THE STRUCTURE OF A SITE WITH THERMO-SUFSION PROCESSES WITHIN BESTYAKH TERRACE OF THE LENA RIVER, ACCORDING TO GEOPHYSICAL DATA

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The new data on geological structure of the area with developing thermo-suffusion processes obtained from electrical resistivity tomography and ground penetrating radar techniques allowed geoelectrical imaging of pressure filtration channels, and outlining potential thermo-suffosional sinkholes and collapse structures. Based on the obtained geophysical characteristics, the phenomenon of permafrost degradation was discovered above the intrapermafrost aquifer, to a depth of the active layer base. Permafrost degradation is one of the forces that lead to groundwater infiltration channel collapse, prompting thereby the development of sinkholes on the land surface. The collapsed top layer of the intrapermafrost aquifer changes the direction of groundwater flow, which, in turn, precludes the warming effect of the groundwater and provokes refreezing of the sand massif around thermo-suffusion sinkholes. We found a correlation between variations in electrical resistivity in permafrost and changes in the vegetation cover concentration: the frozen ground resistivity is higher for shaded areas overgrown with a larch forest, than for areas overgrown with sparse pine forest. The research results have provided insights about the formation mechanism of thermo-suffusion sinkholes, and the geometry of water-bearing taliks of the supra/intrapermafrost complex.

INTRODUCTION

Suffusion is an instrumental factor in developing natural and anthropogenic landscapes. Recent global climate changes have triggered dangerous exogenous processes in the permafrost zone, which among other forcings include suffusion processes whose intensity has shown a 1.6-fold increase in Central Yakutia as compared to the 1960s [Gagarin, 2013]. Unintuitive occurrences of suffusion sinkholes and collapse structures present a potential hazard to motorways and railroads, and in some cases to residential areas. The suffusion hazard risk assessment in such regions requires analyzing the factors, patterns and mechanisms inherent in suffusion processes. The improved thorough understanding about ground waters occurrences, their distribution patterns and formation conditions can be used to estimate groundwater resources. Pressurized groundwater, being largely responsible for the inception of suffusion processes, alternatively, can serve as a source of household and potable water supply for the communities.

The surface process geomorphology interprets thermo-suffusion specific to permafrost areas to be a mechanical removal of fine particles from frozen deposits during their thawing, resulting in the surface subsidence [Embleton and Thorne, 1979]. A unique permafrost-hydrogeological complex confined to the Bestyakh terrace of the Lena river, providing an example of thermo-suffusion evolution, has been studied since the 1940s of the last century [Maksimov and Tolstikhin, 1940; Efimov, 1952; Anisimova, 1969, 1971; Shepelev, 1972, 1987; Boitsov, 2002; Gagarin, 2012, 2013, 2015]. The extensive studies of the Bestyakh terrace of the Lena river have thus far allowed to establish characteristic permafrost-hydrogeological features of its structure; to assess the influence of the rock mass thermal regime variability in the supra- and intrapermafrost waters discharge zone on the thermo-suffusion processes intensity; to analyze the role of hydro-climatic drivers in this process activation and study its annual and long-term dynamics, along with the forms of the surface layer collapse in its wake.

The research primarily aimed to obtain new data on the structure of the thermo-suffusion process-affected site, using modern geophysical technologies, to clarify the existing concepts of the suffusion sinkholes formation mechanism and improve understanding of water conduits geometry in the intrapermafrost taliks complex.
THE OBJECT OF STUDY

The study site is located in Central Yakutia, 50 km south of Nizhny Bestyakh village, within the 4th Lena river floodplain (Bestyakh) terrace whose terrain is relatively flat, while within the studied region it is complicated by the Ulakhan-Taryn stream valley originated from the eponymous spring. Its incision depth is about 30 m. In the lower part, the Bestyakh terrace deposits are represented by up to 50–80 m thick alluvial medium- and fine-grained non-saline sands with a gravel-pebble layer at the base. These deposits are dated to the Middle Pleistocene. Quaternary deposits are underlain by middle Cambrian limestones, which are fractured in the upper part [Kamaletdinov, 1982; Ivanov, 1984].

