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SUBPERMAFROST WATERS IN THE EAST CHUKOTKA'S UPLAND

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The purpose of the article is to reveal the conditions of occurrence and formation of subpermafrost waters, which have been encountered by wells in the Paleozoic, Triassic terrigenous rocks and in the Lower Cretaceous granitoids of the Chukotka Upland. In the Paleozoic sequence, confined subpermafrost waters were encountered at depths from 223 to 340 m. The specific flow rates vary from 0.01 to 0.5 L/(s·m), the composition of the waters is predominantly chloride, and mineralization ranges from 0.2 to 1.3 g/dm^3. In the Triassic rocks, at depths from 100 to 300 m, the piezometric surface of waters is higher than wellhead levels by 3–4 m and up to 58.4 m. The specific yield varies from 0.00001 to 0.25 L/(s·m). The waters are chloride, hydrocarbonate and sulphate, salinity ranges from 0.1 to 3.1 g/dm^3. In the granitoid massifs, the thickness of permafrost near the sea coast is about 100 m; within the watersheds, it is about 450 m. The specific yield varies from 0.0001 to 0.013 L/(s·m). The obtained data, confirmed by magnetotelluric sounding, indicate the development of hydrogeological massifs composed of igneous and metamorphosed rocks in the upland. Structures with quasi-stratum fracture reservoirs, associated with overthrusts and faults, were formed in the terrigenous Triassic sequences. The impermeable fault planes divide the quasi-strata into sections, which are poorly interconnected hydraulically. For this reason, in the Triassic subpermafrost strata, the stagnant or extremely impeded water exchange predominates persisting for more than 400 thousand years; while in the hydrogeological massifs, the water exchange is more active.

Keywords: *Chukotka Upland, permafrost zone, subpermafrost waters, active and extremely impeded water exchange, cryogenic pressure, magnetotelluric sounding.*

INTRODUCTION

The Chukotka Upland is located north of the Arctic Circle and is divided by the meridian 180° into parts: the eastern part drained by the rivers of the East Siberian Sea basin and the western part drained by the Chukchi Sea basin (Fig. 1). During the Second World War, the Valkumey tin ore deposit, located near the seaport of Pevek in the eastern part of the upland, had strategic importance. In subsequent years, the Pervonachalnoye tin ore deposit, Mayskoye gold ore deposit, and gold placers in the basins of the Ichuveem, Pegtymel and other rivers were revealed in this area. Hydrogeological materials were obtained during the prospecting, exploration and mining of the deposits. These data were partially summarized in collective works [*Tolstikhin, 1972; Efimova et al., 1977; Afanasenko et al., 1989*]. These and subsequent publications have focused on groundwaters of suprapermafrost and open taliks as the main sources of freshwater [*Shumikhina, 1999; Glotov and Glotova, 2015; Glotov, 2020*]. The main drawback of the published works is that the specific features of the distribution, occurrence, and formation of subpermafrost waters were not described. The purpose of the present study is to eliminate these disadvantages.

The scientific and practical relevance of this work is determined by the important role of hydrogeological features of subpermafrost strata to provide stability of underground engineering structures, to evaluate the prospects of using these strata as storages for fresh water and other fluids, and to solve a number of geoecological and geophysical problems.

Materials and methods. The analysis and synthesis of the handwritten geological reports and publications, including the author's ones, were used. Data were obtained by drilling and hydrogeological sampling of wells, and underground mining. To obtain geocryological and hydrogeological data, the results of deep magnetotelluric sounding (MTS) on the 2-DV-A reference profile were used for the first time in this area.

The object of the study is the main natural factors of the formation and distribution of groundwater in the eastern part of the Chukotka Upland. The western part is distinct from the eastern one by tectonics and geological history in the Middle Pleistocene–Holocene time. Therefore, the modern permafrost-hydrogeological characteristics of these areas have their own specifics, which we do not consider in this paper.

The subject of the study is the subpermafrost waters, which generally occur in the Paleozoic-Early Mesozoic terrigenous sedimentary rocks and in the Lower Cretaceous intrusive massifs. Groundwaters of volcanogenic covers: seasonally thawed layer, suprapermafrost and open taliks require separate study and have been partially studied previously [*Glotov and Glotova, 2013; Glotov, 2020*].

