

Isotopic Composition of Thermal Waters in Chukotka

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Abstract—Twenty three groups of thermomineral springs in eastern Chukotka with the discharge temperature of 2 to 97°C and mineralization of 1.47 to 37.14 g/l are studied and compared with surface freshwater from their localities. The δD and $\delta^{18}O$ values in surface waters vary from -121.4 to -89.5‰ and from -16.4 to -11.1‰ , respectively, while respective values in thermomineral waters range from -134.2 to -92.5‰ and from -17.6 to -10.5‰ . The δD value in surface waters decreases from the east to west, i.e., toward interior areas of the peninsula. Hydrothermal springs most depleted in deuterium ($\delta D < -120\text{‰}$) are localized in the geodynamically active Kolyuchinskaya–Mechigmen Depression. According to the proposed formation model of Chukotka thermomineral waters, their observed chemical and isotopic characteristics could result from the mixing (in different proportions) of surface waters with the deep-sourced isotopically light mineralized component ($\delta D \approx -138\text{‰}$, $\delta^{18}O \approx -19\text{‰}$, $M = 9.5\text{--}14.7$ g/l). The latter originates most likely from subpermafrost waters subjected to slight cryogenic metamorphism.

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Hot springs are known in the eastern Chukotka Peninsula since the terminal 18th century, although their scientific studies commenced only in the mid-1930s. Information on these springs gained during geological mapping and thematic works is summarized with different details in (Shvetsov, 1957; Kalabin, 1959; Ivanov, 1960; Zavgorodnii, 1962; Zelenkevich, 1963; Gol'dtman, 1967; *Katalog...*, 1969; *Gidrogeologiya...*, 1972). Fragmentary data on the most known springs are contained in (*Chukotka...*, 1995; *Prirodnye...*, 2003). Lists of hydrothermal springs and their overviews are presented by Kryukov in (*Ekosistemy...*, 1981) and Stepina in (Vladimirtseva et al., 2001).

Most springs are located at low altitudes in the vicinity of the seashore. At the same time, thermomineral springs located 40–50 km away from the sea discharge usually at altitudes below +100 m. In terms of the anion composition of waters, most springs are chloride or, less commonly, chloride–hydrocarbonate; in terms of the cation composition, sodium–calcic.

The distribution patterns and salt compositions of thermal waters in Chukotka provided grounds for assuming their genetic relation to seawater. Some researchers believed that seawater feeds immediately hydrothermal springs being infiltrated into coastal rock complexes (Shvetsov, 1937; Stremyakov, 1967; and others). Ivanov (1960) believed that the high salt content in thermal waters could be explained by neither the penetration of recent seawaters to interior areas of the continent nor the influence of their ancient buried or epigenetically transformed counterparts. Instead, he

presumed that “...thermal waters formed on account of interstitial solutions of sea basins and they are significantly younger in geological sense as compared with host formations” (Ivanov, 1961, p. 233).

At the same time, nature of water (H₂O) proper in thermomineral fluids cannot be interpreted adequately without the knowledge of its isotopic composition, which has never been studied. To fill this gap, we sampled in 2002 and 2004 waters from several thermomineral springs of eastern Chukotka.¹ Data on the isotopic composition of hydrogen and oxygen in some water samples were published elsewhere (Cheshko et al., 2004). In the present work, these results are supplemented with information on samples collected later and on samples from other springs examined in 2004 and 2005 by geologists from the *Georegion* Federal State Unitary Enterprise (Anadyr), who kindly donated them for the analysis. In total, 80 samples of thermomineral and surface waters were studied for 23 groups of thermal springs. Figure 1 demonstrates their locations. Tables 1 and 2 present the results of analytical studies.

As applied to Arctic conditions, it is necessary to specify the notion “thermal spring.” In balneology, warm or hot therapeutic waters that cause corresponding physiological feelings are usually called as thermal. In the mining industry, waters with discharge temperatures sufficient for using them for certain purposes

¹ E.A. Vakin from the Institute of Volcanology and Seismology (Far East Division, Russian Academy of Sciences), who died on September 13, 2003, took part in field works of 2002 and analysis of materials obtained.

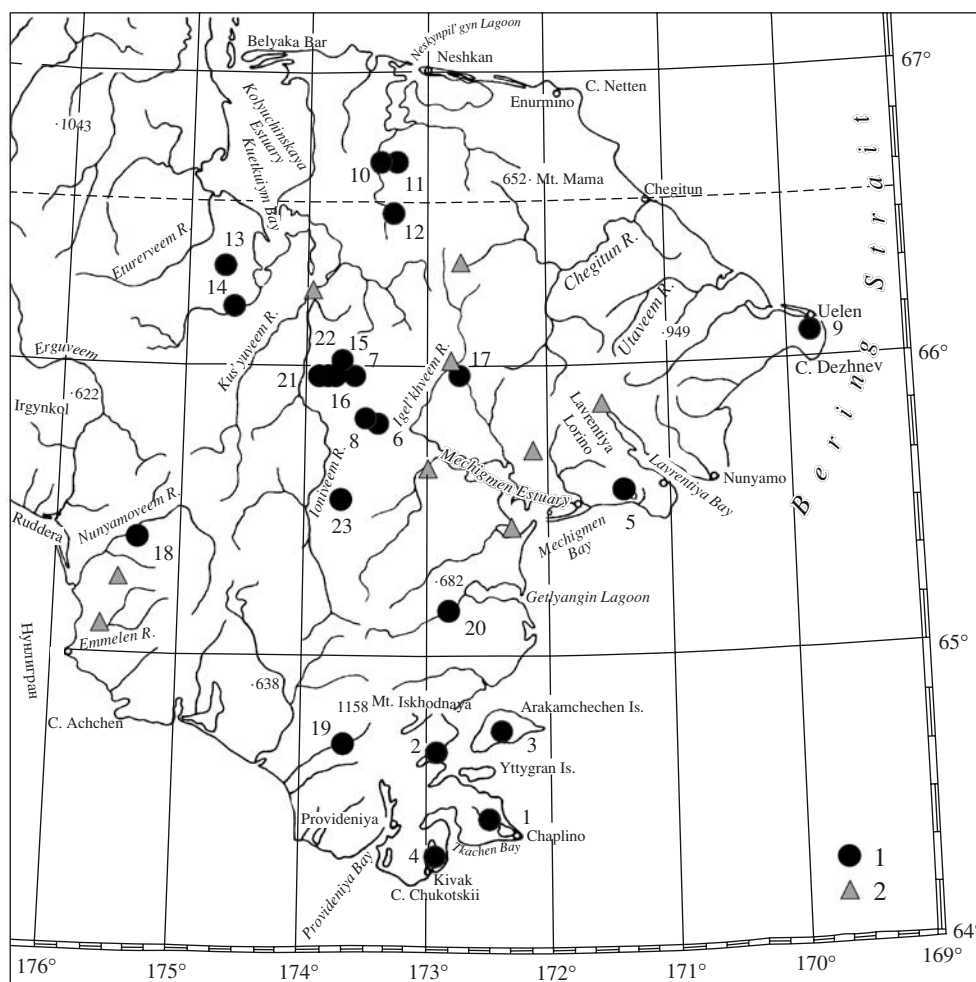


Fig. 1. Thermomineral springs of the eastern Chukotka Peninsula with measured isotopic composition of H_2O . (1) Groups of springs; (2) occurrences of Late Cenozoic basaltic volcanism, after (Akinin and Apt, 1994; Kryukov, 1980; Nedomolkin, 1978; Romanova and Zhukova, 1970a, b). Numerals designate springs (their other names mentioned in publications are given in parentheses): (1) Chaplino, (2) Senyavin, (3) Arakamchechen, (4) Kivak, (5) Kukun (Lorino), (6) Mechigmen (Gil'mimlinei, Khel'khymyveem), (7) Babushkiny Ochki (Bezmyannye), (8) Tumannye, (9) Dezhnev, (10) Neshkan, (11) Teyukei (Tag'ekveem), (12) Kub (Pravo-Tynynvaam), (13) Vytshkhytaveem, (14) Oranzhevye, (15) Olen'i (Ynpynenveem), (16) Arenshkynvaam, (17) Nel'pygenveem (Ngel'veem), (18) Verkhne-Nunyamoveem, (19) Sineveem, (20) Getlyangen, (21) Stupenchatye, (22) Ioni mineral; (23) Pechingtanvaam.

(electric energy production, heat supply, and others) are considered as thermal and sometimes called as heat waters. In the physical (geophysical) sense, waters with temperatures exceeding their average climatic value in the particular area, i.e., all the groundwaters occurring below the layer of annual heat cycle are classed with thermal waters. K. Keilgak, a German hydrogeologist, was first to formulate clearly such a concept in 1912–1917. He emphasized that the notion of warm spring or warm groundwater that corresponds to spring or water, the temperature of which exceeds its average annual value in the particular area, is not permanent and absolute. It is variable to such a degree that waters with temperatures of at least $1^{\circ}C$ in polar regions with the average annual temperature of $0^{\circ}C$ should be designated as “warm” or “thermal” (Keilgak, 1935). The surface dis-

charge of thermal springs is accompanied by advective transport of heat from the Earth's interior, which adds its conductive heat losses. Chukotka is a typical Arctic region with negative average annual surface temperatures (Fig. 2) and universal development of the cryolithozone, i.e., permafrost. Therefore, all springs in this region with their year-round discharge should be considered as thermal. The temperature of examined thermal waters at the surface ranges from $\sim 2^{\circ}C$ in the Nel'pygenveem (Ngel'veem, after Kievskii et al., 2006) springs to $97^{\circ}C$ in one of the thermal jets in the Mechigmen springs. In winter, thermal springs form chrystocrenes at different distances from their discharge areas. Such chrystocrenes are widespread in river valleys of Subarctic regions, where they are usually attributed to discharges of underflows.

Table 1. Hydrogen and oxygen isotope compositions in waters of the eastern Chukotka Peninsula

Number in Fig. 1	Sample	Springs, water occurrences ($\Delta\delta D = \delta D_{\text{therm}} - \delta D_{\text{surf}}$)	$\delta^{18}\text{O}, \text{‰}$	$\delta D, \text{‰}$	T, °C	Dry residue, g/l	Kurlov's formula ¹
1	2	5	6	7	8	9	10
0	Ureliki Settlement (64°26' N, 173°09' W)						
0a	1/02	Descending spring	-13.3	-99.6	2	0.034	
0b	2/02	Creek	-13.6	-97.1	7	0.020	
1	Chaplino (64°25' N, 172°30' W)	$\Delta\delta D = -101.3 - (-99.2) = -2.1\text{‰}$					
1a	21/02	Self-discharging borehole	-13.6	-101.3	88	19.280	Cl98/Na62Ca37
1b	22/02	Eastern group, spring near the basin	-13.2	-101.7	68	18.950	Cl98/Na60Ca39
1c	23/02	Western group, spring	-13.4	-100.5	68	17.960	Cl98/Na59Ca40
1d	24/02	Far group, spring in the dig	-13.1	-100.6	79	18.980	Cl98/Na60Ca39
1e	2r-1/02	Ul'khum River 700 m downstream of the swimming pool	-13.3	-99.1	14	1.500	
1f	2r/02	Ul'khum River 4 km upstream of the swimming pool	-13.8	-99.2	8	0.026	
1g	2r-2/02	Creek at the Mt. Utyug piedmont	-11.1	-89.5			
2	Senyavin (64°44' N, 172°51' W)	$\Delta\delta D = -130.8 - (-106.0) = -24.8\text{‰}$					
2a	30/02	Upper gryphon (no. 1)	-17.4	-130.8	78	1.470	Cl90SO ₄ 6/Na77Ca21
2b	31/02	Lower gryphon (no. 2)	-17.2	-130.5	79	1.500	Cl92SO ₄ 6/Na77Ca21
2c	30-2r/02	Klyuchevaya River downstream of springs	-14.3	-106.9		0.140	
2d	30-1r/02	Klyuchevaya River upstream of springs	-14.1	-106.0	14	0.050	
3	Arakamechehen (64°45' N, 172°18' W)	$\Delta\delta D = -105.2 - (-107.1) = 1.9\text{‰}$					
3a	34/02	Lower gryphon	-13.9	-105.2	37	1.470	Cl90SO ₄ 8/Na82Ca17
3b	32r/02	Pyl'mymlak River upstream of springs	-14.1	-107.1	15	0.070	
3c	33m/02	Seawater in the Lake Arakamechehen area	-1.3	-10.0			
4	Kivak (64°21' N, 172°56' W)	$\Delta\delta D = -96.1 - (-92.8) = -3.3\text{‰}$					
4a	40/02	Discharge near the indoor swimming pool	-12.8	-96.1	43	4.780	Cl98/Na51Ca48
4b	42r/02	Creek flowing into the Kivak Lagoon	-12.1	-92.8			
4c	41m/02	Kivak Lagoon, seawater	-3.4	-26.8			
5	Kukun (65°35' N, 171°29' W)	$\Delta\delta D = -110.5 - (-111.5) = 1\text{‰}$					
5a	50/02	Spring 1 (cube)	-14.1	-110.5	60	5.230	Cl96/Na76Ca21
5b	1/04	Spring 1 (cube)	-14.8	-109.5	56	4.600	
5c	51/02	Spring 2 (discharge in the swimming pool)	-14.6	-109.3	52	4.030	Cl96/Na76Ca21
5d	1a/04	Borehole	-14.2	-109.3	58	4.720	Cl96/Na71Ca27
5e	52r/02	Kukun River, downstream of springs	-13.6	-107.3			
5f	1r/04	Kukun River, upstream of springs	-14.8	-111.5		0.007	
6	Mechigmen (65°48' N, 173°24' W)	$\Delta\delta D = -130.6 - (-111.9) = -18.7\text{‰}$					
6a	60/02	Gryphon 1 on the right wall of the valley	-16.0	-130.6	90	3.930	Cl92HCO ₃ 5/Na88Ca8
6b	62/02	Gryphon 2 in the central part of the field	-14.8	-126.9	64	4.080	Cl92HCO ₃ 6/Na87Ca8
6c	64r/02	Khel'khumyleveem River, upstream of springs	-14.2	-111.9	6	0.170	

Table 1. (Contd.)

