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SURFACE AND GROUND WATERS IN TERRESTRIAL PERMAFROST REGION

SUBPERMAFROST GROUNDWATER IN THE NORTHEASTERN PART OF THE LENA–AMGA INTERFLUVE

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The purpose of this work was to specify the hydrogeological conditions in the poorly studied north-eastern part of the Lena–Amga interfluve. We analyzed archival (1965–1995) and published data on subpermafrost waters and permafrost thickness in the Churapcha and Tattinsky districts of the Republic of Sakha (Yakutia), including new field studies (2009–2022). The research was based on the data from 19 groundwater exploration boreholes, 450 to 650 m in depth. It is shown that the Jurassic and Middle Cambrian aquifer complexes differ in piezometric pressures and chemical composition. Based on the new information, it is suggested to shift the estimated boundary of fissured formation groundwater occurrence in terrigenous carbonate sediments northwards by 50–80 km. A zone with distinct hydrogeological conditions near the Tatta–Tompo fault was identified. Presumably the fault was formed under conditions of horizontal compression, which resulted in compaction of rocks, which reduced permeability along the fault, and increased freezing intensity in strata with low water content during periods of decreased global temperatures.

Keywords: *groundwater, Middle-Cambrian aquifer system, Jurassic aquifer system, Tatta–Tompo fault, hydrostatic level, chemical composition.*

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INTRODUCTION

The presence of a large Lena River in Central Yakutia largely solves the issues of water supply to the main cities and settlements of the Republic of Sakha (Yakutia). However, population in a large part of the republic suffers a shortage of high-quality drinking water, since it is impossible to organize reliable water supply to towns and villages at the expense of surface waters due to the seasonality of the flow of small rivers and high susceptibility to pollution of watercourses and reservoirs. This problem is especially acute on the right bank of the Lena River in the Lena–Amga interfluve. In its northeastern part, on an area of more than 17.5 thousand km^2, there are more than 20 settlements with a population of about 10 thousand people.

Geological exploration in the Lena–Amga interfluve to assess the possibility of meeting the population's water needs at the expense of underground aquifers was started by employees of the Yakut Geological Department in 1965–1966. In the same years, the Institute of Permafrost Studies of the SB Academy of Sciences of the USSR conducted permafrost and hydrogeological studies in the basins of the thermokarst lakes Churapcha and Imite. Under the leadership of A.M. Fedorov, the first exploratory boreholes for above-frozen waters were drilled here. When studying the lake taliks, a conclusion was made about the futility of the groundwater contained in them for the organization of drinking water supply due to their increased mineralization and limited deposits. Further studies of taliks in thermokarst basins of Central Yakutia revealed instability of the chemical composition of groundwater along the section due to a change in the lithological composition of the water-bearing rocks and different conditions of their freezing, as well as high concentrations of ammonium, organic substances and iron, increased water hardness [*Anisimova, 1971; Fedorov, 1976*]. It was found that after the drying of reservoirs, the gradual freezing of closed lake taliks under them is accompanied by an increase in the mineralization of groundwater [*Anisimova, 1971*]. During the operation of boreholes drilled in lake basins, freezing of the drained part of the talik intensifies as water is withdrawn, and without artificial replenishment of reserves, the operation time of water intakes is very limited [*Fedorov, Lavrentiev, 1985*]. In addition, it is often difficult to organize a sanitary protection zone around boreholes for the suprapermafrost waters of lake taliks near populated areas.

One of the options for organizing drinking water supply in settlements is the development of regionally widespread subpermafrost waters. The study of aquifers lying under the permafrost in the northern part of the Lena–Amga interfluve began with drilling boreholes in the village of Churapcha in 1965 and the village of Ytyk-Kuel in 1971. The results of these studies were used to identify hydrogeological structures of the second order in the Yakut Artesian basin (AB), including the Aldan wing of the Yakut Artesian basin with the Amga AB and the Lena–Vilyui AB, one of which was the Nizhnealdansky AB [*Anisimova et al., 1967; Efimov, Zaitsev, 1970*]. Later, when mapping the permafrost-hydrogeological zoning of the East of Siberia (1984) by a team of authors led by O.N. Tolstikhin, the boundaries between hydrogeological structures were clarified, and their names were partially changed. In particular, Lena–Vilyui AB was divided into Lena–Vilyui AB and Lena–Amga AB. The boundary between these hydrogeological structures was drawn by changing the facies-lithological composition of rocks of subpermafrost complexes, namely, by changing the carbonate facies of deposits of Cambrian age (Lena–Amga AB) to terrigenous, composed of Jurassic age formations (Lena–Vilyui AB) [*Shepelev et al., 1984*]. In this article, the description of hydrogeological structures is given according to [*Melnikov, Tolstikhin, 1984*] (Fig. 1).

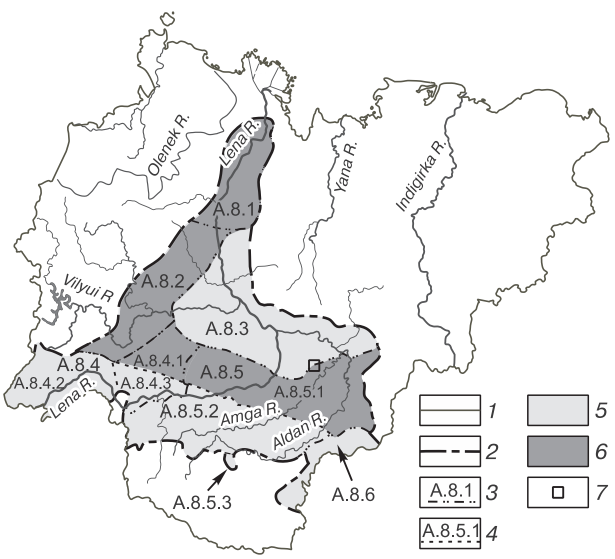

Fig. 1. Scheme of hydrogeological zoning of the Yakut Artesian Basin within Yakutia [*Melnikov et al., 1984*].

