SCIENTIFIC JOURNAL
EARTH'S CRYOSPHERE

Earth's Cryosphere, 2016, vol. XX, No. 2, pp. 3–13 **http://earthcryosphere.ru/**

FUNDAMENTAL PROBLEMS OF EARTH'S CRYOLOGY

MICRORELIEF OF THE PERMAFROST TABLE: STRUCTURE AND ECOLOGICAL FUNCTIONS

A.V. Lupachev[1,3], S.V. Gubin[1], A.A. Veremeeva[1], D.A. Kaverin[2], A.V. Pastukhov[2], A.S. Yakimov[3]

[1] *Institute of Physico-Chemical and Biological Problems in Soil Science, RAS, 2, Institutskaya str., Puschino, 142290, Russia; a.lupachev@gmail.com*
[2] *Institute of Biology, Komi SC, UB RAS, 28, Kommunisticheskaya str., Syktyvkar, 167982, Russia*
[3] *Earth Cryosphere Institute, SB RAS, P/O box 1230, Tyumen, 625000, Russia*

Surface microrelief structure, complexness of soil-vegetation cover, lithological heterogeneity of the active layer, spatial differences of thermal properties of different elements of transient layer and other factors are responsible for the complicated pattern of permafrost table microrelief, which governs accumulation, redistribution and removal of matter and energy from the ecosystem. Spatial difference in structure and properties of the upper layer of permafrost may lead to the cryoconservation of organic matter, biophylic elements, contaminants, viable biota or, contrarily, this material may thaw and contribute into the modern biogeochemical cycle.

Microrelief of the permafrost table, soil-cryogenic complex, cryosols, cryoconservation, organic matter, anthropogenic impact on cryosols

INTRODUCTION

Structural features and qualitative composition of the uppermost permafrost layers have been discussed in the numerous publications by Russian and foreign cryolithologists and soil scientists who conducted research in different regions of the cryolithozone [*Romanovsky, 1977; Shpolyanskaya, 1978; Sukhodrovskii, 1979; Shur, 1988; Vasilevskaya et al., 1993; Yershov, 1995; Bockheim and Hinkel, 2005; Buteau et al., 2005; Harris, 2005; Shur et al., 2005; Goryachkin, 2006*]. However, there is still no clear understanding of the relationship between relief and soil-vegetation cover of the day surface, and the permafrost table meso- and microrelief, despite their obvious affinity. An essential methodological drawback is associated with the fact that the active layer (AL) depth was primarily reflected as a relative value without taking into account surface relief structure [*Ivanova, 1962; Khudyakov, 1983; Vadyunina and Khudyakov, 1983; Vasilevskaya et al., 1993*]. Detailed studies with the focus comprising absolute thickness of the active layer (ALT), showed that the pattern of permafrost table microrelief surface is controlled by many factors, among them are: density of vegetation canopy, organic horizons thickness, intensity of cryogenic mass exchange processes, etc. [*Kokelj et al., 2007; Lupachev and Gubin, 2008*]. First insights about the permafrost table mesorelief structure and its importance for the ecosystem were presented by *Yu.A. Liverovskii* [*1934*] who highlighted the large value of the so called "subsurface permafrost limits whimsicality indicator" which might explain the course of solifluction processes. Later these ideas were underpinned by factual material, including introduction of the microrelief concept [*Pukemo, 1987; Lewkowicz and Clarke, 1998; Ostroumov et al., 1998*]. In terms of zonality, the problem of relationship between the day surface microrelief structure and permafrost table microrelief is partially solved by research works devoted to studying the tundra zone (within distribution of continuous permafrost and shallow (up to 1–1.5 m) ALT) [*Kondratieva and Trush, 1961; Melentiev, 1968; Naumov, 1974; Sharapova, 1987; Shamanova, 1991; Ostroumov et al., 1998*]. Further to the south, where the taiga zone succeeds the forest-tundra, as well as in the areas of island permafrost distribution, ALT progressively increases, in contrast to the amount of related research [*Epshtein, 1961; Zabolotnik and Klimovskii, 1966; Harris, 1998; Kazantseva, 2007; Mazhitova and Kaverin, 2007*].

The contributions of the international program Circumpolar Active Layer Monitoring (CALM) participants addressing the problem of the permafrost table microrelief genesis and functioning are highly valued especially for the results of detailed measurements of thaw depth made in diffent modes: in series during the summer season; with a different measure-

Copyright © 2016 A.V. Lupachev, S.V. Gubin, A.A. Veremeeva, D.A. Kaverin, A.V. Pastukhov, A.S. Yakimov, All rights reserved.

ment spacing; taking into account the day surface microrelief structure; with calculations of the annual ground subsidence, and analysis of the soil-vegetation cover structure, etc. [*Hinkel and Nelson, 2003; Fedorov-Davydov et al., 2004a,b,c; Mazhitova et al., 2004; Zamolodchikov et al., 2004; Mazhitova and Kaverin, 2007; Melnikov, 2012*].The aim of this study was to determine basic patterns of the permafrost table microrelief, and their controlling factors, to identify region-specific structural features of a particular microrelief, and to establish the nature of its influences on the spatial redistribution of matter and energy in the cryogenic ecosystems.

OBJECTS AND METHODS OF STUDY

The key sites are located in the zones of continuous and sporadic permafrost distribution in the European, West-Siberian and North-Eastern sectors of Russian cryolithozone (Fig. 1, Table 1). The study of the permafrost table microrelief pattern at the designated sites was conducted during a time period possibly coincident with the AL reaching its utmost thickness (end August – mid September) and were localized within the watersheds and on gentle (less than 3–4°) slopes. Under these conditions, the relationship between surface microrelief structure and

