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THE INFLUENCE OF LOCAL FACTORS ON THE STRUCTURE OF PERMAFROST, ZHOSALYKEZEN PASS (NORTHERN TIEN SHAN)

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The results of investigating mountain permafrost of the Alpine type with the methods of thermometry and geoelectric survey are presented. The influence of natural and anthropogenic local factors on the structure of permafrost is demonstrated using geoelectric models. Such factors include the slope exposure, tectonics, and the warming and cooling effects of the foundations of buildings. Changing of the slope exposure is expressed in geoelectric models by decreasing resistivity of the high-resistance horizon, violating its continuity and decreasing its thickness. In the area of faults, a discontinuous or sporadic character of the high-resistance horizon, interpreted as permafrost, is observed. During seismic events, the temperature of rocks increases to reach positive values. According to geophysical data, formation of taliks occurs in the foundations of deformed buildings, in the places of accumulation of snow at snow barriers and under sites covered with asphalt.

Permafrost, temperature, electrical resistivity tomography, fault, talik, electrical sounding, electrotomography

INTRODUCTION

Over the recent twenty years, the issue of evaluating and predicting the condition and evolution of permafrost in different countries of the world under conditions of a changing climate has become one of the priorities for permafrost scientists and other specialists. From this viewpoint, mountain permafrost is a unique object of investigation. Given extreme roughness of the landscape, the permafrost conditions may vary with very insignificant distances at the same altitude, from a few to a hundred meters. This allows arranging simultaneous observations of permafrost of different types in the same rather small area of studies – from rare sporadic permafrost on southern slopes to continuous permafrost on northern slopes. Observations over the permafrost temperature are conducted in wells, with geophysical methods used, in addition to drilling, to determine morphometric parameters of permafrost.

The Zhosalykezen Pass is one of the geocryologically unique objects, located on the Ileysky Ala Tau Ridge in northern Tien Shan. Here geothermal observations over the mountain permafrost and the annual thawed layer have been conducted since 1974. In 2013 geophysical studies of the permafrost structure were carried out with the method of vertical geoelectric survey in its modern modification, electric tomography.

THE CHARACTERISTIC OF THE OBJECT UNDER STUDY

The Zhosalykezen Pass ("the Ochre Saddle") is at the watershed of the Prokhodnaya and Osernaya Rivers (the catchment area of the Bolshaya Almaatinka-Uken Almaty River). Its coordinates are 43°02′ northern latitude and 76°55′ eastern longitude, its altitude is 3,336 m. In the early 1950s, the first Kazakhstan building was built on permafrost here, the Tien Shan alpine research station of the Lebedev Physics Institute of the Academy of Sciences of the USSR. Before the beginning of construction, an erroneous judgment was formed based on the shallow prospect holes made that only seasonal ground freezing took place there. Therefore the first heated brick building on a strip foundation was built without considering permafrost under the foundation. This led to the fact that already in the early 1960s the first signs of the building's deformity started to manifest themselves. In this regard, in 1962 the first permafrost studies were carried out at the orders of Kazpromstroyproject by the researchers of the Permafrost Institute (PI) of the Academy of Sciences of the USSR.

As a result of the works conducted, important data were obtained, in particular, in the adit, the excavation of which was conducted in the late 1950s of the last century on a gentle slope of eastern exposure at an absolute altitude of about 3300 meters. The adit

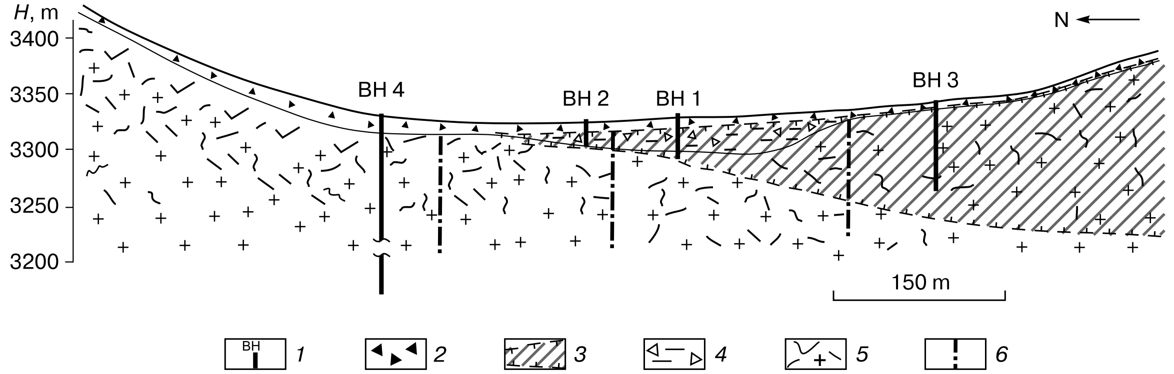

Fig. 1. The geological and geocryological profile of the pass.

1 – numbers of the thermometric boreholes; *2* – slope detritus; *3* – permafrost; *4* – large-boulder moraine deposits with sandy-loamy filler; *5* – bedding rock (granites); *6* – a tectonic fault. *H* – depth, m.

