EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Earth`s Cryosphere, 2019, vol. XXIII, No. 3, pp. 51–57 **http://earthcryosphere.ru/**

METHODS OF CRYOSPHERIC RESEARCH

DOI: 10.21782/EC2541-9994-2019-3(51-57)

REVEALING POTENTIAL THERMO-SUFFOSIONAL SOIL LOOSENING SITES ALONG A-360 LENA FEDERAL HIGHWAY, CENTRAL YAKUTIA

L.A. Gagarin[1,2], K.I. Bazhin[1], V.V. Olenchenko[3], V.V. Ogonerov[1], Wu Qingbai[2]

[1]*Melnikov Permafrost Institute, SB RAS, 36, Merzlotnaya str., Yakutsk, 677010, Russia; gagarinla@gmail.com*
[2] *State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences (CAS), Donggang West Road 320, Lanzhou, Gansu, China (730000)*
[3] *Trofimuk Institute of Petroleum Geology and Geophysics, SB RAS, 3, Acad. Koptyuga ave., Novosibirsk, 630090, Russia*

The article presents results of the studies of thermo-suffosion processes development in the period from 2008 through 2017. Electrical resistivity tomography survey revealed highly dynamic geocryological and hydrogeological conditions at the Ulakhan-Taryn groundwater spring, Central Yakutia. It has been established that the permafrost thickness degraded by 4 m in a 4-year period above the intrapermafrost ground water due to heat effects. As many as five sites of thermo-suffosional soil loosening and potential cover-collapse development were identified along the Lena Federal Highway.

Thermo-suffosion, intrapermafrost waters, suprapermafrost waters, talik, permafrost, electrical resistivity tomography

INTRODUCTION

Electrical resistivity tomography (ERT) method has been successfully applied in the study of permafrost-hydrogeological conditions and structure of taliks [*Fortier et al., 2016; Lorenson et al., 2016; You et al., 2017*]. The highly informative data achieved by this method in solving this kind of problems is based on strong contrasts in electrical resistivity (ER) between frozen and unfrozen rocks [*Hauck and Kneisel, 2008*]. ERT proved itself to be an appropriate technique in the study of thermal suffosion processes within the Bestyakh terrace of the Lena river in Central Yakutia [*Olenchenko et al., 2017*]. Such processes are associated with sand material removal by groundwater fluxes in intrapermafrost aquifers, triggering thereby the formation of thermo-suffosional subsidence (cover-collapse) landforms [*Efimov, 1952; Shepelev, 1972; Gagarin et al., 2016*]. Many of the fresh-formed cover-collapse sinkholes produced by thermal suffosion processes in the vicinity of Ulakhan-Taryn spring are confined to year-round groundwater sources. A-360 Lena Federal Highway (FHW), the only road transport artery connecting Yakutsk, the capital of the Sakha Republic (Yakutia), to the rest of Russia, is located 500 m SE of the area affected by thermal suffosion processes (the 1102–1103-th km stretch).

This segment of the highway assigned to the Ulakhan-Taryn spring area was under reconstruction during the period of 2013–2015. The previously existing earth road was rebuilt to asphalt road, while a crossing over the spring was replaced by a road culvert. The reconstruction involved extensive excavation works in the stream valley which resulted in the pit bottom deepening by 3 m. The authors learned from the civil engineers working on this stretch of roadway, that they had not been aware of the existing nearby large springs and cover-collapse landforms.

As such, the Ulakhan-Taryn spring valley bottom deepening may have caused a discharge of confined intrapermafrost groundwater (GW) source and concomitant initiation of thermal suffosion processes. The resulting sudden and progressively developing thermo-suffosional sinkholes on the day surface (cover-collapse sinkholes) could lead to partial or complete degradation of the roadway.

With this in mind, this study is set out to evaluate potential formation of cover-collapse sinkholes along the A-360 Lena Federal Highway at the 1102–1103-th km stretch.

STUDY SITE

The study site is located 54 km north of Nizhny Bestyakh village, while Yakutsk is situated on the opposite bank of the Lena river.

The investigated thermal suffosion processes transpire within the fourth above-floodplain terrace of the Lena river composed mainly of sands with gravelly-pebble layer at the base [*Kamaletdinov, 1982; Ivanov, 1984*]. The terrace basement is composed of weathered, fractured Lower Cambrian limestone.

Many hydrogeological and geothermal wells drilled to a depth varying from 12 to 520 m in the Ulakhan-Taryn GW spring area at different times (Fig. 1) have provided pertinent data for the area. The upper part of the section is composed of fine-grained sand (to a depth of 45 m) and a medium-grained sand (below 45 m), having the same inhomogeneity coefficient (1.7–2.0) in both the cases [*Gagarin et al., 2016*].