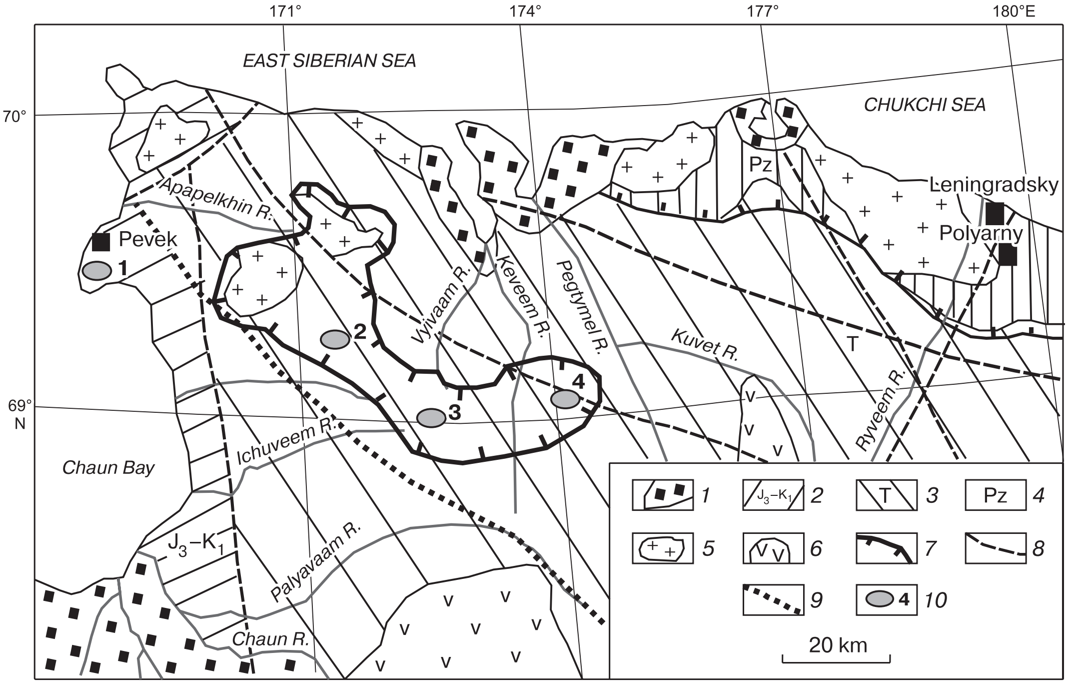

Fig. 1. The geographic and geological scheme of the Chukotka terrane, the fragment of the passive continental margin (east of the Chukotka Upland) [*Zhuravlev and Kalinin, 1999*]:

1 – Cenozoic sediments of the modern depressions; *2* – Upper Jurassic–Lower Cretaceous sedimentary rocks of the Anyuy subterrane; *3* – Triassic and *4* – Paleozoic sedimentary rocks of the Chaun subterrane; *5* – Lower Cretaceous granitoid massifs; *6* – Cretaceous volcanogenic covers; *7* – boundaries of arched uplifts; *8* – deep faults; *9* – geophysical profile 2-DB-V-A; *10* – sites of hydrogeological works, including: Valkumey (1) and Pervonachalnoye (2) tin-ore deposits, Ichuveem area of placer gold deposits (3), and Mayskoye gold-ore deposit (4).

BRIEF DESCRIPTION OF THE STUDY OBJECT

The main natural factors that determine the features of the hydrogeological conditions are relief, rivers, climate, geological structure, and permafrost features [*Pinnecker, 1977*].

The relief of the eastern part of the Chukotka Upland is characterized by subdued watersheds with absolute elevations of 500–800 m. Within this area, there are distinctly dissected ridges and mountain ranges, composed of magmatic rocks, with elevations up to 1500 m, and some tops are up to 1837 m in height. Traces of the Middle and Late Pleistocene mountain-valley glaciations are widespread [*Glushkova and Smirnov, 2020*].

The Palyavaam and Pegtymel rivers are *mountain rivers* with the largest catchment area (up to 17 thousand km^2). Open runoff exists in the period from late May to early November, in small streams – until the end of September. In winter, icings are formed in river channels [*Tolstikhin, 1974; Alekseev et al., 2011*].

The climate is characterized by the mean annual air temperature of around −10 °C; the maximum warm period lasts 100–110 days; the long-term mean annual amount of precipitation is 220–260 mm. About 60 % of precipitation falls in the form of rainfall [*Belikovich et al., 1997*].

In terms of geology, the eastern part of the Chukotka Upland belongs entirely to the Chaun subterrane – the part of the larger Chukotka terrane*, which is a fragment of the Late Paleozoic – Early Cretaceous passive continental margin [*Byalobzhesky et al., 2006*]. The subterrane is composed of the Cambrian (?) regionally metamorphosed chlorite shales and the Devonian sandstones, shales, and limestones; the Lower and Middle Carboniferous sandstones with carbonate cement and conglomerates; the Upper Carboniferous-Permian carbonaceous shales and sandstones, which compose the Velitkenay dome on the coast of the East Siberian Sea. The Lower–Middle Triassic graywackes and clayey shales, the Upper Triassic sandstones, siltstones, and clayey shales are distributed throughout the area. These sedimentary rocks were formed on the continental shelf. In the

* Terrane is a block of the earth's crust of regional sizes, separated from the surrounding area by faults [*Byalobzhesky et al., 2006*].

Lower Cretaceous, they were intruded by granitoids [*Polzunenkov, 2018*].

A specific feature of the Chaun subterrane is the development of arch-thrust structures (uplifts) modifying the folded bedding of the Triassic sequence. The largest of these structures is the Ichuveem structure, up to 100 km long and up to 30 km wide. The dip angles on the structure flanks range from 10 to 50°. Thrust faults with an amplitude of up to first kilometers, faults, and thrust faults are widely developed [*Zhuravlev and Kalinin*, 1999]. Ore deposits are located within such stressed areas [*Volkov et al., 2006*].

In terms of geocryology, the studied region belongs to the area of the continuous permafrost zone, considered as a cryogenic aquiclude [*Fotiev, 2013*]. The permafrost thickness on the tops of watersheds reaches 450 m (Valkumey granitoid massif); in the river valleys, it is up to 340 m. In the watersheds, the temperature of permafrost at the depth of zero annual amplitude (15–20 m) ranges from –9 to –11 °C [*Afanasenko et al., 1989*], in river valleys, it varies from –4.5 to –6.0 °C [*Efimova et al., 1977*].

RESULTS OF HYDROGEOLOGICAL WORKS

Following the structural-stratigraphic principle of distinguishing hydrogeological taxa [*Basic provisions..., 2001*], we consider the hydrogeological stages composed of the Paleozoic regionally metamorphosed and the Triassic sedimentary rocks, which are widespread in the east of the upland, and a group of the Lower Cretaceous granitoid intrusions.