50 m long was bored in the permafrost. The face adit was at the depth of 15 m from the ground surface and was 3 m deep. In 1962, at the depth of 18 m from the day surface, the temperature was –0.8 °C. It is likely that the positive air temperatures in the adit could have caused a warming influence on the permafrost, while the natural ground temperature at the depth of 18 m could have been lower. These figures testify to the fact that the permafrost there was 25–30 m thick. Thus, the first estimate of the permafrost thickness was made for the pass area.

There were boulders the permafrost found in the adit. They constituted 5–10 % of the deposits. The remaining ground consisted of detritus, gruss and fine soil. The bulk density of the frozen ground varied from 1.39 to 2.24 g/cm^3.

Due to continuation of construction of different buildings and structures of the alpine research station of the Lebedev Physics Institute in 1966 and 1973 by the Kazakh State Institute of Engineering Survey (KazSIES), supplementary studies were made at the pass. It was found that the depth of the annual thawed layer varied from 3.3 to 4.7 m. In addition in the borehole 1, 27 m deep drilling was conducted in the granite rock, beginning with 24 m. The temperature in the face borehole was around 0 °C, while the permafrost depth was about 30–35 m.

Currently at the area of about 3 km^2 of the Zhosalykezen Pass there are several buildings and special structures of the Tian Shan alpine research station of the Lebedev Physics Institute, of the Seismology Institute of Kazakhstan, of the Geography Institute of Kazakhstan and of the Kazakhstan alpine geocryological laboratory of the Permafrost Institute, SB RAS.

The pass is in the zones of crush of two connecting tectonic faults of a sublatitudinal trend, which dissect the pass crosswise between the valleys of the Prokhodnaya and Oserskaya Rivers [*Kulikovsky, 1971; Zhdanovich, 2003*]. Related to these faults are the zones of crush (mylonitization) and taliks dividing the permafrost into separate masses.

Thermometric boreholes were drilled in macrofragmental masses of the Upper Pleistocene and Holocene moraines, about 20–25 m thick, underlain by bedding granite rocks. The specific ice content in the moraines varies from 5 to 40 %, while their cryogenic textures are referred to porous-massive and large-schlieren types [*Gorbunov et al., 1996*].

The geological structure and tectonics of the Zhosalykezen Pass were first demonstrated in the geologic-geophysical resistivity profile by *L.G. Filatov et al.* [*1967*]. Based on this study, our geocryological survey allowed us to reveal the general principles in the occurrence and changes in the permafrost depth over a distance of about 500 m (Fig. 1).

At the pass, at the foot of the northern slope, the permafrost depth in borehole 3 is about 100 m (Fig. 1, 2). 200 m down the line, on the horizontal surface of the pass saddle in the tectonic fault zone, the permafrost depth gets reduced to 35–40 m (borehole 1). 80 m further, its depth gets reduced to 13 m (borehole 2); apart from the seismogenic factor, up to 1987 permafrost experienced the impact of the heated building erected on a strip foundation.

According to the drilling data (borehole 4), permafrost is missing at the distance of 200 m from borehole 2 on the slope of southern exposure (Fig. 1, 2).

THE INVESTIGATION METHODS

Since 1974, the Kazakhstan Alpine geocryological laboratory of the Permafrost Institute, SB RAS, has been conducting regular year-round observations over the temperature regimen of permafrost, the annual thawed layer, and seasonally frozen rocks, underlain by non-freezing rocks. These data are the only source of knowledge about the temperature regimen and the behavior of permafrost and annual thawed layer not only for the region in question but also for the entire territory of Central Asia. The geothermal monitoring is carried out across a network of stationary observation points, encompassing different landscapes, depending on the slope exposure and the composition of rocks in the sub-belt of sporadic and discontinuous permafrost. To measure the ground temperature, thermo-resistor sensors MMT-4 with the measurement precision reaching 0.01 °C, which are reliably in use for many years, were used.

In 2013s, geophysical studies were carried out at the pass, using the method of vertical electrical sounding, to be more precise, its modification, electrical resistivity tomography (ERT). The ERT technology is based on multiple electrode measurements and a two-dimensional inversion of the sounding data.

The result is a section of the electrical resistivity of rocks. The resistivity section provides information about the geological and/or geocryological structure of a massif.

The ERT technology differs from the classical vertical electrical sounding by the high spatial density of observation and by the possibility of a two-dimensional approach to interpretation, allowing its use in studying complex geological resistivity profiles.