Boundaries: *1* – Yakutia, *2* – Yakut Artesian Basin (hydrogeological area of the first order), *3* – hydrogeological areas of the second order and their indices, *4* – hydrogeological areas of the third order and their indices, *5* – artesian basins (AB), *6* – cryoartesian basins (CAB), *7* – study area. A.8 – Yakut AB: A.8.1 – Nizhnelensky CAB, A.8.2 – SredneVilyuisky CAB, A.8.3 – Lena–Vilyui AB; A.8.4 – Srednelensky CAB: A.8.4.1 – Kempendyai CAB, A.8.4.2 – Nyusko-Dzherbinsky AB, Berezovsky AB; A.8.5 – Lena–Amga AB: A.8.5.1 – Prilensky CAB, A.8.5.2 – Amga AB, A.8.5.3 – Yukhtino–Yllymakhsky AB; A.8.6 – Uchuro–Maysky AB.

In the next 40 years, within the Lena–Amga and Lena–Vilyui AB, employees of the State Unitary Enterprise RS (Y) YPSE, subsequently transformed into JSC Yakutskgeologiya, continued search and evaluation work on subpermafrost waters to address issues of organizing water supply for population. The drilling points of hydrogeological boreholes were confined to specific localities and distributed unevenly across the area of investigations.

The purpose of the work performed was to clarify the hydrogeological conditions of the insufficiently studied central part of the Lena–Amga interfluve on the basis of a detailed analysis of archival and published data on subpermafrost waters and the distribution of permafrost rocks in this area with the involvement of new field research results.

MATERIALS AND METHODS

When summarizing geological, hydrogeological, geocryological and hydrochemical data, the results of drilling 19 exploratory boreholes for subpermafrost waters were used. The boreholes are located in the northeastern part of the Lena–Amga artesian basin and the southeastern edge of the Lena–Vilyui Artesian basin (Fig. 1). They were drilled between 1965 and 2018 by employees of JSC Yakutskgeologiya, since 2009 – with the direct participation of the authors of the article. The depth of the boreholes is from 450 to 650 m. In the interval of occurrence of permafrost, boreholes were drilled with a continuous down hole with flushing with a water-Hypan solution. After the start of the absorption of the drilling fluid, drilling continued in the core method with core sampling and rinsing with clean water. In order to be able to carry out test filtration work in boreholes, the unstable part of the section was cased. A mesh strainer was installed in the wateriest interval determined during drilling. Then the borehole was developed and the subsequent complex of experimental hydrogeological works was carried out.

Of the 19 boreholes, 9 tapped only the Jurassic aquifer complex, four boreholes tapped Lower Cambrian aquifer rocks, hydrochemical and pilot filtration testing of the joint Lower Jurassic and Middle Cambrian complexes was carried out in 5 boreholes. One of the exploration boreholes, 650 m deep, did not penetrate the base of the cryogenic aquiclude.

The duration of the experimental single pumping was 3–5 days. Based on the results of testing filtration work, the coefficients of water permeability of rocks were calculated according to graphs of the dependence of water level decrease on time for conditions of quasi-stationary fluid flow [*Borevsky et al., 1979*]. With low water-fluidization of rocks, the calculation of the coefficient of water supply was carried out according to the schedule for restoring the level after pumping. Large decrease of the water level during testing filtration operations with relatively low pumping rates, a significant distance (from 2 to 50 km) between boreholes, the inability to use previously drilled exploratory boreholes as observational ones due to the formation of an ice plug with a thickness of 250–300 meters or more in the hole, did not allow to determine the piezoconductivity coefficients of rocks experimentally. This parameter was borrowed from the reference literature when estimating reserves [*Maksimov et al., 1971*]. There are practically no data on the position of the level of subpermafrost waters in the annual and long-term cycle, with the exception of single measurements in the intake borehole in the village of Churapcha. According to available data, in 2017–2022, fluctuations in the piezometric level of subpermafrost waters in it did not exceed 2 m.

When constructing the isolines of the thickness of permafrost rocks, data from drilling boreholes in the territory under consideration were used.

To characterize the chemical composition of subpermafrost waters, the results of analytical studies of water samples taken during testing filtration works were used. The methods of titrometry, potentiometry and capillary electrophoresis were used in laboratory studies of subpermafrost waters performed in the laboratories of JSC Yakutskgeologiya and the Federal State Health Institution Center for Hygiene and Epidemiology in the Republic of Sakha (Yakutia).

ENVIRONMENTAL CONDITIONS

The studied territory is located in Central Yakutia in the area of the junction of the Abalakh erosion-accumulative plain with the Tyungyulun pseudoterrace, which is attributed to the alluvial plain [*Kamaletdinov, 1982; Grinenko et al., 1995*]. The absolute elevation marks vary from 170 to 310 m. A distinctive feature of these geomorphological levels is the widespread occurrence of thermokarst basins with bulgunnyakhs akhs (perennial frost heave mounds).

Morphotectonically, the territory is located within the Lower Aldan depression and the northern part of the Lena–Aldan plateau [*Kovalev, 2021*]. The Lower Aldan depression includes the Ust-Aldan depression and the Tattin depression adjacent to it from the east [*Imaeva et al., 2006*]. Both of them have a crescent shape with an elongated end, cutting into the Lena–Aldan plateau to the southwest. According to L.P. Imaeva et al. [*2006*], the Tatta depression is bounded from the east by the Tatta–Tompo fault, which shifts the contours of the Lower Aldan depression to the west. The Tattin depression in the northern part is complicated by sublatitudinal shear deformation, and in the east it joins the Lena–Aldan plateau.

