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ALTITUDINAL GEOTEMPERATURE ZONATION IN CENTRAL ALTAI

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By the example of the Altai-Sayan mountain region, the role of topography in spatial heterogeneity of permafrost is traced based on the results of multi-year permafrost studies. It has been demonstrated that conditions of heat and water exchange of ground with the external environment within the Altai-Sayan mountain region change according to the altitudinal zonation, i.e. the consistent alternation of altitudinal belts of seasonally frozen ground and permafrost of intermediate, extensive and continuous distribution.

Altai-Sayan mountain region, latitudinal zonality, altitudinal zonation, permafrost distribution, ground temperature

INTRODUCTION

Studying the spatial patterns of changes in the key components of the natural environment is one of the main aims in natural sciences. The general regularities, which are characteristic of the Earth's geosystem functioning, are the result of the interpenetration and interaction of geospheres (lithosphere, atmosphere, hydrosphere, etc.).

The spatial patterns of geosystems development include latitudinal zonality, altitudinal zonation, and meridional sectorality in the distribution of their components. In general, the geographic zonality of the Earth is due to the influence of two main factors, which are the radiant energy of the Sun and the internal energy of the Earth. Latitudinal zonality is best expressed on the vast plains extending over long distances from north to south.

Altitudinal zonation, representing a sequential change of natural conditions and complexes in the mountains from bottom to top, is distinguished based on different orographic factors [*Kalesnik, 1970*]. The altitudinal zones in the mountains from bottom to top change in a sequence close to the change of latitudinal zones when moving from south to north. Another spatial geographical pattern is the meridional sectioning, due to the continental-oceanic system of atmospheric circulation.

The purpose of the article is to identify the spatial patterns of permafrost conditions in the Altai-Sayan mountain land based on the available literature, indirect data obtained during geological exploration, and current regime observations.

PERMAFROST OF THE ALTAI-SAYAN MOUNTAIN LAND

The spatial patterns of the natural environment are diverse. At the same time, with the appearance of permafrost in the landscape structure of the studied region, all the difficulties of understanding landscape and permafrost relationships increase many times. The main regularity of the development of permafrost strata in the Altai-Sayan mountain land, elongated from west to east by 1,500 km and from north to south by 500 km, is altitudinal zonation. The limited data on the frozen ground of Altai and Sayan did not allow until recently making a clear idea of the spatial patterns of the permafrost development. The previously proposed two-story and three-story schemes for the cooling of the lithosphere in the Southern Siberia mountains [*Grigoryev, 1937; Baranov, 1965; Lugovoy, 1970*] are based on the inversion character of changes in ground temperature (up to certain altitudes) and, accordingly, the distribution of permafrost. In particular, one of the leading specialists in regional geocryology I.Ya. Baranov believed that for areas of harsh continental climate where the stable winter inversions were formed (increase in air temperature with absolute height), a two-story lithosphere cooling scheme was characteristic. Moreover, on the lower floor, the development of the frozen ground is determined by the inversion change of its temperature with height, while on the top floor there is a steady decrease in ground temperature. The thermodynamic parameters of the permafrost existence are determined primarily by the features of the ground heat-exchange, depending on the height and latitude of the area [*Lugovoy, 1970*].

The intermountain depressions of the region are distinguished by the peculiarity of permafrost conditions. The permafrost distribution in the intermountain depressions (Todzhinskaya, Chuyskaya) is of sporadic, intermediate, and extensive discontinuous types, and characteristic of the lower geocryological zone [*Shatz, 1978*].

In the highland zone of the mountain land, the heat-exchange conditions are favorable for the existence of the continuous low-temperature and thick frozen strata. The altitude level of the lower boundary of the continuous distribution of frozen strata varies in the Altai-Sayan mountain land. The tendencies of ground temperature changes with height also differ significantly. The data, obtained in the 1970s by the staff of Permafrost Institute of the Siberian Branch of the USSR Academy of Sciences, have shown that the variants of the structure of altitudinal zonation proposed earlier for the region need to be clarified [*Shatz, 1978*]. An analysis of the spatial heterogeneities of climatic elements indicates that the nature of the change in air temperature with height within numerous intermountain depressions is determined not only by their altitudinal position but also by size and degree of isolation. At the same time, the general tendency for ground temperature within the Altai and Sayan mountain land is reduced to its uneven, but steady decrease with height.