Watering of rocks of all stages is associated with the development of zones of superimposed fracturing, which is diverse in origin.

Paleozoic rocks

Subpermafrost waters of Paleozoic rocks were studied in the coastal zone while searching for water supply sources for Leningradsky and Polyarny settlements. Table 1 demonstrates the established hydrogeological characteristics.

Subpermafrost waters in the Upper Paleozoic rocks in the valley of the Ryveem River are confined and characterized by the self-discharge up to 0.8 L/s, the specific flow rate g = 0.12–0.4 L/(s·m), and the transmissivity coefficient k_p = 4–12 m^2/day.

The pumping with 32 m lowering gave 1.35 L/s, g = 0.042 L/(s·m) in the valley of the Pilhinkuul River, 20–25 km to the south of the sea coast. In line with this well, in the river valley, the base of the cryogenic aquiclude was found at the depth of 320 m by drilling in November 1971. The aquifer is 40 m thick. Subpermafrost waters are confined. A static level is higher than the daylight surface by 58.4 m; the self-discharge flow rate at the maximum groundwater head is 1.17 L/s, g = 0.02 L/(s·m), k_p = 1 m^2/day.

By a predominant anion, subpermafrost waters belong to the hydrocarbonate, sulfate and chloride classes; by the total salinity, they vary from fresh (0.2–0.8 g/dm^3) to slightly saline (1.3 g/dm^3).

Waters of the chloride class are widespread in the lower reaches of the Ryveem River. Their total mineralization ranges from 0.6 to 1.1 g/dm^3 with the chlorine-ion content ranging from 189 to 497 g/dm^3.

Waters of the bicarbonate class are fresh; they are common for both coastal and inland areas. The content of bicarbonate ion is up to 445 g/dm^3 with a weak-alkaline reaction. The distribution of these waters is controlled by the presence of aquiferous black clayey shales saturated with organic matter.

Waters of the sulfate class are found in the vicinity of Polyarny settlement. Their mineralization is 0.6–0.8 g/dm^3, and the sulfate-ion content is up to 280 mg/dm^3. Magnesium predominates among cations, which indicates possible ore mineralization associated with basalt or andesite dikes.

Table 1. **Parameters of the water-bearing capacity of the Paleozoic rocks**

Area	Depths of wells, m	Thickness of the cryogenic aquiclude, m	Specific flow rate of wells, L/(s·m)	Mineralization of water, g/dm^3	Content of ions, mg/dm^3
Sea coast (3–5 km from the sea), abs. elevations of wellheads are 10–20 m; the valley of the Ryveem River	$\frac{293-390}{330}$	$\frac{223-335}{228}$	$\frac{0.12-0.49}{0.25}$	M $\frac{0.6-1.1}{0.9}$	Cl $\frac{189-197}{215}$; HCO$_3$ $\frac{102-464}{305}$
Coastal zone (20–25 km from the sea), abs. elevations 20–55.9 m; the valleys of the Pilkhinkuul River and its tributaries	$\frac{330-410}{362.6}$	$\frac{275-340}{301}$	$\frac{0.01-0.3}{0.13}$	M $\frac{0.2-1.3}{0.73}$	Cl $\frac{51-117}{72}$; HCO$_3$ $\frac{97-445}{251}$; SO$_4$ $\frac{35-715}{331}$

Note. *Here and below:* the numerator is from the lowest to the highest values, the denominator is arithmetic mean.

We conclude that the arithmetic-mean parameters of the water-bearing capacity of the Paleozoic rocks indicate their relatively high filtration properties in all penetrated intervals. This is associated with the development of regionally metamorphosed sequences of sedimentary rocks, represented by limestones and sandstones with calcareous cement in the dome structure. Thrust faults are not typical for this structure. Under these conditions, watering mostly occurs along the fault zones, where there are traces of carbonate leaching.

Triassic rocks

Data on the subpermafrost waters of these rocks were obtained during the search for fresh groundwater for water supply in the river valleys and during the exploration of the Pervonachalnoye tin ore deposit, the Mayskoye gold ore deposit, and the Ichuveem gold placer cluster. The sites of all deposits are connected with the Ichuveem arch-thrust uplift, stretching from the Pyrkakaiveem River to the valley of the Keveem River. To study the conditions of the mining of the deposits, hydrogeological boreholes were drilled within all topographic features. Taking into consideration the different purposes of the works performed, the results are presented separately.

Results of the work within the arch-thrust uplift

Table 2 demonstrates the basic hydrogeological parameters in the generalized form. All sites are located in subdued low-mountain terrain in the basins of streams of the 4th and lower orders, characterized by similar conditions in terms of geology. It was revealed that the thickness of the cryogenic aquiclude, hydrodynamic and hydrogeochemical parameters in the neighboring blocks are similar under different landforms. To illustrate this statement, the data on the sites of the Pervonachalnoye deposit was considered. In the upper reaches of the Pyrkakaiveem River, two wells, each 250 m deep, were drilled in January–May 1978 in the area, where the river bed intersects the thrust fault zone (Fig. 2, *A*). The thickness of the cryogenic aquiclude is 201 m in the hanging wall, composed of Middle Triassic polymictic sandstones, i.e., almost 46 m thicker than in the footwall of the thrust fault (Fig. 2, *B*).