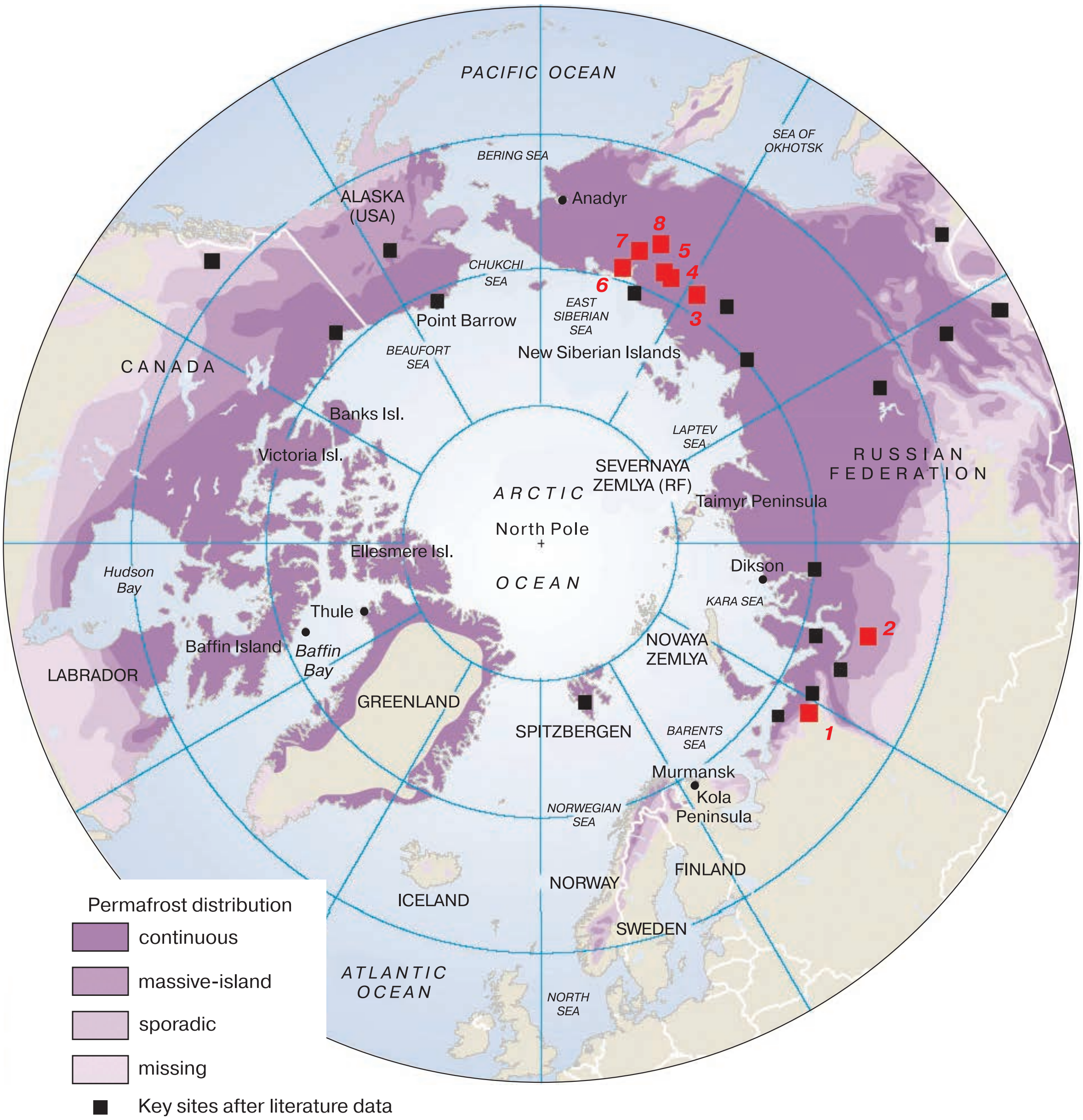

Fig. 1. Locations of key sites of the study on the permafrost distribution schematic map [*Brown et al., 1997*]:
1 – Ayach-Yakha Rv., *2* – Nadym st., *3* – Allaikha Rv., *4* – Khomus-Yuryakh Rv., *5* – Alazea Rv., *6* – sm. settl. Kur'ishka, *7* – Komarov Brook, *8* – Omolon Rv.

Table 1. **Average interannual active layer thickness according to CALM interactive database**

No.	Key site; coordinates	Environmental zone/subzone	Position of levelling profiles in mesorelief	Soil-forming deposits	Permafrost distribution	Average interannual ALT, cm	Vegetation cover. Soils
1	Ayach-Yakha Rv.; 67°35′ N, 64°10″ E	Southern tundra	Gentle slope	Silty loam	Massive-island	79.7	Low shrub-willow lichen-moss. Cryometamorphic gleyzems
2	Nadym st.; 65°20′ N, 72°55″ E	Northern taiga	Peat plateau	Organogenic, underlain by silty sand	Sporadic	130.9	Low shrub-willow lichen-moss. Organogenic peaty soils
3	Allaikha Rv.; 70°33′ N, 147°26″ E	Southern tundra	Watershed – gentle slope – steep slope	Silty loam	Continuous	47.0	Grassy-willow-low shrub pleurocarpous moss-lichen. Cryozems
4	Khomus-Yuryakh Rv.; 70°00′ N, 153°36″ E	Typical tundra	Watershed – gentle slope	Idem	Idem	52.5	Grassy-low shrub lichen-pleurocarpous moss. Cryometamorphic cryozems
5	Alazea Rv.; 69°19′ N, 154°58″ E	Idem	Idem	»	»	50.8	Grassy-low shrub lichen-pleurocarpous moss. Cryometamorphic cryozems
6	Kur'ishka; 69°28′ N, 161°47″ E	»	Watershed	»	»	44–46	Grassy-low shrub lichen-pleurocarpous moss. Cryometamorphic cryozems
7	Komarok Br.; 68°44′ N, 161°25″ E	Northern taiga	Gentle slope	»	»	106–108	Willow-low shrub lichen-pleurocarpous moss larchen thin forest. Gleyzems, cryozems
8	Omolon Rv.; 68°43′ N, 158°54″ E	Idem	Watershed	»	»	41.0	Willow-low shrub lichen-pleurocarpous moss larchen thin forest. Gleyzems, cryozems

permafrost table microrelief is the most pronounced, while the exposition impact is negligible (Fig. 2, *a–c*). As the slope steepness increases (5° and more) the latter flattens under the influences of gravity, solifluction, and warming action of the temporary perched ground water (Fig. 2, *d*).

Microlevelling of the day surface and permafrost table microreliefs was carried out on different elements of the mesorelief with accuracy of 1 cm from horizontally verified, conventionally zero surface. Linear and spatial measurements were spaced at intervals of 10 cm, with the microrelief elements documented for each measuring point. In some cases, the cross-sections were laid within the limits of measured sites and along profiles where thicknesses of genetic soil horizons were measured in parallel with qualitative evaluation of the composition and cryogenic structure of the uppermost (transient) layer. The average multiyear ALT derived from the CALM interactive database is given in Table 1 (http://www.gwu.edu/~calm/).

FACTORS DETERMINING THE PERMAFROST TABLE MICRORELIEF PATTERN

The field studies carried out at key sites under different physico-geographical conditions, along with analysis of the published data allowed to establish a range of driving factors contributing to the complicated pattern structure and degree of the permafrost table microrelief distinction, i.e. dissection intensity, difference in elevations (including in relation to ALT), slope angles, etc.

Soil-vegetation cover zonality. The authors revealed that in the Northern Hemisphere, spatial differentiation of the permafrost table microrelief tends to considerably decline southwardly. This phenomenon is accounted for the growing ALT and the levelling effect of the vegetation cover in the uppermost organogenic horizons (plant litter, peat, humus, and so on), which thickness and canopy density consistently progress in that same direction.

Spatial heterogeneity of the vegetation cover and organogenic soil horizons largely affect the permafrost table microrelief pattern. In the polar desert and arctic tundra zones, fragmented organogenic horizon forms only along the edging of patterned landforms and ground cracks of ice-wedge polygons. Due to its small thickness, and discontinuous coverage of the surface it is not capable of exerting any significant impact on the heat flow redistribution within ALT [*Pavlov, 1979*]. Therefore, the formation of permafrost table microrelief here is totally controlled by the AL lithological heterogeneity.

In the tundra zone, organogenic soil horizon is distributed almost continuously (except for frost boils formation, solifluction and thermokarst disturbances on topsoil). However, spatial distribution of its thickness is exceedingly nonuniform and range