Permafrost thickness varies from 200 to 400 m within the terrace [*Ivanov, 1984*]. Its temperature at the depth of zero annual amplitudes is –0.2...–0.5 °C, decreasing in the Ulakhan-Taryn spring valley to –2.5 °C. The Bestyakh terrace (Lena river) structure is distinguished by extensive development of intrapermafrost taliks, with their upper limits occurring at a depth between 16 and 27 m. Their recharge occurs through insolation-thermal and sublake taliks (“open”, i.e. allowing for a connection between unfrozen zones, and “closed”, i.e. bounded by permafrost). Groundwaters discharge into valleys of streams and rivers cutting their way through the Bestyakh terrace (Lena river), as well as into some lakes. Judging from the recharge and circulation conditions, the groundwaters are ranked as suprapermafrost [*Efimov, 1952*]. The largest groundwater source is confined to the Ulakhan-Taryn spring valley. These springs are conventionally divided into five groups (cirques) marked as A, B, C, D, E. Groundwater temperature at the outflows to the day surface is constant (0.2 °C) during the year. Waters are bicarbonate calcium-magnesium type with salinity (TDS) level about 200 mg/L, which is seasonally variable [*Pavlova et al., 2016*]. Intrapermafrost groundwaters belong to confined type, which is evidenced, for example, by their piezometric level reaching 9 m in the discharge area [*Gagarin et al., 2016*].

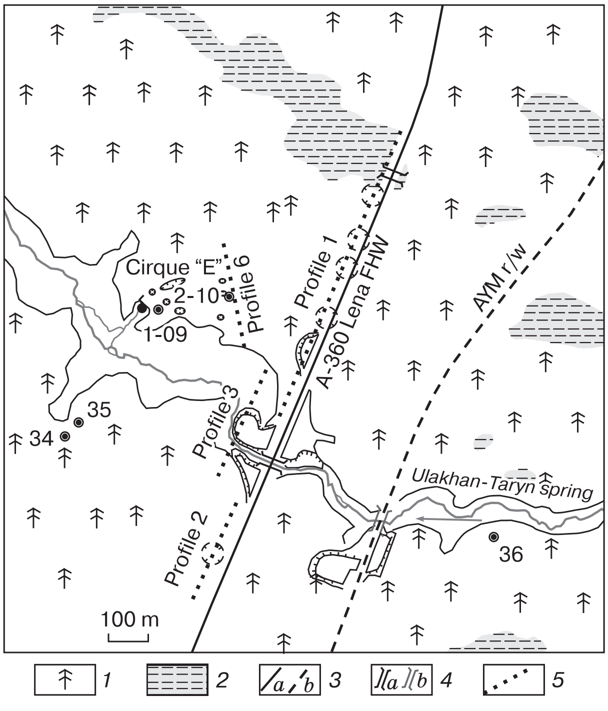

Fig. 1. Scheme of geophysical profiles layout in the area of A-360 Lena Federal Highway crossing Ulakhan-Taryn spring (1104–1105-th km).

1 – forest; *2* – water-logged topographic low; *3* – A-360 Lena Federal Highway (*a*) and Amur-Yakutsk Mainline railway (*b*); *4* – culvert pipe (*a*) and bridge (*b*); *5* – geophysical profile; *6* – man-made earth-embankment; *7* – groundwater source; *8* – cover-collapse sinkhole; *9* – potential cover-collapse sinkhole development; *10* – drillled well and its number.

Groundwaters remove sand material composing the intrapermafrost aquifer and its frozen overburden in significant amounts, giving way to the formation of either caves (above the spring on the Bestyakh terrace slope of the Lena river), or sinkholes, ponors and ravines (on the terrace surface) [*Tolstikhin, 1941; Efimov, 1952; Shepelev, 1972; Gagarin et al., 2016*]. The rates of sinkholes evolution are fairly high. Thus the maximum annual enlargement of the volume of ground subsidence at the expense of thermal suffosion reached 3500 m^3 within cirque E in the Ulahan-Taryn spring area [*Gagarin et al., 2016*]. In this area, cover-collapse sinkholes evolve deep into the terrace in the northeast direction (Fig. 1). The most remote subsidence sinkhole was reported at a distance of 300 m from the GW spring. Note that A-360 Lena Federal Highway is laid further 500 m in the same direction.

GEOPHYSICAL SURVEY METHODS

Determining a potential cover-collapse sinkhole requires the knowledge of the intrapermafrost aquifer geometry. Our research experience has shown that this problem can be effectively solved by application of electrical resistivity tomography (ERT) imaging [*Olenchenko et al., 2017*]. This paper discusses the use of ERT survey in combination with joint profile method.