The electrical sounding profile went along the pass ridge from the southern exposure slope to the northern exposure slope in the alignment of thermometric boreholes. The distance of the boreholes from

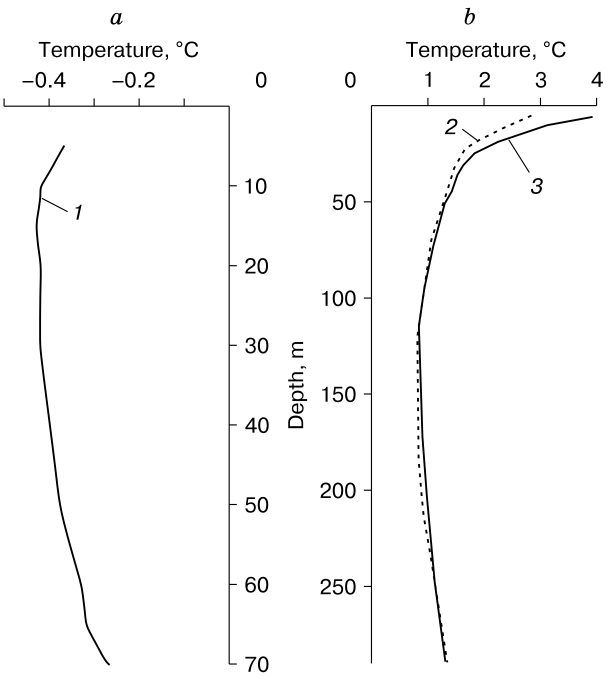

Fig. 2. Distribution of the alpine rock temperature by depths in borehole 3 (*a*) and borehole 4 (*b*) at the Zhosalykezen Pass (absolute altitude 3,330 m).

1 – 22.04.1999; *2* – 09.12.1995; *3* – 05.08.2012.

the profile axis varied from 10 m (borehole 1) to 40 m (boreholes 2, 3). Borehole 4 was located at the distance of 110 m in perpendicular to the profile axis. The profile crossed the areas of natural landscapes and the developed territory affected by the anthropogenic impact on permafrost as the heating factor due to buildings and structures. Sounding was carried out with the Skala-48 multiple-electrode electrical survey station [*Balkov et al., 2014*]. Measurements were made with a series of connected electrodes, corresponding to a symmetrical Schlumberger array with maximum spacing of the feeding line equal to 235 m, which ensured the depths of survey 35–40 m. The resistivity profile inversion of apparent resistivity was conducted in the Res2Dinv software program [*Loke, 2010*].

STUDY RESULTS

At the beginning of the survey (1974) in the area of the Zhosalykezen Pass, the permafrost temperature at the depth of zero annual amplitudes (13–17 m) in the boreholes varied from –0.4 to –0.8 °C. Later over the following 20 years, their temperature in all the boreholes rose by 0.2–0.5 °C [*Gorbunov et al., 1996*]. From 1995 to 2008, the temperature insignificantly varied in the range of –0.20...–0.25 °C. An example of variations in the permafrost temperature regimen at the depth of 20 m over the given period is shown in Fig. 3.

Over the recent 16 years, insignificant (within 0.1 °C) variation of permafrost temperature at different depths (10, 15, 20, 25 m) was simultaneously recorded with periodicity of 10–11 years. Such a cycle was recorded from 1998 to 2008. In 2008–2010, a 0.13–0.15 °C rise in the permafrost temperature was recorded from –0.28 °C in 2008 to –0.13 °C in 2011. From the second half of 2011, a decrease in temperature to –0.20 °C was again recorded. It is to be noted that the permafrost thickness over the entire period of observations was practically the same – about 35–40 m.

In total over the 38-year period, a slightly rising trend (0.01 °C/year) in the permafrost temperature regimen was observed. Should the trend be preserved, in the nearest 20–30 years permafrost will have a practically gradient-free thermal status and the temperature approaching zero.

The climatic conditions in the area of the pass in the early period of observations (1973–1975) were characterized by the following parameters: the average annual air temperature –3.9 °C, the average January temperature –14.2 °C, and the average August temperature +6.4 °C. By 2003, these temperature values rose by 0.4, 0.5, and 0.3 °C accordingly, i.e., the temperature rise gradient was 0.01–0.02 °C/year. Duration of the warm period was about 125 days. There is no frost-free period, and even in June frosts