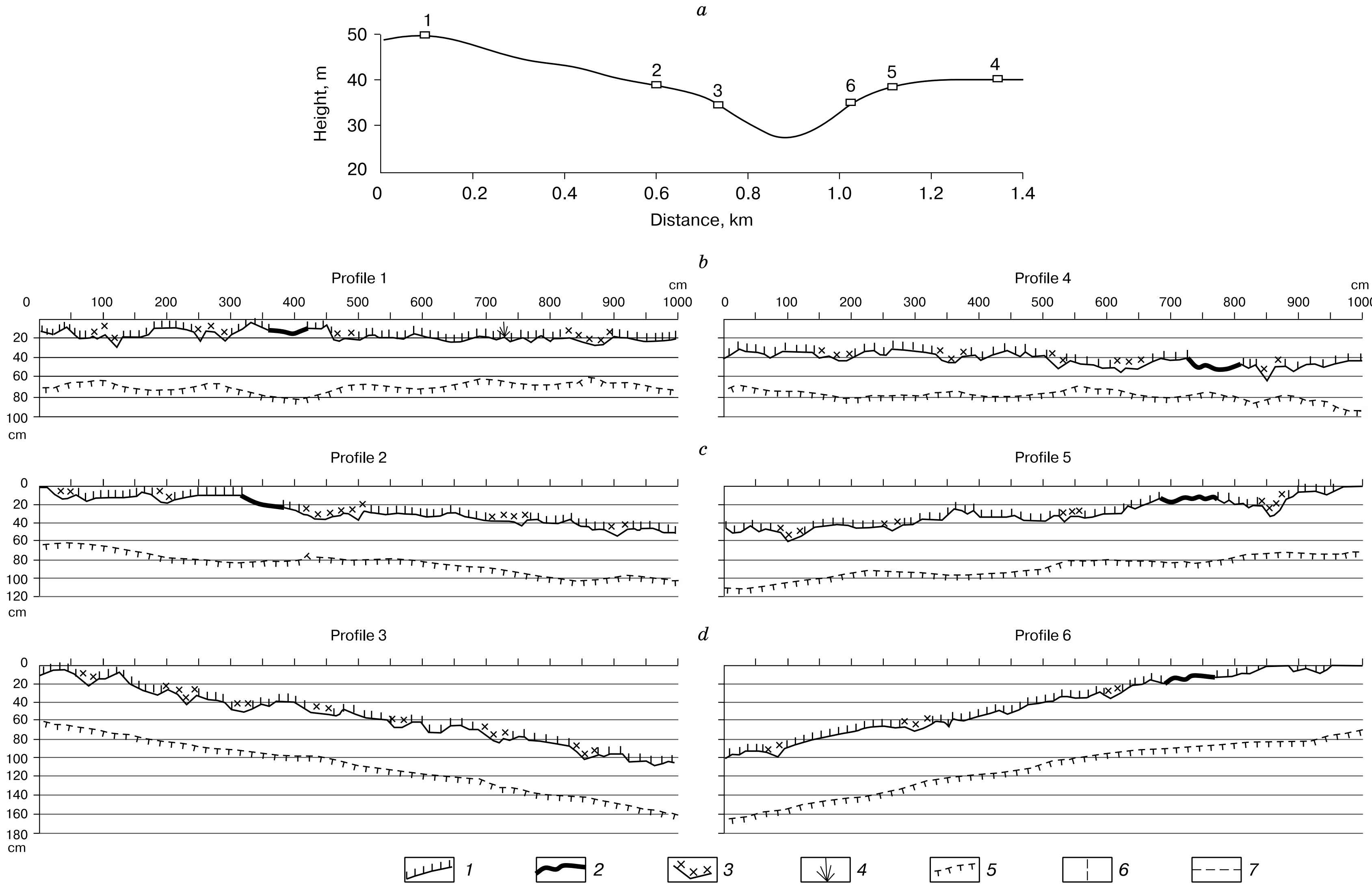

Fig. 2. "Allaikha" key site.

Surface microrelief structure and pattern of permafrost table microrelief: *a* – profiles layout scheme (1–6) microlevelling in mesorelief (on the left – drained yedoma silty-clayey watershed; on the right – waterlogged silty-clayey watershed); *b* – watershed; *c* – gentle slope (<3–5°); *d* – steep slope (>3–5°).
Here and in Fig. 3–5 and 8 – measurements spacing: 10 cm, length and depth are in cm.
1 – polygon; *2* – fresh spot of ground flow-out; *3* – interpolygonal crack; *4* – organogenic sedge-grass hummock; *5* – upper layer of permafrost; *6* – conventional border between separate parts of AL beneath different elements of surface microrelief; *7* – baseline surface level.

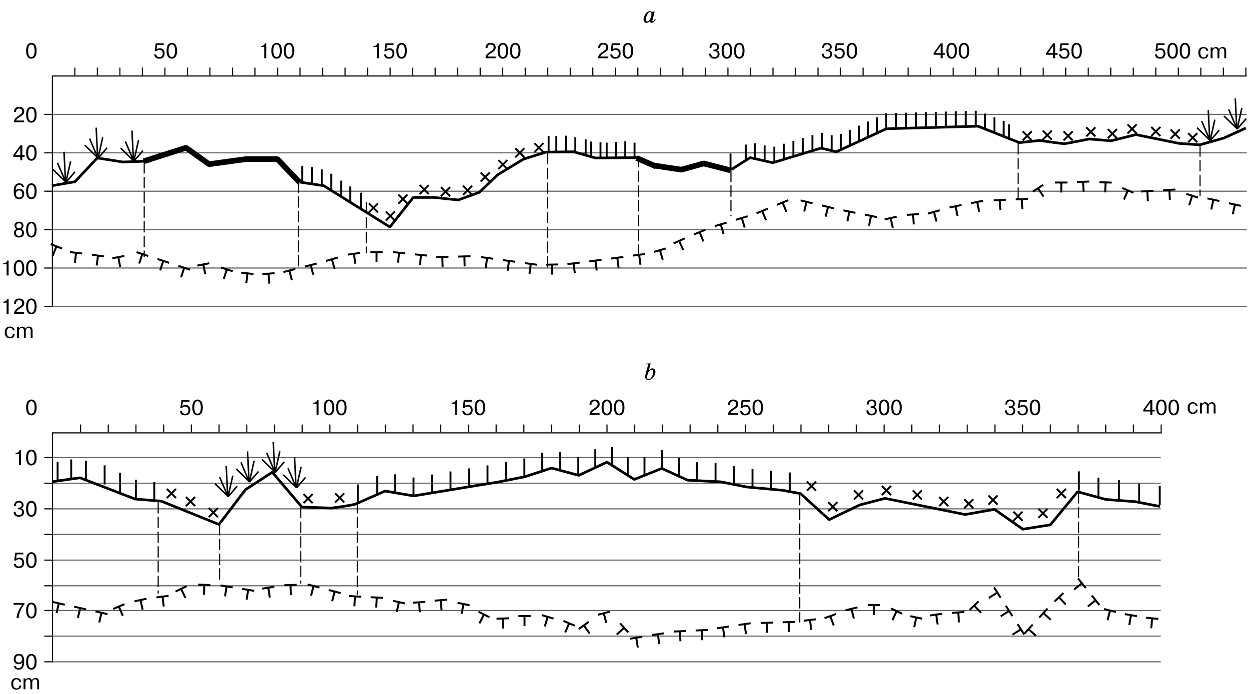

Fig. 3. “Kur’ishka” (*a*) and “Allaikha” (*b*) key sites.

Surface microrelief structure and permafrost table microrelief pattern in the tundra zone, cf. Notations in Fig. 2.