The study area characterized by continuous permafrost distribution with thickness averaging 200 m, which increases in some areas up to 400 m. Permafrost temperature at the depth of annual thermal cycle on flattened sites of the terrace is fairly high (–0.2 °C), whereas in the Ulakhan-Taryn stream valley it falls down to –2.5 °C. A system of widely distributed through and closed taliks of radiation-thermal, hydrogeogenic and hydrogenic types is a characteristic permafrost-hydrogeological feature of the Bestyakh terrace of the Lena river [Efimov, 1952; Anisimova, 1971; Shepelev, 1987; Boitsov, 2002; Mikhailov, 2010].

There are five groups of thermocirques (marked A, B, C, D and E) acting as groundwater discharge areas within the Ulakhan-Taryn stream valley, with only thermocirque E localized in the study area (Fig. 1). Ground waters are pressurized, fresh, bicarbonate calcium-magnesium in composition, their salinity is 0.2 g/L, whose seepage on the day surface occurs most often as pressure streams of varied diameters (up to 0.5 m).

Given that sand is transported in huge amounts by the groundwater flow, collapse structures and sinkholes are formed on the terrace surface, their diameters varying from the first meters to 30 m and a depth from 1–2 to 15 m (Profile 6). As suggested by [Gagarin, 2013], both cryogenic pressure and filtration flow rate will increase at the result of the sediment freezing within the groundwater discharge area. At this, groundwater produces thermal and mechanical effect on the overlying frozen deposits causing thereby their erosion, and prompting formation of cavities in the sand massif whose topmost layer will collapse once the critical ratio between the width and height of the cavity is reached, with a suffosion sinkhole subsequently forming on the surface.

In April 2014, a hydrogeological well (BH 2-14 in Fig. 1) drilled in the study site tapped two aquifers. The first is located in the 2.5–8.0 m interval, with the water level in the borehole established at a depth of 2 m. This aquifer exhibited running properties. The second horizon with a thickness of 3 m, underlain by permafrost, was tapped at a depth of 16 m. The intrapermafrost water level in the borehole was also established at a depth of 2 m, thus suggesting the hydraulic connection between the aquifers.

RESEARCH METHODS

The study site was investigated by the electrical resistivity tomography (ERT) and ground penetrating radar (GPR) methods. The ERT technique belongs to a group of methods of electrical resistivity and represents by itself an advanced modification of vertical electric sounding (VES) method [Bobachev and Gorbunov, 2005; Loke, 2009; Balkov et al., 2012]. The measurements were performed using “Skala-48” multi-electrode equipment [Balkov et al., 2012]. The sequence of electrodes connection was consistent with the forward and reverse pole-dipole arrays, the depth of investigations was about 85 m. The measurement interval along the profile was 5 m. GPR surveys were conducted at the study site along 6 parallel profiles with a length of 230–240 meters each (Fig. 1). One of the profiles (No. 6) was extended in both directions to 595 m by adding 235 m to the profile beginning, and 125 m to its end.

Fig. 1. General scheme of geophysical profiles:
1 – shrubby vegetation; 2 – predominantly coniferous forest; 3 – mixed forest; 4 – peat bog; 5 – thermocirque E; 6 – thermosuffosion sinkholes and collapse structures; 7 – frost mound; 8 – ground water seepages; 9 – geophysical profile and its number.
The data obtained from electrical resistivity sounding were processed using the Res2Dinv and Res3Dinv Software [Lake, 2009], resulting in 2D (cross-sections) and 3D subsurface models. Horizontal sections of the 3D geoelectrical model represent resistivity distribution maps for different depths.