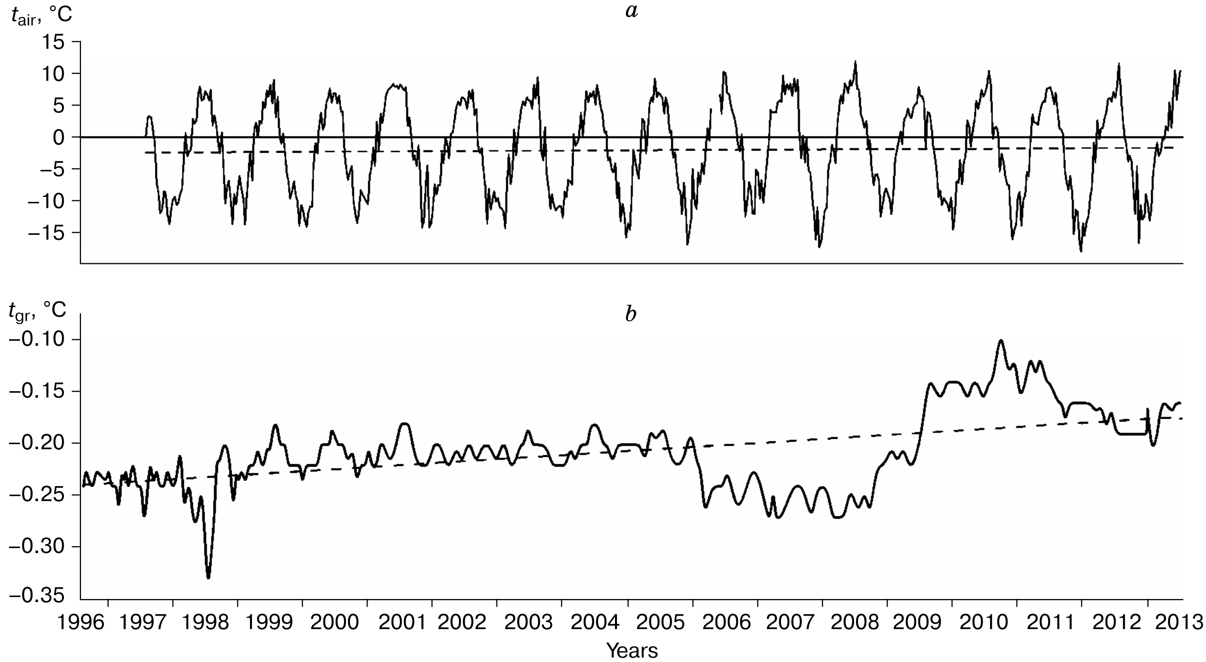

Fig. 3. Changes in the air temperature t_{air} (*a*) and permafrost temperature t_{gr} (*b*) in borehole 1 at the depth of 20 m.

are possible, reaching −5...−6 °C. Steady snow cover gets formed in October to continue till the beginning of June. Due to intense winds, the snow cover formed is not homogeneous, and the depth and density of which essentially vary from place to place, depending on the slope exposure and surface roughness.

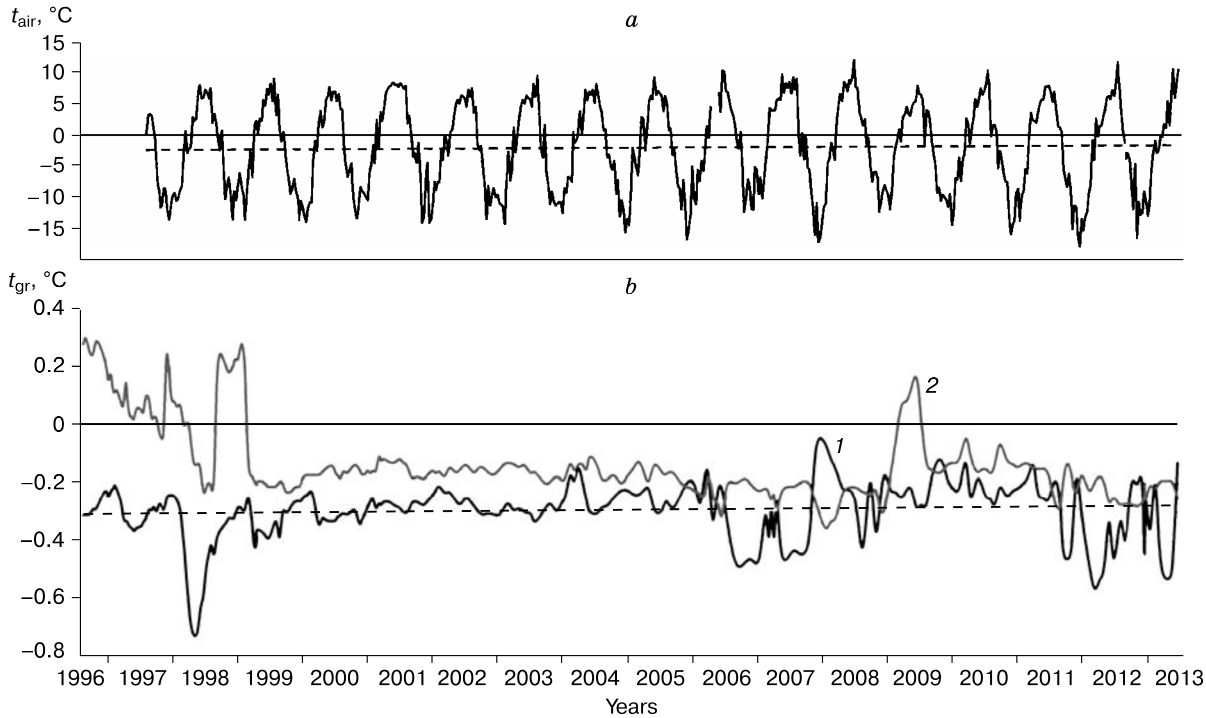

Fig. 4. Changes in the air temperature t_{air} (*a*) and permafrost temperature t_{gr} (*b*) in borehole 2 at the depth of 8.3 m (*1*) and 12.2 m (*2*).