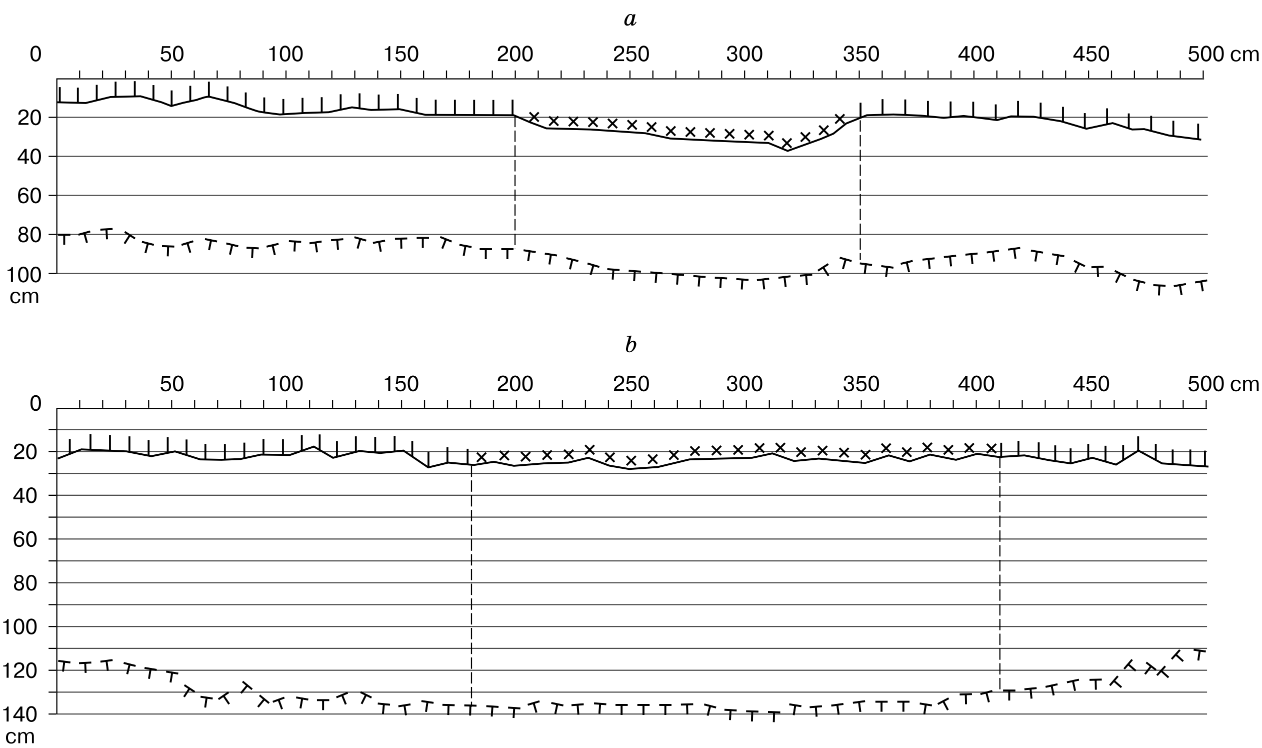

Fig. 4. “Ayach-Yakha” (*a*) and “Komarok” (*b*) key sites.

Surface microrelief structure and permafrost table microrelief pattern in the forest-tundra and northern taiga zones, cf. Notations in Fig. 2.

from 0 cm at bare circles and 2–5 cm in central parts of being or already overgrown polygons, to 20–40 cm and more within interpolygonal cracks.

In separate cases, the thickness of organogenic horizon filling interpolygonal cracks can exceed modern ALT, allowing peaty material penetrate into upper layers of permafrost. Such spatial inhomogeneity of soil-vegetation cover prompts the formation of permafrost table microrelief, which is pronouncedly discernible and dynamic during the thawing season (Fig. 3).

In the forest-tundra and northern taiga, formation of frost boil patterns and ground outflow occur in very rare cases; thickness of the organogenic uppermost horizon increases, levelling thereby differences between elements of the surface microrelief structure. Given that, concurrently, the AL depth is increasing, the permafrost table microrelief pattern largely replicates the surface microrelief structure, except for minor complications caused by spatial differences in cryogenic structure and composition of the transient layer (Fig. 4).

Lithological and grain size composition of AL deposits. Facies characteristics directly control sediments temperature and water regime, AL dynamics, the nature and intensity of cryogenic mass exchange processes. Similarly, the pattern of permafrost table microrelief changes for different composition of permafrost. In the case where the AL is located entirely within the organogenic interval (alas basins, peat plateaus, etc.), permafrost table microrelief substantially inherits surface microrelief structure (Fig. 5, *a*). This relationship is largely controlled by the homogeneity of thermal properties of peat layer that slightly vary spatially. In case of AL limits extending beyond the organogenic layer (at the intersection of intermound depressions, enhanced waterlogging, peat mounds degradation, human impact, etc.) and its penetration into the underlying mineral layer, the pattern of permafrost table microrelief changes notably.

The AL depth in some areas can dramatically increase – by more than 1 m per a 30 cm interval of the profile length – at sites where thin-layered or degraded peatlands are underlain by light-textured deposits and ALT extent exceeds peat layer thickness, (Fig. 5, *b*). This may have been caused by the warming effect of surface watercourses in the intermound depressions and extremely high thermal conductivity of water-saturated sand sediments. In some cases, both seasonally frozen ground and permafrost may

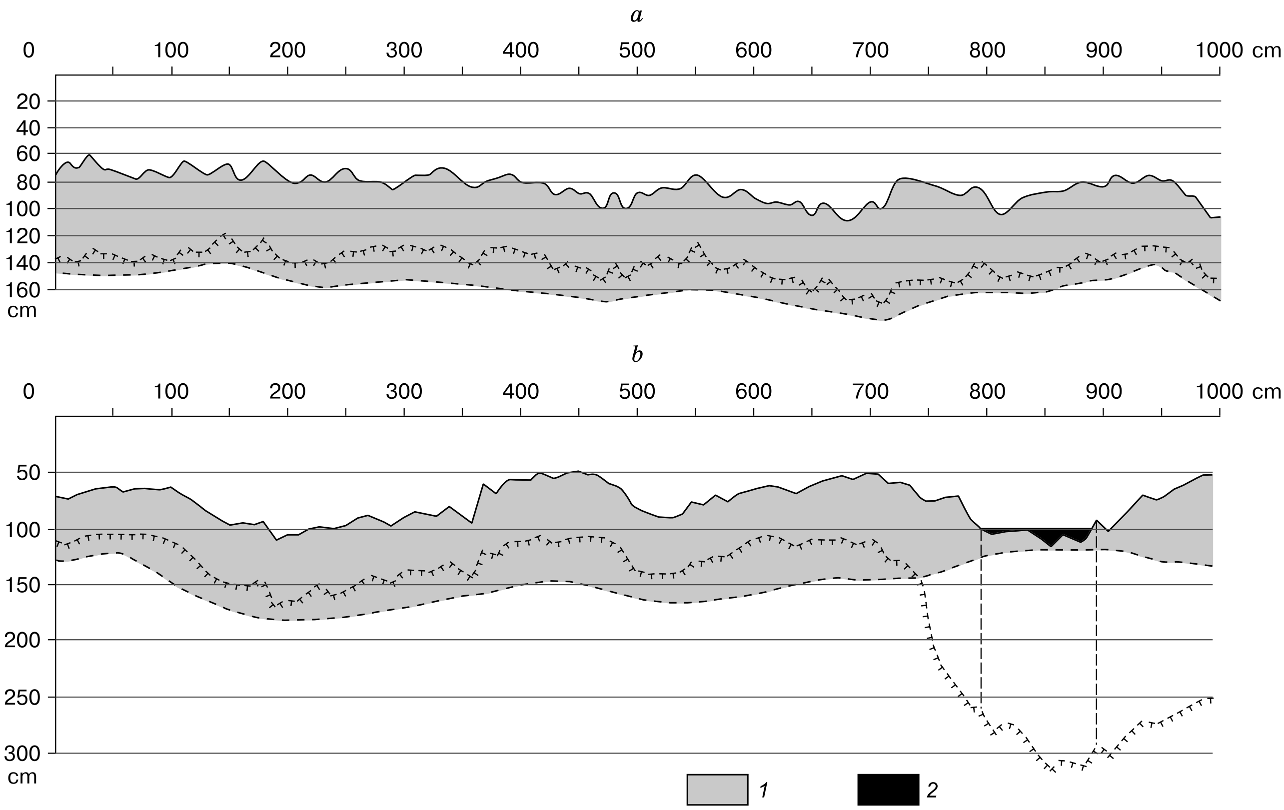

Fig. 5. “Nadym” key site.