Ground penetrating radar (GPR) method is one of the radio-frequency method of electrical prospecting based on a difference in the dielectric constant of rocks. The GPR method was used in combination with ERT as a supplementary method. The use GPR measurements allowed detecting the active layer base position at the time of the surveys, and establishing waterlogged regions in the cross-section. The GPR method was also combined with the OKO-2 subsystem with an antenna unit at central frequency of 150 MHz. The GPR data processing with the use of Geoscan32 Software provided the resulting time cross-sections of reflected electromagnetic signal (radargrams) along the profiles. The reflections on the time cross-sections allowed establishing position of reflectors, while average dielectric permittivity of deposits which constituted 6 RU (relative units) was derived from the diffraction hyperbolas generated by inhomogeneities in the cross-section [Vladov and Starovoitov, 2004]. The experimentally determined dielectric constant value was used for time-to-depth conversion.

The 2014 geophysical surveys were conducted mid-July, when the active layer gained a considerable depth within the study area.

RESULTS AND DISCUSSIONS

Interpretation of the ERT data

Fig. 2, a shows a geoelectrical cross-section along Profile 1 set up in the upper portion of the gully and positioned normal to the strike of thermocirque E (Fig. 1). The profile begins in the floodplain of the Ulakhan-Taryn river, and in the 80–90 m interval intersects the 4th floodplain terrace of the Lena river, with increment of about 14 m. The developing suffosion sinkholes were reported in the vicinity of 120, 180m-points, and a gully – at the 230m-point. Notably, a sinkhole nearby 120m-point was older than a collapse structure in the range of 180m-point, where fresh subsidence cracks were manifest. The gully bottom was covered with water (230m-point).

A high resistivity region (3500–7000 Ohm-m) on the resistivity profile of the stream bed (0–40m-points) is related to the presence of very ice-rich deposits exposed in the cracks of a hydro-laccolite crossed by the profile. From the 7–10 m depth interval a thin low resistivity layer (not more than 400 Ohm-m) is present in the section, interpreted to be an intrapermafrost talik confined to a stream bed. Anomalously high resistivity (5000–15 000 Ohm-m), reflecting the ice-rich permafrost structure of the sedimentary strata, is reported in the lower part of the section.

At the foot of the terrace slope, resistivity tends to decrease to 800–1000 Ohm-m, due to the presence of talik, through which the intrapermafrost waters discharge. Whilst the upper part of the terrace section is composed of high resistivity sands (1200–5000 Ohm-m), which is accounted for their low moisture content within the active layer and their permafrost state at a depth more than 3 m. The lower resistivity zone within the 140–160 m profile interval m at depths from 7 to 14 m is associated with the groundwater filtration area whose aquiclude is the layer of frozen sands (which is impermeable when frozen) with resistivity of 1000–2700 Ohm-m, and those with even greater electrical resistivity (3500–7000 Ohm-m) compose the gully bottom in the vicinity of 230m-point (Fig. 2, a).

The intensive isometric low resistivity anomalies (90–250 Ohm-m) revealed at depths averaging 14 m in the 95–115 m and 175–195 m profile intervals (Fig. 2, a) are of particular interest. The authors believe these low resistivity localites to be associated with major channels of pressure-infiltration of intrapermafrost waters. A currently ongoing subsidence of the surface is reported above one of these channels in the vicinity of 180m-point (sinkhole 2 in Fig. 2). Notably, sands tend to have lower resistivity (800–2000 Ohm-m) above the identified filtration channel, which is indicative of their thawed state. The warming effect of intrapermafrost groundwater may have triggered the permafrost degradation in the overlying stratum, which resulted in the filtration channel cover collapse, with a sinkhole-shaped subsidence subsequently forming on the surface.

Sands covering the filtration channel in the 95–115 m profile interval are characterized by high resistivity (1500–2500 Ohm-m), which implies their frozen state in the zone underlying the seasonal thaw depth and extending into the aquifer top, whose projection on the day surface bear no evidence of either sinkholes or collapse structures, though. Most likely, this filtration channel formed relatively recently, and the thawed zone in the channel cover has not yet developed.