Formations of the Lower Paleozoic, Mesozoic and Cenozoic take part in the geological structure of the sedimentary cover [*Kamaletdinov, Gritsenko, 2000; Kazakova et al., 2021; Marinov et al., 2022*]. Rocks of the Middle Cambrian lie at the base of the section. They are represented by dense dolomites with limestone interlayers. On the eroded surface of carbonate rocks, boreholes have uncovered terrigenous deposits of the Jurassic – multi-grained sandstones, mainly quartz-feldspar composition, with rare interlayers of clay shales and sands [*Balobaev et al., 2003*]. A sand-conglomerate layer with thickness from units to the first tens of meters, sometimes with interlayers of clays lies at the base of the sandstones [*Grinenko, Knyazev, 2008*]. Monoclinal sinking of Lower Cambrian and Jurassic rocks occurs from south to north and northwest. In the same direction, there is an increase in the thickness of Cenozoic formations, which are represented by multi-grained sands and clays of Neogene age, as well as sandy-loamy Quaternary deposits. The thickness of the latter in the studied area is 50–110 m [*Ivanov, 1984; Spector, Spector, 2002*]. In the near-surface part of the section, alluvial and lacustrine-alluvial quaternary formations have high iciness due to texture-forming and secondary wedge ice.

The region of investigations is located in the area of continuous permafrost. Its thickness is not sustained. In the southern part of the territory, the bottom of permafrost rocks lies at a depth of 313–322 m, and in the northern part – at a depth of 396–480 m. The maximum thicknesses of the cryogenic aquiclude covering the permafrost aquifers were detected near the valley of the Tatta River. Here, according to drilling data, the bottom of permafrost rocks has been uncovered at a depth of 500–585 m. One of the boreholes with a depth of 650 m, drilled near the village of Dyabyla in 2014, did not come out of frozen rocks. According to the geothermal measurements and calculation of the geothermal gradient, negative rock temperatures extend to a depth of 750–780 m [*Kirillin et al., 2022*].

Under the thermokarst lakes, the taliks are not open. Their thickness is up to 40–50 m, rarely 100 m. The presence of frequent clay interlayers in the lithological section of taliks determines the weak water recovery of rocks and low operational capabilities for groundwater extraction. The suprapermafrost waters of the taliks, widespread within the territory under consideration, do not seem to have a hydraulic connection with the subpermafrost waters, due to the presence of a powerful cryogenic water barrier (aquiclude) separating them.

SUBPERMAFROST AQUIFERS

In the southern part of the territory under consideration, the Jurassic deposits, represented by sandstones with layers of siltstones, are completely frozen. An aquifer carbonate Middle Cambrian complex lies under permafrost rocks. Its top is located at depths from 313 (Tuora-Kuel village) to 380 (Deering village), and the exposed thickness is 132–289 m (Figs. 2, 3). Limestones and dolomites have different degrees of fracturing and contain fractured-layer waters. The minimum values of the water permeability of carbonate deposits are noted near the Tatta–Tompo fault, where they amount to 0.4 m^2/day. As you move away from the disjunctive, the water permeability of the rocks increases to 26 m^2/day. The depth of the piezometric level of the subpermafrost waters of the Middle Cambrian aquifer complex from the Earth's surface varies from 9 to 107 m.

In the northern and central parts of the studied area, the Jurassic is the first regional aquifer from the surface. It lies under the thickness of permafrost rocks at depths from 396 m (Ytyk-Kuel village) to 535 m (Cherkekh village) (Table 1). Its exposed thickness varies from 50 to 180 m. The subpermafrost waters are contained in sandstones and siltstones. According to the filtration conditions, groundwater is classified as fractured-layer one. According to testing pumping data in boreholes drilled along the Tatta-Tompo fault, the water capacity of terrigenous deposits is 0.3–1.0 m^2/day and increases in the northwestern direction to 15–21 m^2/day. Piezometric groundwater levels in boreholes that have uncovered the Jurassic aquifer complex are set at depths of 150–225 m from the Earth's surface. In a multiyear cycle, the levels of subpermafrost waters are practically not subject to

