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Hydrogeochemistry of Pre-Jurassic Aquifers in West Siberia

D.A. Novikov[a,b, ✉], F.F. Dultsev[a], A.V. Chernykh[a], V.A. Khilko[a], I.I. Yurchik[a], A.F. Sukhorukova[a]

[a] *Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences, pr. Akademika Koptyuga 3, Novosibirsk, 630090, Russia*

[b] *Novosibirsk State University, ul. Pirogova 1, Novosibirsk, 630090, Russia*

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Abstract—For the first time in the last 35 years, hydrogeochemical data on pre-Jurassic complexes in West Siberia have been generalized. Groundwater and brines of Cl–Na and Cl–HCO_3–Na type with total salinity (TDS) varying from 4 to 330 g/L are found to be widespread in the area under study, with the former type dominating. A detailed analysis of the hydrogeochemical data allowed us to assume the presence of three genetic groups of groundwater and brines in the hydrogeologic section: (1) sedimentogenic, (2) lithogenic (revived) and ancient infiltrogenic, and (3) condensatogenic. An integrated analysis of coefficients rNa/rCl, Ca/Cl, (Br/Cl)·10^{-3}, and (Sr/Cl)·10^{-3} and integrated index S of brine metamorphization in the Siberian sedimentary basins has corroborated the fact that groundwater and brines in West Siberia are at the initial stage of metamorphization of their chemical composition. Groundwater and brines in the studied Siberian sedimentary basins show an increase in the degree of metamorphization (catagenetic changes) of their chemical composition in transition from the areas of igneous and metamorphic deposits at the base of the Meso–Cenozoic sedimentary cover of the young West Siberian sedimentary basin to the structures of the ancient Siberian Platform, where ultrastrong Ca–Na and Ca chloride brines are widespread.

Keywords: petroleum hydrogeochemistry; underground water; brines; degree of metamorphization; genetic type; Siberian sedimentary basins; West Siberia

INTRODUCTION

The late 1930s were marked by the discovery of oil- and gas-bearing potential of pre-Jurassic deposits in the marginal areas of the West Siberian artesian basin (WSAB). Previously, their prospects were interpreted as the most promising long before deploying the large-scale prospecting activity in what eventually has been recognized as the West Siberian petroleum province (WSPP). This point of view was advocated by many researchers: M.K. Korovin, N.A. Kudryavtsev, D.L. Stepanov, N.P. Tuaev, M.M. Charygin, and others. Later, however, when the Mesozoic interval proved to bear the major oil and gas potential, the interest in pre-Jurassic rock complexes had largely waned. With commencement of large-scale oil and gas prospecting activity targeting Jurassic and Cretaceous reservoir rocks in the WSPP back in 1960, many petroleum geologists (F.G. Gurari, V.N. Kazarinov, M.K. Kas'yanov, Yu.K. Mironov, I.I. Nesterov, L.I. Rovnin, N.N. Rostovtsev, M.Ya. Rudkevich, A.A. Trofimuk, Yu.G. Erv'e, and others) viewed the pre-Jurassic petroleum complexes as a reserve for future discoveries (Kontorovich et al., 1975; Bochkarev, 1977; Kontorovich and Stasova, 1977; Surkov and Zhero, 1981; Porfil'ev and Klochko, 1982). In recent years, given the high level of geological–geophysical exploration of the Mesozoic sedimentary cover, evidence of increasing interest in this target from subsoil users is supported by the discovery of more than 70 oil and gas fields within its boundaries (Maksimov et al., 1987; Fomin, 1994; Abrosimova and Ryzhkova, 1997).

The Fore-Yenisei zone of West Siberia, being presently of particular interest, is also known as the Fore-Yenisei sedimentary basin. Back in the 1930–1960s, researchers assumed the presence of buried structures of the Siberian Platform in the left-bank area of the Yenisei River (Nalivkin, 1933; Belousov, 1948; Fomichev, 1948; Kosygin and Luchitskii, 1960; Sokolov, 1960; Nakaryakov, 1961; Bogolepov, 1963; Yanshin, 1965). In the 1970s, A.E. Kontorovich, V.S. Surkov, and A.A. Trofimuk (Kontorovich et al., 1975) set their sights on evaluating oil and gas potential in this area, which later gained traction with many researchers and was amply discussed in the papers of V.A. Benenson, N.N. Dashkevich, V.A. Kashtanov, S.A. Stepanov (Dashkevich, 1985; Benenson et al., 1987; Dashkevich and Kashtanov, 1990; Dashkevich et al., 1992), and others. The most complete analyses of the existing views on the geologic and tectonic structure of this area are provided in the collaborative reviews written by A.E. Kontorovich, V.A. Kontorovich, Yu.F. Filippov, S.Yu. Belyaev, V.A. Kashtanov, A.V. Khomenko, and others (Kontorovich and Kontorovich, 2006; Kontorovich et al., 2006; Filippov, 2016, 2017).

✉ Corresponding author.
E-mail address: NovikovDA@ipgg.sbras.ru (D.A. Novikov)

Note that both the hydrogeology and hydrogeochemistry of the West Siberian pre-Jurassic reservoir rocks still remain poorly investigated. The most comprehensive overview by N.M. Kruglikov, V.V. Nelyubin, and O.N. Yakovlev, which provided schematic data on pre-Jurassic rocks of the WSAB, dates back to 1985 (Kruglikov et al., 1985). Later, the teams of researchers from Moscow, Novosibirsk, Tyumen, Tomsk, and in a far greater extent the ones representing the Siberian school of hydrogeochemistry (V.M. Matusevich, A.A. Kartsev, S.L. Shvartsev, N.P. Zapivalov, A.R. Kurchikov, D.A. Novikov, and others) highlighted some aspects of hydrogeology and hydrogeochemistry of the pre-Jurassic complexes in several regions of the WSAB (the Fore-Ural petroleum-bearing region, southern areas of the Yamal Peninsula, Nadym–Taz interfluve, Fore-Yenisei petroleum subprovince, and others) in their works (Shvartsev and Novikov, 2004; Novikov, 2005, 2015, 2017a, 2018a–c; Novikov and Lepokurov, 2005; Zapivalov and Bogatyreva, 2005; Novikov and Shvartsev, 2009; Zakharov and Novikov, 2010; Matusevich et al., 2011; Matusevich and Abdrashitova, 2013, 2014; Novikov and Sukhorukova, 2015; Dultsev and Novikov, 2017, 2018; Dultsev et al., 2018; Novikov et al., 2018a,b; 2020a,b). In this context, new hydrogeological and hydrogeochemical data and overviews on the pre-Jurassic complexes within the WSAB are of genuine scientific interest in the light of development of hydrogeological criteria for their oil and gas potential.