The structure of altitudinal zonation, i.e., the set of altitudinal zones and the sequence of their change, depends on the position of the mountain land in a latitudinal landscape zone and on the relationship with the paths of moisture-bearing air masses, and the number of zones is determined by the height of mountains and the exposure of slopes.

The thickness of the permafrost varies according to the changes in its distribution. So in Central Altai, in the area of the Chagan-Uzun mercury deposit, at a height of 1780 m, its thickness is about 25 m (zone of sporadic distribution), and it increases from 65 m, at a height of 1850 m, to 160 m, at a height of 1930 m (zone of extensive discontinuous distribution). According to the drilling data of the Altai Complex Geological Expedition of Krasnoyarsk Territorial Geological Department, permafrost thickness reaches 400 m at a height of 2920 m (zone of continuous distribution).

Some features of geotemperature field of the Altai-Sayan mountain land have been lit in the proceedings of Trofimuk Institute of Petroleum and Geophysics SB RAS, Institute of the Earth Crust SB RAS, Melnikov Permafrost Institute SB RAS [*Duchkov et al., 1994*].

Thus, within the different regions of the Altai-Sayan mountain land, a steady increase in the area of the permafrost distribution and an increase in its thickness with height are observed, following a decrease in temperature of soils, which is characteristic of the region.

In some areas with relatively mild natural conditions, the altitudinal heterogeneity of ground cooling is reflected only in a change in the depth of seasonal freezing.

The spatial change in permafrost conditions of the Altai-Sayan mountain land is complex. Along with altitudinal zonation, the regularity of meridional sectorality is noted, i.e., the severity of permafrost conditions increases from west to east. The variety of permafrost conditions is characteristic of the entire region and is traced by the change in altitudinal boundaries of geocryological zones [*Shatz, 1978*]. Thus, at 50° N in the western part of the region, the altitudinal limit of permafrost on the slopes of the northern exposure is reduced to 1200–1400 m, and in the eastern part of the region it is at 500–800 m [*Shats, 1978*].

A NEW STAGE IN THE STUDY OF CRYOLITHOZONE

In the last few years, taking into consideration quite poor exploration of the mountainous areas of Southern Siberia in engineering-geocryological terms, the staff of Melnikov Permafrost Institute SB RAS have decided to include the regions of Central Altai in the permafrost-geothermal monitoring system of Siberia. Since 2014, the staff of the Institute for Water and Environmental Problems SB RAS, Altai State University, Gorno-Altaisk State University, Trofimuk Institute of Petroleum and Geophysics SB RAS, OJSC Altai-Geo conducted joint research in the Central and Southern Altai. The work aimed to obtain new information on the seasonally and perennially frozen ground, its altitudinal zonation, and an assessment of the response of the region's natural environment to climate change.

A successful circumstance was the partial coincidence of the studied areas with the route of the proposed Altai gas pipeline, most of which was supposed to be laid along the Ukok Plateau, – a sacred place for the local population. The combination of natural conditions along the route of the gas transmission system leads to the formation of vast mountain steppes and deserted areas, poor infiltration of precipitation, and, as a result, severe bogging. The landscape structure of that territory is described in more detail in the works [*Zheleznyak et al., 2015; Shatz, 2016*].

At the monitoring sites, measurements of ground temperature were carried out using the OnSet automated HOBO logger systems with a four-hour temperature recording interval. That allows us to obtain data on the features of altitudinal zonation of ground temperature, its seasonal variation, extreme values, and to evaluate the dynamics of ground temperature with climate change. Together with the Altai colleagues, the systematization and creation of the database and the geocryological information system 'Altai Cryolithozone' have begun. Currently, 24 sites are equipped with modern logger devices (Fig. 1). The sites have been organized in the areas located in different landscape conditions, including those on the slopes of various exposures in the range of heights from 600 to 3000 m. The depth of the sensors was 1 m. Its choice was determined by the technical capabilities of mine workings preparation and the significant smoothing of the daily temperature fluctuations at that depth. The temperature at a depth of 1 m directly depends on climatic features of the region and conditions of heat exchange on the ground surface.