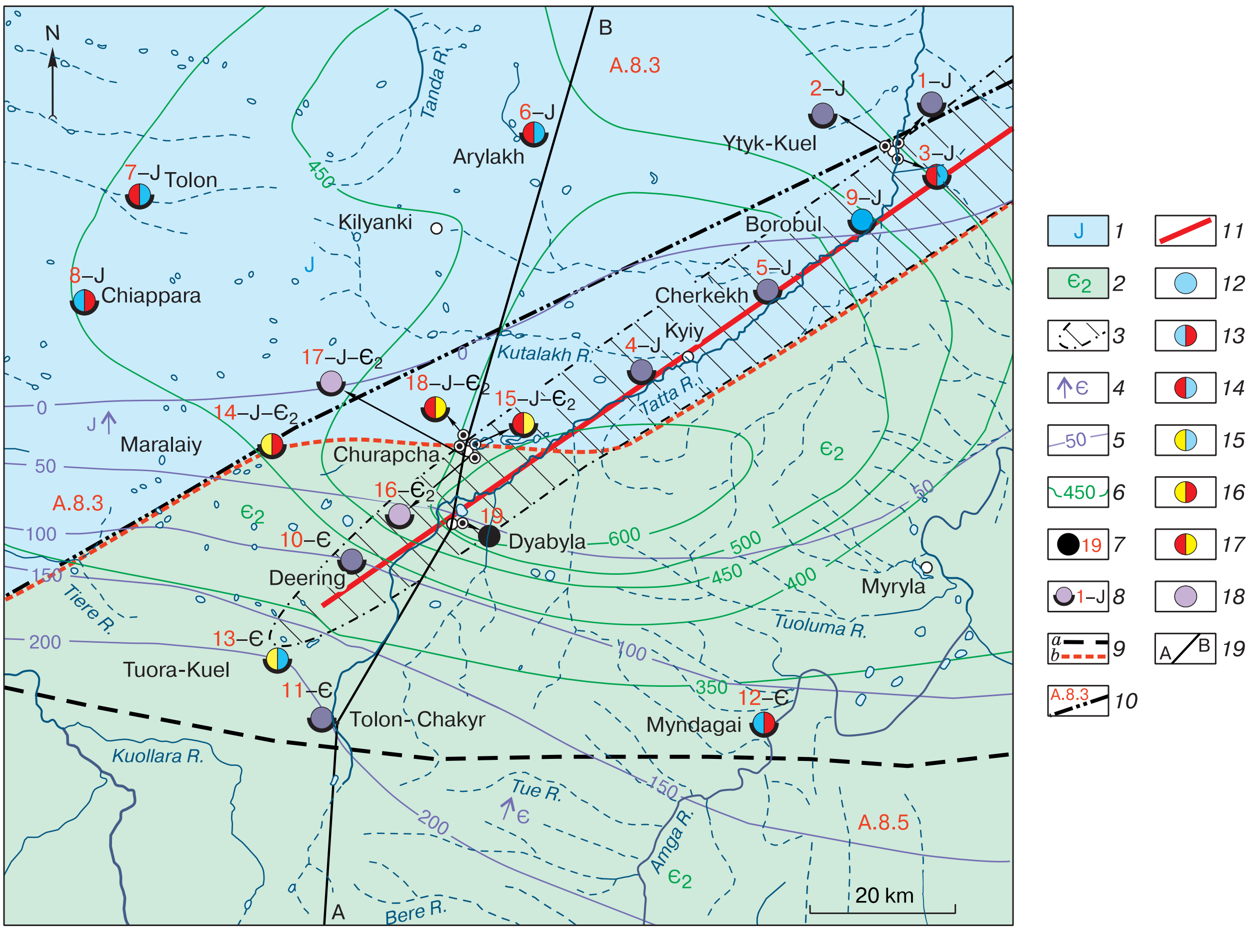

Fig. 2. Map of subpermafrost water distribution in the study area.

1 – Jurassic terrigenous aquifer complex, *2* – Middle Cambrian aquifer carbonate complex; *3* – a zone with special hydrogeological conditions, confined to the Tatta–Tompo fault; *4* – the direction of groundwater movement and the age of the water-bearing rocks; *5* – hydroisopiestic lines (in meters of absolute height); *6* – isolines of cryogenic aquiclude thickness; *7* – the borehole that exposed subpermafrost waters, its number according to Table 1 and the index of the aquifer complex (the colors correspond to the chemical composition of groundwater); *8* – a borehole that has not penetrated the base of permafrost rocks, and its number according to Table 1; *9* – the boundary of the first subpermafrost aquifer complex: (*a*) previously established [*Melnikov, Tolstikhin, 1984*] and (*b*) refined; *10* – index of permafrost hydrogeological structure of the II order (A.8.3 – Lena–Vilyui CAB, A.8.5 – Lena–Amga (AB) and its boundary (according to [*Melnikov, Tolstikhin, 1984*]); *11* – Tatta–Tompo fault (according to [*Imaeva et al., 2006*]); *12–18:* anionic composition of subpermafrost waters: *12* – bicarbonate, *13* – bicarbonate-chloride, *14* – chloride-bicarbonate, *15* – sulfate-bicarbonate, *16* – sulfate-chloride, *17* – chloride-sulfate, *18* – mixed; *19* – cross-section line.

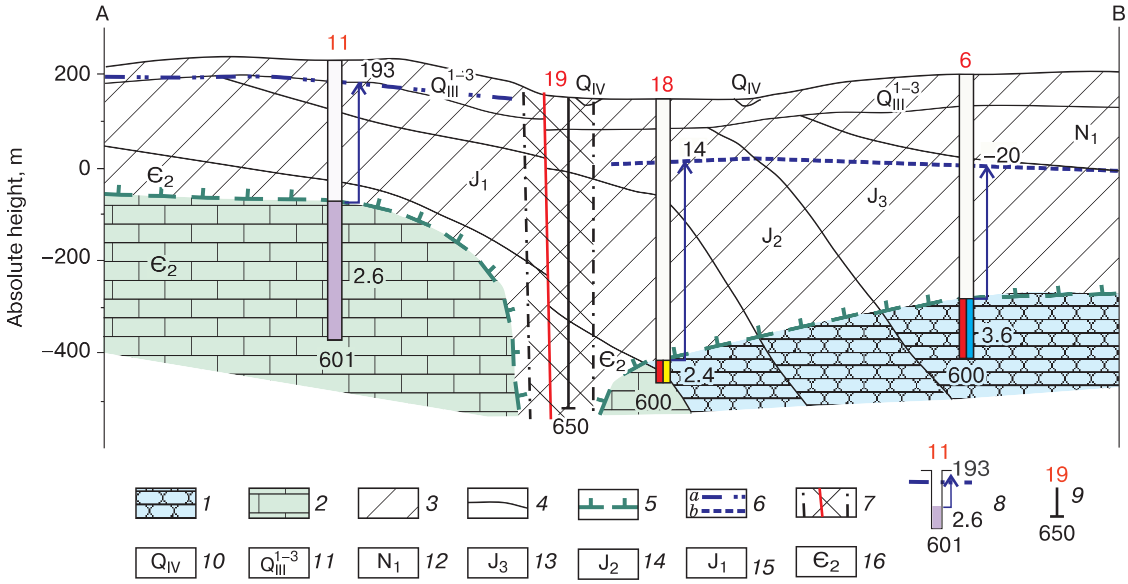

Fig. 3. Permafrost-hydrogeological section along the line A–B in Fig. 2.