FACTUAL EVIDENCE AND RESEARCH METHOD

Pre-Jurassic deposits have been studied from more than 800 wells drilled in West Siberia, while the northern parts of the WSAB remain largely underexplored. The pre-Jurassic reservoir complexes are represented by sedimentary and volcanic rocks. Paleontologic finds in the basement rocks are quite rare across most of the sedimentary basin area, and many are poorly preserved. The K–Ar dating method was used for determinations of the absolute age of either volcanic rocks or their significant admixture in sediments (Bochkarev and Pogorelov, 1973; Kontorovich et al., 1975; Surkov and Zhero, 1981; Bochkarev and Krinochkin, 1988). The maximum thickness of Paleozoic sediments studied by drilling (in the north of the study area) reaches 3–3.5 km. The basin structure is characterized by south–north trending subsidence along the axial part, so that the basement subsidence depth is 3–5 km in the central part and reaches 6–9 km in the north. Importantly, rocks cropping out onto the pre-Jurassic surface are varied both in the lithologic composition and age. The sediments composing the pre-Jurassic basement of the WSAB, which were studied by deep drilling, are divided into three types of rock associations: sedimentary (29%), igneous, and metamorphic (71% in total). The complexity of the geologic settings of the pre-Jurassic complexes of the WSAB manifested itself in the hydrogeochemical characteristics of groundwater having different salinity and composition, dictated by the composition of the rock matrix (Novikov, 2005; Novikov and Shvartsev, 2009; Novikov and Sukhorukova, 2015; Novikov et al., 2018a; Dultsev, 2019).

A detailed analysis of structural styles of the pre-Jurassic rock complexes, which included the aquifer material composition and dating of the host rocks, was based on the paleontological data, well log interpretation charts, and results of well test and hydrogeochemical testing of wells. This enabled the first ever correlation of the available hydrogeochemical data with the eight aquifer complexes based on the analyzed samples (with indication of their quantity): (1) Vendian (13); (2) Cambrian (116); (3) Ordovician (56); (4) Silurian (32); (5) Devonian (143); (6) Carboniferous (62); (7) Triassic deposits (22), and (8) oil- and gas-bearing horizon in the contact zone (65 samples) (Tables 1, 2).

In this paper, all hydrogeochemical evidence available for the central and southern regions of the WSAB was analyzed in detail. Hydrogeochemistry of the pre-Jurassic reservoir complexes was described using the most recent and complete data obtained under the guidance of Academician A.E. Kontorovich for the Fore-Yenisei sedimentary basin, underpinned by the parametric drilling data within the scope of the Vostok project. The comparative analysis of the degree of brine metamorphization involved hydrogeochemical data on the adjacent areas of the Siberian Platform (189 samples) and the Nordvik salt domes of the Anabar–Khatanga basin (97 samples). The electronic database compiled for this research is represented by records of 795 samples of groundwater and brines.

To compare the degree of metamorphization, we used an integrated index *S* of brine metamorphization (after S.L. Shvartsev (2000)), which is applicable to similar research on regions showing the presence of brines in the hydrogeologic cross section. The degree of metamorphization of groundwater and brines is largely determined by the relationships of Ca/Cl, $(Br/Cl)\cdot 10^{-3}$, and $(Sr/Cl)\cdot 10^{-3}$, inasmuch as the phenomenon of metamorphization of groundwater and brines is the most pronounced as increased interaction (following their burial) with Ca, Sr, and Br contained in the host rocks.

RESULTS AND DISCUSSION

Specific characteristics of the chemical composition of groundwater and brines

Groundwater and brines in pre-Jurassic sediments of West Siberia generally have total salinity (TDS) varying from 1.4 to 209.3 g/L and are of sodium chloride type (after Samarina, 1977) (Fig. 1). The hydrogeochemistry of groundwater appears to be the least studied in the northern part of West Siberia, where their salinity in pre-Jurassic sediments is commonly cited as 15–20 g/L. Thus, waters of Cl-HCO_3-Na type with a TDS value as low as 12 g/L were revealed at

Table 1. Hydrogeochemical characteristics of pre-Jurassic complexes of West Siberia