We carried out measurements along four profiles from 315 to 780 m in length using a multi-channel station “Skala-64” (64 electrodes at 5 m spacing) manufactured by KB Electrometry, Novosibirsk. The symmetric location of electrodes was consistent with the principle of Schlumberger electrode configuration. The survey depth reached 80 m. The results were processed using the Res2Dinv and ZonRes2D software [*Bobachev and Gorbunov, 2005*].

Figure 1 shows the layout of profiles: along the road embankment at the 1103-th km of A-360 Lena Highway as far as the right bank of Ulakhan-Taryn spring (Profile 1) and at 1102-th km from the left bank of Ulakhan-Taryn spring (Profile 2); and the one laid across the Ulakhan-Taryn spring valley, 30 m upstream, within the bounds of artificial earth-embankment (Profile 3). Profile 6 was laid back in 2014 in the cross-strike direction of the thermo-suffosion sinkholes development within circus E [*Olenchenko et al., 2017*]. Measurements along this profile were performed in 2015 and 2016 (early summer) and 2017 (late summer). A hydrogeological well # 2-10, which penetrated intrapermafrost talik at a depth of 16 m (2014), is located 20 m westward of Profile 6.

RESEARCH RESULTS

The interpretation of geoelectric sections was based on a priori data on the permafrost-hydrogeological structure of the study area inferred from the hydrogeological wells drilling data [*Olenchenko et al., 2017*].

Based on the 2015 field works results, the active layer and perennially frozen sand bed are distinguished to a depth of 15–25 m (ER range: 1000–5000 Ohm·m) in the upper part of the section along Profile 6 (Fig. 2), with an intrapermafrost aquifer sitting below (ER: 80–230 Ohm·m) and locally underlain (from a depth of 60–70 m) by unfrozen water-saturated (sometimes frozen through their thickness) Middle Cambrian limestones (ER: 200–5600 Ohm·m). The four local low resistivity anomalies identified in the intrapermafrost talik are interpreted as groundwater flowpaths (filtration channels).

The nature of link between resistivity anomalies and groundwater flowpaths is still disputable. On the one hand, well-washed and well-sorted coarse-grained sands having the best reservoir and filtration properties show highest ER values among loose psammites. On the other hand, the authors highlight the propensity for thermal suffosion process development above the linear lower resistivity anomalies, while collapse sinkholes tend to form immediately above the zones of groundwater fluxes. Low resistivity anomalies inherent in thermo-suffosion sinkholes development zones are probably caused by alterations in pore space geometry due to the thermal suffosion processes. Let us assume that in the steady state, a waterlogged sand massif is characterized by a fairly high pore sinuosity coefficient. Thermo-suffosion processes involve removal of sand particles and forma-