1 – fractured formation waters in terrigenous Jurassic rocks, *2* – fractured formation waters in carbonate Middle Cambrian rocks, *3* – cryogenic aquiclude, *4* – boundary of deposits of different ages, *5* – boundary of permafrost; rocks, bergstreaks are directed towards the frozen strata; *6* – piezometric level of subpermafrost waters (*a* – Middle Cambrian rocks, *b* – Jurassic rocks); *7* – a tectonic fault and its zone of influence; *8* – a borehole that exposed a subpermafrost water horizon. The numbers at the top are the borehole number, at the bottom is the borehole depth, m; on the right is the mineralization, g/L, the arrow corresponds to the direction of groundwater pressure. The figure at the arrow is the absolute mark of the piezometric level, m. The colors correspond to the chemical composition of the water in the tested interval (Fig. 2); *9* – permafrost borehole. The numbers at the top are the borehole number, at the bottom is the depth, m. *10* – rocks of modern Quaternary age; *11* – Upper Quaternary rocks; *12* – Miocene rocks; *13* – Upper Jurassic rocks; *14* – Middle Jurassic rocks; *15* – Lower Jurassic rocks; *16* – Middle Cambrian rocks.

Table 1. **Characteristics of hydrogeological boreholes drilled for subpermafrost waters in the research area**

Borehole no. (Fig. 2)	Borehole location	Year of drilling	Height of borehole head, m a.s.l.	Borehole depth, m	Depth interval of the rock complex, m	Permafrost thickness, m	Depth of piezometric groundwater level, m	Absolute height, m a.s.l.	*Q*, L/s	*S*, m	*T*, m^2/day
					Jurassic terrigenous aquifer complex						
1	Ytyk-Kuel	1971	149.0	450.0	402–450	402	150.7	–1.7	1.70	29.95	0.9
2	Ytyk-Kuel	1990	149.0	425.0	396–425	396	168.0	–19.0	n.d.	n.d.	n.d.
3	Ytyk-Kuel	2009	149.5	500.0	400–500	400	168.9	–19.4	3.6	32.37	n.d.
4	Kyiy	1981	165.3	550.0	500–550	500	162.0	3.3	0.46	63.8	n.d.
5	Cherkekh	1984	179.5	590.0	535–570	535	160.0	19.5	1.25	54.5	5.0
6	Arylakh	1991	205.0	600.0	480–600	480	225.0	–20.0	n.d.	n.d.	n.d.
7	Tolon-Bakhsinskii	1991	165.0	495.0	420–495	420	204.5	–39.5	1.9	16	21.0
8	Chyappara	1990	180.0	554.0	410–554	410	206.0	–26.0	1.0	9.5	15.0
9	Borobul	2015	155.7	600.0	473–600	473	178.1	–22.4	1.0	115.74	0.8
					Middle Cambrian carbonate aquifer complex						
10	Diring	1988	208.0	585.0	380–585	380	107.4	106.6	0.5	84.6	0.7
11	Tolon-Chakyr	1991	228.0	601.0	320–601	320	35.0	193.0	1.14	195.7	3.0
12	Myndagai	1991	130.9	454.0	322–454	322	14.1	117.0	1.0	14.5	26.0
13	Tuora-Kuel	1991	228.0	602.0	313–602	313	9.2	219.0	0.63	205.85	0.4
					Middle Cambrian–Jurassic terrigenous carbonate aquifer complex						
14	Maralaiy	1993	207.0	600.0	415–600	415	192.0	15.0	1.47	42.0	4.3
15	Churapcha	1965	170.9	577.0	564–577	563	169.3	1.6	0.4	10.8	0.03
16	Churapcha	1981	170.9	600.4	563–600	563	169.9	1.0	0.68	37.6	0.8
17	Churapcha	2012	181.0	600.2	561–600	561	169.2	12.0	0.6	121.0	0.9
18	Churapcha	2017	181.0	600.0	535–600	535	167.2	14.0	3.1	42.03	33.0
19	Dyabyla	2014	183.0	650.0			Permafrost				

N o t e: *Q* is the flow rate of test pumping, *S* is a decrease in the level of subpermafrost waters at the end of test pumping, *T* is the coefficient of water conductivity of rocks, n.d. is not determined.