Element	Measurement unit	Aquifers							
		Oil-/gas-bearing horizon in contact zone	T	C	D	S	O	Є	V
HCO_3^-	mg/L	36.6–1311.9 (650.4)	18.3–2391.0 (816.0)	91.5–1866.0 (642.1)	55.0–2391.0 (631.5)	122.0–2208.0 (952.3.)	122.0–2965.0 (1053.8)	12.3–976.3 (371.0)	73.0–432.0 (263.1)
SO_4^{2-}	mg/L	0.4–625.0 (94.6)	4.0–504.9 (162.5)	1.2–930.4 (94.2)	0.8–2456.0 (187.9)	1.2–671.0 (93.9)	1.6–295.0 (52.9)	7.0–2664.0 (200.1)	42.5–163.0 (78.6)
Cl^-	g/L	1.2–55.3 (27.4)	0.4–30.1 (10.2)	0.1–48.3 (23.0)	2.7–52.4 (22.1)	1.5–17.6 (8.7)	0.8–24.4 (6.8)	7.5–12.7 (42.8)	34.9–55.1 (48.3)
Br^-	mg/L	8.6–255.2 (109.1)	1.6–190.5 (51.7)	4.9–186.5 (73.9)	2.1–212.8 (76.7)	5.9–89.7 (40.5)	3.6–106.2 (35.7)	8.0–480.0 (161.5)	190.0–237.1 (210.9)
I^-	mg/L	0.2–28.3 (10.3)	1.7–56.0 (13.8)	0.7–37.0 (6.8)	0.5–32.9 (8.4)	0.8–30.4 (11.5)	0.4–20.1 (7.1)	0.03–11.37 (3.38)	0.8–5.9 (2.9)
F^-	mg/L	0.1–110.0 (13.2)	–	0.3–1.6 (1.1)	0.2–120.0 (21.4)	–	–	0.1–2.3 (0.8)	0.8–5.4 (3.9)
Na^+	g/L	1.2–32.7 (15.7)	0.5–17.1 (0.6)	0.8–26.1 (13.1)	2.4–31.0 (12.7)	1.1–11.1 (5.6)	0.6–15.0 (4.5)	2.1–62.6 (21.9)	17.6–35.8 (24.8)
Ca^{2+}	g/L	0.04–3.27 (1.45)	0.01–2.56 (0.47)	0.02–4.21 (1.53)	0.03–4.35 (1.27)	0.01–0.74 (0.30)	0.01–2.27 (0.24)	0.05–12.80 (3.65)	2.8–5.4 (3.8)
Mg^{2+}	g/L	0.04–0.53 (0.19)	0.002–0.295 (0.057)	0.004–0.461 (0.153)	0.003–0.949 (0.187)	0.001–0.261 (0.061)	0.001–0.184 (0.031)	0.03–2.20 (0.56)	0.5–0.8 (0.7)
K^+	g/L	0.2–8.6 (3.7)	0.004–0.347 (0.157)	0.01–1.96 (1.12)	82.0–13.9 (2.1)	0.02–0.24 (0.07)	0.01–0.17 (0.09)	0.1–26.4 (8.7)	0.3–0.6 (0.4)
Sr^{2+}	mg/L	3.5–1350.0 (391.9)	–	71.5–625.0 (451.9)	1.4–795.0 (245.3)	–	–	11.2–622.0 (302.4)	224.0–412.6 (344.7)
Li^+	mg/L	1.5–18.8 (6.3)	–	1.9–7.1 (5.4)	0.04–12.90 (4.10)	–	–	1.1–6.4 (3.2)	1.8–6.7 (3.3)
Rb^+	mg/L	0.2–1.3 (0.6)	–	0.2–1.0 (0.7)	0.0.5–1.52 (0.75)	–	–	0.3–1.3 (0.4)	0.55–0.71 (0.65)
Cs^+	mg/L	0.1	–	–	–	–	–	0.10–0.11 (0.10)–	0.1–4.9 (0.8)
Zn^{2+}	mg/L	0.2	–	0.9–2.9 (2.2)	0.03–7.80 (1.48)	–	–	–	2.3–54.9 (21.7)
Mn^{2+}	mg/L	0.1–4.3 (1.7)	–	1.4–2.9 (1.9)	0.03–9.85 (2.86)	–	–	1.0–6.9 (2.7)	0.6–3.5 (2.2)
NH_4^+	mg/L	4.5–250.0 (87.9)	60	23.0–240.0 (98.9)	0.1–300.0 (77.2)	–	–	0.2–160.0 (72.7)	–
SiO_2	mg/L	1.5–500.0 (51.3)	76	14.0–84.0 (35.7)	0.2–300.0 (38.0)	–	–	0.3–40.0 (16.3)	5.4–26.8 (10.5)
B^+	mg/L	5.4–100.0 (23.5)	–	3.2–38.0 (12.9)	0.5–50.0 (10.1)	1.9–26.7 (12.9)	0.6–42.6 (13.9)	3.6–93.5 (17.1)	7.9–10.7 (9.4)
M	g/L	3.8–90.9 (46.5)	1.4–52.9	2.5–82.2 (38.6)	6.7–86.6 (38.0)	3.0–29.3 (15.2)	1.8–40.7 (12.8)	13.0–209.3 (70.4)	57.7–97.3 (78.0)
*r*Na/*r*Cl	fractions	0.61–1.71 (0.90)	0.83–1.67 (1.04)	0.75–1.43 (0.93)	0.42–1.62 (0.90)	0.87–1.45 (1.05)	0.80–1.51 (1.07)	0.4–1.30 (0.80)	0.71–1.00 (0.79)
Cl/Br	fractions	131–508 (279)	104–397 (228)	123–951 (338)	37–803 (301)	133–551 (253)	83–932 (205)	81–940 (303)	148–267 (236)
Ca/Cl	fractions	0.01–0.10 (0.05)	0.02–0.09 (0.04)	0.01–0.10 (0.06)	0.01–0.13 (0.06)	0.01–0.16 (0.04)	0.01–0.10 (0.03)	0.01–0.18 (0.08)	0.07–0.10 (0.08)
$(Sr/Cl)\cdot10^{-3}$	fractions	0.3–88.5 (16.3)	–	2.5–23.7 (14.8)	0.1–19.9 (8.4)	–	–	0.2–11.9 (7.7)	6.1–7.9 (7.1)
$(Br/Cl)\cdot10^{-3}$	fractions	19.0–72.2 (6.1)	3.1–9.6 (5.1)	0.6–7.5 (3.4)	0.2–27.0 (3.8)	1.8–7.5 (4.5)	0.2–11.9 (5.8)	0.3–12.3 (3.9)	3.7–6.8 (4.4)
S	fractions	109–676 (238)	–	65–377 (261)	21–305	–	–	52–228 (163)	138–173 (156)
Chemical composition of waters (after S.A. Shchukarev)		Cl–Na	Cl–Na, Cl–HCO_3–Na	Cl–Na	Cl–Na	Cl–Na, Cl–HCO_3–Na	Cl–Na, Cl–HCO_3–Na	Cl–Na	Cl–Na
Number of analyses	pcs.	65	22	62	143	32	56	116	13

Note. Dash means "no data available". The number in parentheses is the average.

Table 2. Type analyses of groundwater and brines in pre-Jurassic complexes of West Siberia