The impermeable zone of the thrust with a thickness of up to 5 m is composed of crushed host rocks cemented by mylonitized material. The presence of the confining tectonic screen explains differences between the thicknesses of the cryogenic aquiclude, hydrodynamic parameters, and the chemical composition of water. In the footwall, the water composition is expressed by a formula

$$\mathrm{M}\,0.31\,\frac{\mathrm{Cl}\,56\,(\mathrm{HCO_3})\,38}{\mathrm{Na}\,71\,\mathrm{Ca}\,26}$$

with the chlorine ion content of 112.5 mg/dm^3. In the hanging wall, it is

$$\mathrm{M}\,0.11\,\frac{(\mathrm{HCO_3})\,67\,\mathrm{Cl}\,29}{\mathrm{Na}\,41\,\mathrm{Ca}\,30\,\mathrm{Mg}\,29}$$

with the chlorine ion content of 21.3 mg/dm^3.

Table 2. **Parameters of the water-bearing capacity within the arch-thrust uplift**

Deposit	Depths of wells, m	Permafrost thickness, m	Specific flow rate of wells, L/(s·m)	Mineralization of water, g/dm^3	Content of ions, mg/dm^3
Pervonachalnoye deposit; abs. elevations of wellheads are 152–301 m; 45 wells	$\frac{134.9-453.5}{235.5}$	$\frac{127-218}{149.3}$	$\frac{0.0001-0.25}{0.04}$	M $\frac{0.11-1.6}{0.42}$	Cl $\frac{10.6-258.4}{51.7}$ HCO_3 $\frac{47-1171}{116}$ SO_4 $\frac{12-1085}{108.6}$
Ichuveem gold placer; abs. elevations of wellheads are 90–240 m; 26 wells	$\frac{210-400}{286}$	$\frac{100-238}{159}$	$\frac{0.00003-0.2}{0.034}$	M $\frac{0.6-1.28}{0.84}$	Cl $\frac{14.2-250}{53.5}$ HCO_3 $\frac{134-793}{384.5}$ SO_4 $\frac{4-730}{271}$
Mayskoye deposit; abs. elevations of wellheads are 208.7–297.4 m; 18 wells	$\frac{210-302}{222}$	$\frac{210-260}{235.6}$	$\frac{0.000008-0.026}{0.005}$	M $\frac{0.31-0.98}{0.7}$	Cl $\frac{21.3-184}{78}$ HCO_3 $\frac{171-756}{421}$ SO_4 $\frac{0-375}{79.8}$

On the basis of the pumping test in the hanging wall, $g = 0.003$ L/(s·m), $k_p = 0.09$ m^2/day; in the footwall, $g = 0.004$ L/(s·m), $k_p = 0.12$ m^2/day. The correspondence of the slope of the piezometric surface to the slope of the river bed points to the presence of a hydrodynamic connection, even though it is impeded.

Figure 2, *B* demonstrates data from two wells drilled on the watershed of the Oleniy stream and the Pyrkakaiveem River (Krutoy stockwork). The borehole with the absolute elevation of the wellhead of 208 m revealed the bottom of the cryogenic aquiclude at the depth of 218 m. Confined groundwaters beneath this bottom rose above the daylight surface by 18.6 m, $g = 0.02$ L/(s·m). A formula of the water composition is:

$$\mathrm{M}\,0.6\frac{\mathrm{SO_4}\ 68\ \mathrm{Cl}\ 22}{\mathrm{Ca}\ 47\ \mathrm{Na}\ 29}\ \mathrm{pH}\ 6.8;$$

Fe^{2+} content is 4.5 mg/dm^3. The well in the watershed (34 m above) penetrated permafrost 162 m thick, water rose above the wellhead by 54.3 m, $g = 0.008$ L/(s·m). A formula of the water composition is:

$$\mathrm{M}\,0.85\frac{\mathrm{Cl}\,93}{\mathrm{Na}\,89}\mathrm{pH}\,7.6.$$

According to geological data, there are normal faults between these wells, the fault planes of which are composed of tectonic mylonitized breccia 0.5 m thick. Such fault planes provide hydrogeological differences between the spatially close blocks and limit their water resources. This fact was highlighted by all hydrogeologists, who studied the hydrogeological conditions of mining the ore deposits in the Chukotka Upland.

Therefore, drilling of wells in different sites of the arch-thrust structure showed that the Triassic fractured aquiferous deposits are widespread. However, their water-bearing capacity, in general, is fragmentary, low and uneven in area. Contacts of the fragments are tectonic (cataclased or mylonitized fault planes) or hydrothermal (veins of quartz, kaolinite). Small values of the transmissivity coefficient (less than 0.01 m^2/day) do not induce large water inflows into the workings during underground mining, but the presence of water in fractures makes barriers of all underground workings unstable. Therefore, during the development of subpermafrost ore zones of the Mayskoye gold ore deposit, all underground workings require sheeting, although water inflows are extremely small and characterized as dripping.