According to the temperature distribution in the studied range of heights, three intervals are identified, occupying a certain place in the altitudinal zonation (Table 1, Fig. 1). Based on the analysis of changes in ground temperature and in accordance with the landscape map of the Republic of Altai [*Chernykh, Samoilova, 2011*] the territories located above 2200 m are related to the high mountain areas with cryogenic-erosion-denudation surfaces, steep slopes and tectonogenic escarpments. Those territories are characterized by long periods of the negative ground temperature formation (from 200 days or more), as well as minimum temperatures up to –17 and –20 °C. The amplitude of changes in the mean annual ground temperature at a depth of 1 m is 4.2 °C (from 0.5 to –3.7 °C), that is a zone of negative mean annual temperatures (I) with mostly continuous permafrost distribution.

The landscapes of intermountain-basin and middle-mountain types with active denudation and accumulative activity belong to the zone of high variability of ground temperatures (II). That zone is in the range of heights from 1400–1500 to 2200–2400 m a.s.l., and is characterized by a significant variety of the forest, forest-steppe and steppe types of vegetation which determine the intensity of changes in the ground temperature at a depth of 1 m. The amplitude of change in the mean annual temperature in that zone reaches 5.1 °C (from 4.0 to –1.1 °C), and usually,

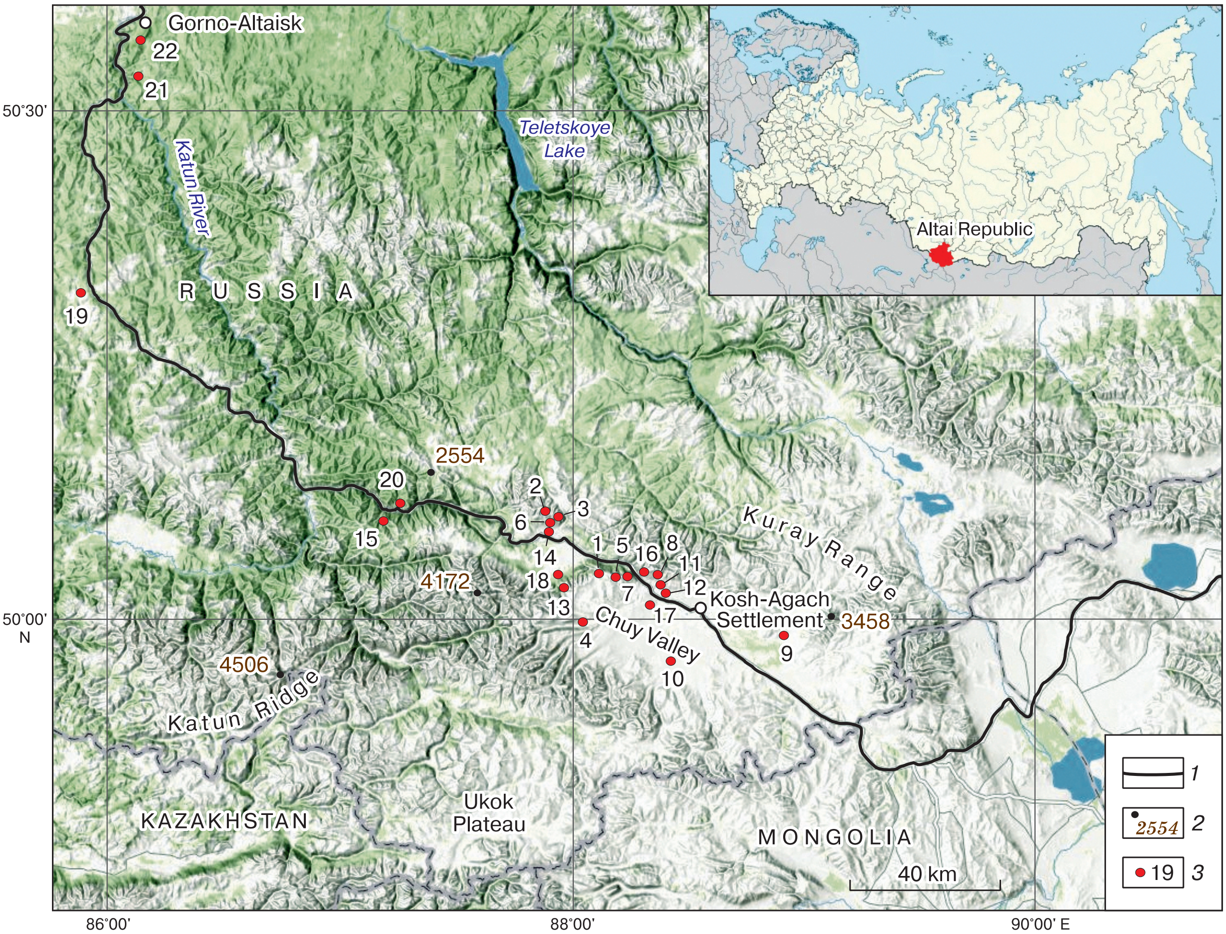

Fig. 1. The scheme of monitoring sites in the Altai-Sayan mountain land.

1 – Highway P256; *2* – an elevation of mountain peak, m a.s.l.; *3* – a monitoring site and its number (see Table 1).

Table 1. **Characteristics of monitoring sites and the mean annual ground temperature at a depth of 1 m**

Number of site	Site name	Abs. height, m	Relief position	Type of vegetation	Sediment composition	Mean annual ground temperature*, °C
1	2	3	4	5	6	7
Zone I: Negative temperature						
1	Sukor	2879	Watershed (alpine zone)	Sparse patches of forbs	Loamy sand-loam deposits with inclusions of gruss-rubble material	–3.7 / –3.2 / –3.3 / –3.4
2	Kuray	2809	Convex watershed (subalpine zone)	Cedar elfin wood and shrubs	Loamy sand-loam deposits with inclusions of gravel and rubble, with their outcrops	– / –2.6 / –2.6 / –2.6
3	Kuray 2	2491	Intermountain glen	Meadow vegetation	Loam and clay with inclusions of rubble; pronounced frost cracking	– / – / –0.1 / 0.1
4	Akairi	2420	Flat watershed	Forbs	Loams and clays with inclusions of rubble, gravel, with their outcrops	– / –0.9 / –0.8 / –0.9