Area, well No.	Interval, m	pH	Elements, mg/L										*M*, g/L
			Cl	HCO_3	SO_4	Na + K	Ca	Mg	Br	SiO_2	I	B	
Oil- and gas-bearing horizon of the contact zone													
Puglalymskaya, 86	2630–2690	8.0	5532	610	254	3515	249	73	15.2	–	–	2	10.2
Kvartovaya, 3	3000–2986	6.6	6430	915	393	4477	168	19	19.2	54	2	3	11.9
Kalinovaya, 9	3006–3057	8.2	19,941	1220	16	10,000	872	158	79.8	500	–	3	33.7
Ostaninskaya, 436	2740–2772	6.3	33,507	189	–	16,000	2244	199	161.6	10	–	16	54.9
Nizhnetabaganskaya, 1	2995–3005	6.0	35,705	567	–	14,040	1499	457	156.5	36	20	19	60.3
Gerasimovskaya, 2	2892–2924	6.4	36,565	793	–	18,800	2400	222	173.0	5	15	13	61.1
Triassic complex													
Inzhegorskaya, 155	2588–2611	8.1	6737	1232	30	4210	320	24	20.6	–	20	2	12.7
Maloatlymskaya, 1	2799–2804	8.4	8597	427	320	5682	193	24	30.4	–	6	3	15.3
Lyantorskaya, 17	2962–3200	6.4	8636	964	–	5653	172	29	29.6	–	11	6	15.5
Chvorovaya, 3	3252–3270	7.5	12,054	18	505	8340	40	–	30.3	–		3	21.4
Zapadno-Kalgachskaya, 1	2153–2238	6.2	29,917	357	–	16,036	2565	296	118.6	–	9	8	49.2
Carboniferous complex													
Nikol'skaya, 1	3273–3284	6.8	4661	794	10	2695	444	49	4.9	–	5	–	8.7
Novoportovskaya, 218	3002–3404	7.4	3546	1866	17	3200	22	13	9.9	–	17	4	9.0
Verkhnekombarskaya, 291	2790–2902	8.2	10,992	823	8	6759	337	151	35.8	–	6	2	18.6
Sel'veikinskaya, 2	3116–3159	7.3	36,588	519	–	20,610	2571	185	182.0	24	–	37	60.2
Verkhnekombarskaya, 293	2794–2799	6.8	44,245	763	–	23,995	385	306	179.1	36	–	36	72.8
Devonian complex													
Ellei-Igaiskaya, 2	4165–4180	7.5	12070	683	826	8519	560	–	25.0	13	1	2	23.2
Severo-Orekhovskaya, 560	3050–3167	7.4	28,368	305	6	15,334	2615	79	107.0	–	8	8	46.9
Zapadno-Luginetskaya, 183	2708–2727	5.9	39,050	488	39	18,700	2160	504	168.5	16	–	12	60.7
Gerasimovskaya, 2	2980–2997	6.4	39,405	793	–	18,800	2520	510	175.6	–	25	13	65.7
Kalinovaya, 1	2849–2860	5.8	44,505	757	1	12,000	2180	302	155.2	–	–	15	73.4
Silurian complex													
Novoportovskaya, 210	3240–3248	7.0	3612	1964	88	2900	40	17	11.9	–	18	3	8.8
Novoportovskaya, 91	2720–2736	6.4	4468	1708	12	3636	26	10	13.3	–	12	4	10.0
Vikulovskaya, 1	1940–2049	6.8	11,540	665	2	6506	681	182	36.0	–	18	9	12.7
Var'eganskaya, 99	3455–3608	8.6	8333	207	132	5290	174	2	15.1	–	2	3	14.2
Kulaiskaya, 1	2350–2436	6.4	13,490	1068	10	8389	597	26	53.3	–	15	5	23.8
Ordovician complex													
Yuzhnaya, 402	2635–2652	8.1	4964	891	–	3500	120	13	8.6	–	2	3	9.5
Talinskaya, 110	2387–2441	8.2	8936	1037	123	5968	136	11	9.6	–	13	3	16.4
Em-Egovskaya, 126	2576–2584	8.2	10,990	2965	33	7691	382	6	72.3	–	16	20	22.3
Talinskaya, 123	2462–2474	8.0	13,652	610	–	7114	1000	97	33.0	–	1	5	23.0
Nyarginskaya, 1	2660–2768	7.4	14,183	976	62	8392	842	122	87.0	–	8	2	24.1
Cambrian complex													
Vezdekhodnaya, 2	3152–3204	6.4	31,344	409	16	16,241	286	516	81.5	12	2	8	51.2
Vezdekhodnaya, 4	3442–3564	6.8	31,047	329	37	21,000	2670	433	117.9	6	5	2	57.8
Vezdekhodnaya, 3	3515–3563	8.1	50,500	244	35	23,900	4168	657	283.3	–	–	3	82.3
Vostok, 4	3520–3532	6.7	49,700	29	2070	27,020	3800	840	210.0	–	24	–	84.2
Vostok, 4	4993–5036	6.6	126,913	220	698	62,576	12,800	1800	430.0	–	94	–	209.3
Vendian complex													
Vostok, 3	4552–4656	6.4	36,920	432	127	17,600	3100	600	200.0	11	–	1	58.7
Vostok, 3	4190–4200	6.3	50,320	342	–	23,250	3351	597	190.0	27	–	6	69.1
Vostok, 3	4956–4962	6.4	52,520	305	50	25,500	4500	780	237.1	10	–	1	83.7
Vostok, 3	4673–4683	6.1	51,480	323	–	27,250	5393	615	192.5	9	–	4	85.4
Vostok, 3	4720–4734	5.6	54,200	177	–	28,750	3536	630	205.0	6	–	4	89.8

Note. Dash means "no data available".