Surface microrelief structure and upper layer of permafrost and upper layer of permafrost on peat mounds (*a*) and intermound hollow (*b*). (Lower boundary of organogenic sediments is calculated from averaged drilling data.)
1 – organogenic sediments; *2* – water. cf. Notations in Fig. 2.

fail to merge during the autumn-winter freezing, which results in the initiation of latent permafrost degradation [*Mazhitova, 2008; Melnikov, 2012*].

Apart from sandy sediments, warming effect of the AL moisture is remarkably manifested in glacier-marine stony-sandy deposits. Long-term monitoring of AL on Svalbard showed that in areas that feature a developed cryogenic sorting the difference in elevation between the elements of the upper layer of permafrost and surface microrelief structure may reach 60–80 cm in the period of intensive snow melting, with slope angle of the upper layer of permafrost approaching 40° or more [*Repelewska-Pekalowa and Pekala, 2004*].

Deposits with heavy particle size distribution exhibit a different pattern of microrelief structure of the upper layer of permafrost. In contrast to stony and sandy soils, silty-clayey and clayey deposits have significantly greater water-retaining capacity, providing therefore a variety of qualitative composition and cryolithological structure of soils and transient layer of permafrost, both vertically and horizontally [*Konishchev, 1965; Shamanova, 1991; Lupachev and Gubin, 2008*].

Thus, the structure of transient layer of permafrost, underlying soils of the nanopolygonal tundra in northern part of Yakutia (Fig. 6, *a*) exhibit such constituent elements as: silty loam with different cryotexture (from thin-schlieren to ataxitic), frozen mixture of peat-mineral material, pure ice (Fig. 6, *b*). This variety of spatial structure determines differences in the permafrost table microrelief in the range from 15 to 40 cm within a 50 cm stretch of the profile, while slope angles of the upper layer of permafrost reach 15–20° during periods of maximum seasonal thawing (Fig. 6, *c*).

Changing distinction of the permafrost table microrelief pattern during the thaw period. It has been established that permafrost table microrelief pattern is most discernible during the first half of the thaw season when differences in thermal properties of organogenic horizons of soil material are most pro-

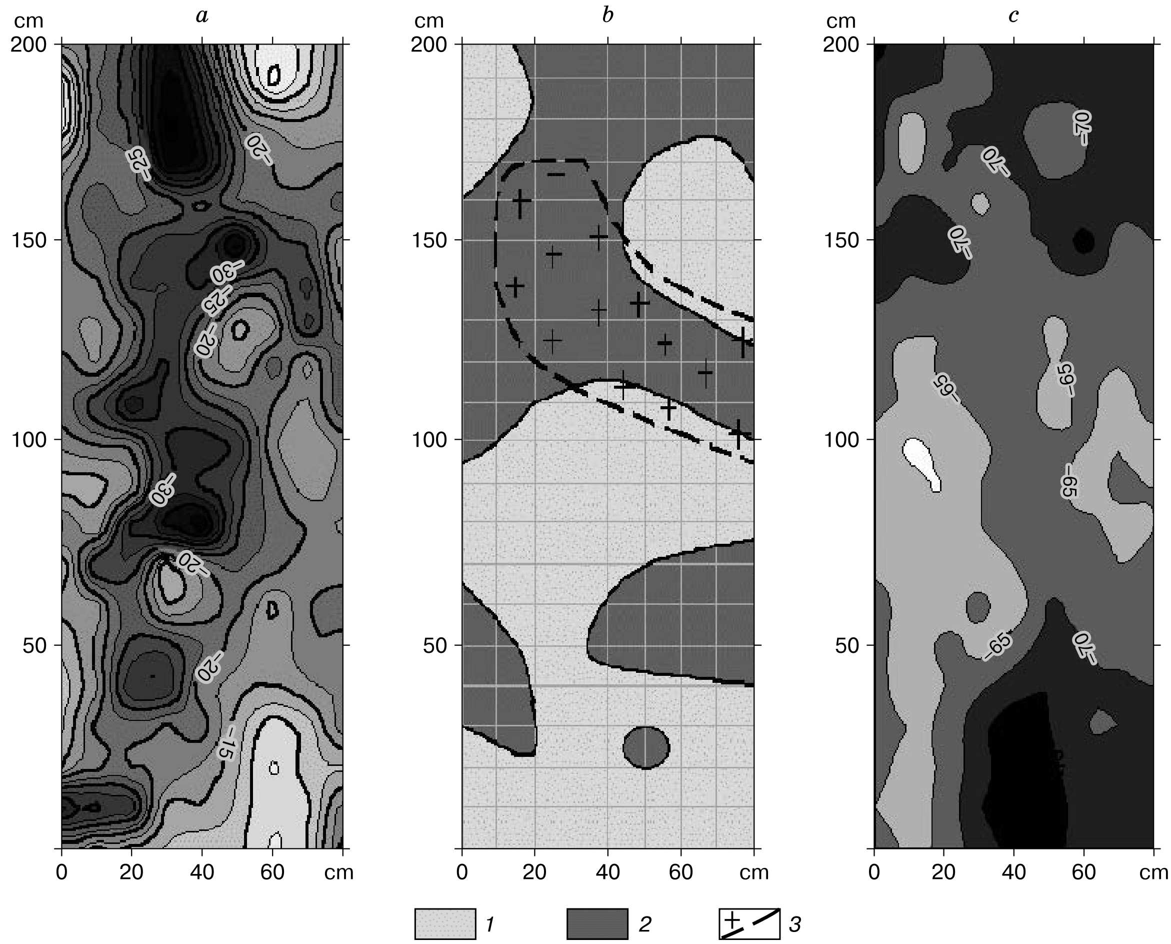

Fig. 6. "Khomus-Yuryakh" key site.

a – surface microrelief structure; *b* – main elements of spatial structure of the transient layer of permafrost: *1* – silty clay with reticulate and thin-schlieren cryotexture; *2* – ogranomineral material; *3* – pure ice overlaid by thin layer (5–10 cm) of frozen ogranomineral material; *c* – pattern of permafrost table microrelief. Spacing between isolines: 5 cm (*a*, *c*).

nounced on different elements of the surface microrelief structure. In the second half of summer, when the lower limit of AL completely penetrates mineral horizon of the soil profile, the permafrost table microrelief becomes largely levelled and its pattern regain distinctiveness only at the very end of the thaw period, when the lower boundary reaches the transient layer of permafrost, which thickness has spatially inhomogeneous cryogenic structure and qualitative composition.

The impact from seasonal development of the permafrost table microrelief is most appearing on AL deposits with heavy particle size distribution, which is reflected in the soil profile structure. During first years after formation of frost boil pattern (mineral material outflows on the polygon ground), spatial differences in thermal properties of the upper layers of permafrost terrain are the highest [*Pavlov, 1979*]. Areas completely free from vegetation begin to thaw earlier and more intensely, than the marginal parts of nanopolygons. In the first half of the summer season, the permafrost table microrelief forms a bowl-shaped thaw beneath the bare sites, providing space for meltwater accumulation, establishing the anaerobic mode, and formation of thick and stable nucleus of gleyization [*Fedorov-Davydov et al., 2004a*]. When bare circles become overgrown, permafrost table microrelief tends to be more levelled, while conditions for locally persistent stagnation of suprapermafrost water cease to exist, which results in nucleus of gleyization losing color/intensity and essentially reducing in size.