The authors attribute the remarkably high surface resistivity in the area of an old sinkhole (sinkhole 1 in Fig. 2, a) to the sediment freezing through after the inception of subsidence. A barrage formed on the filtration flow path by the collapsed aquifer cover prompting thereby the reduction of groundwater flow and change in the direction of its paths. Given that the warming effect of groundwater increasingly declines thereat, the rock mass is gradually subjected to freezing.

From a depth of about 40 m, the section is in part characterized by low resistivity (<400 Ohm-m) and is found to be completely thawed, whereas high resis-
Activity zones within the 150–190 m profile interval, from a depth of about 60 m, are interpreted to be the frozen carbonate deposits composing the base of the Bestyakh terrace.

**GPR data analysis**

The GPR profile holds the information on the structure of the upper part of the cross-section to a depth of 10 m (Fig. 2, b). The radargram for the stream floodplain shows an intensive reflector (M in Fig. 2, b) at a depth of 2.0–3.5 m, corresponding to the current position of the active layer base. Within the 130–155 m profile interval of the terrace surface, the GPR data show reflectors corresponding to the upper limit of the active layer (labeled K in Fig. 2, b) and the aquifer cover (labeled B in Fig. 2, b).
According to the GPR data, the upper limit of the active layer occurs at a depth of about 3 m, and that of the aquifer – at a depth of 8 m, which has good agreement with the ERT results. The radargram regions accounting for developing sinkholes are characterized by reflections in the zones of disturbed structure. Whilst the reflections beneath the freshly formed sinkhole 2 are discernible at a greater depth than beneath the old sinkhole (sinkhole 1 in Fig. 2, a).

At a first approximation, the radargram and geoelectric cross-section showed a fairly good correlation between the identified reflectors from the media differing in dielectric permittivity and the boundaries on the ERT imagery (Fig. 2, c). Reflector M specifies the position of the permafrost table in the stream floodplain. Given that the active layer has a very low moisture content in the upper part of the terrace section, the deposits are not differentiated in terms of resistivity there.

However, the GPR data show that the upper limit of the active layer is distinctly distinguished. The lower resistivity zone in the 140–160 m profile interval is marked on the radargram by a fragmentary imaged reflector B whose signal phase changes. This indicates that the electromagnetic wave propagates through the nonconducting into conducting (watered) medium, bearing a strong evidence that ERT and GPR data complement each other.

**Comparing drilling data and geophysical survey results**

In Fig. 3 shows the geoelectrical cross-sections (along Profiles 5 and 6) that include the borehole BH 2-14 projection and marked aquifers. The well is located at a distance of 20 m from each of the profiles. Notably, BH 2-14 represents a wild-cat well drilled in April 2014, prior to conducting geophysical studies. The ERT survey application in July 2014 revealed that the drilled well did not penetrate any of the filtration channels identified by the ERT data.

On the cross-section along Profile 5, the upper aquifer is distinguished by a local low resistivity zone, while the lower aquifer is not identifiable because of either the small dimensions or the unavailable ERT survey during that period. On the section along Profile 6, the drilled well projection on the profile coincides with location of high resistivity deposits, which are largely represented by frozen sands. However, the geoelectrical cross-section pattern changes significa-

![Fig. 3. Geoelectrical cross-sections along Profiles 5, 6 and BH 2-14 projection on the cross-sections.](image-url)
tly to the right of the borehole projection, which implies that this part differs from the drilling results.

A comparison analysis of the drilling and ERT data has shown that the geocryological cross-section based on the drilling results obtained in April is out of keeping with the geoelectrical cross-sections for Profiles 5 and 6 obtained in July. On the one hand, this reminds us that we are dealing with a highly dynamic hydrogeological system with variable geometry and discharges. It is therefore very likely that the aquifers detected in April were not the same water bodies in July.

On the other hand, we should bear it in mind that the borehole is located at a distance of 20 m from each profile. Having analyzed the resistivity cross-sections, we can safely say that neither of them contains a layer longer than 20 m, persistent in terms of thickness and electrical resistivity. Comparison of the obtained cross-section of borehole distanced from the profile with the geoelectrical imaging would not be completely correct, though.