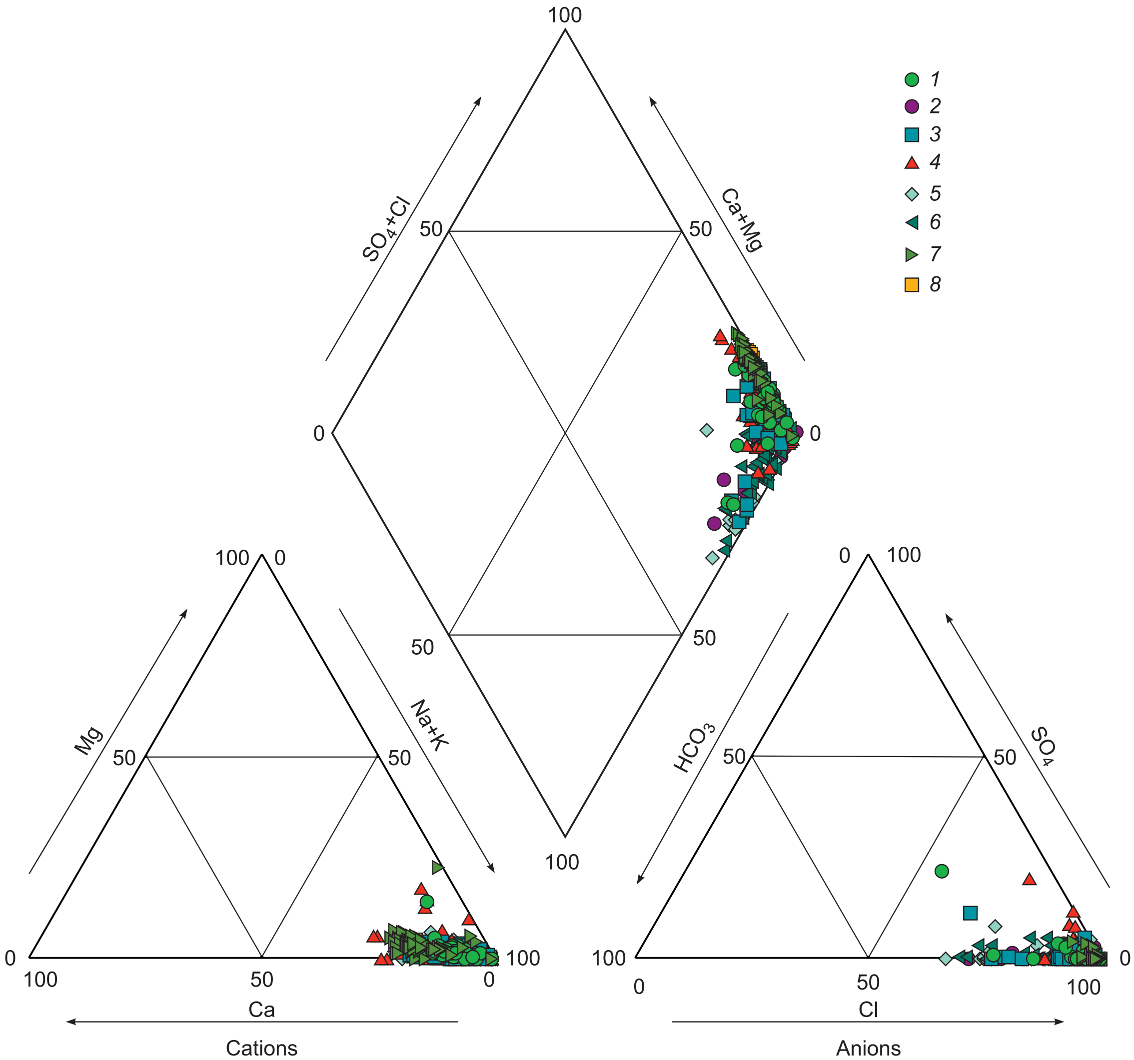

Fig. 1. Piper plot for the chemical composition of groundwater and brines in pre-Jurassic complexes of West Siberia. Aquifer complex: *1*, oil- and gas-bearing horizon of the contact zone; *2*, Triassic; *3*, Carboniferous; *4*, Devonian; *5*, Silurian; *6*, Ordovician; *7*, Cambrian; *8*, Vendian.

the Novoportovskoe oil–gas condensate field located on the southeastern Yamal Peninsula (Novikov, 2005).

From the hydrogeological standpoint, the oldest deposits within the WSAB are of Vendian age, being thus far the best studied in the Fore-Yenisei sedimentary basin from the drilling data (Vostok-3 well). Weak brines of *the Vendian aquifer complex* are of sodium chloride type, with TDS varying from 57.7 (4552–4656 m depth) to 97.7 g/L (4895–4903 m) (Novikov and Shvartsev, 2009). The microcomponent composition of the studied brines is characterized by the high contents of bromine (up to 237.1 g/L), strontium (up to 412.6 g/L), and zinc (up to 54.9 g/L), while the other components (I, Li, Rb, Cs, Mn, B, and F) are present in minor amounts (Table 1).

Waters of sodium chloride type in the Cambrian aquifer are characterized by higher salinity, varying in the range from 13.3 (2234–2244 m interval, well No. 1, North Lymbel'skaya area) to 209.3 g/L (Vostok-4 well, 4993–5036 m). The microcomponent composition is largely dominated by boron (up to 93.5 mg/L), ammonium (up to 160 mg/L), and strontium (up to 622 mg/L) (Table 1). The TDS values tend to increase toward the west (the Em-Egovskaya area) and southeast (Vezdekhodnaya area), while their decrease is observed toward the northeast.

In *the Ordovician aquifer*, sodium chloride waters have salinity that varies from 1.8 (2619–2636 m, Talinskaya-144 well) to 40.7 g/L (2598–3080 m, Yuzhnaya-396 well), averaging 12.8 g/L (Table 1). The waters with the highest salinity typify the central part of the basin, with a decrease in TDS values trending northward and westward.

The chloride and sodium bicarbonate chloride groundwater of *the Silurian aquifer* is characterized by salinity from 3.0 (1794–1800 m, Mendeleevskaya-2 well) to 29.3 g/L (1779–1786 m, Karabashskaya-5 well), with TDS values averaging 15.2 g/L (Table 1). The waters with the highest salinity are found in the southern and western parts of the basin, with the exception of the Mendeleevskaya area. A decrease in the TDS values is observed in the northern direction, toward the wells drilled within the Novoportovskaya area.

Groundwater and weakly saline brines in *the Devonian aquifer* have a high sodium chloride content and TDS varying in a wide range: from 6.7 (Novoportovskaya-217 well, 3046–3101 m) to 86.6 g/L (Verkh-Tarskaya-3 well, 2692–2704 m), averaging 38.0 g/L. Among the microcomponents, the concentrations of strontium (up to 795 mg/L), ammonium, and silica (up to 300 mg/L) are prevailing, while the contents of other microcomponents generally do not exceed several tens of mg/L, except for boron (up to 50 mg/L) and lithium (up to 12.9 mg/L) (Table 1). The most saline brines are confined to the WSAB center, whereas the TDS values decrease toward the basin boundaries.

The groundwater of *the Carboniferous aquifer* is of sodium chloride type, with its TDS values varying from 2.5 (2673–2864 m, Novoportovskaya-102 well) to 82.2 g/L (2765–2788 m, Verkhnekombarskaya-293 well), averaging 38.6 g/L. The microcomponent composition is overwhelmingly dominated by ammonium (up to 240 mg/L) and strontium (up to 625 mg/L); the lowest concentrations are reported for rubidium, zinc, manganese, and lithium (Table 1). The WSAB groundwater salinity levels are found to be the highest in the northwestern and southeastern regions, and the lowest levels are observed in the northern and southern parts.

The Permian aquifer within the WSAB area is very limited in areal extent (which largely accounts for the erosion processes taking place from Late Carboniferous through Early Triassic) and has thus far been largely underexplored from a hydrogeochemical perspective.

The groundwater of the *Triassic complex* is predominantly of chloride and sodium bicarbonate–chloride composition, with TDS varying from 1.4 g/L (Talinskaya-963 well, depth 2390–2517 m) to 52.9 g/L (Galyanovskaya-2 well, depth 2623–2922 m) (Table 1). An increase in TDS values along the lateral occurs from the WSAB western margin toward the southeast.