5	Sukor 2	2415	Watershed (alpine zone)	–	Loamy sand-loam deposits with inclusions of gravel and rubble	–0.5 / –0.3 / –0.5 / –0.4
6	Kuray 3	2410	Slope (subalpine zone)	Dense alpine forbs	Loamy sand deposits with inclusions of gravel and rubble	– / 0.3 / 0.5 / 0.4
Zone II: High variability of temperature						
7	Sukor 3	2188	Flat watershed (subalpine zone)	Sparse forbs	Loamy sand-loam deposits, below a depth of 0.5 m those with inclusions of gravel and rubble up to 50 %	1.3 / 2.8 / 2.2 / 2.1
8	Krasnaya vyshka	2013	Convex watershed (subalpine zone)	Sparse forbs	Boulders and pebbles with sand-sandy loam aggregate	2.2 / 3.1 / 2.6 / 2.6
9	Kokorya	1906	Intermountain basin (subalpine zone)	Steppe vegetation	Sand-sandy loam deposits with inclusions of rubble and small pebble up to 10 %	0.6 / 1.2 / – / 0.9
10	Kubai-Tash	1865	Intermountain basin (subalpine zone)	Sparse patches of forbs	Sand and sandy loam with outcrops of individual boulders and pebbles	– / – / 1.9 / 1.9
11	Chagan-Uzun	1852	Flat watershed (subalpine zone)	–	Sand-sandy loam deposits with rare inclusions of pebbles	– / – / –0.3 / –0.3
12	Tuyaryk	1845	Flat watershed (subalpine zone)	Sparse patches of forbs	Sand-sandy loam deposits with inclusions of pebble, gravel and rubble	–1.1 / –1.0 / – / –1.1
13	Chyoltyk	1838	Lower part of slope of north-western exposition; mountain taiga zone	Larch up to 10–15 m high, shrubs, forbs, moss-lichen subsoil	Loam-clay deposits with inclusions of gravel-rubble material and pebbles up to 30 %	– / – / –0.3 / –0.3
14	Kuray 4	1838	Slope of south exposition	Meadow vegetation	Loam-sandy loam deposits with inclusions of rubble and gravel	2.2 / – / 4.0 / 3.1
15	Atchik	1829	Slope of north-east exposition; mountain taiga zone	Larch up to 15–20 m high	Platy shale with loamy aggregate	–0.1 / 0.6 / 0.8 / 0.4
16	Chagan-Uzun 2	1823	Denudation terrace of intermountain basin	Sparse forest	Sandy loam, clayey loam with inclusions of gravel up to 10 %	– / –0.1 / – / –0.1
17	Churyak-Kiuel	1814	Intermountain basin	Individual patches of meadow forbs	Dry, loose sandy loam with inclusions of pebbles and boulders	– / 0.9 / 0.5 / 0.7
18	Ertetchi	1687	Intermountain basin	Meadow vegetation	Boulder-pebble deposits with sandy loam-loam aggregate	– / 2.0 / 2.9 / 2.5
19	Seminsky	1617	Intermountain saddle	Larch up to 10–15 m high, dense forbs	Intensively humified sandy loam with inclusions of rubble	1.7 / 2.5 / 2.3 / 2.2
Zone III: Positive temperature						
20	Tutugai	1406	Watershed	Larch, cedar, spruce up to 15–20 m high, dense forbs	Sandy loam with inclusions of rubble and gravel	4.2 / 5.6 / 6.0 / 5.3