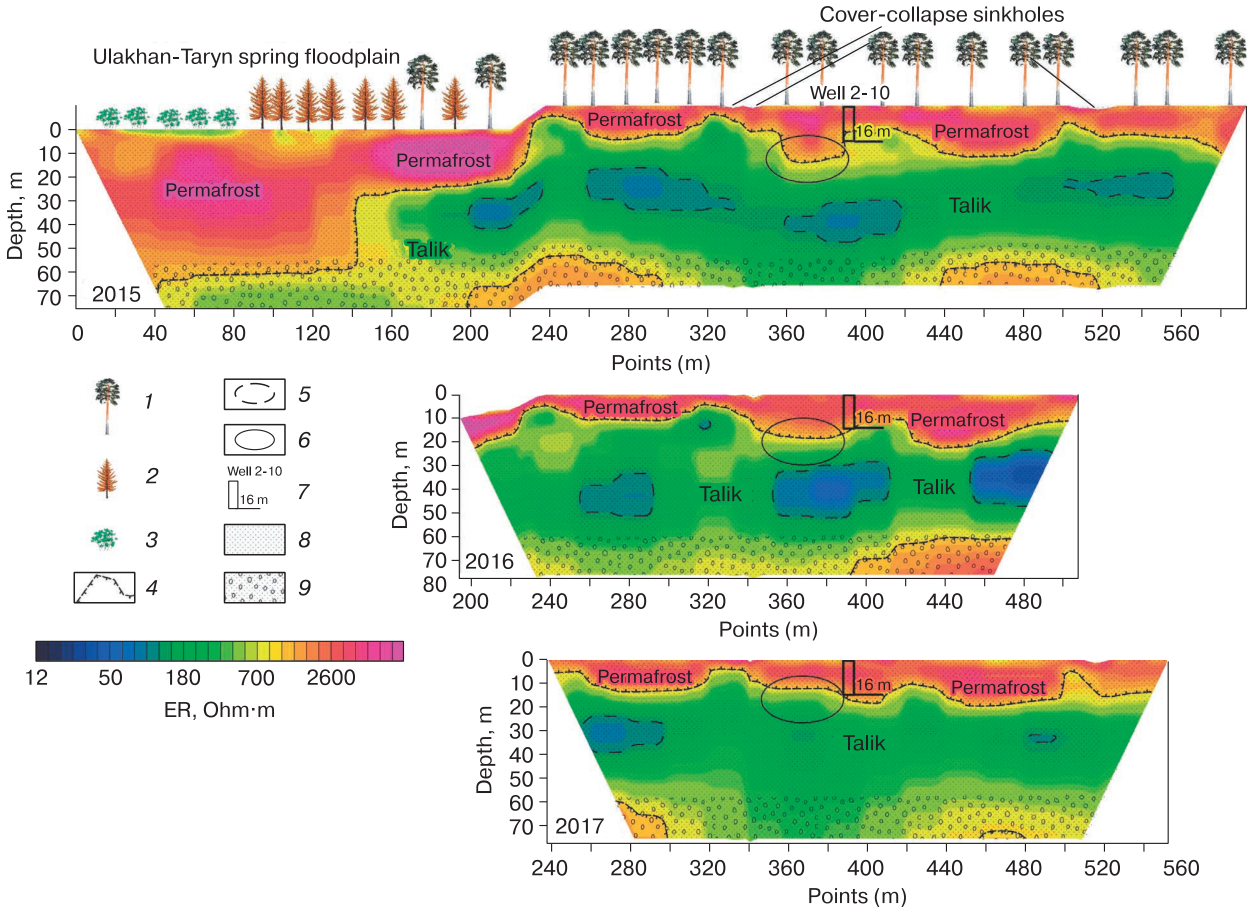

Fig. 2. Geoelectric section of Profile 6 in the area of cirque E of Ulakhan-Taryn GW spring (2015–2017).

1 – pine-tree; *2* – larch; *3* – shrubs; *4* – permafrost boundary; *5* – groundwater flowpaths; *6* – zone of permafrost degradation; *7* – drilled well (top symbol shows its number, bottom symbol is its depth); *8* – sand; *9* – sandy gravel-pebble fill.

tion of through flowpaths, thereby enabling a free passage of electric current and ultimately leads to a decrease in pore sinuosity coefficient in the Archie's equation and ER values of rocks. The work of [*Aliyarov and Ramazanov, 2010*] has shown that an increase in sands saturation with water entails a decrease in pore sinuosity, which, in the authors' opinion, is quite logical, given that enhanced water saturation is liable for simplification of pore channels geometry and hence their hydraulic conductivity. However, according to the drilling data, sands in the intrapermafrost horizon of the Bestyakh terrace (Lena river), are water-logged. Therefore, both pore geometry and lower sinuosity can be influenced only by particle removal through groundwater flowpaths.

Results of the repeated measurements (2016) on the profile segment laid beyond the Ulakhan-Taryn spring floodplain yielded a changed pattern of resistivities (Fig. 2). Thus upward degradation of permafrost was observed at the profile points 345–395 m in the period from 2015 to 2016, which is reflected in the layer reducing from 23 to 19 m thickness (ER range: 1000–3400 Ohm·m), while the permafrost base occurrence depth decreased by 4 m. This was likely facilitated by a continued heat transfer between the frozen top wall of the aquifer and groundwater flow during the said period of time. Figure 2 shows that horizontal resistivity distribution in the 15–60 m depth interval varied greatly from 2015 to 2017. The analyzed GW flows, having resistivities up to 230 Ohm·m, tend to change their location in space, which implies the migration of groundwater flowpaths. At this, an active development of thermo-suffosional sinkholes was observed within the considered profile segment (in the projection on the day surface) during 2015 and 2016.

The state of permafrost reported in 2017 can be viewed as relatively stable. The difference in the permafrost base position on geoelectric profiles between 2016 and 2017 is within the measurement error and does not exceed 2 m (Fig. 2). However, by comparison with 2016, an increase in resistivity and a lack of distinctly low ER values were observed within the intrapermafrost aquifer. The authors interpret this increase in resistivity as a reduction in the GW flow intensity invoking thermal suffosion process. It should be noted that the thermal suffosion-driven surface subsidence was observed neither in 2016 nor in 2017 in this profile stretch. Hence, erosion of rock material caused by groundwater flow in this time period has either ceased or temporarily decreased in its intensity.

Previous studies have shown that resistivities measured in the taliks with varying degree of moisture content of sands of the Bestyakh terrace (Lena river) vary widely, between 80 and 1000 Ohm·m [*Olenchenko et al., 2017*]. Groundwater flows in the intrapermafrost horizon liable for thermal suffosion are marked by low resistivities (<400 Ohm·m) in the geoelectric section. Cover-collapse sinkholes are generally associated with the zones of thin permafrost distribution, with groundwater flows localized beneath them (ER: 80–400 Ohm·m). These criteria were used to reveal areas of potential thermo-suffosional decompaction of rock material along the A-360 Lena Federal Highway.