Results of works on the study of subpermafrost waters in the river valleys

In conditions of the continuous cryogenic aquiclude, river valleys are the most promising source of water supply. In mountain areas, the valleys are usually attributed to fault zones, including fault planes of trust faults, strike-slip faults, and normal faults. A generalization of the available material shows that open taliks in the river valleys in the eastern part of the Chukotka Upland are rare and associated with graben valleys, filled by loose glacial or alluvial sediments more than 10–15 m thick [*Glotov, 2020*]. Such

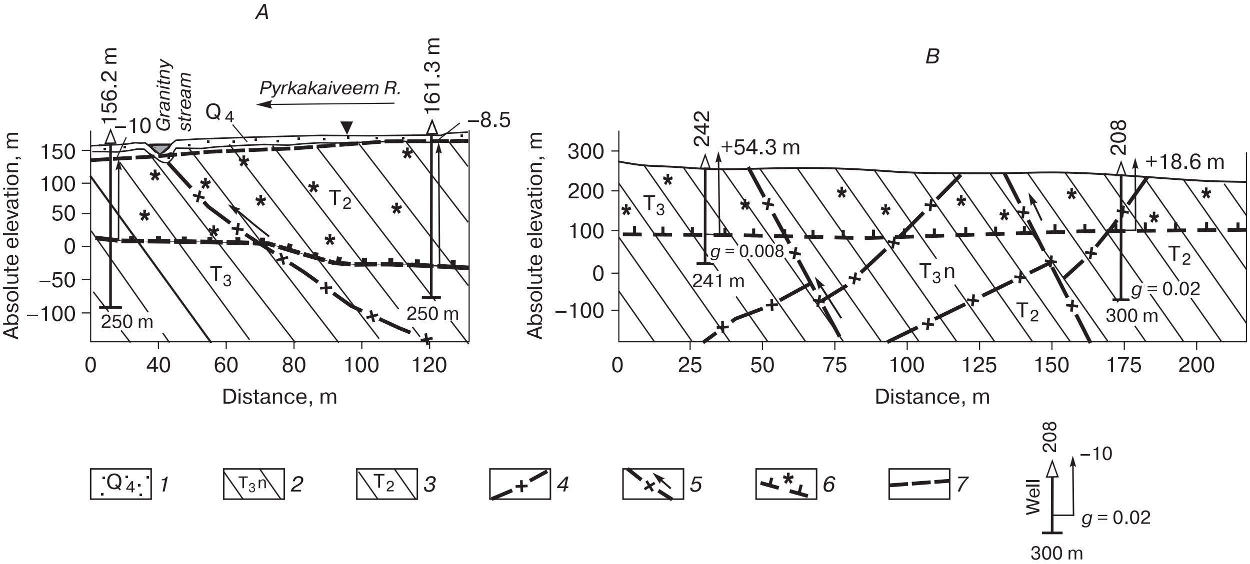

Fig. 2. The schematic hydrogeological cross sections along the valley of the Pyrkakaiveem River near the Granitny stream (*A*) and along the watershed of Oleniy stream – Pyrkakaiveem River (*B*):

1 – Quaternary alluvial sediments; *2* – Upper Triassic, Norian Stage – interbedding of clayey shales, siltstones, and fine-grained sandstones; *3* – Middle Triassic sedimentary rocks, sandstones and siltstones; *4* – thrust faults, hydrothermally transformed mylonites in a thrust plane; *5* – normal faults, cataclasites in a fault plane; *6* – permafrost base; *7* – a level of subpermafrost waters in the river valley. Well: figures below – well depth, m; figures above – an absolute elevation of a wellhead, m; *g* – specific flow rate, L/(s×m); an arrow – a height of subpermafrost water rise, m; plus – above the wellhead, minus – below the wellhead.

Table 3. **Parameters of the water-bearing capacity of the Triassic sedimentary rocks in the river valleys**

Area	Depths of wells, m	Permafrost thickness, m	Specific flow rate of wells, L/(s·m)	Mineralization of water, g/dm^3	Content of ions, mg/dm^3
Coastal area; abs. elevations 5–80 m; up to 9 km from the coast of the Chaum Bay; 20 wells	$\frac{300-602}{386}$	$\frac{140-250}{175}$	$\frac{0.0007-0.09}{0.02}$	M $\frac{0.19-3.1}{1.73}$	Cl $\frac{2.56-445}{80.6}$ HCO_3 $\frac{78-507.5}{180.4}$ SO_4 $\frac{0.1-60}{31.4}$
Inland area; abs. elevations 156–302 m; 11 wells	$\frac{201-300}{286}$	$\frac{120-240}{191.5}$	$\frac{0.0005-0.28}{0.04}$	M $\frac{0.13-2.6}{0.66}$	Cl $\frac{2.3-445}{80.6}$ HCO_3 $\frac{97.6-829.5}{294}$ SO_4 $\frac{0.6-44.5}{23}$

areas have been revealed only in the basin of the Pegtymel River. Therefore, Table 3 demonstrates the summarized results of drilling and sampling of the wells situated in the areas outside the zones with open taliks.

There are noticeable differences in the hydrogeological parameters of the coastal zone. In terms of geology, it is located on the eastern flank of the Anyuy subterrane. The inland area belongs to the Chaun subterrane (Table 3).

In general, the total mineralization and the chlorine ion content are higher in coastal areas than in inland areas; however, the water transmissivity of rocks in the first one is 2.2 times lower than in the second one.

It should be noted that subpermafrost waters by their composition belong to the hydrocarbonate, chloride, and sulfate classes, typical for the subpermafrost waters of the Paleozoic formations and Triassic deposits in the arch-thrust uplifts.

A group of intrusive massifs

Hydrogeological characteristics of this group were obtained only during the development of Valkumey tin ore deposit attributed to the granitoid massif of the same name. This massif is represented by Pevek Mountain, characterized by subdued relief with the absolute elevation of 616 m. During underground mining at the elevations from +150 to –250 m, it was established that the cryogenic aquiclude is continuous. In the coastal zone, its thickness is about 100 m. The assumed thickness of the cryogenic aquiclude in the upper part of the slope (at the top of the mountain) is about 400–450 m.