Table 1, continued

1	2	3	4	5	6	7
21	Manzherok	1005	Watershed	Larch, cedar, spruce up to 15–20 m high, dense forbs	Interbedding of wet sandy loam and intensively humified loam with inclusions of rubble and gravel	5.3 / 5.7 / 6.1 / 5.7
22	Tugaya	631	Watershed	Larch, cedar, spruce up to 10–12 m high, dense forbs	Sandy loam and loam with inclusions of rubble and gravel	6.4 / 7.0 / 7.3 / 6.9

*In the numerator: thermometric data for 2014–15/2015–16/2016–17 correspondingly. In the denominator: mean annual temperature.

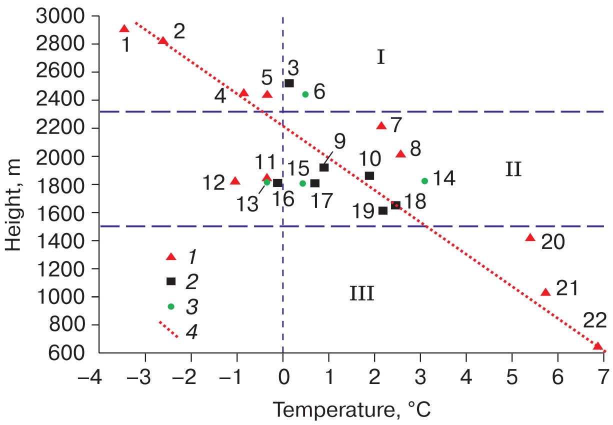

Fig. 2. Change in ground temperature (at a depth of 1 m) with height for various relief elements in the central part of the Altai-Sayan mountain land.

Mean annual ground temperature: *1* – in watershed areas (peaks, ridges); *2* – in intermountain depressions and basins; *3* – on slopes; *4* – approximation line for watersheds. I, II, III – altitudinal zones (see Table 1).

the greatest variability is observed in the positive range. Only in a narrow altitudinal interval of 1700–1900 m, the areas with negative ground temperatures from 0 to –1.1 °C prevail. The dependence of ground temperature on height in that zone (Fig. 2) is more complex than that in the other two due to the local climatic, geobotanical, and soil features.

The landscape belt II mainly includes the lower parts of the slope foots, composed, as a rule, of colluvial-deluvial deposits, and the tongues of inactive or weakly active rock glaciers with a low ice content. That zone is characterized by the extensive, intermediate and sporadic discontinuous distribution of permafrost.

Below absolute heights of 1,500 m, the ground temperature in an active layer has rather high positive values from 2 °C and more, reaching a maximum of 7.0 °C. It is quite natural that permafrost is impossible here at such a high mean annual temperature in the active layer. Moreover, on the monitoring geothermal sites Manzherok (1005 m) and mt. Tugaya (631 m), as shown by geothermal measurements during the year, even a seasonally frozen layer is not formed (Fig. 3). That is explained by the considerable thickness of snow cover (1.5 m or more). Thus, the heights below 1500 m can be attributed to the zone of positive ground temperature (III) in the complete absence of permafrost.