The *oil- and gas-bearing horizon confined to the contact zone* is dominated by sodium chloride groundwater and low-salinity brines with TDS varying widely from 3.8 (2773–2787 m, well No. 438 in the Ostaninskaya area) to 90.9 g/L (1733–1791 m, Chachanskaya-2 well), averaging 46.5 g/L. In the microcomponent composition, the highest concentrations were reported for strontium (up to 1350 mg/L), silica (up to 500 mg/L), ammonium (up to 250 mg/L), and boron (up to 100 mg/L) (Table 1).

The observed explicably increasing trend in the concentrations of major macro- and microcomponents concomitantly with an increase in the salinity of groundwater typifies all the pre-Jurassic reservoir complexes. Thus, Na^+ and Cl^- dominating among cations and anions, reach 63 and 127 g/L, respectively. The amounts of macrocomponents Ca^{2+} (12.8 g/L), Mg^{2+} (2.2 g/L), SO_4^{2-} (0.5 g/L), HCO_3^- (3.0 g/L) are ranked as minor. The concentrations of the main microcomponents vary widely for I (0.2–56.0 mg/L), Br (1.6–480 mg/L), B (0.5–100 mg/L), F (0.1–14.4 mg/L), SiO_2 (0.2–500 mg/L), and NH_4 (0.1–300 mg/L). The background waters of the pre-Jurassic complexes are generally sodium chloride with TDS averaging 40–50 g/L, while the concentrations of the components listed below are found within the values in the parentheses: HCO_3^- (700 mg/L), SO_4^{2-} (55 mg/L), Na^+ (14.8 g/L), I^- (10.0 mg/L), Br (110.6 mg/L), etc.

The hydrogeochemical anomalies in the amounts of microcomponents (mg/L) revealed and contoured within the pre-Jurassic rock complexes (Fig. 2) are as follows: (1) I >12; (2) Br > 120; (3) B > 60; and (4) NH_4 >100. Most anomalies are confined to geologic structures with the discovered accumulations of hydrocarbons. These anomalies were previously investigated in the study of the aqueous dispersion halos of hydrocarbon deposits (Novikov, 2005; Zakharov and Novikov, 2010; Novikov et al., 2018a; Chernykh, 2019). Thus, among the "traditional" microcomponents, the highest concentrations of iodine were reported from the following areas: Galyanovskaya (42.3–49.9 mg/L; well No. 2; depth 2623–2922 m), Lyantorskaya (56.0 mg/L; well No. 17; depth 2874–2893 m), Verkhne-Kombarskaya (36.4 mg/L; well No. 293; depth 2794–2799 m), and Sel'veikinskaya (37.0 mg/L; well No. 2; depth 3116–3159 m). Anomalous concentrations of bromine (>120 mg/L) were detected within the Krasnoleninsk arch (Krasnoleninskaya and Galyanovskaya areas), the Ob–Irtysh interfluve (Verkhnekombarskaya, Gerasimovskaya, Zarechnaya, Maloichskaya, and other areas), and the Fore-Yenisei sedimentary basin (Vezdekhodnaya, Kalinovaya, and other areas). Anomalous amounts of boron (>60 mg/L) are characteristic of brines from the Ostaninskaya and North Ostaninskaya areas and Vostok-4 well. Ammonium concentrations (>100 mg/L) were established in as many as 14 areas in the southern part of the WSAB (Rechnaya, Verkhnekombarskaya, Gerasimovskaya, etc.). Hydrogeochemical anomalies of complex nature with respect to rubidium (>1 mg/L), lithium (>7 mg/L), strontium (>450 mg/L), zinc (>2 mg/L), and manganese (>2 mg/L) are confined to the southern and southeastern regions of West Siberia. The zone of enhanced concentrations includes brines from several hydrocarbon fields (Tambaevskoe, Gerasimovskoe, South Tambaevskoe, Urmanskoe, Archinskoe, Severo-Kalinovoe, and Nizhnetabaganskoe) from the Chuzik–Chizhapka oil and gas accumulation zone and the Fore-Yenisei sedimentary basin. Silica (or silicon dioxide) is one of the key compounds controlling the water–rock interactions (Shvartzev, 1991). We found earlier that its concentrations in excess of 60–80 mg/L in the catagenesis zone lead to groundwater saturation with respect to albite and even microcline (Novikov, 2016, 2019; Novikov et al., 2019). In the study area, anomalously high concentrations of SiO_2 (over 100 mg/L) were detected in the Urmanskaya, Kalinovaya, Nizhnetabaganskaya, Tabaganskaya, Severo-Kalinovaya, and Severo-Ostaninskaya areas. Thus, the WSAB is dominated by sodium chloride brines with TDS as high as 50–70 g/L. This can be