Influences of local factors on geoelectric structure of the cross-section

Local factors influencing the structure of permafrost include slope exposition, relief elements, vegetation type, areas of snowdrift accumulation, surface shading, bogginess and others whose action/interplay is largely responsible for changes in permafrost temperature, ice content, active layer depth and represent the signatures that permeate geoelectrical fields. The ERT measurements along the incremented Profile 6 allowed assessing the permafrost strata structure at the interface of the relief elements – the Bestyakh terrace surface and the of the Ulakhan-Taryn stream valley. This profile was extended into the Ulakhan-Taryn stream floodplain and onto the terrace surface. Its length totaled 595 m. Figure 4 shows the geoelectrical cross-section along the profile line and its interpretation.

Likewise Profile 1, the upper part of the cross-section >15–25 m in depth within the terrace is characterized by high resistivities (1000–5000 Ohm-m),

![Geoelectrical cross-section (a) along Profile 6 and its interpretation (b):](image-url)

Fig. 4. Geoelectrical cross-section (a) along Profile 6 and its interpretation (b):

1 – Middle and Upper Quaternary alluvial deposits of the Bestyakh terrace, sands up to 60 m in thickness; 2 – gravel-pebble material; 3 – interbedding of sands and sand-loams; 4 – Lower Cambrian deposits, limestones, dolomites with marl interlayers; 5 – highly fissured fault zone within the bedrock; 6 – very ice-rich deposits, interlayers of ice; 7 – permafrost limit; 8 – electrical data-derived permafrost temperature; 9 – sinkholes: young (a), old (b); 10 – filtration channel in the intrapermafrost talik; 11 – sparse pine forest; 12 – dense larch forest with thick undergrowth; 13 – shrubs; 14 – grassy vegetation of floodplain wetland.
which is accounted for by the frozen state of sands and by their low moisture content in the active layer (Fig. 4, a).

The lower sitting, 35–45 m thick, stratum with a resistivity ranging between 80 and 230 Ohm-m is interpreted to be thawed sands whose moisture content is varied. The top of the high resistivity deposits (800–5600 Ohm-m) represented according to a priori data by frozen Middle Cambrian limestone is identified at the bottom of the cross-section, from the depth of 60–70 m. Their electrical resistivity is not persistent along the strike. In the 350–400 m interval, the bedrock resistivity reduces to 200 Ohm-m, probably due to the presence of the water-logged fault zone in the bedrock.

Geoelectrical section of the Ulakhan-Taryn stream valley is characterized by very high resistivity (2600–6800 Ohm-m), which is attributed to the occurrence of ice-rich rocks in the upper part of the section and, accordingly, their low temperature. Only the near-surface part of the section (0–150 m profile interval) shows lower resistivities, decreased to 1000–500 Ohm-m. The description of the geoelectrical section in the stream floodplain and terrace junction zone indicates to the intrapermafrost talik partially expanding into the floodplain.

According to the geocryological interpretation of the resistivity cross-section (Fig. 4, b), the permafrost thickness reaches its maximum within the Ulakhan-Taryn stream floodplain, while local high resistivity zones correspond to the areas of developing ice-rich deposits and tabular massive ice. The seasonal thaw depth in the peat-bog part of the floodplain appears not more than 1 m. To estimate deposits temperature, we used a relationship between resistivity and their temperature [Recommendations..., 1987; SP-11-105-97, 2004]. As such, the structure of permafrost stratum derived from the ERT data is in good keeping with the results of the studies in the past years by the VES method and by drilling [Belykh et al., 1985].