Profile 1 is laid across the strike of transit zone of the intrapermafrost aquifer and is confined to the road foundation (Fig. 1). The ERT survey was carried out along this profile in the first days of October 2017, the time when soils thawed to the maximum (3.5–4.0 m) were facing the onset of their winter freezing. The low resistivity (400–800 Ohm·m) zone is recognized in the upper part of the geoelectric section (250–780 m survey points) to a depth from 1.5–2 to 7–12 m (Fig. 3, *a*) which is interpreted as subaerial unfrozen zone. Such taliks can form on the Bestyakh terrace (Lena river) under present climatic conditions [*Shender et al., 1996; Shepelev et al., 2002; Gagarin, 2015*]. High resistivities (up to 3600 Ohm·m) identified on the 350–500 m points line to a depth of 3–5 m (Fig. 3, *a*) are associated with coarse-aggregate-type technogenic deposits (crushed carbonate rocks) occurring in the upper part of the geologic section (road foundation), rather than with soil seasonal freezing alone.

On Profile 1 (points: from 0 to 200 m), a low-resistivity (<160 Ohm·m) unfrozen zone (Fig. 3, *a*) extending from the surface to a depth of 4.5 m is localized within a local bog basin. The lower part of the section is featured, accordingly, by high-resistivity very ice-rich low-temperature permafrost (ER: 2000–80 000 Ohm·m). A local low resistivity anomaly (120–700 Ohm·m) revealed on the 100–150 m profile stretch at depths of 13–29 m was provoked by effects of metal culvert pipe inbuilt in the road embankment (Fig. 3, *a*).

Within the terrace planation surface (200–680 m profile stretch), higher-temperature permafrost (ER 1000–5000 Ohm·m) occurs to a depth averaging 24 m (Fig. 3, *a*), which reduces to 12–16 m along the 200–240, 320–370, 420–460 and 625–670 m points. Beginning from 680 m point, resistivity values show an increasing trend (up to 8000–90 000 Ohm·m) to a depth of 42 m, which is probably caused by the presence of permafrost near the spring valley slope. The intrapermafrost aquifer is recognized on the geoelectric section (200–750 m points) (Fig. 3, *a*), with resistivities varying from 25 to 400 Ohm·m. Positions of its upper and lower limits are also variable throughout the stretch. The lowest resistivities (25–60 Ohm·m) are reported from the zones of thermo-suffosional transfer of substances by groundwater flow in the pore space. However, not each of the low resistivity anomaly zone is associated with a decrease in thickness of the underlying permafrost. The GW flowpaths may change from year to year. Groundwaters have had the most persistent effect in areas underlain by permafrost having a minimum thicknesses. The described phenomenon can be traced within points 200–250, 330–370, 430–470 and 620–670 m (Fig. 3, *a*). Permafrost overlying the lowest resistivity zone (<70 Ohm·m) is found to be the thinnest. Given that subaerial supapermafrost taliks <10 m in thickness are located above such zones, the strength of intrapermafrost aquifer top is viewed as the lowest within them, as compared to the adjacent area. The authors therefore argue that cover-collapse sinkholes