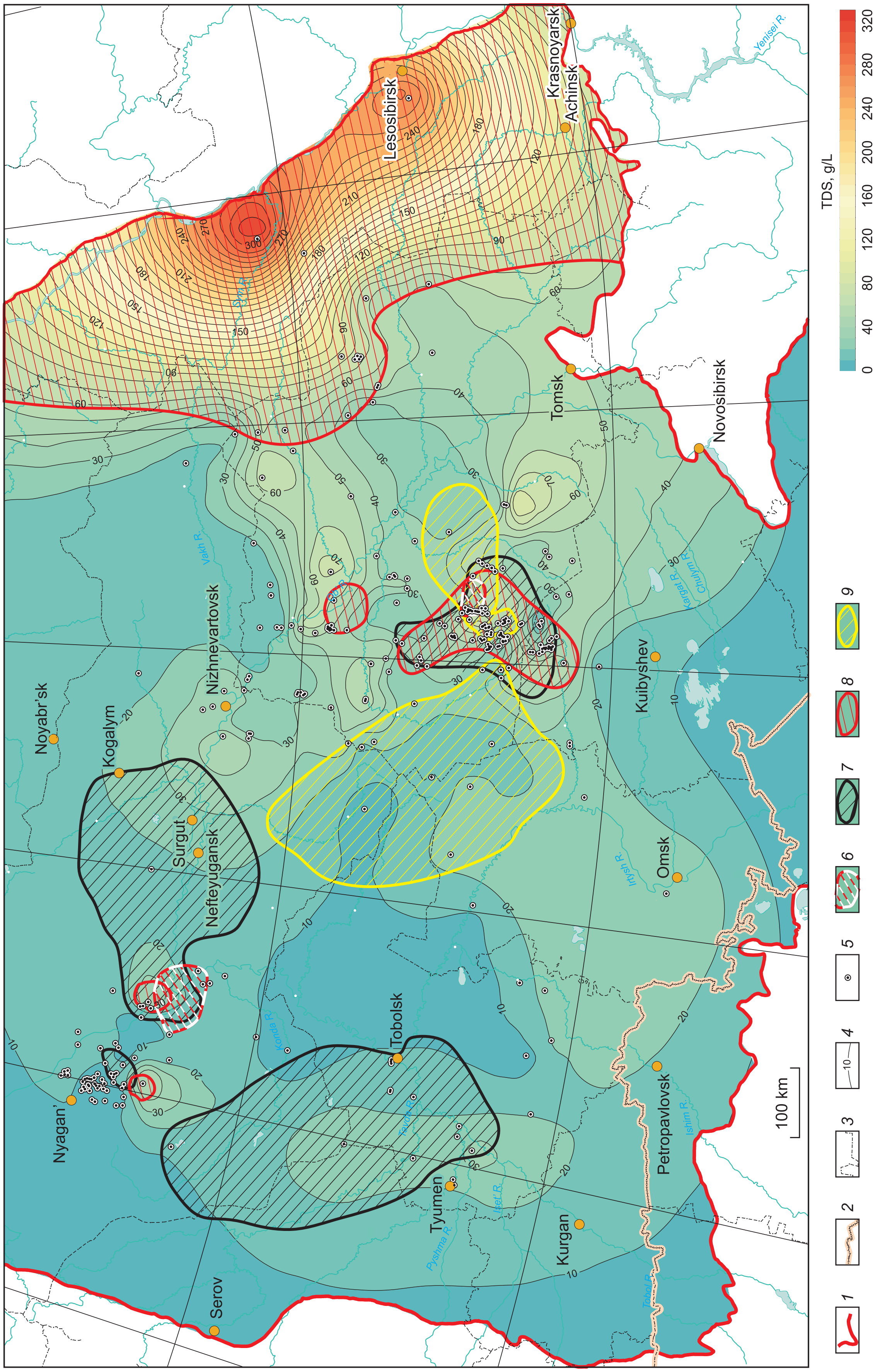

Fig. 2. Map of groundwater salinity and hydrogeochemical anomalies in pre-Jurassic complexes of West Siberia. Boundaries: *1*, West Siberian sedimentary basin; *2*, state borders; *3*, administrative borders; *4*, isosalinity contour lines of groundwater and brines, g/L; *5*, deep wells. Hydrogeochemical anomalies in content (mg/L): *8*, B >60; *9*, I >12; *10*, Br >120; *11*, NH_4 >100.

accounted for the absence of halogen-rich sediments in the geologic section, which occur widely in the adjacent areas of the ancient Siberian Platform, where their thickness often reaches 400 m and more (Novikov, 2017b).

Genetic types of groundwater and brines. Identifying the origin of groundwater is one of the key issues in modern hydrogeochemistry. Since the beginning of the last century, several classification schemes of the genetic types of groundwater and brines in the sedimentary basins have been proposed (V.A. Sulin, A.A. Kartsev, E.V. Pinneker, S.L. Shvartsev, and others) and advantageously applied to hydrogeological studies. According to the classical works of S.A. Shchukarev, V.A. Sulin, N.M. Kruglikov, A.A. Rozin, Ya.A. Khodzhakuliev, S.B. Vagin, A.A. Kartsev, M.I. Subbota, V.V. Nelyubin, O.N. Yakovlev, V.M. Matusevich (Sulin, 1947; Kartsev, 1972; Pinneker, 1979; Shvartsev, 1996), the genetic type of waters can be preliminarily established using the so-called genetic coefficients reflecting the relationships between different macro- and microcomponents in their composition: rNa/rCl, Cl/Br, Ca/Cl, $r(HCO_3 + CO_3)/r(Ca + Mg)$, B/Br, (Br/Cl)·$10^{-3}$, (Sr/Cl)·$10^{-3}$, rNa/(rCa + rMg), rNa + rMg/rCa, rCa/rMg, rSO_4·100/rCl, $rHCO_3$·100/rCl, Br·10^3/M, I·10^3/M, NH_4·10^3/M, Br/I, HCO_3/SO_4, (M/H)·100, (rCa/rNa)·100, etc. (Kruglikov et al., 1985; Shvartsev, 2000; Shvartsev and Novikov, 2004; Novikov, 2005; Novikov and Lepokurov, 2005; Novikov and Shvartsev, 2009; Novikov and Sukhorukova, 2015; Novikov, 2017a, 2018a).

Attempts at developing the genetic classification of groundwater have been made by many scholars, in particular Eduard Suess, R.A. Daly, A.A. Kozyrev, G.N. Kamenskii, N.I. Tolstikhin, A.M. Ovchinnikov, E.T. Degens, H. Schoeller, A.A. Kartsev, D.E. White, E.V. Pinneker, and others (Kamenskii, 1947; White, 1971; Pinneker, 1979; Kartsev et al., 1986; Kartsev, 1992; Zekster and Dzhamalov, 2007). Previously, G.N. Kamenskii (1947) identified three genetic cycles of groundwater: (1) infiltration, or continental, associated with infiltration of atmospheric water and a complex of geochemical processes occurring in the uppermost crust; (2) marine, or sedimentational, associated with the burial of marine waters during sedimentation and their deeper metamorphization; (3) metamorphic, or magmatic, type is associated with the formation of deep groundwater. Since it has thus far been almost impossible to distinguish between magmatic and metamorphic waters, it would be only logical to unite the two cycles into one, metamorphic–magmatic. Material manifestations of any of these cycles cannot always be isolated in the pure form because of their interaction resulting in mixed genetic types of groundwater. Displacement of sedimentogenic waters by infiltrogenic waters can serve as an example of such interactions between the cycles (Shvartsev, 1982). Note that the genetic types of waters distinguished in many classifications include metamorphic, volcanogenic, etc. However, what these notions imply is actually not genetic types, but rather mixed waters of different origins.

The notions and definitions of the origin and genetic types of groundwater used in the present paper are given in accordance with the classifications developed by A.A. Kartsev and S.L. Shvartsev (Kartsev et al., 1986, 2015; Kartsev, 1992; Shvartsev, 1996; Novikov, 2017a) and the results of our own studies of the Siberian sedimentary basins (Shvartsev and Novikov, 2004; Novikov, 2005; Novikov and Lepokurov, 2005; Novikov and Sukhorukova, 2015; Novikov, 2017a, 2018d), which are basically reduced to the following.