Redistribution of matter and energy over the permafrost table. Accumulation of the viable biota on the cryogenic aquiclude surface [*Parinkina, 1989*], the presence of peaks in water-soluble organic matter concentrations [*Karavaeva and Targulian, 1960*], biophylic elements [*Ostroumov et al., 2001*], exchangeable cation [*Kokelj and Burn, 2005*], fine-dispersed particles [*Naumov, 1974*] have been repeatedly referred to in the literature. A cryoconservation action of the active layer changing into permanent frozen state has been established [*Gilichinsky et al., 1995; Shatilovich et al., 2005; Yashina et al., 2012*].

This confirms the authors' insight about ecological function of the permafrost table as a geochemical barrier for vertical migration of biota, elements and compounds. However, the function of lateral redistribution of matter and energy over the permafrost table surface during the warm season in cryogenic ecosystems has thus far been scarcely investigated.

A.S. Kerzhentsev [*1992*] pointed out that the existence of relatively stable "intrasoil suprapermafrost waterflows", through which moisture and dissolved compounds discharge during the permafrost thawing in the summer in the East Baikal region. He also defined the patterns and dynamics of cyclical development of the meso- and microrelief of the upper layer of permafrost.

The authors suggest that such redistribution can considerably determine spatial structure of the transient layer surface microrelief, where formation of pronouncedly discernible and persistent over time positive and negative landforms takes place, which includes denudation (removal of solutes, compounds and mineral material) and transit/accumulation zones (Fig. 7, *c*) [*Stepanov, 2006*]. During the seasonal thaw, the conditions of strongly waterlogged suprapermafrost horizons assisted by the thawing of very ice-rich cryostructures are responsible for significant differences in elevation and slope angles between the elements of the permafrost table microrelief, which can dramatically intensify movement processes of soil solutes and suspensions, as well as coarser material over the sloping permafrost layer, and ultimately lead to suprapermafrost migration and redistribution of significant amounts of matter in this layer [*Lupachev and Gubin, 2012*]. It has thus been revealed that coarse organic matter accumulated and redistributed within negative forms of the permafrost table microrelief, with its content in the frozen material being sometimes 3–6 times higher, than that in the material composing the positive forms (Fig. 7, *b*).

The importance of significant influence of illuvial processes on the formation of suprapermafrost cryogenic soil horizons is therefore reinvigorated. The authors' own data suggest the possibility of lateral redistribution of coarse organic substances [*Ibidem*]. Likewise, more mobile water-soluble compounds are redistributed inside the profiles and between individual elements of the soil complex. However, the relationship between amounts of matter and energy coming to the permafrost boundary in sub-vertical direction (the so-called "suprapermafrost illuviation") and those redistributed in subhorizontal direction (supposedly, "suprapermafrost elluviation") remains unclear.

Anthropogenic impact on the structure of micro and meso-relief of the upper layer of permafrost and cryoconservation of contaminants. The paper authored by *A.S. Kerzhentsev* [*1992*] describes one of the pioneering experiments on anthropogenic influence on the structure of permafrost table microrelief. The reclamation measures (plowing, mulching straw on soil surface, and so on) applied during 1–2 years resulted in redirecting the intrasoil and suprapermafrost drainage and thereby precluding solifluction-driven disturbance of the road on the soil surface.

Analogous changes in the permafrost table microrelief pattern are widely spread under natural or anthropogenic disturbances of the earth's surface (removal of soil-vegetation cover, deforestation, fires, road building, construction of buildings, removal of soil, solifluction, thermokarst, etc.).

The authors set up a testing ground within the Vorkuta tundra key site, where as thick as about 10 cm organogenic cover was removed. Two years

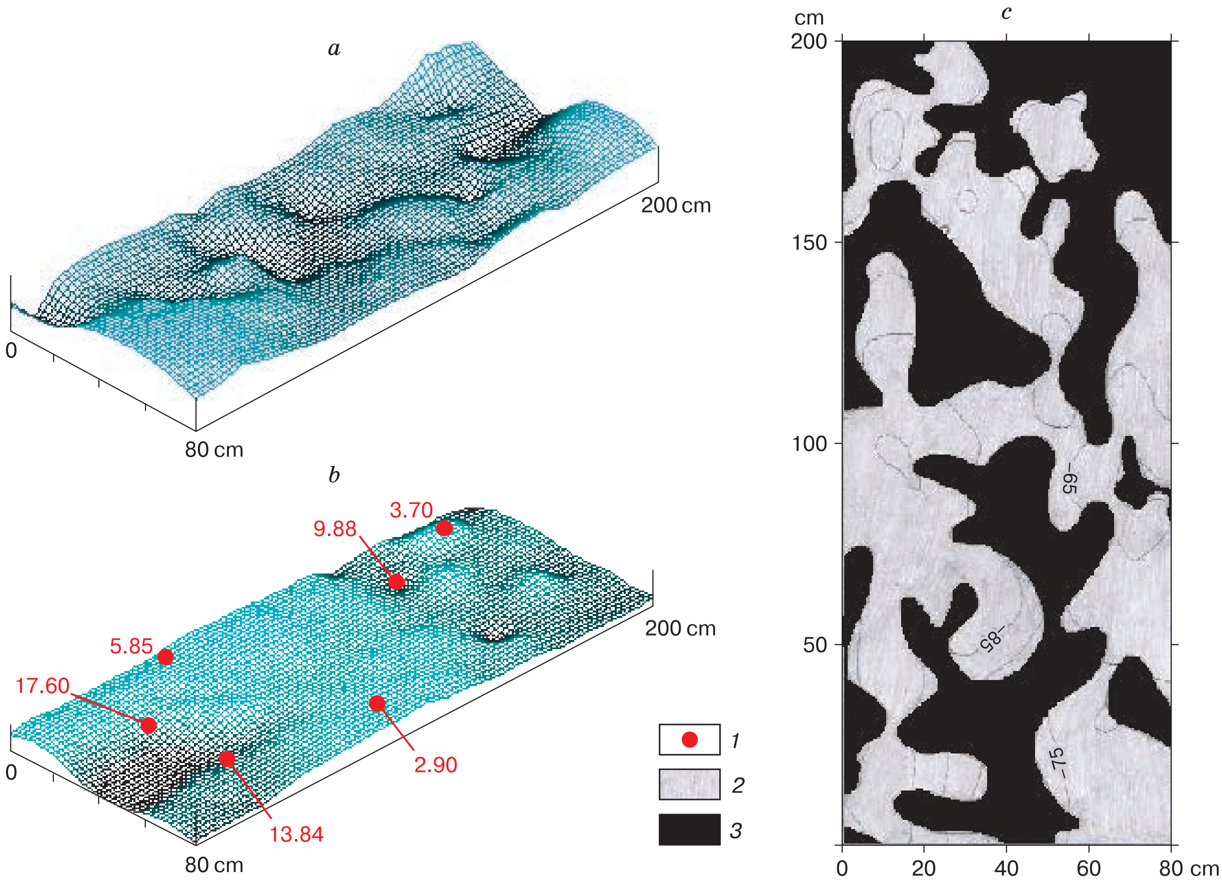

Fig. 7. "Khomus-Yuryakh" key site.

3D representation of surface microrelief structure (*a*), upper layer of permafrost (*b*); *c* – zones of denudation and transit/ accumulation in the permafrost table microrelief.
1 – total organic carbon concentration, %; *2* – denudation zone; *3* – transit/accumulation zone.

later, the micro-levelling was applied to both day surface and surface of the upper layer of permafrost The measurement results showed that the day surface subsidence constituted 50–60 cm, while permafrost table lowered 80–100 cm deeper. With the removed 1 m^2 of organogenic cover, the disturbance impact coverage exceeded 10 m^2 of the permafrost table (Fig. 8).