1	2	5	6	7	8	9	10
7	Babushkiny Oehki (66°00' N, 173°36' W) $\Delta\delta D = -134.2 - (-109.9) = -24.3\%$						
7a	Northern gryphon		-17.5	-134.2	20	9.260	Cl174HCO ₃ 21/Na55Ca33Mg10
7b	Northern gryphon		-17.1	-132.2	21	9.580	Cl180HCO ₃ 20/Na56Ca32Mg9
7c	Southern gryphon		-17.1	-131.9	14	9.150	Cl175HCO ₃ 20SO ₄ 5/Na58Ca33Mg6
7d	Southern gryphon		-16.6	-130.9	18		
7e	Spring near the piedmont of the travertine cone		-17.6	-133.7	14	9.280	Cl174HCO ₃ 20SO ₄ 5/Na57Ca32Mg8
7f	River in the springs area		-14.3	-109.9			
7g	Lake Ioni		-14.8	-112.5			
7h	Lake Ioni		-15.0	-115.2			
7i	Well at the Lake Ioni coast		-15.8	-119.0	7		
8	Tumannye (65°49' N, 173°27' W)						
8a	Group 1, spring		-16.2	-131.7	59		
8b	Group 2, spring		-16.9	-131.6	55	3.400	Cl191HCO ₃ 6/Na86Ca11
9	Dezhnev (66°06' N, 169°49' W) $\Delta\delta D = -96.9 - (-98.2) = 1.3\%$						
9a	Borehole Verkhnyaya		-13.2	-96.9	69	19.600	Cl199/Na72Ca26
9b	Borehole Tsentral'naya (near the swimming pool)		-12.6	-95.9	60	19.760	Cl199/Na71Ca27
9c	Borehole Nizhnyaya (near the dig)		-13.4	-97.2	53	19.290	Cl199/Na72Ca26
9d	Goryachii Creek, 700 m downstream of springs		-12.9	-96.6		0.520	
9e	Goryachii Creek, 300 m upstream of Borehole Verkhnyaya		-13.7	-98.2			
10	Neshkan (66°43' N, 173°18' W) $\Delta\delta D = -120.1 - (-108.5) = -11.6\%$						
10a	Upper group, spring		-14.5	-120.1	52	37.140	Cl100/Na69Ca28
10b	Aanrylynekveem River, lower reaches		-13.9	-108.5		13.440	
11	Teyukei (66°42' N, 173°10' W) $\Delta\delta D = -113.4 - (-109.0) = -4.4\%$						
11a	Mineral water spring		-14.6	-113.4	6	17.640	Cl1100/Na67Ca31
11b	Left tributary of the Teyukeiveem River		-14.3	-109.0	12	0.120	
12	Kub (66°31' N, 173°14' W) $\Delta\delta D = -119.3 - (-108.1) = -11.2\%$						
12a	Spring		-15.5	-119.3	7	4.480	Cl188HCO ₃ 11/Na80Ca16Mg4
12b	Kub Creek, 200 m upstream of springs		-14.7	-108.1	14	0.065	
12c	Pravaya Tynynvaam River		-14.6	-109.0			
13	Vytkhytyaveem (66°19' N, 174°37' W) $\Delta\delta D = -124.0 - (-119.7) = -4.3\%$						
13a	Spring		-16.9	-124.0	65	3.450	Cl190HCO ₃ 10/Na74Ca26
13b	Vytkhytyaveem River, upstream of springs		-16.4	-119.7	17	0.034	
14	Oranzhevye (66°12' N, 174°34' W) $\Delta\delta D = -118.6 - (-119.3) = 0.7\%$						
14a	Spring		-14.7	-118.6	14	36.230	Cl199/Na52Ca46
14b	Kal' kheurveem River		-16.2	-120.1		0.030	
14c	Ulyuveem River		-15.6	-119.3		0.080	

Table 1. (Contd.)

1	2	5	6	7	8	9	10
15	Olen'i (66°01' N, 173°41') $\Delta\delta D = -92.5 - (-109.1) = 16.6\%$						
15a	11/04 Saline lake		-10.5	-92.5	15	8.530	Cl82HCO ₃ 17/Na53Mg41Ca4
15b	An-17(2i)/05 Spring 1		-11.0	-98.5	18.3	0.100	
15c	11r/04 River in the springs area		-14.7	-109.1	14	0.020	
15d	10r/04 Ioniveem River		-15.2	-116.6			
15e	An-17(2r)/05 River in the springs area		-14.3	-108.5			
16	Arenyshkynvaam (65°59' N, 173°42' W) $\Delta\delta D = -122.4 - (-100.1) = -22.3\%$						
16a	12/04 Spring		-15.4	-122.4	12	8.370	Cl93HCO ₃ 6/Na65Ca24
16b	An-18(3i)/05 Spring 6		-16.8	-133.3	6.2		
16c	An-18(3r)/05 Creek		-12.9	-100.1			
17	Nel'pygenveem (65°58' N, 172°47' W) $\Delta\delta D = -122.6 - (-108.6) = -14.0\%$						
17a	14/04 Spring		-14.4	-122.6	7	6.870	Cl62HCO ₃ 37/Na59Mg23Ca16
17b	An-13(1i)/05 Spring 1		-15.8	-122.9	1.7		
17c	14r/04 Nel'pygenveem River, upstream of springs		-14.5	-108.6	15	0.070	
17d	An-13(1r)/05 Nel'pygenveem River		-14.3	-107.9			
18	Verkhne-Nunyamoveem (65°25' N, 173°18' W) $\Delta\delta D = -128.4 - (-121.4) = -7.0\%$						
18a	An-27(8i)/05 Spring 35		-17.1	-128.4	36		
18b	An-27(8r)/05 Creek		-16.2	-121.4			
19	Sineveem (64°37' N, 173°49' W)						
19a	An-26(9i)/05 Spring 6		-14.6	-111.1	43		
20	Getlyangen (65°12' N, 172°47' W) $\Delta\delta D = -118.9 - (-110.7) = -8.2\%$						
20a	An-22(7i)/05 Spring 8/2		-15.4	-118.9	43	4.453 ²	
20b	An-22(7r)/05 Creek		-14.8	-110.7			
21	Stupenchatye (64°59' N, 173°54' W) $\Delta\delta D = -131.1 - (-102.1) = -29.0\%$						
21a	An-21(5i)/05 Spring 1		-17.3	-131.1	2.7	7.277 ²	
21b	An-21(5r)/05 Creek		-11.2	-102.1			
22	Ioni mineral (65°59' N, 173°50' W) $\Delta\delta D = -128.2 - (-109.4) = -18.8\%$						
22a	An-20(4i)/05 Spring 3		-16.6	-128.2	5	7.287 ²	
22b	An-20(4r)/05 Creek		-14.3	-109.4			
23	Pechingtanvaam (65°34' N, 173°42' W) $\Delta\delta D = -131.2 - (-118.5) = -12.7\%$						
23a	An-6i/05 Spring 6		-16.7	-131.2	28	2.106 ²	
23b	An-6r/05 Creek		-15.9	-118.5			

Notes: ¹ Numerals designate the share of ion in mg-equiv.² After (Kievskii et al., 2006).

Table 2. Chemical composition of waters in the examined hydrothermal springs of the Chukotka Peninsula

Number in Table 1	Sample	Spring, sampling site	Concentration, mg/l								Dry residue, g/l	
			t, °C	pH	Na	K	Ca	Mg*	HCO ₃	Cl		SO ₄
1a	21/02	Chaplino, self-discharging borehole	87.5	8.61	4800	108	2505	0.95	122	11630	225	19.28
1b	22/02	Chaplino, Vostochnaya group, spring	67.8	8.03	4280	110	2425	0.94	98	10990	225	18.95
1c	23/02	Chaplino, Zapadnaya group, spring	68.1	7.22	4170	105	2455	0.82	14.6	10780	204	17.96
1d	24/02	Chaplino, Dal'naya group, spring	79.0	6.25	4300	109	2455	0.88	14.6	10990	232	18.98
2a	30/02	Senyavin, upper gryphon (no. 1)	78.0	8.63	386	11.7	92.2	0.10	49	717	62	1.47
2b	31/02	Senyavin, lower gryphon (no. 2)	78.7	8.59	375	12	88.2	0.09	29	717	62	1.50
3a	34/02	Arakamchechen, lower gryphon	37.4	8.36	400	9.3	72.1	0.55	34	730	84	1.47
4a	40/02	Kivak, discharge near the indoor swimming pool	43.1	8.15	875	19	721	0.40	22	2610	63	4.78
5a	50/02	Kukun, spring 1 (cube)	60.0	6.98	1330	82.5	321	1.16	81	2590	82	5.23
5c	51/02	Kukun, spring 2 (discharge in the swimming pool)	52.0	7.40	1070	68	260	0.99	73	2120	49	4.03
5d	1a/04	Kukun, spring	58.0	6.97	940	74	300	1.13	98	2630	81	4.72
6a	60/02	Mechigmen, gryphon 1 on the right wall of the valley	89.7	7.05	1240	77	104	1.81	190	2050	80	3.93
6b	62/02	Mechigmen, gryphon 2 in the central part of the field	64.3	6.89	1280	78	108	1.86	217	2100	81	4.08
7a	70/02	Babushkiny Ochkki, northern gryphon	20.1	6.45	1790	167	930	153	1928	3860	340	9.26
7b	2/04	Babushkiny Ochkki, northern gryphon	21.0	6.31	1950	170	960	158	1810	4260	360	9.58
7c	71/02	Babushkiny Ochkki, southern gryphon	13.7	6.66	1930	168	954	115	1897	4080	391	9.15
7e	72/02	Babushkiny Ochkki, spring near the piedmont of the arch	14.2		1910	161	932	149	1890	3990	342	9.28
8b	81/02	Tumannye, group 2, spring	55.1		1000	68.6	108	2.83	207	1710	72	3.40
9a	90/02	Dezhnev, Borehole Verkhnyaya	69.0	5.93	5400	204	1723	2.24	24	11600	99	19.60
9b	91/02	Dezhnev, Borehole Tsentral'naya	60.1	7.83	5000	200	1683	2.32	24	11350	92	19.76
9c	92/02	Dezhnev, Borehole Nizhnyaya	52.8		5100	211	1611	2.38	19.5	11990	100	19.29
10a	3/04	Neshkan, upper group, spring	52.0	6.05	9800	710	3400	24.8	122	22400	3	37.14
11a	4/04	Teyukei, spring	6.0	6.25	4200	210	1700	17.4	79	9900	3	17.64
12a	6/04	Kub, spring	7.0		1300	93	240	38.0	550	2490	5	4.48
13a	7/04	Vytkhytyaveem, spring	65.0	6.46	880	33	276	1.18	330	1780	7	3.45
14a	8/04	Oranzhevye, spring	14.0	6.40	6900	400	5350	67	232	20950	17	36.23
15a	11/04	Olen'i, saline lake	15.0	7.58	1580	93	100	650	1420	3900	29	8.53
16a	12/04	Arenyshkynvaam, spring	12.0		1840	110	590	124	488	4330	27	8.37
17a	14/04	Nel'pygenveem, spring	7.0	6.59	1470	56	360	308	2460	2410	30	6.87

* Mg content was determined by the ICP-MS technique.

CHEMICAL COMPOSITION OF THERMAL WATERS

Many springs discharge gases usually dominated by nitrogen. Only gases from the Babushkiny Ochki and Olen'i springs near Lake Ioni and those from the Nel'pygenveem springs located further to the east (Fig. 1, points 7, 15, and 17, respectively) largely consist of carbon dioxide (~80–90 vol %). In some other springs, such as Stupenchatye (Point 21), Mechigmen (Point 6), and others, the gaseous phase also contains up to 30–60 vol % of CO₂ (the remainder is represented by N₂). In general, relatively CO₂-rich springs are mostly confined to the Kolyuchinskaya–Mechigmen Depression that represents a zone of recent geodynamic activity, which is evident from sporadic manifestations of Late Cenozoic basaltic volcanism and concentration of recent seismic events (Romanova and Zhukova, 1970a, 1970b; Kryukov, 1980; Vladimirtseva et al., 2001; and others).