The subpermafrost waters, encountered by underground mining, occur in the submeridional zones of the faults that also host the ore bodies. The head in the coastal zone does not exceed 10 m above the mouth. Perhaps, below the watershed, subpermafrost waters do not contact the cryogenic aquiclude and their levels are free.

The long-term observations of water inflows into underground workings show that all aquiferous faults are poorly interconnected hydrodynamically. After opening of the aquiferous zone, the water inflow varies from the first units up to 30 m^3/day. In 10–15 days, the inflow decreases by 2–3 times. In 2–3 weeks, sometimes, up to 5–6 months, it decreases until draining. The water bearing capacity of the fault zones before their uncovering can be estimated on the basis of the pumping data from advance wells, which have been drilled from the bottom of the workings on different horizons (Table 4).

Table 4. **Pumping data from advance wells in underground workings [*Glotov and Glotova, 2003*]**

No.	Abs. elevation, m	Absolute mark of the depth of penetration of aquifers, m	Pumping results		
			Constant flow rate in the first 5 days, L/s	Lowering from static level, m	Specific flow rate, L/(s·m)
1	+10	–167	0.02	48.5	0.0004
2	+10	–90	0.35	90.0	0.0040
3	–50	–75	0.75	60.0	0.0130
4	–100	–130	0.015	110.0	0.0001
5	–100	–180	1.00	110.0	0.0090

The attention should be paid on the existence of the relatively water-rich objects ("pockets") in ore zones. According to the chief geologist of the mine A.D. Kharyutkin, such "pockets" are characterized by abundance of calcite veins in the fractured zone.

The subpermafrost waters are characterized by the sodium-calcium chloride or calcium-sodium composition. By the total mineralization, they are fresh (up to 1 g/dm^3), brackish (1–20 g/dm^3), saline (0–40 g/dm^3), and brine (more than 40 g/dm^3) [*Glotov and Glotova, 2003*].

Freshwaters are encountered by the workings located at a distance of 0.5 km or more from the Chaun Bay. They occur below the bottom of the cryogenic aquiclude as lenses in faults, forming the zone of fresh waters underlain by brackish waters.

Saline waters and brines occur beneath the bottom of the Chaun Bay as isolated lenses with salinity up to 300–320 g/dm^3. One of them with the composition of water

$$\mathrm{M}\ 314 \frac{\mathrm{Cl}\ 100}{\mathrm{Mg}\ 73\ \mathrm{Na}\ 26}\ \mathrm{pH}\ 6.8$$

was encountered during underground mining of an ore vein in the Pribrezhny site on 19.03.1970. The presence of these waters indicates the cryogenic metamorphization at the temperatures from -10 to -15 °C [*Abramov, 2014*]. It is possible that cryopegs were formed near the day surface and then penetrated to deeper horizons.

Study of the tritium content in the samples taken by D.V. Efimova from self-discharging wells on the –100-m horizon on 18.07.1974 [*Efimova et al., 1978*] showed that brackish water, the composition of which is reflected by a formula

$$\mathrm{M}\ 37.9 \frac{\mathrm{Cl}\ 98}{\mathrm{Ca}\ 70\ (\mathrm{Na} + \mathrm{K})\ 22},$$

contains 83 TU or 9.9 Bq/L; in the water of the Chaun Bay, it is 13.4 Bq/L. These values correspond to natural values of tritium in natural waters of the zone of active water exchange. However, subpermafrost waters, encountered in the Valkumey massif, where there is the continuous cryogenic aquiclude, are distributed in the zone of impeded water exchange, as evidenced by the presence of ions of divalent iron in sulfate brine. It is possible that tritium-containing air of the mine penetrates into the dried zones of faults; and, when air moisture is condensed, tritium-bearing waters are formed, diluting brackish waters. The formation of tritium could also occur during the natural decay of radioactive components.

Concluding the hydrogeological characteristics of the Paleozoic and Triassic sedimentary rocks and a group of intrusive rocks, we will focus on some common features in the Chukotka Upland.

1. Subpermafrost waters in the Triassic sedimentary rocks are confined everywhere, including the watersheds above the possible sources of groundwater feeding. In the group of intrusive massifs, subpermafrost waters may have a free level within the near-watershed areas.

2. Water transmissivity below the cryogenic aquiclude in the Paleozoic regionally metamorphosed formations, studied in the river valleys, is tens of times higher than the same parameter in the Triassic sedimentary rocks and intrusive massifs.

3. In terms of the chemical composition, waters of the hydrocarbonate class, waters of the chloride class in the coastal lowlands, and waters of the sulfate class in the zones of hydrothermal sulfide mineralization are most common. According to the total mineralization, waters of low salinity and fresh waters predominate. However, the high bicarbonate content is possible in waters of any class of both hydrogeological stages.

HYDROGEOLOGICAL FEATURES OF THE SOUTH OF THE CHUKOTKA UPLAND ON THE BASIS OF MAGNETOTELLURIC SOUNDING

Magnetotelluric sounding (MTS) was performed in 2002–2004 by the group from Karpinsky Russian Geological Research Institute (VSEGEI) along the profile 2-DV-A from Pevek Mountain to the Valunistoye mine. Figure 3 illustrates a fragment of the profile, the depth of which is limited to 3000 m, because it is close to the total thickness of the Triassic sedimentary rocks in this site of the works. The profile runs along the southwestern flank of the Ichuveem arch-thrust uplift to the upper reaches of the Palyavaam River. The geoelectric section crosses the Upper Jurassic – Lower Cretaceous sedimentary-volcanogenic sequence at a distance of about 12–15 km from Pevek. This sequence is a part of the Anyuy subterrane. Further up to 40 km, the section crosses the zone of the Pevek submeridional deep fault, dividing the Anyuy and Chaun subterranes.