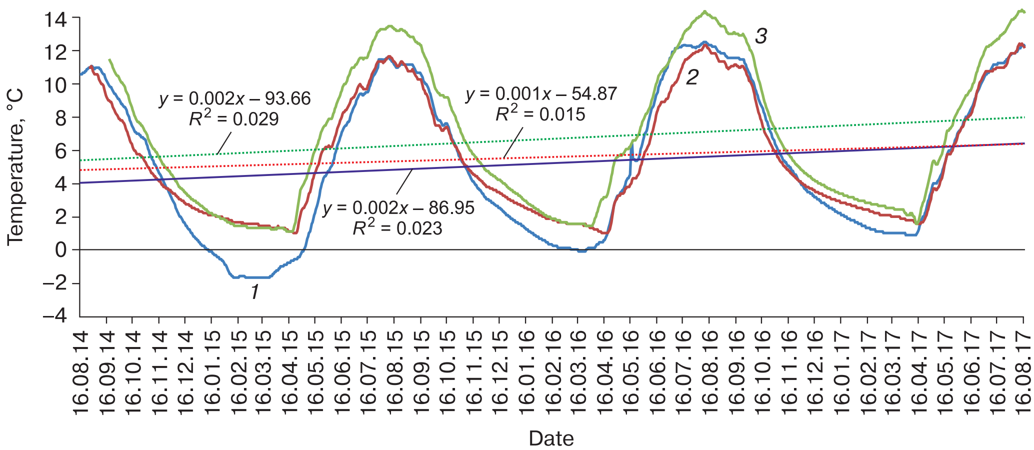

Fig. 3. The course of changes in ground temperature in the mountains (at a depth of 1 m), and its linear trend.

1 – Tutugay (1406 m); *2* – Manzherok (1005 m); *3* – Tugaya (631 m).

Analysis of the mean annual temperature of soils in an active layer for all the orographic monitoring elements of the Altai mountain land indicates the manifestation of the altitudinal zonation regularity (Fig. 2). At that, it should be noted that in the height ranges of 1400–1500 to 2200–2400 m, the relationship between temperature and height is more complex.

CONCLUSIONS

The regularities of changes in ground temperature with height within the limits of the Altai-Sayan mountain land – one of the most diverse regions of Siberia in natural respect – have been considered. The change in ground temperature (at a depth of 1 m) and the distributional features of frozen ground have been estimated. At the lowest heights, there is a zone with seasonally frozen ground, which is replaced by the higher permafrost zones of the discontinuous (sporadic, intermediate and extensive) and continuous distribution. Along with the increase in the terrain height, the thickness of permafrost strata also increases, varying in certain areas of the Altai Mountains from 25 m (at elevation of 1780 m) to 400 m (at absolute height of 2920 m).

Based on regime observations of changes in the ground temperature, the authors identified three intervals that differ in the distribution and ground temperature conditions and occupy a specific place in altitudinal zonation of the region.

Zone I: High-mountain areas (absolute height over 2200 m) of continuous distribution of permafrost, characterized by the mean annual ground temperatures (at a depth of 1 m) of below –0.4 °C and a small amplitude of its change (4.2 °C).

Zone II: Middle-mountain areas (absolute height from 2200 to 1500 m) with landscapes of the intermountain-basin and middle-mountain types, characterized by the extensive discontinuous and (more often) intermediate and sporadic discontinuous distribution of permafrost. The mean annual ground temperature at a depth of 1 m varies from +4.0 to –1.1 °C, and the amplitude of changes in mean annual temperature is 5.1 °C. Those areas are transitional from permafrost to the zone with seasonally freezing ground.

Zone III: Low mountain areas (absolute height below 1500 m), characterized by the absence of permafrost, and in some cases (below the depth of 0.5 m), the absence of a seasonally frozen layer. The mean annual ground temperature (at a depth of 1 m) is almost everywhere more than +2.0 °C.

In the Altai-Sayan mountain land, the spatial change in permafrost conditions is quite complex. Along with altitudinal zonality, the pattern of meridional sectorality is traced there, which introduces adjustments to the formation of natural, including geocryological, conditions.

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