The integral mineralization of thermomineral waters is highly variable: from ~1.5 g/l in the Senyavin springs (Point 2) to ~20 g/l in the Chaplino and Dezhnev springs (points 1 and 9, respectively). In the Neshkan (Point 10) and Oranzhevye (Point 14) springs, it exceeds values typical of seawater (Table 2). Relative contents of some mineral components in thermal waters of Chukotka differ from their values in seawater. For example, it is known that the Cl/Br value for seawater is as high as 292. Based on this ratio, the Chukotka thermal waters are divided into two groups. In the first group, which includes springs of the Bering Sea coast, this coefficient is lower as compared with that in seawater (<200). The second group unites CO₂-rich springs of the Lake Ioni and Chukchi Sea coast areas, where its values range from 370 to 433.

In terms of anion compositions, waters of most springs are classed as chloride and chloride–hydrocarbonate types with Cl ion and HCO₃ ion concentrations amounting to at least 90 and 17–37 mg-equiv %, respectively (Fig. 3). The last type is characteristic of the above-mentioned CO₂-rich springs of the Kolyuchinskaya–Mechigmen zone and its peripheral areas. Sulfates in Chukotka thermal waters are usually present as insignificant admixture: their contents are <82 mg/l in 14 groups of springs (in four cases, <10 mg/l) and up to 100 mg/l or higher only in the coastal Chaplino, Dezhnev, and Babushkiny Ochki springs (100, 232, and 391 mg/l, respectively).

In terms of cation compositions, waters under consideration are of the sodium–calcic type. The Ca ion concentration in them ranges from ~10 to 48 mg-equiv % (Fig. 3), which exceeds the concentration in seawater, positively correlates with the total mineralization (Fig. 4) and contents of Cl, Na, K, Rb, Sr, and some other elements. The Mg ion in Chukotka thermomineral waters is almost always subordinate. Its content in waters of 13 groups of springs is <100 mg/l (in six cases, <10 mg/l) and increases to 130 and 184 mg/l only in CO₂-rich waters of the Lake Ioni area in the

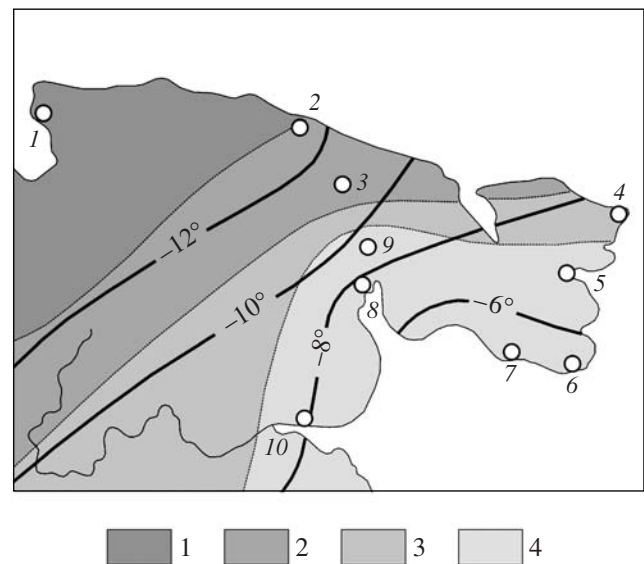


Fig. 2. Average annual air temperatures and total atmospheric precipitation in Chukotka, after (*Gidrogeologiya...*, 1972). (1–4) Total precipitation, mm: (1) 200–300, (2) 300–400, (3) 400–500, (4) 500–600. Numerals designate meteorological stations and investigation sites of frost conditions: (1) Pevek, (2) Cape Schmidt, (3) Iul'tin Settlement, (4) Uelen Settlement, (5) Lorino Settlement, (6) Provideniya Bay (Ureliki Settlement), (7) Nunligran Settlement, (8) Egvekinot Settlement; (9) Amguema Settlement, (10) Anadyr.

Babushkiny Ochki and Arenyshkynvaam (Point 16) springs, respectively. In waters of the Nel'pygenveem and Olen'i springs, the Mg ion concentration is 270 and 690 mg/l (or 23 and 41 mg-equiv %), respectively.

The enrichment in Ca against the background of SO₄ and Mg depletion is a most distinct feature of the Chukotka thermomineral waters that makes them different from seawater. This may be a consequence of exchange reactions in the water–rock system at temperatures exceeding 200°C (Krainov et al., 2004). Highly mineralized Cl–Ca brines are characteristic of the decelerated exchange zone developed at lower hydrogeological levels. In such brines, dissolved matter and its carrier are either syngenetic, when they are primarily sedimentogenic (isotopically heavy) waters of normal sea or saliferous basins, or genetically different, when they are brines resulted from the leaching of evaporitic sequences by the fresh meteorogenic (isotopically light) waters.

The sulfate and magnesium deficiency is usually attributed to metamorphism of sedimentogenic seawaters, when Mg²⁺ is fixed in clay minerals and carbonates, while SO₄²⁻ is removed during sulfate reduction. Isotopic study of the sulfate sulfur composition in six groups of springs revealed that the δ³⁴S value in the Dezhnev and Mechigmen thermal waters, where SO₄ concentrations are less than 100 mg/l, varies from 19.9 to 20.2‰ (Polyak et al., 2004). They correspond to typ-

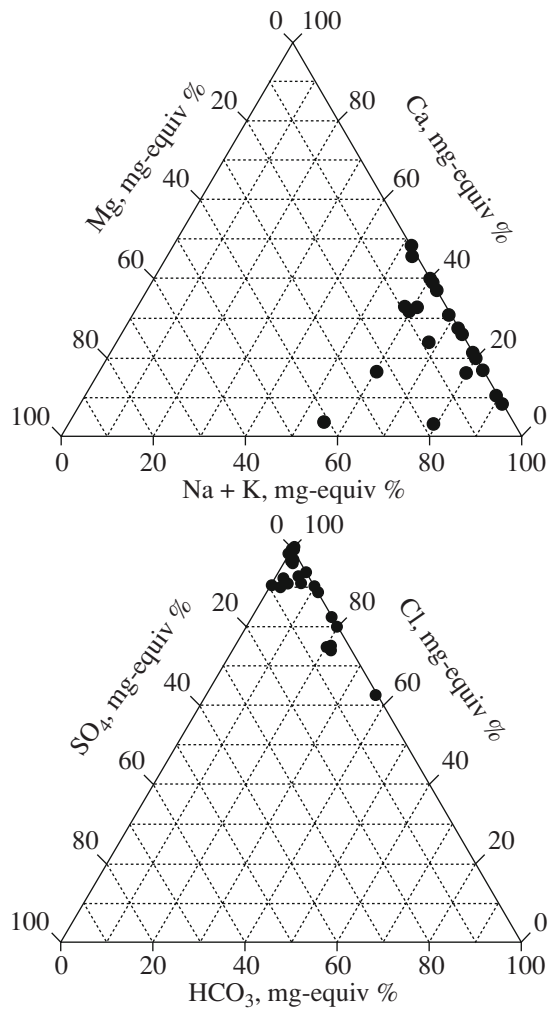


Fig. 3. Chemical composition of thermomineral waters in Chukotka.

ical $\delta^{34}\text{S}$ values of sulfate in seawater. The increase in sulfate concentrations in other springs is accompanied by the drop of this value to +11.7‰ (e.g., the Babushkiny Ochkı spring), indicating admixture of the isotopically lighter sulfur. This admixture in groundwater may be provided by the oxidation of dispersed sulfides. This is confirmed by some growth of S, Fe, and Al concentrations in thermal waters, although heavy metals do not demonstrate similar growth.

The observed correlation between $\delta^{34}\text{S}$ values and sulfate concentrations could be determined by sulfate reduction in the closed system, because exhaustion of dissolved sulfate should result in the transformation of the sulfur isotopic composition due to ^{32}S isotope fixing in the sulfide phase. The greater the reduction degree of sulfate sulfur, the heavier the isotopic composition of sulfate ion against the background of decrease of its concentration in the solution. Thus, sulfate reduction in groundwater is accompanied by lightening of the primary isotopic composition of sulfate sulfur in them;

i.e., the latter becomes closer to that in springs with maximal concentration of this element and, consequently, substantially different from its composition in seawater. At the same time, it seems strange that the $\delta^{34}\text{S}$ value in waters of the Dezhnev and Mechigmen springs appeared to be exactly equal (not lower or higher) to that in seawater.

Similar to other areas of the cryolithozone development, occurrence of highly mineralized waters with negative temperatures (the so-called cryopegs), which are formed under the permafrost sequence due to water phase freezing during the formation of subsurface ice, represents a peculiar feature of the subsurface hydrosphere in Chukotka (Tolstikhin, 1941; Ponomarev, 1960; *Gidrogeologiya...*, 1972; Kononova, 1974; Fotiev, 1978; and others). The initial temperature of cryogenic transformation of groundwaters depends on their primary mineralization: seawater (~35 g/l) remains liquid at temperatures of -1.8 to -1.9°C , while brines with mineralization of 200 g/kg preserve their liquid state even at -20°C . Cryogenic metamorphism of subsurface solutions is accompanied by both the growth of total mineralization and its qualitative changes. "Crystallization of freshwater ... in a freezing solution ... is accompanied by decrease in Ca^{2+} concentrations against the background of simultaneous increase in Na^+ and Mg^{2+} ... contents" (Fotiev, 1978, p. 38). In contrast, cryogenic concentration of seawater is accompanied first by increase in contents of NaHCO_3 , Na_2SO_4 and chlorides of Na, Mg, and Ca and then by decrease in contents of sodium sulfate at temperatures of -8 to -23°C (Fotiev, 1978, Fig. 6). It is unclear so far to what extent such a decrease explains the above-mentioned SO_4^{2-} deficiency in thermal waters of Chukotka relative to its content in seawater.

Phase transformations of water are accompanied by isotope fractionation, i.e., transfer of D and ^{18}O into the newly forming ice (Vetshtein, 1982), resulting in the isotopically lighter composition of water and higher salt load of corresponding cryopegs. Variations in the δD and $\delta^{18}\text{O}$ values in the frozen sequence are determined by isotope fractionation in the water-ice system during the crystallization and melting of ice under changeable climatic conditions. In closed systems (without additional water influx), the isotopic composition of the newly forming ice becomes successively heavier. This is responsible for its significant variations within a single ice body: for example, δD values in its different parts may differ by 30‰ (Vasil'chuk and Kotlyakov, 2000). At the same time, variability of the isotopic composition in subsurface ice may reflect climate-dependent variations in the isotopic composition of atmospheric precipitation during cryozone development. Published data on the isotopic composition of Chukotka subsurface ice are cited below. Unfortunately, the isotopic composition of waters in cryopegs of the Chukotka region is unknown so far. Available data on their chemical composition are presented in

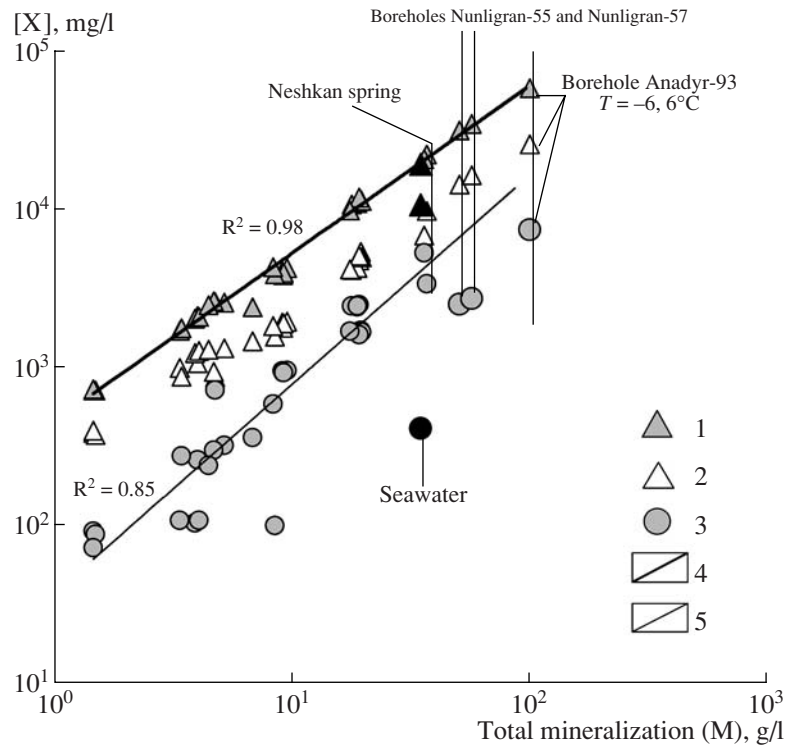


Fig. 4. Total mineralization (M) and concentrations of Cl, Na, and Ca ions ([X]) in groundwaters of Chukotka. (1–3) Concentration: (1) Cl, (2) Na, (3) Ca; (4, 5) regression lines: (4) [Cl]-M, (5) [Ca]-M. Solid symbols of elements correspond to seawater.