Note that in alpine northern Tien Shan climate warming has been observed over the recent 70 years. The average annual temperature variation trend at the meteorological stations Tuyuksu-1 (the absolute altitude 3,450 m) and Mynzhylki (the absolute altitude 3,017 m) over the said period was 0.02 °C/year [*Piven, 2007*].

The seismogenic factor exerts certain influence on the thermal regimen and the permafrost depth. In the seismically active region of northern Tien Shan, measurable earthquakes regularly occur, which may be accompanied by a rise in the density of thermal flux from the entrails of the earth along the tectonic faults. In particular, the most likely cause of the insignificant permafrost density – 12–13 m in the area of borehole 2 (Fig. 1) and 35–40 m in the area of borehole 1 is the location of the boreholes near tectonic faults. In addition, occasional rise of temperature up to positive values near the mountain foot at the depth of 12.2 m during increased seismic activity is recorded (Fig. 4).

For example, in October 2011 and in January 2013, 2–3 days after earthquakes with the intensity of 2 and 4 points according to the MSK-64 scale, the temperature rose by 0.10–0.18 °C, according to the data provided by the Seismology Institute of Kazakhstan. Later, due to attenuation of the seismic activity, the temperature at this depth decreased again and practically regained its previous values recorded before the earthquake (–0.27 and –0.29 °C).

The change in the permafrost depth and the character of its structure can be clearly seen in the geoelectric section (Fig. 5, *a*).

Continuous permafrost on the northern exposure slope is characterized by the high values of resistivity ρ = 4,500–11,000 ohm·m. Maximum resistivity corresponds to minimum permafrost temperature at the depth of 10–15 m, recorded by temperature logging of borehole 3 (Fig. 2, *a*). The depth of the high-resistance horizon exceeds the depth of the survey.

As the profile moved towards to the southern exposure slope (from south to north), permafrost resistivity got reduced to 2,000–5,000 ohm·m, the geoelectric section became unstable, and in the area of tectonic disturbance decrease in the high-resistance horizon was observed. Reduction of ρ is related to the growth of permafrost temperature, caused by both the change in the slope exposure and, possibly, by the increased thermal flow from the entrails of the earth along the tectonic fault.

On the horizontal surface of the saddle in the area of the tectonic fault, the high-resistance horizon associated with permafrost becomes fragmentary, reflecting sporadic distribution of permafrost (Fig. 5, *a*). The value of ρ here varies from 780 to 5,000 ohm·m, depending on the lithological composition, temperature and ice content. At the foundation of the resistivity profile, rocks with resistance of about 50 ohm·m correspond to mylonites of the zone of crush, as such a low value of resistivity of alpine rocks can be explained only by the presence of the loamy fraction. On the southern slope, the resistivity of the slope detritus and of crevassed granites is 780–1,600 ohm·m, suggesting their thawed condition – borehole 4 (Fig. 1, 2, *b*).

In accordance with the character of resistivity distribution along the profile from south to north, areas of continuous (I), discontinuous (II) and sporadic (III) types of permafrost distribution can be identified (Fig. 5, *b*). Both the structure of the high-resistance horizon (from the continuous type to the discontinuous and sporadic types) and its resistivity accordingly change. Total decrease of the value ρ of the high-resistance horizon, when the permafrost distribution type is changed from the continuous to sporadic type, is related to the increase of permafrost temperature.

Thus, the geoelectric section is in good agreement with the geocryological ideas of the permafrost structure of the Zhosalykezen Pass obtained as a result of analyzing thermometric data of many years of observations.

The above data refer to the areas of natural permafrost development. Somewhat different was the change in the thermal regimen of permafrost in the developed territory under the impact of human economic activity. Borehole 2 (Fig. 1) was located at the distance of about 3 meters from a heated brick building built on a strip foundation without permafrost consideration in the 1970s of the twentieth century. In the process of building use, the rise of the permafrost temperature and the increase in the depth of the annual thawed layer took place, which contributed to formation of a certain thawing cup under the building. That was accompanied by the irregular rock stratification during thawing and by the appearance of significant building deformities with annual increase in the intensity of the manifestation of the destructive effect. In the end, the building got deformed and had to be torn down in 1986–1987.

After the heating impact of the building terminated, aggradation of permafrost to the natural conditions started. Since 1995, the temperature has been –0.2...–0.3 °C (Fig. 4), which is similar to the permafrost temperature under natural conditions (Fig. 3).