Local high resistivity zones (3000–4700 Ohm-m) of frozen deposits in the upper layer are interpreted to have a lower temperature (–0.75 °C). Areas of the day surface underlain by these, are colonized by dense larch forest with thick undergrowth shading the surface. In the areas of pine forest growth, resistivity of the upper layer of frozen deposits tends to be lower, varying between 1500 and 2500 Ohm-m, which according to the temperature-dependent resistivity of sand [Recommendations..., 1987; SP-105-11-97, 2004] corresponds to ~0.25 °C. The temperature values obtained from ERT measurements are close to thermometric data on the permafrost temperature for this area (~0.2 °C) [Gagarin, 2013].

A low resistivity zone (<75 Ohm-m) identified in the intrapermafrost talik, is interpreted to be the groundwater filtration zone (300–350 m profile interval). In such areas, the upper frozen horizon thickness progressively reduces, down to the seasonal thaw depth. On the surface areas, corresponding to these, suffusion sinkholes are currently developing. Localities of older suffusion sinkholes are marked by an increase in thickness of high resistivity layer which is associated with the deposits experiencing freezing in the absence of warming effect from the groundwater runoff. As the latter ceases, this is followed by an increase in resistivity of the intrapermafrost talik waters.

3D geoelectrical resistivity model analysis

The ERT areal measurements interpretation resulted in a three-dimensional geoelectrical model (Fig. 5). In the volume model, a semitransparent region accounts for high resistivity rocks. Intervals with resistivity less than 400 Ohm-m are limited by a continuous isosurface, which, actually, delineates the groundwater filtration paths (underground streams) within the intrapermafrost talik extent. A low resistivity pipe-like body represents an intrapermafrost horizon whose groundwaters discharge occurs in cirque E.

The resistivity distribution pattern was considered in the context of the area where thermosuffosion sinkholes gradually form. Figure 6 shows maps of resistivity distribution (isoOhm maps). These represent 7 and 15 m depth slices of the 3D resistivity model. The 7 m-depth slice reflects either frozen or thawed state of the deposits at a depth close to the active layer base depth. According to the drilling and thermometry data, the maximal seasonal thaw depth...
in the study area is 4–6 m [Gagarin, 2015]. The probability of thermo-suffosion sinkholes occurrence proves to be high in regions containing low resistivity zones (thawed sands). For example, a low resistivity anomaly on Profile 6 is accounted for fresh collapse structures formed on the surface. It would be logical to expect that collapse structures are soon to start forming along the linear low resistivity anomaly (<550 Ohm-m) intersecting Profiles 6, 5 and 4. A part of the sinkholes and collapse structures is subsumed into a high resistivity region (>2500 Ohm-m). At present, these collapse structures have ceased to develop, giving way to permafrost degradation beneath them. The local low resistivity zone between Profiles 2 and 3 is confined to the terrace slope foot. This site comprises a groundwater discharge zone.

The 15 m depth slice reflects the groundwater filtration paths distribution across the area. Inasmuch as the occurrence depth of the topmost frozen layer base averages 20 m, low resistivity areas (<1000 Ohm-m) feature the thawing zones above the filtration channels on the map of isoOhms (Fig. 6). Collapse structures tend to form explicitly above the lower electrical resistivity zones.

**Fig. 6.** Maps of electrical resistivity distribution at depths of 7 m (a), 15 m (b) electrical data and interpretation scheme (c):

1 - ground water flows in the intrapermafrost talik; 2 - sinkhole/collapse structures susceptibility and hazard sites. Other legends cf. Fig. 1.
The electrical resistivity tomography technique thus enables us to identify the groundwater filtration paths in the intrapermafrost taliks and predict the localities of thermo-suffusion sinkholes development.