Table 3. Figure 4 demonstrates the correlation of water mineralization with Cl, Na, and Ca concentrations. The plot shows data points corresponding to these cryopegs.

Chukotka cryopegs are variable in terms of their mineralization type. For example, waters recovered near the town of Anadyr and Nunligran settlement are close in this respect to seawater, while waters observed near the town of Pevek differ from the latter in terms of their cation composition: Ca and Mg contents are higher as compared with Na concentration. The Ca/Mg value in cryopegs penetrated by Borehole Pevek-10 is practically similar to that in Borehole Anadyr-93 (1.55 and 1.52, respectively). In boreholes drilled in the Nunligran settlement, this ratio is substantially lower (0.84–0.98). This is likely explained by regional differences in the composition of primary waters subjected to cryogenic metamorphism and/or by peculiarities of this process in different areas of Chukotka.

As was mentioned, the Neshkan and Oranzheveye springs (Fig. 1, points 10 and 14, respectively) discharge waters with mineralization higher than in seawater. Corresponding data points in plots demonstrating correlation of Cl, Na, and Ca concentrations with the total mineralization form trends similar to data points of both other thermomineral springs and cryopegs of the Nunligran and Anadyr areas (Fig. 4). Taking into consideration this similarity and differences mentioned above between Chukotka cryopegs in the total salt contents, one can assume the contribution of

subpermafrost waters with different degrees of mineralization and cryogenic metamorphism to the formation of the salt composition in different thermal waters. According to Fotiev, the last process results, however, in an enrichment of freezing waters with Mg, while corresponding thermal waters become depleted in this element. Thus, the role of cryometamorphism in the formation of their chemical composition is unclear.

METHODS

The chemical composition of liquid and gaseous phases in thermomineral fluids was determined in line with standard techniques at the Geological Institute, Moscow. The water isotopic composition (δD and $\delta^{18}O$) was analyzed in the IGEM RAS at the Finningan DELTA^{phis} mass-spectrometer. δD values were measured by the method of direct decomposition of water at hot (800°C) metallic chrome using (Finningan H/Device); measurement accuracy of H isotopic composition was $\pm 0.2\%$. The $\delta^{18}O$ values were determined using the classical method of isotopic equilibrating of water samples with CO_2 at $t = 25^\circ C$. Reproducibility of $\delta^{18}O$ measurements in parallel experiments was $\pm 0.15\%$. The total accuracy was at least $\pm 0.25\%$. All measurements were controlled using standard MAGATE (IAEA) samples OH-1, OH-2, OH-3, and OH-4.

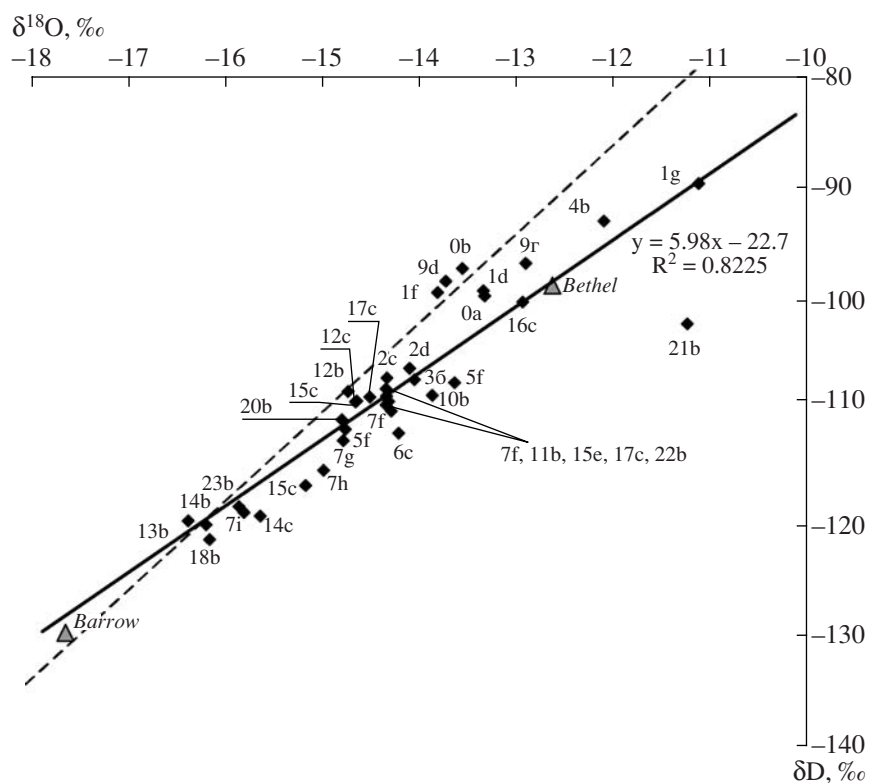


Fig. 5. Isotopic composition of surface waters in eastern Chukotka at the examined discharge sites of thermomineral fluids. Data points correspond to numbers in column 1 of Table 1. Solid and dashed lines are the regression and Craig lines, respectively. Triangles designate average annual δD and $\delta^{18}O$ values of atmospheric precipitation obtained at the Bethel ($60.78^\circ N$) and Barrow ($71.30^\circ N$) stations (Yurtsever and Gat, 1981).

OXYGEN AND HYDROGEN ISOTOPE COMPOSITION IN CHUKOTKA WATERS

Table 1 presents data on deuterium and ^{18}O contents in waters of the Chukotka region. δD and $\delta^{18}O$ values are given relative to the international SMOW standard. Table 4 summarizes variations in these values in water reservoirs that are of interest in the context of the problem in question. The table demonstrates that waters of the Bering Sea are close in their isotopic composition to average seawater, although they are slightly depleted in heavy isotopes due to their freshening in the coastal zone. On the contrary, surface (creeks, rivers, and lakes) and thermomineral waters of the Chukotka Peninsula are characterized by substantially different isotopic compositions of hydrogen and oxygen.

Surface Waters

Surface water reservoirs (rivers, creeks, lakes, and wells) fed by atmospheric precipitation and surface flow were sampled at 21 of 23 examined discharge localities of hydrothermal springs. In the δD – $\delta^{18}O$ diagram, location of all 36 data points available for surface waters (Table 5, selection 1) is controlled by linear dependence $\delta D \approx 6\delta^{18}O - 22.7$ (Fig. 5). This dependence differs slightly from the global “Craig line” $\delta D =$

$8\delta^{18}O + 10$ that reflects the isotopic lightening of atmospheric precipitation toward higher latitudes (Craig, 1961). Data points of average annual (average weighted relative to integral precipitation during the year) δD and $\delta^{18}O$ values in atmospheric precipitation of neighboring Alaska, where it was studied at the Bethel and Barrow meteorological stations (Yurtsever and Gat, 1981), fall practically onto the “Chukotka” trend. Data points of these two Alaskan meteorological stations, which are located slightly south and north of the study area, respectively, limit the spectrum of δD and $\delta^{18}O$ values obtained for surface waters of the Chukotka Peninsula. Chukotka surface waters appear to be slightly richer in deuterium and ^{18}O as compared with atmospheric precipitation at the Bethel Station only in four cases. This enrichment is best manifested in two small creeks near the Chaplino and Kivak thermomineral springs, where it reflects probably their dominant feeding by summer precipitation. In addition, the isotopic composition of H_2O in small creeks should be slightly enriched in deuterium and ^{18}O due to evaporation (at least, more strongly than in rivers). Therefore, water samples from rivers reflect the isotopic composition of meteorogenic waters more adequately. Except for samples taken from small creeks and lower reaches of rivers draining springs and a sample with the strange anomalous result

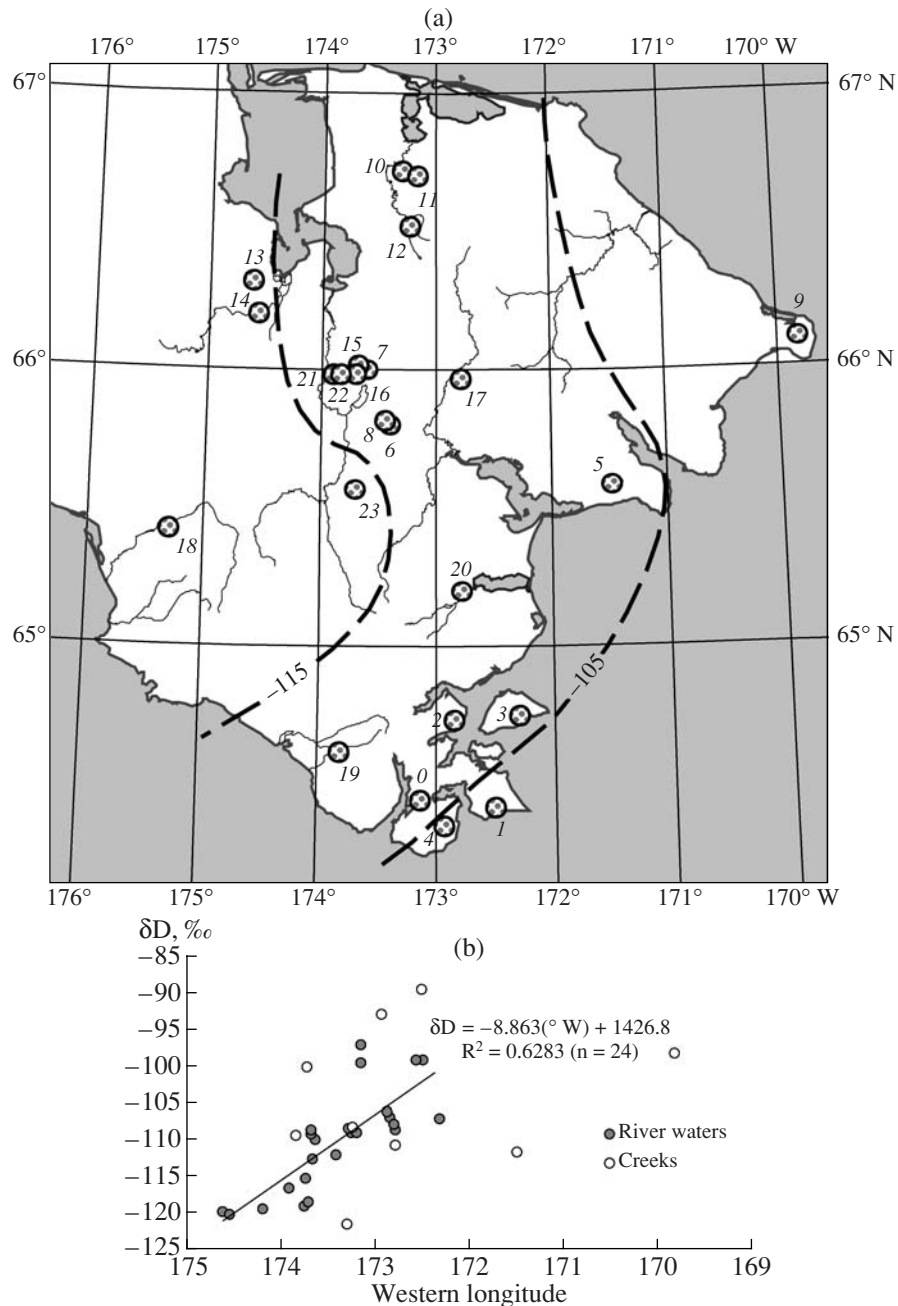


Fig. 6. Lateral variations in the δD values in surface waters near thermomineral springs of eastern Chukotka (numbers in Fig. 1). (a) Schematic δD isolines; (b) correlation between δD values in river waters and longitude of sampling sites (straight line shows the trend).

(Table 1, Point 21b), the distribution of 25 data points available for surface waters is governed by linear dependence with the correlation coefficient $R = 0.93$ (Table 5, Selection 2).

Atmospheric precipitation of Alaska demonstrates a distinct universal lightening of its isotopic composition toward higher latitudes. In contrast, Chukotka waters show a substantially more distinct longitudinal trend: decrease in δD and $\delta^{18}O$ values from the east to west in interior areas of the peninsula (Fig. 6a). Correlation

between the hydrogen isotope composition in surface waters and western longitude of the sampling point can be formally approximated by the regression equation $\delta D = -8.863(\text{deg}) + 1426.8$, where (deg) corresponds to western longitude of the particular point determined with an accuracy of $0.01n^{\circ}$ (Fig. 6b). In the selection under consideration (n = 24), this correlation is statistically significant: $R^2 = 0.6283$; i.e., $|R| = 0.792 > R_{\text{crit}} = 0.390$.