Up to 150 km, the section of the profile is represented by the Triassic sedimentary rocks, which are underlain by the Paleozoic sedimentary rocks at a depth of more than 3000 m. The sedimentary rocks are ruptured by dikes and massifs of magmatic rocks, broken by numerous normal faults and thrust faults. The complete geoelectric sections are presented online at VSEGEI website: Section-2-DV-A_Geoelec_raz_0-225 km.jpg (https://vsegei.ru/ru/info/gisatlas/dvfo/chukotsky_ao/index.php).

Using results of the MTS in geologically and geocryologically similar areas of the Northeast of Russia [*Khasanov and Sharafutdinov, 2011*], the author distinguished the blocks of monolithic magmatic and metamorphosed rocks with electrical resistivity (ER) > 398 Ohm·m in the studied geoelectric section. Their water-bearing capacity is manifested in the form of narrow sub-vertical bands with an electri-

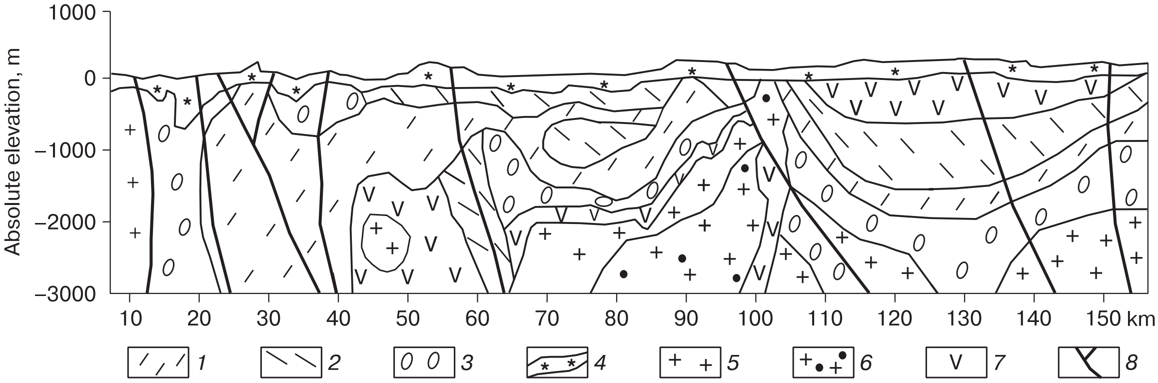

Fig. 3. The geoelectric section of the southern margin of the Chukotka Upland in the segment of 10–150 km from Pevek.

Based on an enlarged fragment of the geoelectric and seismic profile 2-DV-A (*vsegei.ru/ru/info.../2021*). Electrical resistivity of the zones (Ohm·m): *1* – <25.1; *2* – 25.1–32.8; *3* – 32.8–158; *4* – 158–358; *5* – 358–1000; *6* – 1000–10,000; *7* – >10,000; *8* – fault.

cal resistivity of 25.1–39.8 Ohm·m. By conditions of the groundwater occurrence, such blocks are typical hydrogeological massifs.

The near-surface continuous band, which shape partly repeats the topography, is also characterized by high electrical resistivity. Its thickness varies from 200 to 400 m. Two belts with approximately equal thickness are distinguished in the band: the upper belt with ER from 158 to 251 Ohm·m, and the lower belt with ER of 252–398 Ohm·m. The author considers the continuous band as permafrost, which consists of the upper belt – an ice-bearing layer of regionally fractured rocks and the lower belt – frozen rocks lying deeper than the zone of hypergene fracturing.

The cryogenic aquiclude lies on the Triassic subpermafrost sedimentary formations with relatively low resistivity, their ER ranges from less than 25.1 to 158 Ohm·m. The ER value in this case reflects water transmissivity of rocks or specific flow rates of the wells and groundwater mineralization determined by pumping. For example, in the profile interval of 102–105 km in the valley of the Sredny Inchoun River, permafrost lies on the layer with ER less than 25.1 Ohm·m. Earlier, the well 302 m deep was drilled here. Confined subpermafrost waters were encountered at the depth of 217 m and the water level rose above the wellhead by 34.6 m. In pumping on 26.06.1991, a constant flow rate of 12.5 L/s was obtained at 67.4-m lowering, g = 0.19 L/(s·m), k_p = 20 m^2/day. A formula of the water composition is

$$\mathrm{M}\ 0.82\ \frac{\mathrm{HCO_3}\ 79\ \mathrm{Cl}\ 21}{\mathrm{Na}\ 72\ \mathrm{Mg}\ 19}\ \mathrm{pH}\ 6.3.$$

The content of bicarbonate ion is 756 mg/dm^3. The data of this well reflect the hydrogeological features of the most low-resistance zone. Subpermafrost strata are traced along the entire profile up to about 150 km, which is associated with the extensive development of thrust faults. Therefore, the MTS results quite clearly reflect the general hydrogeological and permafrost features of the studied blocks of the earth's crust.