The related literature examples provide numerous evidence of vertical migration of TPH (total petroleum hydrocarbons) from the AL to the upper layers of permafrost and their further accumulation therein. In the Canadian Arctic, the uppermost meter of the permafrost layer showed a significant oil contaminants concentrations – up to 1500–5000 mg/kg (TPH in the AL is 15 000–20 000 mg/kg) [*Biggar et al., 1998*].

Similar research was also conducted in Bolshezemelskaya tundra, where TPH-in-soil concentrations at a depth of 50–70 cm from the surface of permafrost table were comparable with measured contaminants in the active layer (600–800 mg/kg) [*Chuvilin and Miklyaeva, 2005*]. The identified pattern of permafrost table microrelief structure is very likely to be largely responsible for the transit and accumulation of contaminants in cryogenic ecosystems subjected to anthropogenic impact.

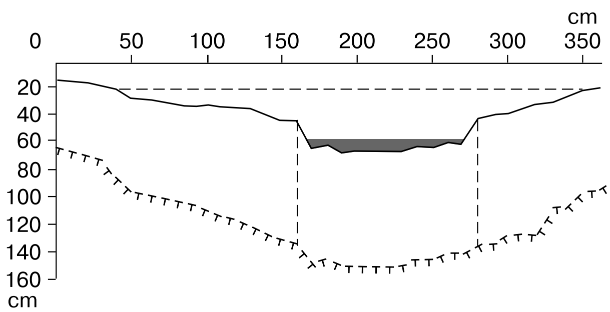

Fig. 8. "Ayach-Yakha" key site.

Surface microrelief structure and permafrost table microrelief under anthropogenic disturbance. cf. Notations in Fig. 2 and 5.

CONCLUSIONS

The presence of distinctly discernible, persistent over time permafrost table microrelief has been established. Its distinction degree is controlled by its position in the mesorelief (the highest degree is associated with flat surfaces of the watershed areas, gentle slopes and in depressions, the lowest – with steep slopes), ALT and intensity of cryogenic massexchange processes.

Spatial homogeneity of lithological composition of AL deposits and soil-vegetation cover are responsible for the affinity between surface microrelief structure and permafrost table microrelief.

Seasonal thawing processes largely determine the permafrost table microrelief dynamics. In the first half of the summer season the permafrost table microrelief pattern is most discernible, when differences in thermal properties of the material of organogenic soil horizons are most pronounced. In the second half of the summer permafrost table microrelief becomes essentially levelled and regains distinctiveness only at the very end of the thaw period, when the lower boundary reaches the spatially inhomogeneous transient layer of permafrost.

The permafrost table microrelief governs lateral redistribution of matter and energy within and between cryogenic ecosystems. The permafrost table microrelief pattern showed the presence of stable zones of matter and energy accumulation, transit and denudation.

In localities where permanent frozen deposits are associated with the climatic limit of their existence (non-merging permafrost, sporadic distribution, etc.), permafrost table microrelief is capable of provoking their degradation.

Anthropogenic impact on the soil surface is reflected in changes in the permafrost table microrelief pattern, which results in redistribution of subsurface soil and suprapermafrost drainage modified zones of accumulation, and subsequent cryoconservation (under refreezing) or removal of matter and energy into the subordinate landscapes (with developing thermokarst processes).

The work was supported by RSF (grant 14-14-01115); RFBR (projects 14-05-31368mol_a, 14-05-31111mol_a, 15-04-03960a); the RF President Council on Grants for leading scientific schools (НШ-3929.2014.5) interdisciplinary integration project SB RAS No. 144.

References

Biggar, K.W., Nahir, M., Haidar, S., 1998. Migration of petroleum contaminants into permafrost, in: Proc. of the 7th Intern. Conf. "Permafrost" (Yellowknife, June 23–27, 1998). Coll. Nordicana No. 55, Canada, Yellowknife, pp. 43–49.

Bockheim, J.G., Hinkel, K.M., 2005. Characteristics and Significance of the Transition Zone in Drained Thaw-Lake Basins of the Arctic Coastal Plain, Alaska. Arctic 58 (4), 406–417.

Brown, J., Ferrians, O.J. (Jr.), Heginbottom, J.A., Melnikov, E.S. (Eds), 1997. Circum-Arctic map of permafrost and ground-ice conditions. Washington, DC: U.S. Geol. Surv. in Cooperation with the Circum-Pacific Council for Energy and Mineral Resources. Circum-Pacific Map Series CP-45, scale 1:10 000 000, 1 sheet.

Buteau, S., Fortier, R., Allard, M., 2005. Rate-controlled cone penetration tests in permafrost. Can. Geotech. J., vol. 42, 184–197.

Chuvilin, E.M., Miklyaeva, E.C., 2005. Field experiment for estimation of oil contaminants concentrations in the upper horizons of permafrost. Kriosfera Zemli IX (2), 60–66.

Epshtein, G.M., 1961. Some regularities in seasonal freeze-thaw of soils in the area of island permafrost distribution (by the example of the upper Amur Valley), in: Merzlotnye issledovania, Moscow Univ. Press, Moscow, iss. II, pp. 45–58. (in Russian)

Fedorov-Davydov, D.G., Gubin, S.V., Makeev, O.V., 2004a. Free iron content and potential for gleyification in soils of the Kolyma lowland. Pochvovedenie, No. 2, 158–170.

Fedorov-Davydov, D.G., Davydov, S.P., Davydova, A.I., et al., 2004b. Spatial-temporal regularities of the seasonal thawing of soils in the north of the Kolyma lowland. Kriosfera Zemli VIII (4), 15–26.

Fedorov-Davydov, D.G., Sorokovikov, V.A., Ostroumov V.E., et al., 2004c. Spatial and temporal observations of seasonal thaw in the northern Kolyma Lowland. Polar Geography 28 (4), 308–325.

Gilichinsky, D., Wagener, S., Vishnivetskaya, T., 1995. Permafrost Microbiology. Permafrost and Periglacial Processes, vol. 6, 281–291.

Goryachkin, S.V., 2006. Structure, genesis and evolution of soil cover of the boreal-arctic areas of ETR: Extended abstract of Dr. Sci. (Geogr.) Dissertation. Moscow, 48 pp. (in Russian)

Harris, S.A, 1998. Nonsorted circles on Plateau Mountain, S.W. Alberta, Canada, in: Proc. of the 7th Intern. Conf. "Permafrost" (Yellowknife, June 23–27, 1998). Coll. Nordicana No. 55, Canada, Yellowknife, pp. 441–448.

Harris, S.A., 2005. Multilayered nature of the active layer in the areas of distribution of high-temperature permafrost deposits of Canada. Kriosfera Zemli IX (4), 3–12.

Hinkel, K.M., Nelson, F.E., 2003. Spatial and temporal patterns of active layer thickness at Circumpolar Active Layer Monitoring (CALM) sites in Northern Alaska, 1995–2000. J. Geophys. Res., vol. 108, No. 102 (D2), 8168.

Ivanova, E.N., 1962. Some regularities in the structure of soil cover in the tundra and forest-tundra within the Ob Bay coastal areas, in: O pochvakh Urala, Zapadnoi I Tsentralnoi Sibiri. Izd-vo AN SSSR, Moscow, pp. 49–116. (in Russian)

Karavaeva, N.A., Targulian, V.O., 1960. On peculiarities of humus distribution in the tundra soils of Northern Yakutia. Pochvovedenie, No. 12, 36–45.

Kazantseva, L.A., 2007. Spatial variability of landscape and geocryological conditions of natural and disturbed ecosystems of the northern taiga in Western Siberia. Kriosfera Zemli XI (2), 14–18.