Table 3. Parameters of cryopegs in the Chukotka Peninsula

Object	T, °C	M, g/l	Concentrations of components, mg/l/mg-equiv %								Coefficients (mg-equiv/mg-equiv)					Source ¹
			Na + K	Mg	Ca	Cl	SO ₄	HCO ₃	Na/Cl	Ca/Cl	Mg/Cl	SO ₄ /Cl	Ca/Mg			
Pevek, Borehole 10, 0.2–0.3 km away from the sea	-2	38	1316	3124	8070	25206	232	68	0.08	0.57	0.36	0.01	1.57	1		
			8	36	56	99	0.8	0.2								
Nunligran Settle- ment, Borehole 57, 3 km away from the sea	<-0.4 (-2.5)	50.9	14471	1820	2518	31900	100	91	0.70	0.14	0.17	0.00	0.84	1		
			70	16	14	99.5	0.3	0.2								
Nunligran Settle- ment, Borehole 55, 0.4 km away from the sea	<-0.4 (-2.5)	57.4	16531	1702	2744	35100	250	49	0.73	0.14	0.14	0.01	0.98	1		
			72	14	14	99.2	0.7	0.1								
Anadyr, Borehole 93, penetration 5 m	-6.6	100.7	26000	3000	7500	59000	2750	2440	0.68	0.23	0.15	0.03	1.52	2		
			64.7	14	21.3	94.5	2.2	2.3								
Kazachka Depres- sion	-2.2	80.2							0.64	0.16	0.23	0.02		3		
Sea		35.0	11147	1294	413	19353	2712	142	0.89	0.04	0.19	0.10	0.19	4		
			78.7	18.1	3.2	90.5	9.3	0.1								
Spring Neshkan ²	52	37.1	10510	61	3400	22400	3	122	0.72	0.27	0.01	0.00	33.79	5		
			72.1	0.3	27.6	99.7	<0.01	0.3								

Notes: ¹ Source: (1) (*Gidroteologiya...*, 1972); (2) (Ponomarev, 1960); (3) (Fotiev, 1978); (4) (Horn, 1972); (5) Our data.

² Data are given for comparison.

Table 4. Variation ranges of δD and $\delta^{18}O$ in different H_2O reservoirs

Type of natural water	$\delta D, ‰$		$\delta^{18}O, ‰$	
	min	max	min	max
Bering Sea ¹	-26.82	-10.05	-3.38	-1.31
Alaska, atmospheric precipitation ²	-129.80	-98.60	-17.64	-12.63
Chukotka				
surface waters	-121.41	-89.46	-16.38	-11.12
thermomineral waters	-134.22 ³	-96.91 ⁴	-17.52 ³	-12.62 ⁴
subsurface ice ⁵	-223.6 ⁶	-79.6 ⁷	-29.2 ⁶	-11.2 ⁷
	-191.5 ⁸	-90.2 ⁹	-24.9 ⁸	-12.5 ⁹

Notes: ¹ Our measurements: minimal and maximal values are in the Kivak Lagoon and Senyavin Strait, respectively.

² Average annual parameters determined at the Bethel (60.78° N) and Barrow (71.30° N) meteorological stations (Yurtsever and Gat, 1981).

³ Babyshkiny Ochki springs.

⁴ Dezhnev springs; water from the Lake Olen'i (Ynpyneveem) springs is isotopically even heavier: δD and $\delta^{18}O$ values are -92.45 and -10.52‰, respectively.

⁵ After (Vasil'chuk, 1992; Vasil'chuk and Kotlyakov, 2000). Italics designate samples calculated using equation $\delta D = 8\delta^{18}O + 10$ (Craig, 1961).

⁶ Regenerated vein ice (20600 yr) in the Amguema River valley. In regenerated vein ice dated back to <40 ka near Anadyr, the measured $\delta^{18}O$ and calculated δD values are -27.3 and -208.4‰.

⁷ Recent structural ices at the initial part of the Mechigmen Estuary.

⁸ Holocene regenerated vein ice, Pekul'nei Range.

⁹ Recent structural ice, Onemen Bay, ~20 km away from Anadyr.

Thermomineral Waters

Thermomineral waters of the Chukotka region are generally depleted in ^{18}O and deuterium as compared with their surface counterparts (Tables 1, 4). The scatter range of δD and $\delta^{18}O$ values in them is wider: 41.8 and 7.1‰, respectively. In surface water, these parameters are 31.9 and 5.3‰, respectively. Water from the mineralized (8.53 g/l) and warm (15°C) Olen'i springs appeared to be isotopically heaviest: $\delta D = -92.5‰$ and $\delta^{18}O = -10.5‰$ (Table 1, Point 15a). This is probably explained by loss of the isotopically light water due to evaporation and shift of the isotopic composition toward enrichment of the remaining water in the heavy oxygen and hydrogen isotopes.

In the δD - $\delta^{18}O$ plot (Fig. 7), half of data points fall into the field corresponding to surface waters. This provides grounds for impression that the corresponding thermomineral springs are fed only by local infiltration waters, as it follows from the concepts of practically complete spatial coincidence between feeding and discharge zones of such circulation systems (Shvetsov, 1951; Ponomarev, 1960). Comparison of δD values in thermomineral and surface waters reveals, however, that thermal waters in 16 groups of springs are depleted to a variable extent in deuterium relative to the neighboring surface waters.

Similar to surface waters, the lateral distribution of δD values in thermomineral solutions also reveals spa-

tial (although principally different) regularity. In the southern and eastern Chukotka Peninsula, the isotopic composition of thermomineral waters in most springs is close to that of local freshwaters and their data points form a regression line with the similar slope in Fig. 7 (Table 5, Selection 3). In the Senyavin and Verkhne-Nunyamoveem groups of springs (points 2 and 18, respectively) in this part of the peninsula, the δD values are substantially lower than in surface waters. Nevertheless, their data points 2a, 2b, and 18a are located almost at the same "surface" trend (cf. regression equations in selections 2 and 3 in Table 5). These points, anomalous for the southeastern Chukotka Peninsula, appear simultaneously in the field of thermomineral waters (Fig. 7) that are most depleted in deuterium ($\delta D < -120‰$). The latter points are located, however, in the Kolyuchinskaya-Mechigmen Depression rather than the westernmost part of the area, where surface waters are most depleted in this isotope (Fig. 8a). This inference is substantiated by concentration of data points available for thermomineral waters in the area between 172.8° and 173.8° W (Fig. 8b), i.e., by lack of correlation between δD values and longitude of the corresponding sample point notable in surface waters.

At the same time, springs depleted in deuterium demonstrate a substantial enrichment in the heavy isotope ^{18}O (relative the Craig line) and form flatter trends in the δD - $\delta^{18}O$ plot (Fig. 7). The similarity between

Table 5. Parameters of particular selections of paired $\delta^{18}\text{O}$ and δD values in waters of the Chukotka Peninsula

Selection no.	Selections	Numbers of groups of springs in Fig. 1, Numbers of samples in column 1 of Table 1	n	Equation of regression	R ²	R	R _{crit}
Surface waters							
1	All samples	All (0–7, 9–18, 20, 22, 23)	36	$5.9828x - 22.7057$	0.8225	0.9069	0.329
2	Without samples from creeks and lower reaches of rivers	(without 1g, 4b, 5e, 5f, 9d, 9e, 12b, 16c, 18b, 20b, 21b, 22b)	25	$7.4609x - 0.9950$	0.8734	0.9346	0.335
Thermomineral springs							
3	Southeastern margins, anomalies* included	1–5, 9, 18–20	18	$7.5879x + 0.5510$	0.9713	0.9855	0.468
4	Southeastern margins without anomalies*	1, 3–5, 9, 19, 20	15	$8.059x + 6.9705$	0.9059	0.9518	0.514
5	Central areas	6–8, 15–17, 21–23	16	$3.5905x - 70.7614$	0.7095	0.8423	0.497
6	Central areas without the Pechingtanvaam springs	6–8, 15–17, 21–22	15	$3.5779x - 70.9298$	0.7079	0.8414	0.514
7	Northern margin	10–14	5	$2.8740x - 75.3126$	0.5565	0.746	0.878
8	Central areas + northern margin	6–8, 10–17, 21–23	21	$4.7684x - 50.2403$	0.6973	0.8351	0.433
9	Central areas + northern margin + anomalies of southeastern Chukotka*	2, 6–8, 10–18, 21–23	24	$4.4765x - 54.6683$	0.6958	0.8227	0.390

* “Anomalous” springs of southeastern Chukotka: Senyavin (no. 2) and Verkhne-Nunyamoveem (no. 18).

regression equations in selections 5 and 6 (Table 5) shows that the Pechingtanvaam springs (Point 23) are closer to their counterparts in the Kolyuchinskaya–Mechigmen zone than to the southern springs in terms of the isotopic composition of water.

Selection 7 (Table 5), which includes a small number of samples from thermomineral springs nearest to the Neshkan Lagoon and Kolyuchinskaya Estuary, lacks correlation between δD and $\delta^{18}\text{O}$ values ($|R| < R_{\text{crit}}$). Nevertheless, when this selection is united with Selection 8 (Kolyuchinskaya–Mechigmen zone) and Selection 9 (“anomalous” springs in the southern part of the peninsula), correlation between δD and $\delta^{18}\text{O}$ values appears to be statistically significant ($|R| > R_{\text{crit}}$).

Minimal δD values in waters of the Kolyuchinskaya–Mechigmen springs reflect their distinct regional specificity. It is of extreme interest that the specificity is also evident from other isotopic–geochemical features of springs, which make them different from their counterparts discharging beyond the depression. In addition to the above-mentioned enrichment of their gaseous phase in carbon dioxide, specific isotopic parameters of carbon in the carbon dioxide, as well as of helium and nitrogen that are present in this phase, are also notable. All these parameters are independent from each other, and their coordinated spatial

variability deserves special analysis, which will be made in other publications.

DISCUSSION

Probable Factors Responsible for Isotopic Specifics of Thermomineral Waters

The performed study demonstrates that approximately half of hydrothermal springs are depleted in deuterium and ^{18}O as compared with local surface waters. Provided that these hydrothermal springs are fed only by atmospheric precipitation (i.e., they were formed on account of the precipitation), such a deficiency might be explained by the fact that all the samples were taken in July–August. In contrast, winter precipitation, which prevails usually in the subsurface infiltration flow that feed springs, is depleted in deuterium and ^{18}O .

Isotopic differences between thermomineral and local surface waters may in principle be explained by different altitudes of their feeding provinces. It is known that increase in altitude results in depletion of atmospheric precipitation in heavy isotopes with gradients $\Delta\delta\text{D}/\Delta h = 1.5\text{--}4\text{‰}$ and $\Delta\delta^{18}\text{O}/\Delta h = 0.15\text{--}0.5\text{‰}$ per every 100 m of altitude (Yurtsever and Gat, 1981). In this case, feeding areas of thermomineral waters should be located at least 500–600 m above their discharge

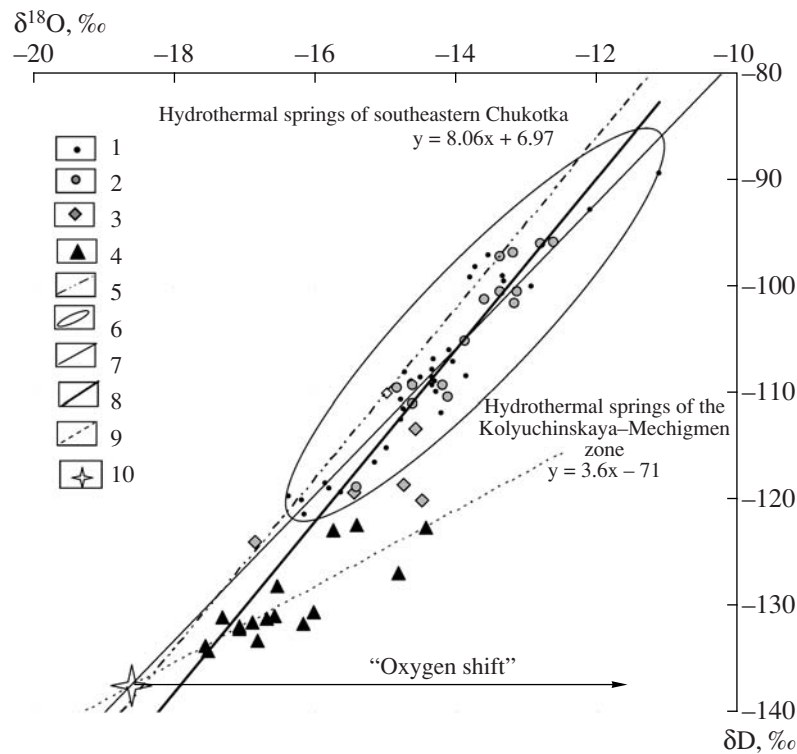


Fig. 7. Hydrogen and oxygen isotope compositions in surface waters and thermomineral springs of eastern Chukotka. (1) Data points of local surface waters; (2–4) data points of waters from thermomineral springs: (2) southern and eastern margins of the peninsula, (3) northern margin (vicinities of Neshkan Lagoon and Kolyuchinskaya Estuary), (4) central areas (Kolyuchinskaya–Mechigmen Depression and its framing); (5) Craig line; (6) field of data points corresponding to local surface waters; (7) regression line for local surface waters; (8, 9) regression lines for thermomineral springs of the peninsula: (8) southeastern marginal area, (9) central area; (10) deep-sourced component A (for explanation, see the text).

localities. In the Kolyuchinskaya–Mechigmen Depression, the relief amplitude amounts to 700–800 m, and the Senyavin springs (Point 2) discharge near Mt. Iskhodnaya (1158 m) representing the highest summit in eastern Chukotka. Therefore, such an explanation of isotopic lightening of thermal waters relative to local surface waters is theoretically admissible.