Opposite the torn down building another one-story building built on a strip foundation is now getting deformed (Fig. 6, *a*). The greatest soil subsidence at the foundation is recorded at the southern side of the building, where the wall is heated most. In addition, the proximity of the tectonic disturbance ensures the permafrost temperature to be around 0 °C; therefore the slightest changes in the thermal balance result in the permafrost degradation at the foundation. At the geoelectric section, the geocryological situation is manifested at the foundation of the build-

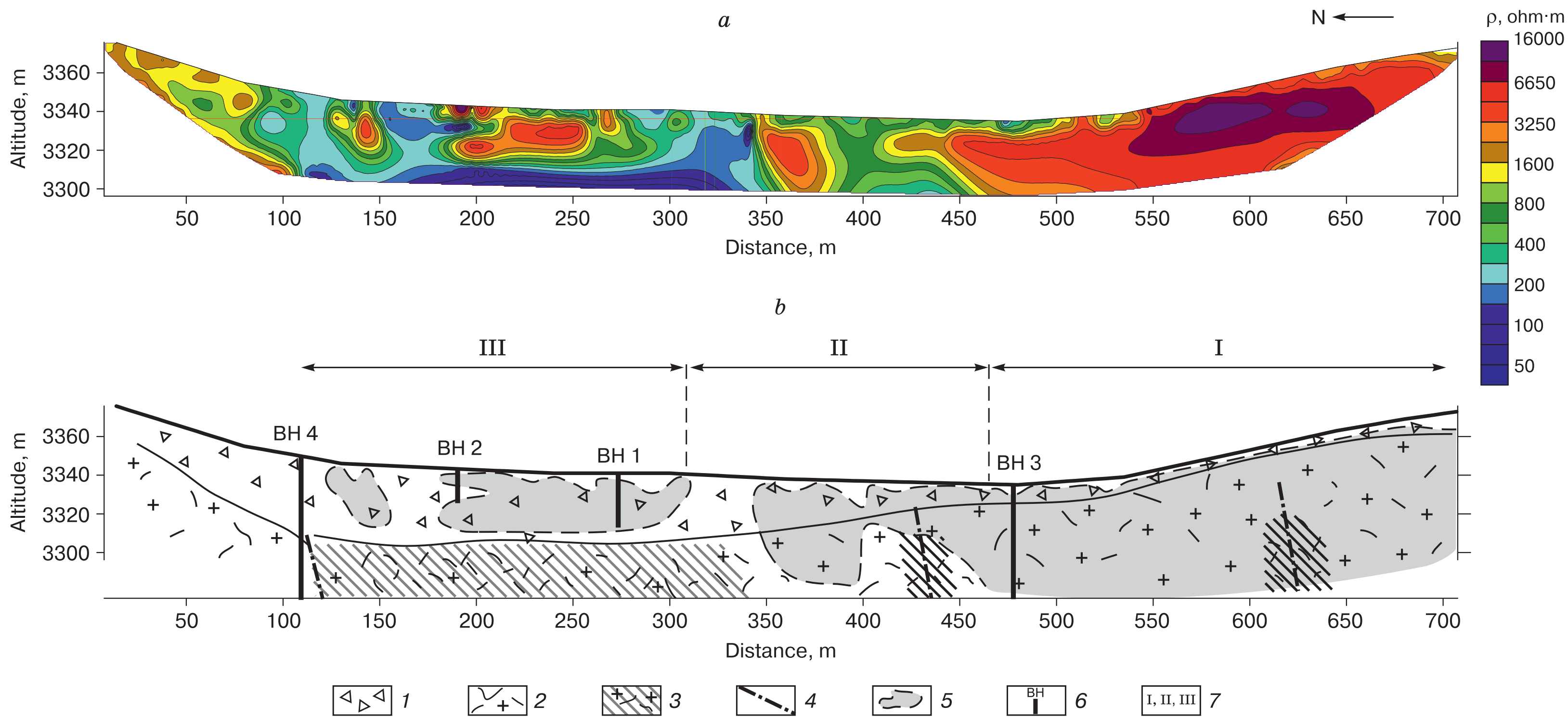

Fig. 5. The geoelectric profile of the Zhosalykezen Pass (*a*) and its interpretation (*b*):

1 – slope and moraine deposits; *2* – crevassed granites; *3* – zones of crush and mylonitization; *4* – tectonic disturbances; *5* – permafrost; *6* – projections of the thermometric boreholes on the profile; *7* – distribution areas of permafrost of different types: I – continuous; II – discontinuous; III – sporadic.