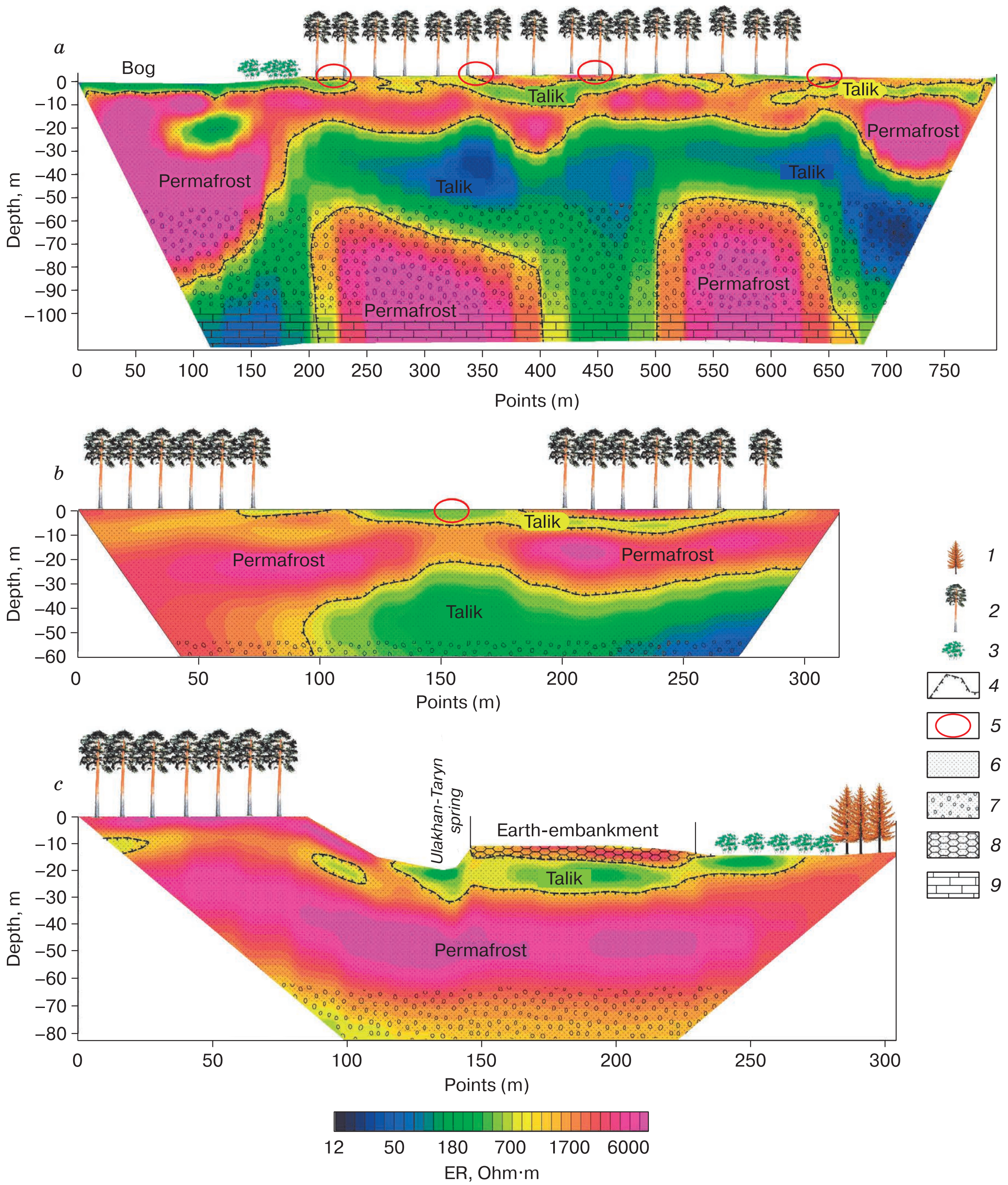

Fig. 3. Geoelectric section along the A-360 Lena Federal Highway derived from Profiles 1 (*a*), 2 (*b*) and 3 (*b*).

1 – larch; *2* – pine-tree; *3* – shrubs; *4* – permafrost boundary; *5* – potential cover-collapse sinkhole development; *6* – sand; *7* – sandy gravel-pebble fill; *8* – sand admixed with grus and crushed rock; *9* – limestone.

will most likely evolve within these intervals of Profile 1.

The alternating low-resistivity (40–700 Ohm·m) and high-resistivity (1300–20 000 Ohm·m) zones at base of the geoelectric section of Profile 1, from a depth of 60 m downward (Fig. 3, *a*) are interpreted as thawed and frozen sediments, respectively. According to the well # 36 data (Fig. 1), its section from a depth of 100 m and below is composed of weathered limestone. This bedrock in weathering cracks probably contain both ice and clay particles retaining water in the liquid phase. This gives reason to the authors for explaining significant variation of resistivity (40–20 000 Ohm·m). Given that the measuring tool sensitivity decreases with depth, this leads to an ambiguous solution of the inverse problem. Inasmuch as these regions are located below the identified intrapermafrost unfrozen layer, their interpretation on the geoelectric section can therefore be considered conventional.

Profile 2 is also located across the strike of the intrapermafrost aquifer transit zone (Fig. 1). Unlike Profile 1, Profile 2 was laid 15 m away from the road embankment and ran from the left Bank of the Ulakhan-Taryn spring through a pine forest, crossing a local topographic low whose surface is flat and overgrown with meadow vegetation. A zone with resistivity varying from 400 to 770 Ohm·m revealed at the 110–290 m points (Fig. 3, *b*) is interpreted by the authors as subaerial unfrozen zone. By the beginning of October the active layer had been frozen to a depth of 1.5–2.0 m within the Bestyakh terrace of the Lena river (observations during the measurements) [*Gagarin, 2015*]. Pre-winter moisture content of sands within AL across its whole thickness does not exceed 5–6 % [*Shender et al., 1996*]. The former evidence attests to the fact that the existing at that time thickness of the freezing active layer fails to be inferred from the ERT data, inasmuch as the distance between the electrodes (5 m) considerably exceeds this value. Whereas the latter evidence does not allow to differentiate between dry unfrozen sands and high-temperature frozen sands [*Bobachev and Gorbunov, 2005*]. The active layer experiencing freezing is therefore unidentifiable on the geoelectric section.