Table 2. **Chemical composition of subpermafrost waters**

Borehole no. (Fig. 2)	Borehole location	Sampling date	pH	Units	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{2+}	CO_3^{2-}	SO_4^{2-}	Cl^{-}	F^{-}	Li^{+}	TDS
Jurassic terrigenous aquifer complex															
1	Ytyk-Kuel	Sept 30, 2011	8.6	mg/L	5.3	4.00	280.20		369.00	0	129.60	345.90	3.7	0.19	949
				mg-equiv.	0.26	0.33	16.46		3.03	0	2.70	9.75			
2	Ytyk-Kuel	July 20, 1970	8.0	mg/L	20.64	14.96	304.53		286.70	24.0	143.58	248.7	4.5	n.d.	899
				mg-equiv.	1.03	1.23	13.24		4.70	0.80	2.99	7.02			
3	Ytyk-Kuel	Apr. 15, 2015	9.0	mg/L	2.11	0.87	329.8	1.07	287	94	53.21	199.28	n.d.	0.23	824
				mg-equiv.	0.11	0.07	14.35	0.03	4.71	3.13	1.11	5.62			
4	Kyiy	Dec. 11, 1981	7.7	mg/L	57.31	67.32	410.67		344.75	0	553.00	322.60	3.8	n.d.	1583
				mg-equiv.	2.86	5.54	17.86		5.65	0	11.51	9.10			
5	Cherkekh	Mar. 11, 1984	8.3	mg/L	18.53	11.24	294.58		417.85	0	211.05	121.27	1.4	n.d.	866
				mg-equiv.	0.93	0.92	12.81		6.85	0	4.40	3.42			
6	Arylakh	Feb. 27, 1991	8.9	mg/L	18.04	196.69	752.83	55.42	1964.84	161	1	483.58	5.7	n.d.	2651
				mg-equiv.	0.90	16.18	32.73	1.42	32.21	5.37	0.02	13.68			
7	Tolon-Bakhsinski	Jan. 18, 1991	9.3	mg/L	2.65	2.09	586.10	1.50	693.04	0	6.58	598.60	5.7	0.14	1544
				mg-equiv.	0.13	0.17	28.03	0.04	11.36	0	0.14	16.88			
8	Chyappara	Feb. 10, 1993	8.9	mg/L	8.73	2.02	749.61	1.88	832.08	0	68.23	645.19	7.2	n.d.	1892
				mg-equiv.	0.44	0.17	32.61	0.05	13.64	0	1.42	18.20			
9	Borobul	June 8, 2015	9.2	mg/L	2.00	1.22	165.00	0.90	335.50	0	8.64	28.36	2.2	0.07	589
				mg-equiv.	0.10	0.10	7.17	0.02	5.50	0	0.18	0.80			
Middle Cambrian carbonate aquifer complex															
10	Diring	Aug. 18, 1989	7.6	mg/L	44.80	23.20	145.36	4.60	162.10	0	139.90	158.30	n.d.	n.d.	597
				mg-equiv.	2.24	1.91	6.32	0.12	2.66	0	2.91	4.47			
11	Tolon-Chakyr	June 6, 1991	8.8	mg/L	8.29	6.99	790.00	2.39	557.53	0	786.60	316.23	8.9	0.96	2189
				mg-equiv.	0.41	0.58	33.39	0.06	9.14	0	16.38	8.92			
12	Myndagai	June 14, 1989	8.0	mg/L	16.03	13.37	201.80	18.75	161.70	0	0	300.64	0.7	0.19	631
				mg-equiv.	0.80	1.10	8.78	0.45	2.65	0	0	8.48			
13	Tuora-Kuel	Sept. 17, 1991	–	mg/L	4.31	0.74	500.00	2.24	768.26	0	205.49	111.32	7.6	0.89	1208
				mg-equiv.	0.21	0.06	21.74	0.06	12.59	0,30	4.28	3.14			
Middle Cambrian–Jurassic terrigenous carbonate aquifer complex															
14	Maralaiy	Sept. 15, 1993	8.0	mg/L	69.17	32.84	210.00	6.80	127.03	0	200.39	340.71	1.3	0.81	923
				mg-equiv.	3.45	3.31	9.04	0.17	2.01	0	4.11	9.42			
16	Churapcha	Sept. 2, 1981	7.7	mg/L	58.32	87.86	274.50		414.92	0	403.78	244.98	2.0	n.d.	1277
				mg-equiv.	2.91	7.23	11.94		6.80	0	8.41	6.91			
17	Churapcha	Aug. 3, 2012	7.5	mg/L	56.60	31.20	146.00	4.70	143.30	0	290.00	123.00	2.3	0.16	723
				mg-equiv.	2.82	2.57	6.35	0.12	2.35	0	6.04	3.47			
18	Churapcha	Apr. 7, 2018	7.6	mg/L	218.4	142.50	285.0	8.80	280.00	0	1119.28	224.60	1.9	0.02	2139
				mg-equiv.	10.90	11.720	12.39	0.23	4.59	0	23.30	6.34			

Note: n.d. is not determined. TDS – total dissolved solids (dry residue).

change, as evidenced by measurements in boreholes No. 2 and No. 3 in the village of Ytyk-Kuel: in 1990 and 2009, the water level was at a depth of 168.0 and 168.9 m, respectively.

In the area of the village of Churapcha and the village of Maralaya, the permafrost waters confined to the deposits of the Middle Cambrian and Jurassic were studied together. Here, the Jurassic aquifer complex is composed of quartz-feldspar fine-grained sandstones with interlayers of dense siltstones and basal conglomerates at the base. Its thickness in Churapcha village is 3–11 m, and to the west (Maralaya village) it increases to 65 m. The Cambrian aquifer complex was discovered at a depth of 490–570 m under the Jurassic. According to testing pumping data, the water capacity of rocks of jointly tested aquifer complexes varies from 0.8 to 33.0 m^2/day. Piezometric levels of permafrost waters lie at depths of 167–192 m from the Earth's surface. According to one-time measurements, the water level in borehole No. 18 (Churapcha village) in 2017–2022 was at a depth of 167–169 m.

The mineralization of the subpermafrost waters of the Jurassic and Middle Cambrian aquifers varies from 0.6 to 2.6 g/L (Table 2). According to the hydrogen index, the waters are slightly alkaline and alkaline (pH 7.6–9.2). The anionic composition of the subpermafrost waters of the Middle Cambrian rocks is mainly sulfate-chloride or sulfate-bicarbonate, and the Jurassic aquifer complex is mainly chloride-bicarbonate. The cationic composition is mainly dominated by sodium ions. In brackish waters, the contents of sodium, fluorine, lithium are increased, sometimes of general hardness, when using such waters for drinking purposes, water treatment is required.