The depletion of thermomineral waters in deuterium relative to local surface waters could also reflect other (colder) paleoclimatic conditions of their feeding areas. However, local differences between these conditions within the Chukotka Peninsula seem improbable. Therefore, contribution of the water component with low δD and $\delta^{18}O$ values (lower than in surface waters of the study area) into the formation of thermomineral waters is the most probable factor responsible for their deuterium deficiency as compared with surface waters.

Such values are characteristic, for example, of subsurface ice. In Chukotka, its isotopic composition was studied only for uppermost parts of the geological section in separate outcrops near Lake Koolen, in the Anadyr area, and in the Tanyurer (Pekul'nei Range) and Amguema river valleys (Vasil'chuk, 1992; Vasil'chuk and Kotlyakov, 2000). Table 4 and Fig. 9 present the results of these studies. It is seen that δD and $\delta^{18}O$ val-

ues in ice of the Chukotka Peninsula are highly variable. Such a wide scatter is attributed to variability of formation settings of ice bodies: degree of closeness of hydrological systems and climatic conditions. For example, radiocarbon dating of sequences enclosing ice bodies revealed that $\delta^{18}O$ values in Upper Pleistocene ice which is believed to be related to colder climatic conditions in the past (Vasil'chuk and Kotlyakov, 2000) are generally 3–7‰ lighter than in recent ice.

Feeding of thermal waters by meltwaters of a degrading frozen sequence is refuted by the following unavoidable inference from such assumption: subglacial in the discharge zone of thermal waters should permanently grow; otherwise, “ice” feeding of the hydrothermal system by water (consequently, influx of light H and O isotopes) should stop. The growth of subglacial is considered a nonstationary process in many respects: it should be accompanied by changes in geometry of the ascending hydrothermal flow and corresponding changes in its temperature and yield. The scale and rate of such a process should depend on thickness of the frozen sequence, yield of hydrothermal waters, and their temperature.

When considering the probable role of subsurface ice in the formation of thermal waters, one should take

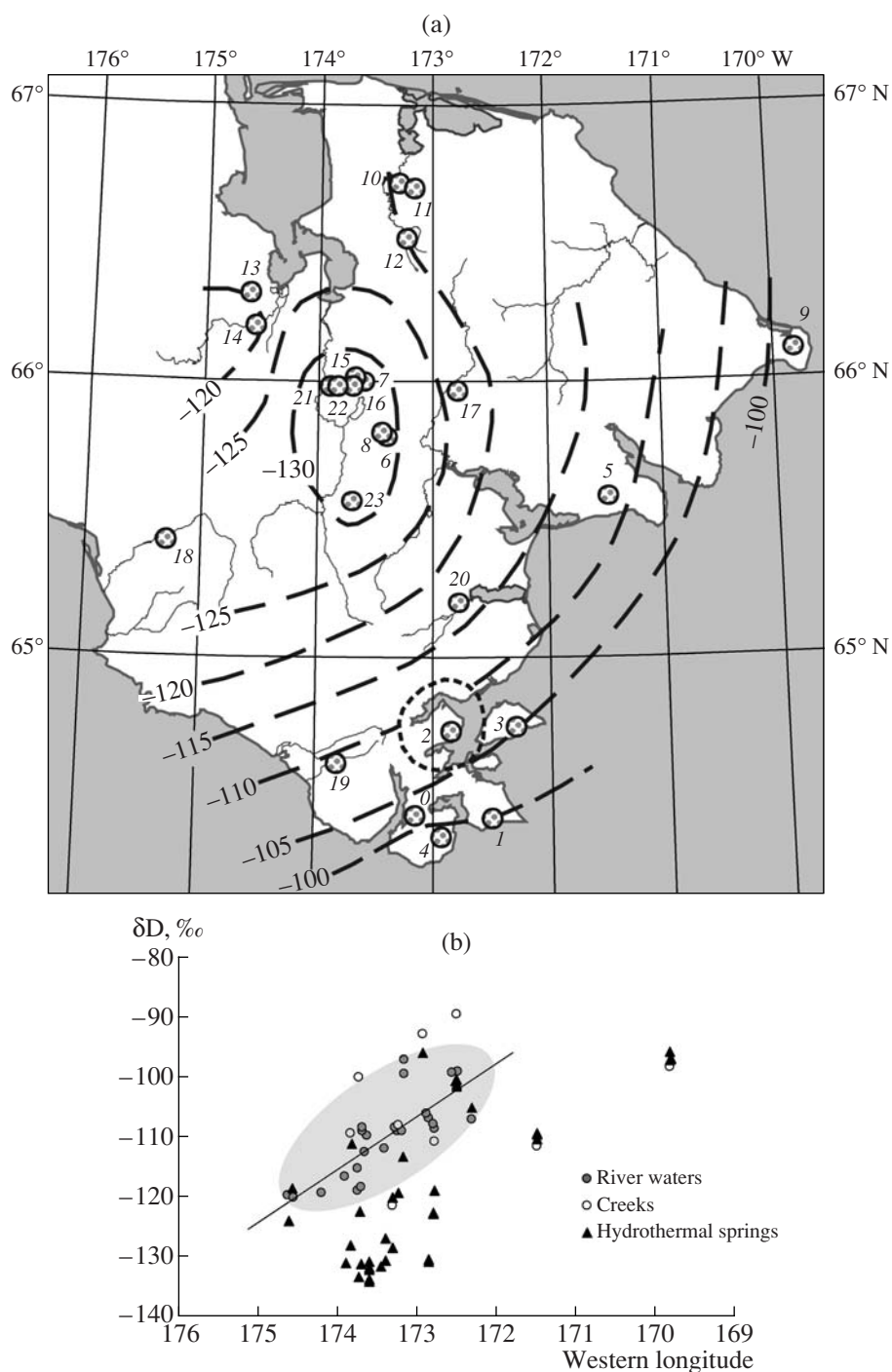


Fig. 8. Lateral variations in the δD values in waters of thermomineral springs in eastern Chukotka (numbers in Fig. 1). (a) Schematic δD isolines: dashed line contours the Senyavin negative δD anomaly (out of scale); (b) correlation between δD values in river waters and longitude of sampling sites. The hatched area corresponds to the field of data points obtained for river waters. The straight line shows the trend in Fig. 6b.

into account the fact that this ice is characterized by very low mineralization: its maximal value usually does not exceed 124 mg/l (average 35–69 mg/l) in varieties studied in the Chukotka (Vasil'chuk, 1992). Mixing of waters formed during the melting of such ice with infiltrating meteoric waters, i.e., two fresh com-

ponents, cannot provide mineralized waters that discharge in hydrothermal springs.

Such waters could seemingly originate from the mixing with seawaters. Figure 10 demonstrates, however, lack of universal correlation between chlorine and deuterium concentrations in thermomineral waters. The

conjecture that Chukotka thermal waters resulted from the mixing of seawaters with the isotopically light meteorogenic variety automatically implies the existence of isotopically diverse freshwater reservoirs with δD values ranging from -110 to $-250‰$. Such a range of values is substantially wider as compared with those established in surface waters of the Chukotka Peninsula. At the same time, this range is similar to that observed in subsurface ice bodies (Table 4). Hypothetical speculations on diversity of ice-related freshwater reservoirs with a single (purely "marine") source for mineralization of thermal waters cannot explain the above-mentioned differences in the mineralization spectrum observed between thermomineral waters and this source: excess of Ca and deficiency Mg and SO_4 relative to seawater.

Moreover, such speculations cannot explain the formation of thermomineral waters with mineralization exceeding the value in seawater, which discharge in the Neshkan and Oranzhevy springs (Fig. 1, Table 1, points 10 and 14). Judging from all these features, only the above-mentioned cryopegs, i.e., highly mineralized groundwaters (with negative temperatures), which occur in some areas of Chukotka, may provide dissolved salts for the thermomineral waters. Due to isotopic lightening of the subpermafrost water during its freezing, δD and $\delta^{18}O$ values in cryopegs are lower than in the conjugate subsurface ice. Unfortunately, direct data on δD and $\delta^{18}O$ values in cryopegs of Chukotka and their lateral variability are unavailable so far. Therefore, their real role in the formation of the isotopic composition of waters in the springs examined remains unknown.

In any event, the occurrence of waters depleted in heavy hydrogen and oxygen isotopes (relative to local surface waters) in thermomineral springs of Chukotka is beyond doubt.

Isotopic Composition of Deep-Sourced Component A

If we assume that some deep-sourced component is common for all deuterium-deficient (relative to local surface waters) thermomineral springs, its isotopic parameters may be determined using the following technique. In the δD – $\delta^{18}O$ diagram, thermomineral waters with particularly distinct deuterium deficiency (Table 5, Selection 5) provide a regression line $\delta D = 3.6\delta^{18}O - 70.1$. The regression line of surface waters (Selection 2) is characterized by a steeper slope. Since a hypothetical "hydrogen-light" deep-sourced component should be diluted to some extent by surface waters during the discharge, the intersection point of regression lines obtained for selections 2 and 5 in the δD – $\delta^{18}O$ diagram should correspond to the isotopic composition of water characterizing the required component, i.e., to point A in Fig. 7, where $\delta^{18}O = \approx -19‰$ and $\delta D = \approx -138‰$.

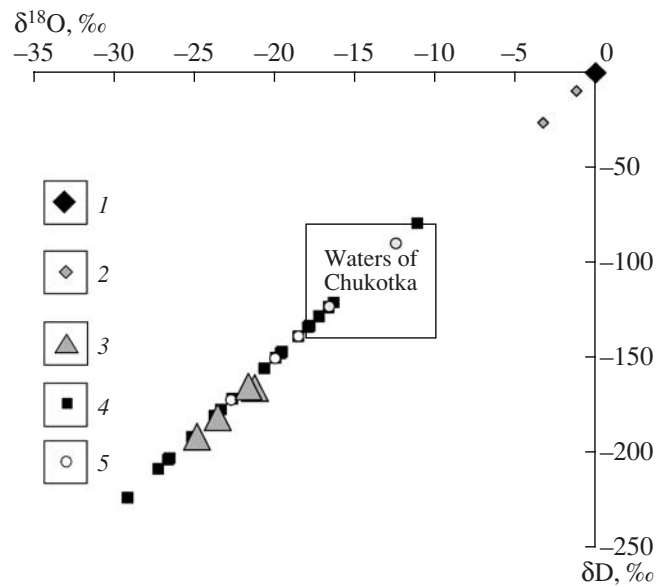


Fig. 9. Isotopic composition of H_2O in different reservoirs of Chukotka. (1) SMOW; (2) coastal waters of the Bering Sea near Arakamchechen Island and in the Kivak Lagoon (Table 4); (3–5) compositions of subsurface ice, after (Vasil'chuk, 1992; Vasil'chuk and Kotlyakov, 2000): (3) based on measured δD and $\delta^{18}O$ values, (4) based on $\delta^{18}O$ measurements and δD calculations using the Craig line, (5) based on δD measurements and $\delta^{18}O$ calculations using the Craig line. The hatched rectangle comprises data points obtained for thermomineral springs of eastern Chukotka and local surface waters.

The isotopic composition of water discharged in thermomineral springs may be formed in two ways. In the case of simple mixing of component A with surface waters, data points corresponding to isotopic compositions of mixtures should be located along the surface water line in the δD – $\delta^{18}O$ diagram. Precisely this is characteristic of thermal waters in southeastern Chukotka: equations of regression lines in selections 2 and 3 are practically identical. Deuterium-deficient thermomineral waters demonstrate a distinct shift of data points to the right from the surface water line. This implies a variation in the isotopic composition of component A prior to its mixing with surface waters.

Variation of the isotopic composition of water in subsurface reservoirs is related to its interaction with host rocks at elevated temperatures. Therefore, the hydrogen isotope composition in thermomineral waters depends only on proportion of component A mixed with surface waters, while the oxygen isotope composition also depends from interaction of this component with rocks (the possible alternative explanation of the origin of Selection 5 is considered below).