Permafrost deposits along Profile 2 (Fig. 3, *b*) are characterized by resistivities in the range from 1000 to 9000 Ohm·m, while within the 0–100 m points the survey depth precluded clear identification of their base. In the areas of intrapermafrost aquifer development (resistivity: 40–400 Ohm·m), specifically, within the 100–325 m points the permafrost thickness is not more than 34 m. Importantly, the thinnest (15 m) permafrost layer and high resistivities (1350–2200 Ohm·m) are observed beneath a local topographic low, within the 110–180 m profile interval, as compared with adjacent areas (Fig. 3, *b*). The subaerial talik has probably existed there for at least several years, with its warming effect entailing degradation of the underlying permafrost. The formation of a cover-collapse sinkhole is thus highly possible, specifically, within this stretch of Profile 2.

Results of ERT survey along Profile 3 enabled recognition of the man-made earth-embankment (points: 140–230 m) impacts on the geocryological state in the Ulakhan-Taryn spring valley (Fig. 1, 3). The embankment is composed of carbonate rock debris and is filled with sand having different grain size; its visible thickness measures 6–7 m. According to GPR data, the sand fill thickness varies here from 5 to 7–8 m, whereas resistivities range from 1200 to 4000 Ohm·m. The geoelectric section analysis has revealed a closed talik (thickness: up to 12 m) (Fig. 3, *c*) confined to the Ulakhan-Taryn spring channel and is imaged in the section as a region with resistivity varying from 170 to 1000 Ohm·m in the 120–140 m profile interval. A tussock bog zone is observed on the 230–270 m profile stretch (Fig. 3, *c*), with low resistivities (200–1000 Ohm·m) reported from beneath it, similarly to the zone beneath the spring channel (120–140 m profile stretch). The unfrozen zone under the bog reaches 5–7 m in thickness. The two regions merge into a single talik zone through the 10–12 m talik (with similar resistivities), which is buried under the man-made road embankment (Fig. 3, *c*).

Naturally deposited unfrozen zones in the left bank are marked by discrete low-resistivity lenses (680–1000 Ohm·m) at the 0–25 and 90–105 m points (Fig. 3, *c*), reaching 5–7 m in thickness. The taliks are connected by a 1000–2000 Ohm·m layer characteristic of the perennially frozen sands of the Bestyakh terrace (Lena river), which however strikingly contrasts with the higher and lower occurring higher-resistivity layers (3500–9000 Ohm·m). Besides, this layer tends to follow the contours of the topography and is connected with the valley talik. A subaerial talik is probably experiencing freezing there, which entails the enhanced resistivity in the section. This assumption is confirmed by the landscape conditions on the day surface overgrown by a mature dense pine forest with single larch trees.

The lower part of Profile 3 is composed of frozen through sands (ER: 2700–9000 Ohm·m) and frozen rocks (1000–2000 Ohm·m), which are most likely unfrozen, water-saturated (ER: 600–1000 Ohm·m) on the 100–150 m profile stretch (Fig. 3, *c*).

CONCLUSIONS

Monitoring of the year-to-year ER variations of rocks allowed to analyze highly dynamic permafrost-hydrogeological conditions in the area of thermal suffosion processes development.

It has been established that the uppermost permafrost layer thickness has decreased by 4 m under the impacts of intrapermafrost groundwater fluxes over the time span of 4 years (Fig. 2).

The interpretation of geoelectric sections obtained in different years enabled characterization of the intrapermafrost groundwater flowpaths as unstable, which is reflected in resistivity variability viewed as increase or decrease in local regions of the reference layer with resistivity reduced to 400 Ohm·m. The investigated layer is interpreted as water-bearing talik (aquifer).

The lowering resistivity in rocks within groundwater flow zone was probably caused by decreased pore sinuosity in the thermal suffosion-affected sands. The sinuosity coefficient influences the ER value in the Archie formula describing a relationship between resistivity, porosity and pore space geometry.

The geophysical data interpretation allowed an inference about a possibility for existence of suprapermafrost subaerial taliks in the upper part of the section (to a depth of 10 m) potentially capable of having a hydraulic connection with the intrapermafrost aquifer.

The ERT survey revealed five areas of potential surface subsidence (Fig. 3, *a*, *b*). Such zones tend to be underlain by permafrost having lowest values of thickness, likewise resistivities (20–200 Ohm·m) in the underlying layers (i.e. in the intrapermafrost aquifer), while a subaerial talik develops from the surface downward.