DISCUSSION

On the basis of drilling and sampling of wells, underground mining, and interpretation of MTS results, we can conclude that there are two classes of waters distributed in the subpermafrost setting – local fracture waters and quasi-stratum fracture waters. The local-fracture waters are typical for magmatic rock massifs and for the dome of the Paleozoic regionally metamorphosed sequences. These waters also occur in the Mesozoic lithified sedimentary sequences. Taking into account the fact that the thickness of the cryogenic aquiclude on them exceeds the depth of hypergenic fracturing, these massifs can be considered analogous to the hydrogeological massifs previously identified in Eastern Siberia [*Shepelev et al., 1983*]. While the local fracture waters are sufficiently studied and their relationship with fault zones is quite clear, the quasi-stratum fracture waters are poorly studied. Therefore, we emphasize that the quasi-stratum fracturing develops in monolithic sedimentary rocks, when their blocks move along thrust faults. The tectonophysical consequences of such displacements are actively studied [*Seminsky, 2003; Danielsen and Dahlin, 2009; Seminsky et al., 2016*]. According to the established concepts, at the stage preceding the displacement of blocks (strata), the zones of paragenetically connected ruptures arise due to geological pressure. These are the leading fractures of shear and rupture, which form the fracturing zone. With further growing of pressure, fractures enlarge; main fault planes arise; a layer of tectonically crushed rocks (cataclasites), which are often cemented by clays produced by friction (mylonites), is formed along a strike of the fault planes. The thickness of this layer in our case does not exceed 10 m. However, because of low water permeability, it can be considered as a confining barrier, which divides the fracturing zone, developed earlier, into two quasi-stratum reservoirs, poorly connected in terms of hydrogeodynamics.

Tectonic activity is also manifested in the formation of sub-vertical faults or fractures, which are filled with hydrothermal quartz, kaolin, ore minerals, etc. These vein formations are also poorly permeable and, together with the fault planes, form a network of relatively impermeable screens, which divide the quasi-stratum fracture reservoirs into fragments or sections. These screens generally impede water exchange, but do not prevent transmission of hydrostatic pressure. This fact is confirmed by the connection of the field of piezometric levels with slopes of the day surface. Their hydrodynamic isolation is confirmed by rapid (from 2–3 days to several weeks) drawdown of water resources during pumping (up to drainage) of initially water-bearing rocks and by differences in the chemical composition of water in the neighboring sections.

The author believes that the long-term maintaining of the cryogenic head, generated during freezing under conditions of impeded outflow of subpermafrost waters, is also explained by poor interconnection of the aquiferous sections. The relatively small size of freezing sections prevents the accumulation of significant volumes of cryogenically metamorphosed water and the creating of the heads, sufficient to destroy natural impermeable barriers. Due to poorly studied permafrost history of the Chukotka Upland, the data on the geographically close region of Arctic Yakutia have been involved to analyze the development of permafrost in the Pleistocene and Holocene [*Gavrilov et al., 2000; Gavrilov and Tumskoy, 2001; Anisimov et al., 2002*].

These data suggest that over the last 420 thousand years, the spatial distribution of discontinuous permafrost in the Chukotka Upland has not changed dramatically. However, during the Holocene warming, the permafrost degraded with a decrease of its thickness, apparently, no less than 1.5 times. Therefore, in the mountain areas and river valleys, the fragmentary structure of the subpermafrost aquiferous strata determined impeded water exchange and allowed to preserve the cryogenic head and groundwaters formed more than 420 thousand years ago. The long-term contact of the groundwaters and host rocks contributed to enrichment of waters with salts of carbonic acid due to interaction with carbonaceous-clayey shales and with a chlorine ion leached from them. Activity of water exchange is higher in the hydrogeological massifs of the fault zones. Therefore, it is possible that the subpermafrost waters here is close to the modern age.

CONCLUSIONS

Therefore, the results of drilling, underground mining, and magnetotelluric sounding show the specific features of hydrogeological conditions in the subpermafrost units in the east of the Chukotka Upland and lead to the following conclusions and recommendations:

1. According to the conditions of the groundwater distribution and occurrence in the area of the Chukotka Upland, the hydrogeological massifs with local fracture waters were formed in the granitoid massifs and in the Paleozoic metamorphosed rocks. A classic example of such a massif is the Valkumey massif. The unique natural reservoir was formed on the tectonically active arch-thrust uplifts. This reservoir consists of fractured aquiferous rocks, divided into sections by relatively impermeable screens. The last ones are represented by tectonic breccias, cemented by mylonite, friction clays, quartz and kaolin, as well as by hydrothermal quartz and/or kaolin veins.

2. The sectional structure of the subpermafrost units contributed to the formation of a cryogenic head pressure under all topographic features, including watersheds, with the head level higher than the daylight surface and maintaining these heads up to the present time. The hydrogeological structural features outside the arch-thrust uplifts are poorly studied. Drilling in the river valleys suggests the existence of the subpermafrost sectional structure in these areas.

It is possible that the existence of confined subpermafrost waters in the watersheds with a static level up to 54.3 m above the wellhead may be related to the presence of local open taliks in the upper reaches of streams, for example, in the bottoms of former glacial cirques or kars. Similar taliks are known in the western part of the Chukotka Upland, and may exist in the eastern part, too.

3. Existence of the subpermafrost sections with the impeded water exchange at shallow depths is favorable for the creation of underground storage of liquid products – fresh water for potable water supply, oil products, toxic liquid waste, etc.

4. It is necessary to conduct long-term regime observations of the level, pressure, and composition of subpermafrost waters, to study the age specifics of groundwaters in the entire area of the Chukotka Upland and in the adjacent areas not only in river valleys, but also in watersheds.

5. We recommend implementing the MTS methods into the practice of areal and local permafrost-hydrogeological studies.

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