Share of Component A in Waters of Thermomineral Springs

After determining δD_A and knowing the value of the "hydrogen isotope shift" ($\Delta\delta D = \delta D_{\text{therm}} - \delta D_{\text{surf}}$, where

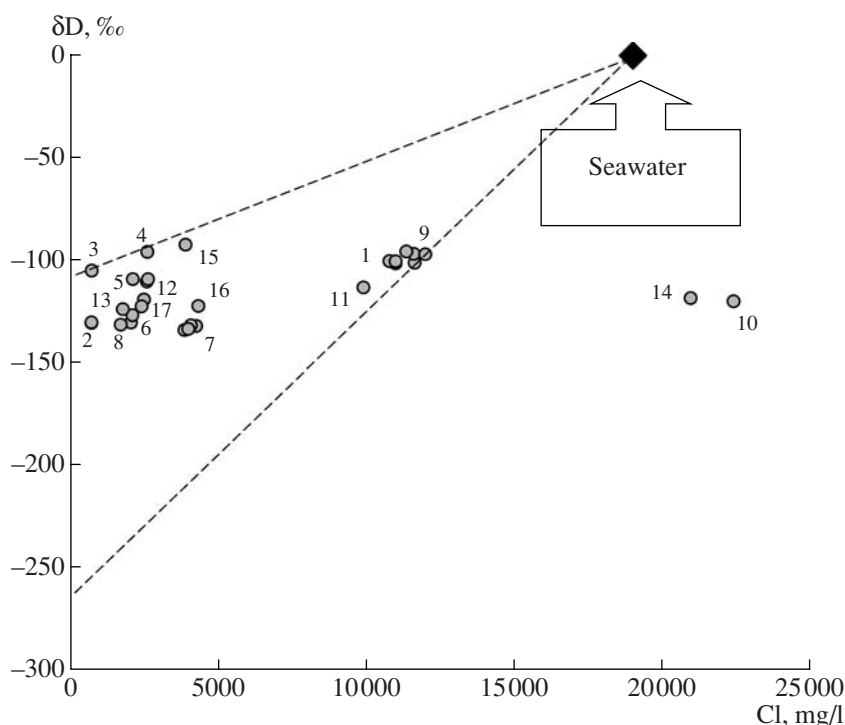


Fig. 10. Correlation between the hydrogen isotope composition in H₂O and Cl ion concentration in thermal waters of eastern Chukotka. Numerals correspond to numbers of groups of springs in Fig. 1.

(therm) and (surf) designate thermal and local surface waters), we can calculate the share of component A (X_A) in particular thermomineral water regardless of the interaction degree of this component with rocks in line with the following equation:

$$X_A = (\delta D_{\text{therm}} - \delta D_{\text{surf}}) / (\delta D_A - \delta D_{\text{surf}}). \quad (1)$$

Correspondingly, the share of surface waters $X_{\text{surf}} = (1 - X_A)$ is determined as

$$X_{\text{surf}} = (\delta D_{\text{therm}} - \delta D_A) / (\delta D_{\text{surf}} - \delta D_A). \quad (2)$$

Equation (2) shows that the deuterium excess in thermomineral waters (relative to component A) should reflect its dilution degree by near-surface waters with the higher δD value: the closer the hydrogen isotope composition in thermal waters to that in the deep-sourced component A, the lower the dilution degree of component A.

In principle, local and infiltration meteorogenic waters, as well as thalassic varieties buried during sedimentation or driven from the recent sea basin into the continental hydrothermal systems, can be characterized by higher δD values as compared with thermomineral waters. Such a phenomenon is observed in some coastal circulation systems (Kononov and Tkachenko, 1974). Therefore, the assessment of X_A in the thermomineral springs depends on the presumed nature of the diluting component and technique of δD determination in these waters.

The δD_{surf} value used in Eqs. (1) and (2) is an averaged parameter that characterizes the isotopic composition of surface waters in the particular discharge locality of hydrothermal springs. As is known, this composition is season-dependent. Therefore, the use of random estimates of δD as its characteristics for the calculation of X_A (or X_{surf}) introduces a certain error. The error could seemingly be reduced using the δD value in surface waters based on its above-mentioned correlation with the longitude. In this case, however, another error due to curvature of δD_{surf} isolines relative to meridians (Fig. 6) is possible. For the hypothetical admixture of seawater, the δD value of -20‰ was accepted in accordance with our measurements in waters of the Kivak Lagoon and Senyavin Strait (Table 4).

In five examined thermomineral water localities (points 3, 5, 9, 14, and 15), δD values is higher (isotopically heavier) than in the local surface water, indicating that mixing of the latter water with component A could not form the isotopic composition of the thermomineral water. For these localities, calculated δD_{surf} values based on the correlation with longitude (points 3 and 5) rather than the values measured in springs were used or seawater was conditionally accepted as a diluting component. The last assumption seems possible for the coastal Dezhnev springs (Point 9), less probable for the Oranzhevye springs (Point 14), and improbable for the Olen'i springs. Therefore, the X_A value for the last springs was not determined.

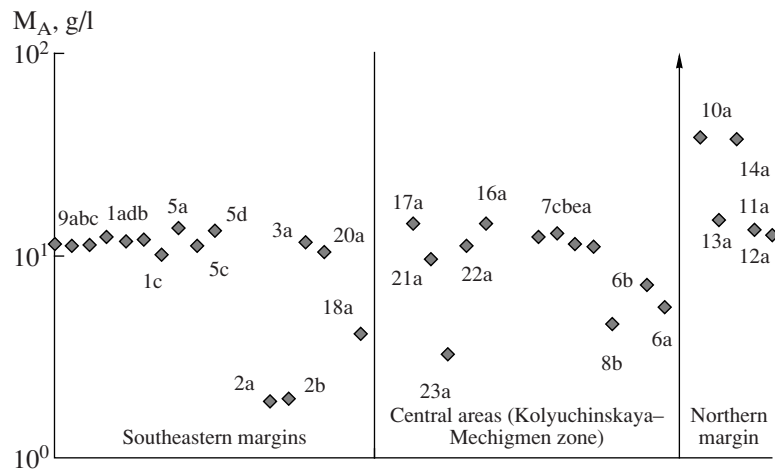


Fig. 11. Mineralization of component A in various areas of Chukotka. Numerals of data points correspond to numbers in column 1 of Table 1.

The calculation results are given in Table 6 (column 4). They show that all samples taken in a single locality of hydrothermal spring discharge reflect almost the same share of component A. In contrast, its value ranges from 0.07 to 0.88 and lacks regional specifics in different discharge localities.

Salt Composition of Component A

Mineralization of component A (M_A) may be estimated on the basis of its calculated share (X_A) in the springs examined and the following assumptions: (i) component A provides both H_2O and dissolved salts; (ii) this component is diluted by local surface waters, which are practically barren of salts ($M_{surf} \sim 0$). The M_A value was determined in 20 of 22 spring groups. This value was 9.5–14.7 g/l in 13 groups, <7 g/l (1.9 g/l in some places) in five groups, and 36.5–37.5 mg/l in two groups located at the northern margin of the study region (Table 6, Fig. 11). Two last values were obtained for the Neshkan and Oranzhevy springs in the northernmost part of the peninsula (points 10 and 14; mineralization 37.16 and 36.23 g/l, respectively).

For 15 groups of springs, where local surface waters ($M_{surf} = 0$) were believed to serve as a diluting agent, $M_{therm} = M_A \times X_A$ and $M_A = M_{therm}/X_A$. For other five groups of springs with mineralization exceeding 17 g/l, the Oranzhevy (Point 14), Neshkan (Point 10), and Teyukei (Point 11) springs in northernmost Chukotka, as well as for the Dezhnev and Chaplino springs (points 1 and 9, respectively) in the easternmost and southeastern parts of the peninsula, seawaters with δD values of -20% and $M_{SW} = 35\%$ were accepted as a diluting agent. In these cases, $M_{therm} = M_A \times X_A + M_{SW} \times (1 - X_A)$ and $M_A = [M_{therm} - M_{SW} \times (1 - X_A)]/X_A$ (if real M_{SW} values are lower, the M_A value should be higher than the calculated one). In the Teyukei, Dezhnev, and Chaplino springs, the M_A values

were 13.1, 10.1–12.2, and 11.0–11.4 g/l, respectively, i.e., similar to their estimates for most other springs of thermomineral waters with local surface waters assumed as the diluting component. This provides an impression that mineralization of component A is uniform throughout the entire Chukotka Peninsula and close to 10–12 g/l. The formal average from M_A estimates obtained for all 20 groups of springs (after their preliminary averaging for different samples of the same group) is 11.8 g/l.

In the case of the Oranzhevy springs (Point 14), assumption of dilution of component A by fresh surface waters leads to an absurd result: X_A and M_A values appear to be negative. Consequently, assumption of dilution of the deep-sourced component by seawater has no alternative. In this case, we obtain $M_A = 36.5$ g/l, which exceeds insignificantly mineralization of discharged thermal waters. Therefore, seawater is also believed to represent a diluting agent in the Neshkan springs. Complete exclusion of possibility of the contribution of recent seawater to the formation of hydrothermal solutions in (Cheshko et al., 2004) was too categorical, as is evident from the data presented in our paper.

Concentration of Ca_A in component A calculated similarly as the M_A value at the Ca content in seawater equal to 413 mg/l does not change the mineralization type of the deep-sourced component relative to waters of springs, where the share of Ca is substantially higher than in seawater (Table 6, columns 6 and 7). At the same time, in the case of positive correlation between M_A and Ca_A values, the latter values are highly variable within a narrow interval of the most widespread M_A estimates available for Chukotka (Fig. 12). This fact suggests different metamorphism degrees of groundwaters in the study region.

M_A estimates are substantially lower as compared with their average values in three groups of springs—the Senyavin springs located in the southeastern part of

Table 6. Parameters of the deep-sourced component A

Number in Table 1	Group of springs	Sample	X(A)	M(A), g/l	Ca _A , g/l	Ca _T , g/l	T(A), °C
1	2	3	4	5	6	7	8
9a	Dezhnev (m) ¹	90/02	0.65	11.4	2.651	1.723	105
9c		92/02	0.66	11.0	2.441	1.611	80
9b		91/02	0.64	11.3	2.630	1.683	93
		average		0.650	11.23		
1a	Chaplino (m) ¹	21/02	0.69	12.2	3.630	2.505	127
1d		24/02	0.68	11.6	3.610	2.455	115
1b		22/02	0.69	11.8	3.514	2.425	98
1c		23/02	0.68	10.1	3.610	2.455	99
	average		0.685	11.42			101
5a	Kukun	50/02	0.39	13.5	0.823	0.321	153
5c		51/02	0.36	11.1	0.722	0.260	141
5d		1a/04	0.36	13.0			158
5f		1/04	0.37			0.300	151
	average		0.37	12.53			150.7
4a	Kivak	40/02	0.07			0.721	
2a	Senyavin	30/02	0.78	1.9	0.118	0.092	100
2b		31/02	0.77	2.0	0.115	0.088	103
	average		0.775	1.95			101.5
3a	Arakamchechen	34/02	0.13	11.4	0.555	0.072	280
20a	Getlyangen	An-22(7i)/05	0.43	10.3	1.074	0.462 ²	98
19a	Sineveem	An-26(9i)/05	0.20		3.350	0.670 ²	213
18a	Verkhne-Nunyamoveem	An-27(8i)/05	0.43	4.0	0.647	0.278 ²	83
10a	Neshkan (m) ¹	3/04	0.85	37.5	4.000	3.400	61
14a	Oranzhevye (m) ¹	8/04	0.84	36.5	6.369	5.350	16
11a	Teyukei (m) ¹	4/04	0.79	13.1	2.152	1.700	7
13a	Vytkhytyaveem	7/04	0.23	14.7	1.200	0.276	274
12a	Kub	6/04	0.36	12.5	0.667	0.240	18
17b	Nel'pygenveem	An-13(1i)/05	0.50				2
17a		14/04	0.49	14.1	0.735	0.360	13
21a	Stupenchatye	An-21(5i)/05	0.77	9.5	1.870	1.440 ²	3
23a	Pechingtanvaam	An-6i/05	0.66	3.2	0.255	0.168 ²	
22a	Ioni	An-20(4i)/05	0.66	11.0	2.182	1.440 ²	7
16a	Arenyshkynvaam	12/04	0.59	14.1	1.000	0.590	20
16b		An-18(3i)/05	0.88				7
	average		0.735				13.5
7d	Babushkiny Ochki	2a/04	0.71				25
7c		71/02	0.75	12.2	1.272	0.954	18
7b		2/04	0.76	12.6	1.263	0.960	27
7e		72/02	0.83	11.2	1.123	0.932	17
7a		70/02	0.85	10.9	1.094	0.930	23
		average		0.780	11.7		
8b	Tumannye	81/02	0.76	4.5	0.142	0.108	72
8a		80/02	0.76				77
	average		0.760				74.5
6b	Mechigmen	62/02	0.58	7.1	0.186	0.108	110
6a		60/02	0.72	5.4	0.184	0.104	124
	average		0.650				117

Notes: ¹ Seawater was a presumable diluting agent.² After (Kievskii et al., 2006).