DISCUSSION

Permafrost and hydrogeological conditions are difficult within the territory under consideration, which is due to the lithological-facial substitution of water-bearing rocks, variability in the thickness of cryogenic aquiclude and the presence of disjunctive tectonics. The manifestation of disjunctive tectonics can be traced in the Tatta River valley based on aerial photographs and geological data [*Imaeva et al., 2006*].

Taking into account these factors, two areas can be distinguished here, differing in hydrogeological features. One of them is located in the central, southern and southwestern parts of the studied area. On the southern margin of this area, the subpermafrost waters are confined to Cambrian carbonate rocks and lie directly under Jurassic permafrost rocks at a depth of 313–322 m. The subpermafrost waters are confined, their piezometric levels are set near the Earth's surface at absolute elevations of 117–219 m. The Cambrian aquifer complex outcrops in the zone of intermittent permafrost on the northern slope of the Aldan anteklysis are probably its regional feeding area [*Efimov, Zaitsev, 1970*]. Local supply by surface waters and partial discharge are possible in the adjacent southern territory through the open lake taliks confined to tectonic faults [*Balobaev et al., 2003*].

Cambrian aquifer complex is fresh and slightly salty. Their mineralization varies from 0.7 to 2.6 g/L. According to the value of the hydrogen index, they are slightly alkaline and alkaline (pH 7.7–9.1). The anionic composition of permafrost waters is mixed, the first place belongs to bicarbonate ions or sulfate ions (26–64 and 21–47% mg/eq., respectively), chlorides occupy the third place (up to 16–25% mg/eq) (Fig. 4). According to the cationic composition of water they are sodium ones (80–98% mg/eq.).

In the central part of the area under consideration, between the latitudes of the village of Teley-Deering in the south and the village of Churapcha in the north, there is a sharp increase in the thickness of Jurassic sandstones and siltstones. The slope with which carbonate rocks sink under terrigenous Jurassic rocks increases from south to north from 0.001 to 0.015. In the same direction, an increase in the thickness of permafrost rocks is observed. Groundwater confined to the upland part of the Jurassic and Upper Cambrian formations lies at a depth of 415–563 m. In the border zone, where the lithological and facial composition of the water-bearing rocks is changing, there is a redistribution of pressure in the permafrost complexes. Here, groundwater levels in boreholes are set at absolute levels of 1–15 m.

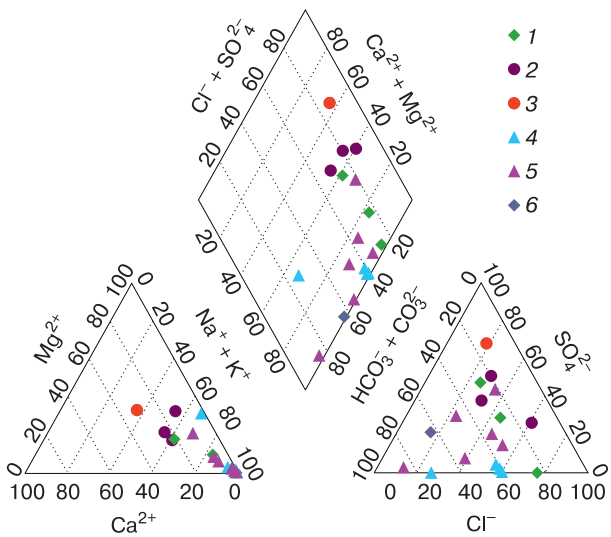

Fig. 4. Piper diagram of the chemical composition of subpermafrost waters:

1 – Cambrian aquifer complex; *2, 3* – Jurassic–Cambrian aquifer complex (*2* – in the southern and southwestern part of the territory, *3* – in the northern part); *4* – Jurassic aquifer complex; *5, 6* – in the Tatta–Tompo fault zone: *5* – Jurassic aquifer complex; *6* – Cambrian aquifer complex.

The role of chloride ions and magnesium ions in the formation of the chemical type of water increases against the background of a decrease in the concentration of bicarbonate ions, the content of which does not exceed 4–20% mg/eq. As a result, the waters acquire a sulfate-chloride or chloride-sulfate, magnesium-sodium or sodium-magnesium composition. By the amount of mineralization (0.8–2.5 g/L), the subpermafrost waters are fresh and slightly saline, by the value of the hydrogen index they are slightly alkaline.

The second area is located north of Churapcha village, where a terrigenous Jurassic aquifer complex lies under a cryogenic aquiclude at a depth of 415–480 m. A distinctive feature of groundwater in this area is their low piezometric levels, which are set at absolute levels below the level of the world ocean by 20–41 m. Comparable levels of subpermafrost waters associated with Jurassic sandstones and siltstones were noted during drilling in the adjacent territory to the north and west of the studied area: in the village Tyungyul –36.8 m, village Bayaga –24.4 m, as well as on the left bank of the Lena River near Yakutsk on the territory of the settlements of Markha and Zhatai from –4.0 to –34.0 m [*Balobaev et al., 2003; Pavlova et al., 2023*]. The reason for the decrease in the subpressure of permafrost waters may be the high hydrodynamic closeness of the Jurassic aquifer complex within the studied area. It is difficult to assess the conditions for replenishing their reserves. No open taliks have been established within the study area. Probably, the feeding area of the terrigenous Jurassic aquifer complex, widespread in the Lena–Amga interfluve, is located in the northeast and is confined to the open talik under the Aldan River, and the overflow of groundwater from the Cambrian aquifer complex is also not excluded.