The identified buried talik beneath an extensive man-made sand filled site (location: 1103-th km of the A-360 Lena Federal Highway) and hydraulically connected with both the underflow and floodplain taliks of the Ulakhan-Taryn spring is seen to be one of the areas of potential thermal suffosion processes development.

The work was financially supported by the Russian Basic Research Foundation (Project No. 15-45-05053-p_vostok_a), and grant from the Open Fund Project of SKLFSE (No. SKLFSE201701).

References

Aliyarov, R.Yu., Ramazanov, R.A., 2010. Changes in the reservoir bed resistivity while developing the oil and gas pools. Karotazhnik, No. 3, 78–90.

Bobachev, A.A., Gorbunov, A.A., 2005. 2D geoelectrical prospecting by resistivity and induced polarization technique: tools, methodology, software. Razvedka i Ohrana Nedr, No. 12, 52–54.

Gagarin, L.A., 2015. Assessment of recent conditions for development of subaerial talik in Central Yakutia. In: Proc. of the XXI All-Russian Conference on Groundwater in Siberia and Far East, IMZ SO RAN, Yakutsk, pp. 76–80. (in Russian)

Gagarin, L.A., Semernya, A.A., Lebedeva, L.S., 2016. Assessment of thermal suffosion in Central Yakutia by the example of Ulakhan-tarin site. Geoecologia, Inzhenernaya Geologia, Gidrologia, Geokriologia (Geoecology, Engineering Geology, Hydrogeology, Geocryology), No. 3, 252–262.

Efimov, A.I., 1952. Non-freezing fresh spring Ulanakh-Taryn in Central Yakutia. In: Permafrost Investigations in Yakutia Republic. Izd-vo AN SSSR, Moscow, No. 3, pp. 60–105. (in Russian)

Fortier, R., Lemieux, J.M., Molson, J.W.H., et al., 2016. Geophysical investigation and monitoring of thermo-hydraulic conditions of closed talik and icing of the Kuuguluk River at Salluit, northern Quebec, Canada. AGU Fall Meeting Abstracts, San Fransisco, USA, NS23B-02.

Hauck, C., Kneisel, C., 2008. Applied geophysics in periglacial environments. Cambridge University Press, Cambridge, vol. 240, 238 pp.

Ivanov, M.S., 1984. Cryogenic Structure of Quaternary Deposits in the Leno-Aldan Depression. Nauka, Novosibirsk, 126 pp. (in Russian)

Kamaletdinov, V.A., 1982. The structure and pedestal relief of the cover of Quaternary sediments in the Lena-Amgin interfluve area. In: Cenozoic Geology of Yakutia. YaF SO AN SSSR, Yakutsk, pp. 94–103. (in Russian)

Lorenson, T.D., Swarzenski, P.W., Conaway C.H., et al., 2016. Extensive cryopegs on Barter Island, North Slope, Alaska. AGU Fall Meeting Abstracts, San Fransisco, USA, GC31H-1199.

Olenchenko, V.V., Gagarin, L.A., Khristoforov, I.I., Kolesnikov, A.B., Efremov, V.S., 2017. The structure of a site with thermo-suffosion processes within Bestyakh terrace of the Lena River, according to geophysical data. Earth's Cryosphere XXI (5), 14–23.

Pavlova, N.A., Kolesnikov, A.B., Efremov, V.S., Shepelev, V.V., 2016. Groundwater chemistry in intrapermafrost taliks in Central Yakutia. Vodnye Resursy (Water Resources), 43 (2), 353–363.

Shender, N.I., Boitsov, A.V., Tetel'baum, A.S., 1996. Formation of taliks and high-temperature frozen rocks in Central Yakutia. In: Proceeding of the First Conference of Geocryologists. Moscow University Press, Moscow, vol. 3, pp. 290–297. (in Russian)

Shepelev, V.V., 1972. Assessment of erosion and suffosion processes of springs in Central Yakutia. Izvestia vuzov. Geologia i Razvedka, No. 9, 88–99.

Shepelev, V.V., Boitsov, A.V., Oberman, N.G., et al., 2002. Monitoring of Groundwaters of Permafrost Zone. IMZ SO RAN, Yakutsk, 172 pp. (in Russian)

Tolstikhin, N.I., 1941. Ground Water of the Frozen Zone of the Lithosphere. Gosgeoltekhizdat, Moscow, 201 pp. (in Russian)

You, Y., Yu, Q., Pan, X., et al., 2017. Geophysical imaging of permafrost and talik configuration beneath a thermokarst lake. Permafrost and Periglacial Processes 28 (2), 470–476.

Received April 16, 2018
Revised version received December 4, 2018
Accepted December 14, 2018