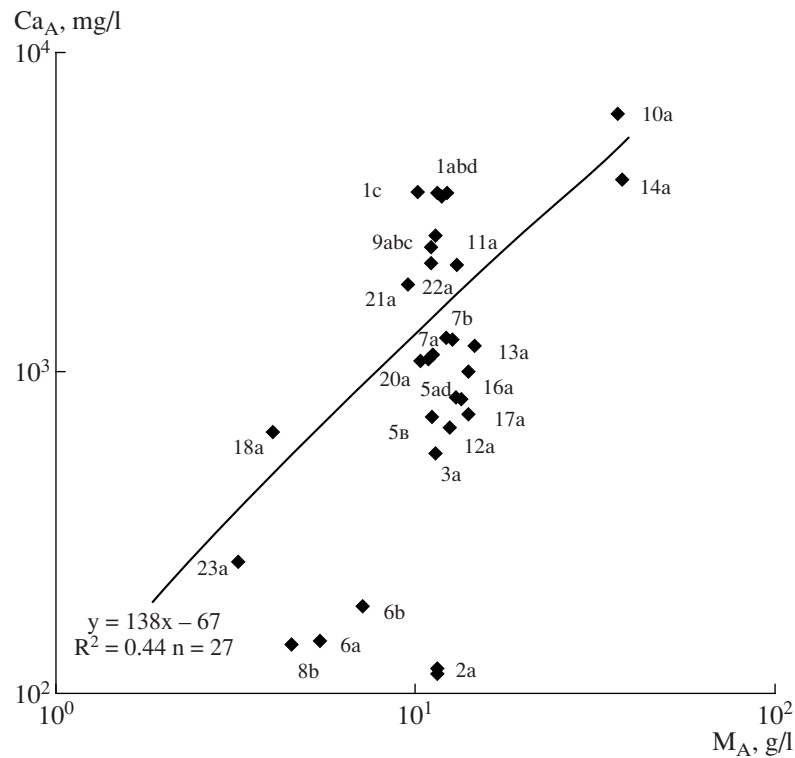


Fig. 12. Concentration of Ca ion and total mineralization of the deep-sourced component A in hydrothermal springs of Chukotka. Numerals of data points correspond to numbers in column 1 of Table 1.

the peninsula (Point 2) and closely spaced Mechigmen and Tumanye springs in the Kolyuchinskaya–Mechigmen Depression (points 6 and 8, respectively). The Senyavin hydrothermal springs, where the M_A value is minimal (<2 g/l), are completely isolated from the sea, although they discharge only ~ 1 km away from the shoreline and are characterized by the most deuterium-deficient (-24‰) waters among all springs of Chukotka relative to local fresh surface waters. At the same time, they are neighbors of the Chaplino and Arakamchechen springs (points 1 and 3), where M_A is estimated at ~ 11 g/l, which represents a background value for the Chukotka Peninsula. The nature of these Senyavin minimums and their spread remain unclear. Coincidence of anomalous values for different parameters of the Senyavin springs seems hardly incidental: the formation of these fresh, depleted in D and ^{18}O , and hot (79°C) waters may be related to disturbance of the subsurface hydrosphere by the deep thermal source.

Temperature of Component A

Based on X_A estimates, we also determined the temperature of component A. Such an approach is rather conditional, because assessment of T_A in a particular spring should take into account not only proportions of the mixed deep-sourced and cold surface waters, but also cooling degree of the deep-sourced water during its ascent.

In Fig. 13, data points of Chukotka thermomineral springs form two (upper and lower) fields. The upper field includes thermal springs located at the southeastern margin of the peninsula (Fig. 1, Table 1, points 1–5, 9, and 18–20), the Neshkan and Vytkhytyaveem springs at the northern margin (points 10 and 13, respectively), and the Mechigmen and Tumanye springs of the Kolyuchinskaya–Mechigmen zone (points 6 and 8, respectively). Such a distribution of data points implies similarity of conditions that determine the temperature of these hydrothermal solutions. They demonstrate quite natural positive correlation between the temperature of discharged waters ($T^\circ\text{C}$) and the share of component A (X_A): $T^\circ\text{C} = 56.55X_A + 31.216$ ($n = 16$; $R > 0.8 > R_{\text{crit}} = 0.497$).

This dependence reflects the geothermal specifics of different thermal springs, although does not allow exact assessment temperatures of the deep-sourced component and diluting agent. For example, the above regression equation implies that the temperature of the diluting agent (at $X_A = 0$) is close to 30°C . This value is substantially higher than the temperature of atmospheric precipitation infiltrating in rocks and is approximately equal to probable temperatures at a depth of 1.0–1.5 km under conditions of the background conductive heat flow (*Geotermicheskaya...*, 1972; *Teplovoi rezhim...*, 1970). According to this trend, the temperature of the deep-sourced component A (at $X_A = 100\%$) in hydrothermal springs of southeastern Chukotka should be

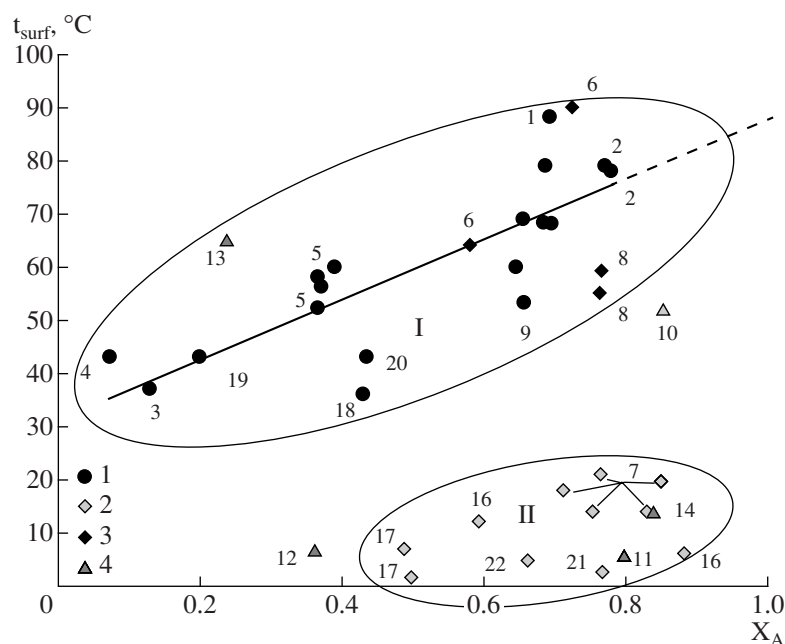


Fig. 13. Correlation between the temperature of discharged waters and the share of component A in them in various areas of Chukotka. (1–4) Data points of thermomineral springs in various areas of Chukotka (Fig. 1): (1) southeastern margin, (2) central areas, (3) Mechigmen and Tumannye springs, (4) northern margin. Ovals corresponds to fields of data points obtained for (I) central areas of Chukotka and (II) its southeastern margin. The straight line in oval I is a regression line for hydrothermal springs of southeastern Chukotka $\delta D = 56.55\delta^{18}O + 31.22$ ($R^2 = 0.65$, $n = 18$).

$<90^\circ\text{C}$, which is lower than the real values recorded in discharge areas of the hottest springs, such as the Mechigmen spring (97°C in one of the jets) and Chaplino (92°C in Borehole 23, according to (Suvorova, 1972)) springs, where $X_A \sim 60\text{--}70\%$. Temperature estimates obtained for separate samples seem more reliable. In six groups of thermomineral springs in southeastern Chukotka, the estimates vary from 83 to 150°C (average 106°C). In two other groups (Sineveem and Arakamchechen springs; points 19 and 3, respectively), the temperature of component A ranges from 213 to 280°C . Such values seem overestimated and require confirmation by other methods.

The lower field comprises data points obtained for the remaining thermomineral springs of the Kolyuchinskaya–Mechigmen zone (points 7, 16, 17, 21, and 22) and three springs located in the northernmost part of the peninsula (points 11, 12, and 14). Such distribution pattern implies similar (but different from those inherent to the southeastern areas of the peninsula) formation conditions of springs. These springs are characterized by substantially lower discharge temperatures ($<22^\circ\text{C}$). Visual correlation between the temperature of thermal waters and the share of the deep-sourced component in them is illusory, since $R < R_{\text{crit}}$. At the same time, data obtained for this selection apparently indicate that temperature of the diluting component (with $X_A = 0$) was close to 0°C and temperature of component A was low ($<30^\circ\text{C}$). In fact, this temperature most likely reflects a cooling effect of the ascending flow of component A

prior to its mixing with the diluting near-surface waters. Such a specific feature of thermal waters in the lower field is not quite clear. This may be related to a thicker cryolithozone in central areas of eastern Chukotka than in its coastal areas. The temperature specifics of these hydrothermal springs correlates with their minimal δD values (Fig. 8) and, correspondingly, maximal values of the hydrogen isotope shift $\Delta\delta D$ and share of the deep-sourced component X_A (up to 88%). Therefore, we can propose an alternative explanation of the trend in Selection 8 (Table 5): this flat trend $\delta D = 4.7684 \delta^{18}O - 50.2403$ likely reflects the mixing of component A with the melting H_2O delivered from the relatively deuterium- and ^{18}O -rich subsurface ice rather than (and, possibly, not only) the “oxygen isotope shift.”

All the aforesaid allows the following assumption: the deep-sourced component A represents a subpermafrost meteorogenic well-homogenized infiltration water that percolated in the interstitial–fissure space of rocks for a substantially long time and acquired a notable mineralization ($10\text{--}12$ g/l, on average). Its isotopic parameters are probably related to the fact that the meteorogenic feeding is dominated by snow waters rather than the summer (relatively enriched in deuterium and ^{18}O) atmospheric precipitation. In terms of its position in the hydrodynamic zoning of the geological section, component A corresponds most likely to the zone of relatively slow water exchange.

At the same time, we cannot say that issue of the formation of hydrothermal springs in the Chukotka Penin-

sula has been solved. Due to deficiency of borehole observations and, consequently, hydrogeological and cryological characteristics of the section, their specifics in different structural–tectonic settings of the peninsula remain unclear. Data on the distribution of cryopegs and their isotopic compositions are also missing. Therefore, it is rather difficult to judge about the role of cryopegs in the formation of thermomineral waters. Mechanism of the heat feeding of hydrothermal systems is also unclear. This aspect is particularly important in the context of probable use of the thermal energy potential of hydrothermal springs, a pressing issue for Chukotka. Finally, analysis of data on the total and isotopic compositions of the gaseous phase in thermomineral fluids, as well as correlation of these data with the chemical composition and temperature of discharged waters, wait special consideration.

CONCLUSIONS

Average annual temperature in the eastern Chukotka Peninsula with the universally developed cryolithozone is negative. Therefore, all springs discharging the year round in this region should be considered thermal springs. We studied thermomineral waters from 23 groups of such springs with the total mineralization ranging from 1.47 to 37.14 g/l and the discharge temperature ranging from 2 to 97°C. The results obtained were compared with the nearby surface freshwaters.

In surface waters, δD varies from -121.4 to -89.5‰ ; $\delta^{18}O$, from -16.4 to -11.1‰ . These values are consistent with variations in the isotopic composition of atmospheric precipitation at similar latitudes of Alaska. The δD and $\delta^{18}O$ values obtained for the surface waters decrease from the east to west, i.e., toward interior areas of the land.

In thermomineral waters, δD ranges from -134.2 to -92.5‰ ; $\delta^{18}O$ from -17.6 to -10.5‰ . Approximately in one-half of sampling localities, such waters are depleted in deuterium as compared with surface H_2O , indicating a contribution of the isotopically light component to their formation. Based on analysis of trends of data points obtained for the surface and thermomineral waters in the δD – $\delta^{18}O$ plot, we reconstructed the isotopic composition of the deep-sourced component A ($\delta D = \approx -138\text{‰}$ and $\delta^{18}O = \approx -19\text{‰}$) and estimated its share (X_A) in particular samples. Lateral distribution of δD in thermomineral waters shows that hydrothermal solutions with the minimal deuterium content ($\delta D < -120\text{‰}$) are confined to the Kolyuchinskaya–Mechigmen Depression that represents a zone of neotectonic activity. In addition, they differ from thermomineral waters discharging beyond the depression by relatively higher ^{18}O concentrations and other isotopic–geochemical properties (the gaseous phase composition, as well as $\delta^{13}C_{CO_2}$, $^3He/^4He$, and $\delta^{15}N$ values).

Based on the X_A values in particular thermomineral springs, we estimated the total mineralization of this component (M_A) with assumptions of different diluting agents. The M_A value ranges from 9.5 to 14.7 g/l (average ~ 12 g/l) in most springs studied over the entire Chukotka Peninsula. In five most mineralized coastal springs, seawater likely represents such a diluting component. In three of these five cases, estimates of M_A were also close to its regional average value. In two other groups of springs with mineralization of 37.16 and 36.23 g/l, seawater subjected to metamorphism (consequently, depletion in Mg and sulfates) and some concentration of most likely cryogenic nature serves as both the diluting agent and deep-sourced component A.

Temperature estimates obtained for component A are more conditional, because such estimates depend on the dilution degree of deep solutions by cold surface water and the cooling rate of ascending deep waters. Nevertheless, they indicate substantial regional differences in the thermal regime of springs.

Judging from isotopic characteristics and total mineralization, the deep-sourced component A represents a subpermafrost well-homogenized meteorogenic infiltration H_2O that percolated within the interstitial–fissure space of rocks for a relatively long time and acquired a notable mineralization. With respect to its position in the vertical hydrodynamic zoning of the geological section, component A likely corresponds to the zone with a relatively slow water exchange.

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