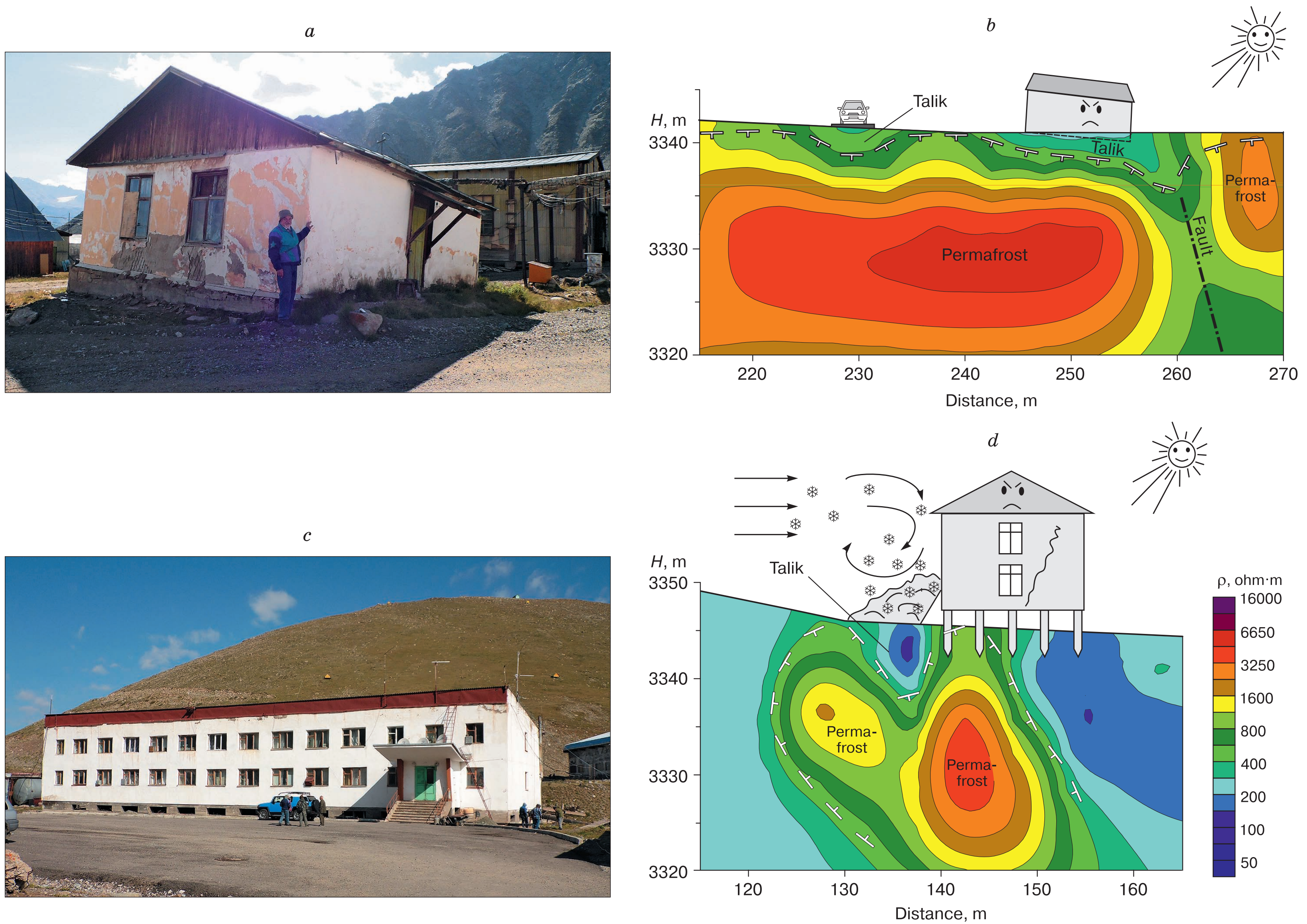

Fig. 6. Deformed buildings erected on a strip foundation on permafrost (*a*) and with ventilated cellar (*c*), and geoelectric profiles (*b*, *d*).

ing and in the adjacent territory (Fig. 6, *b*). In the near-the-surface part of the geoelectric section under the building, a talik is recorded as an asymmetric area of decreased resistivity. The size of the low resistivity area (the talik thickness) increases towards the maximum building subsidence. Another local anomaly of the low resistivity, interpreted as a talik, is recorded under the asphalt-paved area and the motor road (Fig. 6, *b*). Lower in the geoelectric section, the soils are characterized by the high values of $\rho = 800–5000$ ohm·m, suggesting their frozen condition.

Another building built on the first principle (with permafrost preserved) on a pile foundation with a ventilated cellar is also subject to deformities (Fig. 6, *c*). They are manifested on the building facade as subsidence cracks up to 2 cm wide. The emergence of deformities of such a type may be related both to a different carrying capacity of the soil under the foundation and to the seismic impact. It is quite likely that both these factors influence the building stability. On the side of the building, the ERT profile passed, a fragment of the geoelectric section of which is shown in Fig. 6, *d*. In the geoelectric section permafrost is identified by a high-resistance anomaly. The anomaly shape reflects the impact of the local factors on the permafrost structure.

On the northern side under the building, a rise of the high-resistance area towards the surface is recorded, which probably reflects newly formed permafrost in the ventilated cellar in the shaded area. At the same time, on the southern (sunny) side of the building the soils are characterized by the low values of $\rho = 100–200$ ohm·m and are interpreted as thawed. Thawed and frozen rocks under the building foundation have different physical and mechanical characteristics, which, given a seismic impact, may result in varying deformities of the structure and in the emergence of cracks. On the windward side of the building, there is a snow-stopping barrier, which prevents snow drifting of the ventilated cellar. In the winter period, a large amount of snow gets accumulated – up to 3–4 m. The snow drift causes a warming effect, resulting in the formation of a talik, expressed as a local anomaly of low resistivity in the geoelectric section (Fig. 6, *c*).

