, which is accounted for a limited distribution of ice-rich rocks, as well as for the fact that the thickness of dispersed deposits, which are usually characterized by high ice content (biogenic, old river beds and floodplain alluvial), remain mostly in the unfrozen state. Nevertheless, some small-sized thermokarst subsidences are found at the head of Gross creek, in areas of glacial deposits distribution, as well as on watersheds, where they take the form of funnel-shaped structures formed by locally melted out altiplain ice.

Icing (aufeis), which is formed by the freezing of outflowing either suprapermafrost groundwater of the AL or groundwater from the underflow taliks, has limited distribution in the area. Patches of aufeis from suprapermafrost waters in this area are usually a product of uneven freezing of the aquifers in slope deposits and ravine alluvium. Being small in size (its area measures first hundred square meters; the thickness of ice likely not exceeding 1 m), they are relatively rare and found mainly in the ravine bottoms and at the foot of the slopes. The role played by the processes of icing is not critical for the formation of terrain in the area. The impact of icing on the relief was observed as a relatively small-size ice-coated glade and reliably traced only in the upper reaches of the Maly Usu Creek valley.

Solifluction (soil creep). The development of soil creep in the investigated area is most favored by the medium-steepness and partly gentle slopes, made up from the surface by gravel and small boulders with sand-loam and sandy aggregates, however, the development of vegetation cover discourages the solifluction processes: given that the rooting zone binds the moistened rocks, their creep down the slope is largely arrested. In the deposit area, the development of solifluction is also impeded due to small amounts of fine material in the rocks.

Consequently, neither solifluction processes have had wide occurrence, nor distinct solifluction landforms developed within the study area. However, the former tend to be occurring as low intensity processes almost ubiquitously, with their manifestations found mainly on gently sloping parts of the near-watershed divides, mostly at the base, where they are promoted by higher moisture content of rocks and may culminate in the formation of tongue-shaped solifluction lobes. These are elongated down the slope as slightly convex positive forms of microrelief with a relatively pronounced bench (tread) in the lower part of the tongue and a flat rear part, almost merging with the slope surface (Fig. 5, *b*). Such solifluction tongues usually measure 8–15 m in length and from 2 to 4 m in width; the frontal slope (riser) height is about 0.2–0.4 m. With soil and vegetation layer missing on their surface, fine earth does not transpire either, and is detectable only from a depth of about 0.2 m below surface.

The essentially different solifluction features observed in the lower parts of slopes, in themselves, usually represent fragments of rubble and small blocks scattered around on the sodded surface of slope (Fig. 5, *c*) and have a shape of very gently sloping dome, 1–2 m in diameter and 0.2–0.3 m in height. From the surface they are made up by small-block clasts. Along the foot of the slope such features are organized in chains, sometimes separated from each other by tens of meters. Their origin can be defined as the injection induced solifluction, which form as a result of the expulsion ("splash") of stone material during the freezing of the strongly water-wet active layer in winter, when thawed rocks become squeezed between the permafrost table and the base of the refreezing layer of the rocks, which experienced thawing during the summer. The developing therewith ground pressure leads to the rupture of the frozen rock shelter and promotes the expulsion of thawed rocks onto the slope surface. The configuration of such landforms gradually acquire final shape, as fine earth (melkozem) is washed away from their surface during the summer season.

CONCLUSIONS

The phenomenon of the environmental settings in the Tabornoe deposit area consists in specific features of the geocryological conditions established in the course of this research. Some of them were found to be fairly nonintuitive.

1. An extremely high contrasting distribution of the average annual temperature of rocks is observed

across the entire area. Inasmuch as the watershed divides outtop (by about 250 m) the valley bottoms, the temperature of rocks change from –5...–6 to 1...2 °C with decreasing elevations, which can happen within one slope of a valley (in plan view) within the length of first hundreds meters. The spatial configuration of permafrost is therefore very complex: its thickness in watershed areas can exceed 400–500 m, rapidly decreasing down the slope, while in the valley bottoms permafrost is either totally missing or have a sporadic distributuon.

2. Despite considerable absolute elevations of thalwegs in the valleys (>1050–1100 m), the latter are characterized by a wide distribution of unfrozen rocks. At this, the valley taliks reach hundreds of meters in width, and almost all of them are interpreted to be through in relation to permafrost. Apart from a highly warming effect of the snow cover during the winter season, the summer-time processes accompanying additional convective heat input into the rocks during the surface water absorption by coarse alluvial deposits of the valleys are involved in the formation of taliks.

3. The mathematical modeling enabled the authors to establish the principal possibility of the formation of through taliks in the considered environmental settings even in narrow valleys of small watercourses. Whilst their persistent existence can be maintained solely by conductive heat exchange, without additional heat input from the ground waters.

4. The established specific pattern of redistribution of the deep heat flux concentrating in the direction of the cooled watersheds, where the flux density has shown almost two-fold increase at the surface, against the background deep-earth value. In this case, the heat flux in the valley bottoms has a downward trend and is redistributed towards the watershed divides, where it is stacked with the depth component.

5. A relatively small depth of seasonal thaw of rocks and its low variability are noted for different types of geocryological conditions, which explains the monotonous structure of the loose cover formed within the corroms and stone fields on watershed divides, predominating across the study area.

6. Cryo-elluvial and cryogenic slope processes and phenomena (e.g. felsensees and stone polygons, corroms, snow avalanches and mudflows, solifluction) are the most widespread and actively developing in the area of South-Ugui group of deposits, due to the relatively severe geocryological conditions in the watershed divides and slopes.

The proper cryogenic geological processes and phenomena, such as formation of ice wedges, thermokarst, cryogenic heaving of rocks and icing, are largely impeded by the predominance of unfrozen rocks in the valley bottoms, as well as the absence of sufficiently thick dispersed deposits. Whereas the processes of waterlogging and bog formation, most inherent in and paragenetically associated with cryogenic geological processes and phenomena, are poorly developed, given the specific hydrogeological situation, which is characterized, in particular, either by good drainage of the river valley bottoms or the predominance of highly dissected relief that precludes the excessive waterlogging of the surface.

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Received May 26, 2016