RESULTS AND FINDINGS

The results of using the ERT method showed that an intrapermafrost talik has developed within the 20–60 m depth interval within the study area. These inferences are consistent with the results of previous studies based on drilling and vertical electric sounding [Belykh et al., 1985]. However, given that the wells and VES points were located along a sparse observational network, neither drilling, nor VES data could provide insights about the groundwater infiltration channels in the intrapermafrost talik. The existence of filtration channels can be inferred only from the presence of pressure seepages of ground waters forming caves in the slope of the Bestyakh terrace in the Ulakhan-Taryn stream valley. The 2D ERT data interpretation on the resistivity sections allowed for the first time identifying local isometric anomalies of low electrical resistivity representing a geoelectrical image of the pressure filtration channels. It has been established that sinkholes and collapse structures develop specifically above such low resistivity zones. Analysis of the geoelectrical cross-sections has shown that the upper frozen horizon increasingly decreased in thickness above the pressure filtration paths to the extent, at times commensurate with the seasonal thaw depth. Thus, the ERT data corroborate the assumption that groundwaters produce substantial thermal effect on the overlying frozen deposits. Given that, when thawing, the upper horizon periodically collapses sinkholes and collapse structures will thereby form on the surface.

The geoelectrical data also allowed suggesting that following the formation of a sinkhole or a collapse structure, the collapsed rock mass either reduces or changes in other way the groundwater flow paths. In this case, once groundwater has ceased to produce thermal effect in the collapse zone, permafrost will subsequently begin to recover, within the area that experienced collapse, which rests on the knowledge of very high resistivity of sands in the vicinity of old sinkholes, and that water tends to accumulate in the bottom of such structures, indicating the presence of a frozen aquiclude.

Analysis of the lateral distribution of permafrost resistivity in the upper part of the cross-section revealed a relationship between electrical resistivity and the type of vegetation on the terrain surface. In those places where vegetation is thicker and represented by larch growth, resistivity of frozen rocks tends to be higher, than in places colonized by sparse growth of pine. The authors consider this relationship to be indirect, dependent on temperature of frozen rocks. The vegetation cover notably affects the heat exchange between soil and atmosphere [Ershov, 2002]. During summer, the solar radiation retained by thick vegetation cover facilitates the cooling of rocks. Thus, the temperature of permafrost underlying areas covered by thick larch forest will be lower, and in equal measure, the seasonal thaw depth. In the course of the 2015 field studies, a landscape description was carried out for the Ulakhan-Taryn spring area. Thermo-suffusion gulling is found to prompt significant alterations in the landscape through the changing relief and permafrost-hydrogeological conditions, which is most likely to be followed by the onset of vegetation succession in their wake. The zone of the actively developing suffusion sinkholes (for example, in the cirque E) is overgrown by sparse pine forest, while the sites of old gullies are dominated by larch, moss, and tussock bogs. The homogeneous lithologies in the upper part of the terrace section allows to suggest that variations of resistivity in the frozen horizon are primarily controlled by the temperature.

CONCLUSION

The geophysical studies integrated with field observations have prompted the following conclusions:

The two-dimensional ERT data resulting in geoelectrical images of the groundwater pressure filtration paths marked on resistivity cross-sections by isometric low resistivity anomalies. The regions above these paths (channels) are characterized by the decreasing thickness of high-resistivity layer, which is interpreted to be a permafrost horizon, down to measuring equal with the seasonal thaw depth. Suffusion sinkholes and collapse structures form in places where such intervals are projected onto the surface. Areas of possible formation of thermo-suffson sinkholes are delineated by characteristic elongated regions of reduced electrical resistivity on the 3D resistivity model slices along the permafrost table.

When forming, a suffusion sinkhole provokes the cover collapse above the pressure filtration channel resulting in the appearing barrage and changes in the direction of groundwater flows, and causing the waning of warming effect of the groundwater in the collapse zone. Subsequently, the rock mass refreezing takes place, which is expressed in high resistivity of the the cross-section in the region of old sinkholes and collapse structures.

Changes in resistivity in the frozen layer correlate well with the vegetation pattern on the surface, which is largely dictated by the rocks temperature. On shaded areas overgrown with larch forest, the frozen rocks resistivity is thus higher than at the base of a sparse pine stand.

The combined application of GPR and ERT methods have generally proven to be in fairly good
agreement with the thermometry and drilling data. Application of these methods to the subsurface monitoring to produce a qualitative forecast estimate for suffusion processes, down to predicting zones of the day surface potential for collapse hazard.

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