According to the magnitude of mineralization (1.2–3.6 g/L), the subpermafrost waters of the Jurassic rocks are brackish, and the pH value is alkaline. A feature of their chemical composition is the bicarbonate-chloride or chloride-bicarbonate anionic composition, and sulfate-free (sulfate ion content 6–9 mg/L, rarely up to 46–53 mg/L). Sodium dominates among the cations, the concentration of which varies between 145–752 mg/L, which is 87–99% mg/eq. of the sum of the main cations. In general, the chemical composition of the subpermafrost waters of the Jurassic aquifer complex in the studied area is close to the composition of the waters opened by boreholes in Jurassic rocks directly under cryogenic aquiclude in other areas of Central Yakutia [*Pavlova et al., 2023*].

A local zone with peculiar hydrogeological conditions is clearly visible within the research area. Geographically, it can be traced along the valley of the Tatta River, laid down by the neotectonically active Tatta–Tompo fault [*Imaeva et al., 2006*]. The basis for the allocation of this zone is a complex of identified anomalies, including the maximum thickness of permafrost rocks (from 500 to 750–780 m), low filtration properties of water-containing Jurassic and Middle Cambrian rocks, absolute piezometric levels of groundwater from positive (20 m) to negative (–22 m), variegated anionic composition of subpermafrost waters, which can be explained only by the specific conditions of its formation. It is likely that rocks have undergone dynamic compaction in the Tatta–Tompo fault zone, which may explain their reduced permeability compared to the surrounding area.

The influence of the Tatta–Tompo fault on the permafrost and hydrogeological conditions of the territory can be explained by the results of geological exploration carried out in the area of Churapcha village by the State Unitary Enterprise RS (Ya) YAPSE under the leadership of V.L. Zemlyaniy in 1980–1983 and with the participation of the author's team in 2012–2017. On the territory of the village, the permafrost waters of Jurassic and Middle Cambrian rocks lie at a depth of 561–565 m. The most permeable intervals were noted in a thin (3 m) uplifted part of the Jurassic rocks. Testing pumping has established a slight watering of Cambrian carbonate rocks to a depth of 600 m. Boreholes in the village of Churapcha allow to obtain flow rates of no more than 50 m^3/day.

To the south of this settlement, in the direction of the Tatta–Tompo fault, there is a significant increase in the thickness of permafrost rocks. In the area of the village of Dyabyla, 10 km from the village of Churapcha, a 650 m deep bore hole has been stopped in permafrost rocks, and their estimated thickness is 750–780 m [*Kirillin et al., 2022*]. The maximum thickness of the permafrost rocks (PR) is confined to the junction of the Tatta–Tompo fault with a sharp change in the depth of the top of the Middle Cambrian rocks (a break of the profile). The high thickness of the PR is probably due to a decrease in the melting temperature of ice with an increase in pressure in a stressed frozen rock massive that have experienced compressive forces.

To the northeast of Churapcha village, the depth of long-term rock freezing decreases and at a distance of 2 km from it is 530 m. The subpermafrost waters are contained in quartz-feldspar fine-grained sandstones and quarried fractured limestones with dolomite interlayers. An increase in the thickness of the Jurassic aquifer complex to 11 m made it possible, according to testing filtration work, to estimate reserves at this site in the amount of 267 m^3/day.

CONCLUSIONS

Based on the analysis of new hydrogeological, geocryological and hydrochemical data in combination with the results of the work of predecessors, the location of the boundary between the subpermafrost Jurassic and Middle Cambrian aquifer complexes in the poorly studied northeastern part of the Lena–Amga interfluve has been clarified. The Cambrian carbonate aquifer complex is the first subpermafrost in the southern and central parts of the region, up to the latitude of Churapcha village, which is 50–80 km north of the previously established boundary of its distribution. The piezometric surface of the subpermafrost waters of Cambrian rocks has a general inclination towards the immersion of the aquifer complex and an increase in the thickness of the overlapping cryogenic aquiclude. The absolute marks of piezometric levels of subpermafrost waters from south to north decrease from 117–219 m to 1–15 m. In the northern part of the district, an aquifer complex of Jurassic rocks is in contact with a long-term cryogenic aquiclude. The levels of subpermafrost waters in boreholes are set at negative absolute levels.

The decrease in the piezometric surface of the subpermafrost waters in the north, northwest direction, noted in general in the territory under consideration, indicates the lateral movement of the subpermafrost waters.

The limestones and dolomites of the Middle Cambrian contain alkaline fresh and slightly saline waters of sulfate-chloride, chloride-sulfate magnesium-sodium or sodium-magnesium composition. Groundwater confined to terrigenous Jurassic rocks is alkaline slightly saline bicarbonate-chloride or chloride-bicarbonate sodium. When using subpermafrost waters for drinking purposes, it is necessary to take into account the need for their water treatment due to the increased content of sodium, fluorine, lithium, and sometimes general hardness.

A zone with special geocryological and hydrogeological conditions has been identified, which is traced by the Tatta–Tompo tectonic fault. In the field of influence of the fault, maximum PR thicknesses, low filtration properties of rocks and a mottled chemical composition of subpermafrost waters are noted. Presumably, the formation of the fault was accompanied by compaction of rocks along it, which could lead to reduced water permeability and an increase in the intensity of freezing of relatively low-watered strata in cold epochs, as well as a decrease in the melting temperature of ice with an increase in pressure in a stressed frozen rock massive.

Adjusted ideas about the permafrost-hydrogeological conditions of the studied territory can be used to develop proposals for a systematic search for subpermafrost waters and solving problems of drinking, household and technical water supply in the settlements of the district.

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