DISCUSSION

The impact of the seismogenic factor on the rise of temperature and reduction of the permafrost thickness was recorded in Inner Tien Shan on the northwestern macro-slope of Ak-Shyirak Ridge. Here beyond the tectonic fault Pleistocene moraine deposits at the altitude of 4,070–4,030 m are 240 m deep frozen and have the temperature of –4.3 °C. In the boreholes located in the area of the tectonic fault, the high density of the deep-earth thermal flows rises the rock temperature to –2.2 °C and significantly (up to 145 m) decreases the permafrost thickness [*Gorbunov et al., 1996*].

The impact of tectonics on the permafrost morphology is corroborated by the materials of special studies in the other seismically active mountainous regions. In the Chuiskaya Depression (Mountainous Altay), the width of which is about 30 km, the drilling and geoelectrical sounding data obtained in 1977 showed the permafrost bottom depth in the zone of the tectonic fault to be 73 m. After the earthquake of 2003 with the magnitude of 7.3, the permafrost capacity decreased to 30 m due to its degradation on the bottom side under the influence of increased thermal flow along the tectonic fault from the entrails of the earth [*Olenchenko et al., 2011*]. The impact of the tectonic factor on the geological structure and the permafrost zone has been recorded in the southern areas of Yakutia [*Buldovich et al., 1976*].

The results of electrical sounding at the Zhosalykezen Pass have shown that the high-resistance horizon, associated with permafrost, has reduced thickness and discontinuous or sporadic structure in the intersection of tectonic disturbances. The temperature rise of the alpine rocks recorded in the thermometric boreholes in the period of earthquakes allows one to presume that reduction of permafrost thickness and the sporadic type of permafrost structure in the saddle of the Zhosalykezen Pass are related to the thawing impact of the thermal flow along the tectonic fault.

It is clear that the impact of the tectonic factor on the permafrost structure of the pass overlays the effect of the change of slope exposure from northern to southern sides. According to electrical sounding (Fig. 5), with the total decrease in the permafrost thickness, there are local changes in the permafrost structure in the zones of tectonic faults.

The anthropogenic impact is another local factor determining the permafrost structure of the Zhosalykezen Pass. The warming effect of the building on a strip foundation resulted in the formation of a talik in the high-temperature permafrost area of the tectonic fault, which, in its turn, caused the building deformity (Fig. 6, *a*, *b*). If engineering structures contribute to accumulation of snow, this may also result in formation of taliks in the permafrost (Fig. 6, *d*). At the same time, the conditions of a ventilated cellar contribute to further formation of permafrost. Thus, slight changes in the radiation and heat balance in the opposite directions may lead both to degradation and aggradation of permafrost.

CONCLUSIONS

The geothermal observations conducted in the area of the Zhosalykezen Pass over the recent 38 years have revealed a slight response of permafrost to the current climate warming: the rising trend in the temperature regimen of the permafrost was 0.01 °C/year. This indicates rather high thermal resistance of permafrost in northern Tien Shan to climatic changes.

The impact of the local factors on the permafrost distribution, temperature, and thickness at the pass has been determined. Such factors include slope exposure, fault tectonics, and the anthropogenic impact.

When the slope exposure changes from northern to southern one, a logical change in the permafrost distribution is recorded. Continuous permafrost on a northern exposure slope is characterized by high (4,500–11,000 ohm·m) resistivity values and by permafrost thickness of about 100 m. On a southern slope, according to the drilling, permafrost is missing, which is confirmed by the low resistivity values (780–1,600 ohm·m).

The influence of tectonics in the area of fault intersection on the horizontal surface of the pass saddle ensures a discontinuous and/or sporadic character of permafrost distribution. The geoelectric section becomes unstable, and resistivity changes from 780 to 5,000 ohm·m. Here a rise of temperature at the permafrost bottom was recorded up to positive values in the period of increased seismic activity, while the permafrost thickness decreased from 40 to 13 m.

The impact of the anthropogenic factor on the permafrost structure of the Zhosalykezen Pass is expressed in the rise of temperature and in the increase of the depth of the annual thawed layer under heated buildings erected on a strip foundation without considering permafrost, which contributes to formation of certain thawing and talik cups under them, which can be identified in the geoelectric section as areas of decreased resistivity.

Formation of a talik is recorded geophysically within the snow barrier area, where the snow drift has a heating effect.

The signs of newly formed permafrost were found under the building erected on a pile foundation with a ventilated cellar, where a rise in resistivity of soils in the near-the-surface layer was recorded.

Thus, modern geophysical studies have allowed the specific features of permafrost morphology of the Zhosalykezen Pass to be revealed and the impact of local factors on its structure to be evaluated.

The specific features of the alpine permafrost, in particular, its locality, provide an opportunity of conducting research and monitoring of the condition of permafrost of all types of its distribution in a relatively small territory. From this viewpoint, the Zhosalykezen Pass is a testing ground for organizing and conducting geophysical, geothermal, and geocryological observations over the condition and behavior of permafrost and of annual thawed rocks in different landscapes, including scientific tourism. Such studies allow revealing and evaluating the impact of different local factors on the current condition of the alpine permafrost zone and making scenarios of its development in the future in relation to climatic changes and the ever increasing anthropogenic impact on the alpine ecosystems.

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