Kerzhentsev, A.S., 1992. Spatial and temporal variability of soils. Nauka, Moscow, 110 pp. (in Russian)

Khudyakov, O.I., 1983. Cryogenesis and soil-forming processes. ONTI NTsBI AN SSSR, Pushchino, 196 pp. (in Russian)

Kokelj, S.V., Burn, C.R., 2005. Geochemistry of the active layer and near surface permafrost, Mackenzie delta region, Northwest Territories, Canada. Can. J. Earth Sci., vol. 42, 37–48.

Kokelj, S.V., Burn, C.R., Tarnocai, C., 2007. The structure and dynamics of Earth Hummocks in the Subarctic Forest near Inuvik, Northwest Territories, Canada. Arctic, Antarctic and Alpine Res. 39 (1), 99–109.

Kondratieva, K.A., Trush, N.I., 1961. To the problem of measuring depth of seasonal thaw and freeze of ground, in: Merzlotnye issledovania. Moscow Univ. Press, Moscow, iss. II, pp. 59–70. (in Russian)

Konishchev, V.N., 1965. Peculiarities of ice segregation in the active layer and morphology of covering loessoid formations, in: Podzemnyi loyd / Popov, A.I. (Ed.). Moscow Univ. Press, Moscow, pp. 172–182. (in Russian)

Lewkowicz, A.G., Clarke, S., 1998. Late-summer solifluction and active layer depths, Fosheim Peninsula, Ellesmere Island, Canada, in: Proc. of the 7th Intern. Conf. "Permafrost" (Yellowknife, June 23–27, 1998). Coll. Nordicana No. 55, Canada, Yellowknife, pp. 641–646.

Liverovskii, Yu.A., 1934. Soils of tundras of the Northern Region. Izd-vo AN SSSR, Leningrad (Tr. Polyarnoi komissii; iss. 19), 112 pp. (in Russian)

Lupachev, A.V., Gubin, S.V., 2008. Role of soil-forming processes in the formation of transient layer of permafrost. Kriosfera Zemli XII (2), 75–83.

Lupachev, A.V., Gubin, S.V., 2012. Suprapermafrost organic-accumulative horizons in the tundra cryozems of northern Yakutia. Pochvovedenie, No. 1, 1–12.

Mazhitova, G.G., 2008. Soil temperature regime in the zone of discontinuous permafrost in the northeast of European Russia. Pochvovedenie, No. 1, 54–67.

Mazhitova, G.G., Kaverin, D.A., 2007. Dynamics of seasonal thaw depth and surface settlement at the site of the Circumpolar Active Layer Monitoring (CALM) in the European part of Russia. Kriosfera Zemli IX (4), 20–30.

Mazhitova, G., Malkova, G., Chestnykh, O., et al., 2004. Active layer spatial and temporal variability at European Russian Circumpolar Active Layer Monitoring (CALM) sites. Permafrost and Periglacial Processes, vol. 15, 123–139.

Melentiev, V.S., 1968. Polygonal plateau relief forms and their effect on temperature regime of the active layer deposits, in: Merzlotnye issledovania. Moscow Univ. Press, Moscow, iss. VIII, pp. 75–80. (in Russian)

Melnikov, V.P. (Ed.), 2012. Complex monitoring of the northern taiga geosystems of Western Siberia. Geo Publichers, Novosibirsk, 207 pp. (in Russian)

Naumov, E.M., 1974. Cryoarid soils of the north cold pole, in: Merzlota i pochva. Iss. III. Genezis, geografia i klassifikatsia merzlotnykh pochv. Kn. isd-vo, Yakutsk, pp. 104–110. (in Russian)

Ostroumov, V., Hoover, R., Ostroumova, N., et al., 2001. Redistribution of soluble components during ice segregation in freezing ground. Cold Region Sci. and Technol., vol. 32, 175–182.

Ostroumov, V., Siegert, Ch., Alekseev, A., et al., 1998. Permafrost as a frozen geochemical barrier, in: Proc. of the 7th Intern. Conf. "Permafrost" (Yellowknife, June 23–27, 1998). Coll. Nordicana No. 55, Canada, Yellowknife, pp. 855–859.

Parinkina, O.M., 1989. Microbial flora of the tundra soils. Nauka, Leningrad, 179 pp. (in Russian)

Pavlov, A.V., 1979. Thermal physics of landscapes. Nauka, Moscow, 283 pp. (in Russsian)

Pukemo, M.N., 1987. Cryogenic processes and associated landforms of West Spitsbergen island, in: Kriogennye protsessy / Popov, A.I. (Ed.). Moscow Univ. Press, Moscow, pp. 129–141. (in Russian)

Repelewska-Pekalowa, J., Pekala, K., 2004. Active-layer dynamics at the Calypsostranda CALM site, Recherche Fiord region, Spitsbergen. Polar Geography 28 (4), 326–340.

Romanovsky, N.N., 1977. Formation of polygonal ice wedge structures. Nauka, Novosibirsk, 215 pp. (in Russian)

Shamanova, I.I., 1991. Modern thermokarst on the coastal lowlands of Yakutia and Chukotka, in: Merzlye porody i kriogennye protsessy / Dubikov, G.I. (Ed.). Sb. nauch. tr., Nauka, Moscow, pp. 102–107. (in Russian)

Sharapova, T.A., 1987. Dynamics of cryogenic structure of spot–medalions, in: Kriogennye protsessy / Popov, A.I. (Ed.). Moscow Univ. Press, Moscow, pp. 153–158. (in Russian)

Shatilovich, A.V., Shmakova, L.A., Gudkov, A.V., et al., 2005. Viable *Protozoa* from permafrost deposits and buried soils. Dokl. RAN 401 (5), 715–717.

Shpolyanskaya, N.A., 1978. Permafrost of Transbaikalia. Nauka, Moscow, 132 pp. (in Russian)

Shur, Yu.L., 1988. Upper horizon of permafrost strata and thermokarst. Nauka, Novosibirsk, 212 pp. (in Russian)

Shur, Y.L., Hinkel, K.M., Nelson, F.E., 2005. The transient layer: implications for geocryology and climate change science. Permafrost and Periglacial Processes, vol. 16, 5–17.

Stepanov, I.N., 2006. The relief plasticity theory and new thematic maps. Nauka, Moscow, 203 pp. (in Russian)

Sukhodrovskii, V.L., 1979. Exogenous relief formation in cryolithozone. Nauka, Moscow, 280 pp. (in Russian)

Vadyunina, A.F., Khudyakov, O.I., 1974. Distribution of tundra soils on the relief elements and their physical charcteristics, in: Merzlota i pochva. Iss. III. Genezis, geografia i klassifiktsia merzlotnych pochv. Kn. izd-vo, Yakutsk, pp. 79–94. (in Russian)

Vasilevskaya, V.D., Karavaeva, N.A., Naumov, E.M., 1993. Formation of the structure of soil cover of the polar regions. Pochvovedenie, No. 7, 44–55.

Yashina, S., Gubin, S., Maksimovich, S., et al. 2012. Regeneration of whole fertile plants from 30,000-y-old fruit tissue buried in Siberian permafrost, in: Proc. of the National Academy of Sciences. February 21, 2012, doi: 10.1073/pnas.1118386109.

Yershov, E.D. (Ed.), 1995. Foundations of Geocryology. Moscow Univ. Press, Moscow, pt. 1, 368 pp. (in Russian)

Zabolotnik, S.I., Klimovskii, I.V., 1966. Seasonal freeze-thaw of grounds in the Chara depression, in: Geokriologicheskie uslovia Zabaikalskogo Severa. Nauka, Moscow, pp. 162–172. (in Russian)

Zamolodchikov, D.G., Kotov, A.N., Karelin D.V., et al., 2004. Active layer monitoring in Northeast Russia: spatial, seasonal and interannual variability. Polar Geography 28 (4), 286–307.

Received March 10, 2015