The origin of groundwater is interpreted as an integrated process of groundwater formation affected by natural factors and evolution of groundwater systems as well as by human activities. Origination of water in the lithosphere as a natural phenomenon can be a result of vapor condensation, infiltration of surface waters, sedimentation-driven burial of waters in sedimentary basins, etc. The interactions between the waters and host rocks, along with mixing of waters of different origins and other factors, give these waters their characteristic chemical composition (Kartsev et al., 2015).

Sedimentogenic waters (saline waters and brines) include aqueous solutions arriving in the sedimentary basin during deposition in the marine environments. This type should include aqueous solutions originating from lakes and lagoons of marine origin, usually salt-bearing (saline), sometimes desalinated (Kartsev et al., 1986).

Aqueous solutions (usually fresh or brackish; less frequently, saline) of vapor (atmospheric) origin which penetrated the sedimentary rocks by infiltration during hypergenesis should be called *ancient (fossil) infiltrogenic* waters.

According to (Kartsev et al., 1986, 2015) and other works, the *lithogenic (revived)* type of waters involves catagenic aqueous solutions released during thermodehydration of various minerals in sedimentary rocks. In West Siberia, they are found in Cretaceous and Jurassic reservoirs at a depth of 2 km and below (Kartsev et al., 1986; Shvartsev and Novikov, 2004; Novikov and Sukhorukova, 2015). The solvent is represented mainly by water molecules released from the chemically bound state, whereas the dissolved components are composed of the substances of sedimentary rock.

The authors agree with V.V. Nelyubin and O.N. Yakovlev (1981) as to the mechanism of the formation of *condensatogenic waters*. These are stratal waters having the background composition and salinity, admixed with fresh (nonsaline) condensation water released from the water–carbon mixture during its vertical migration, under the variable temperatures and pressures. The formation and preservation of water fringes from condensatogenic waters are also favored by the formation of hydrocarbon accumulations through rapid vertical migration (i.e., expulsion) of hydrocarbons from the zones of oil and gas generation and accumulation into traps (Kolodii, 1975).

Results of the geological and geophysical studies of pre-Jurassic deposits of the WSAB and detailed analysis of hydrogeochemical data (Table 3; Fig. 3) suggest the presence of three genetic groups of groundwater and brines within

Table 3. Genetic characteristics of types of groundwater and brine samples from pre-Jurassic complexes of West Siberia

Area, well No.	Interval, m	*M*, g/L	*r*Na/*r*Cl	Cl/Br	Ca/Cl	B/Br	(Sr/Cl)·10^{-3}	(Br/Cl)·10^{-3}	*S*	Genetic types
Oil- and gas-bearing horizon of the contact zone										
Puglalymskaya, 86	2630–2690	10.2	0.98	364	0.04	–	–	2.7	30	II
Kvartovaya, 3	3000–2986	11.9	1.07	335	0.03	0.12	–	3.0	21	III
Kalinovaya, 9	3006–3057	33.7	0.77	250	0.04	–	7.8	4.0	149	I
Ostaninskaya, 436	2740–2772	54.9	0.74	207	0.07	–	28.7	4.8	474	I
Nizhnetabaganskaya, 1	2995–3005	60.3	0.61	228	0.04	0.13	7.9	4.4	151	I
Triassic complex										
Inzhegorskaya, 155	2588–2611	12.7	0.96	328	0.05	0.95	–	3.1	32	III
Maloatlymskaya, 1	2799–2804	15.3	1.02	283	0.02	0.19	–	3.5	21	II
Lyantorskaya, 17	2962–3200	15.5	1.01	292	0.02	0.37	–	3.4	20	II
Chvorovaya, 3	3252–3270	21.4	1.07	398	0.00	–	–	2.5	9	II
Zapadno-Kalgachskaya, 1	2153–2238	49.2	0.83	252	0.09	0.08	–	4.0	53	I
Carboniferous complex										
Nikol'skaya, 1	3273–3284	8.7	0.89	951	0.10	1.03	–	1.1	48	III
Novoportovskaya, 218	3002–3404	9.0	1.39	356	0.01	1.71	–	2.8	11	III
Verkhnekombarskaya, 291	2790–2902	18.6	0.95	307	0.03	0.17	–	3.3	24	II
Sel'veikinskaya, 2	3116–3159	60.2	0.87	201	0.07	–	–	5.0	48	I
Verkhnekombarskaya, 293	2794–2799	72.8	0.84	247	0.01	–	–	4.0	16	I
Devonian complex										
Ellei-Igaiskaya, 2	4165–4180	23.2	1.09	483	0.05	0.04	–	2.1	28	II
Severo-Orekhovskaya, 560	3050–3167	46.9	0.83	265	0.09	0.07	–	3.8	55	I
Zapadno-Luginetskaya, 183	2708–2727	60.7	0.74	232	0.06	–	8.3	4.3	163	I
Gerasimovskaya, 2	2980–2997	65.7	0.74	224	0.06	0.14	15.8	4.5	280	I
Kalinovaya, 1	2849–2860	73.4	0.42	287	0.05	–	11.0	3.5	197	I
Silurian complex										
Novoportovskaya, 210	3240–3248	8.8	1.24	304	0.01	1.54	–	3.3	15	III
Novoportovskaya, 91	2720–2736	10.0	1.26	336	0.01	0.92	–	3.0	12	III
Vikulovskaya, 1	1940–2049	12.7	0.87	321	0.06	0.49	–	3.1	37	II
Var'eganskaya, 99	3455–3608	14.2	0.98	551	0.02	0.15	–	1.8	15	II
Kulaiskaya, 1	2350–2436	23.8	0.96	253	0.04	0.29	–	4.0	33	II
Ordovician complex										
Yuzhnaya, 402	2635–2652	9.5	1.09	575	0.02	0.27	–	1.7	17	II
Talinskaya, 110	2387–2441	16.4	1.03	933	0.02	1.38	–	1.1	10	III
Em-Egovskaya, 126	2576–2584	22.3	1.08	152	0.03	0.22	–	6.6	36	II
Talinskaya, 123	2462–2474	23.0	0.80	414	0.07	0.02	–	2.4	42	II
Nyarginskaya, 1	2660–2768	24.1	0.91	163	0.06	0.09	7.1	6.1	152	II
Cambrian complex										
Vezdekhodnaya, 2	3152–3204	51.2	1.03	384	0.01	0.10	8.1	2.6	134	I
Vezdekhodnaya, 4	3442–3564	57.8	1.04	263	0.09	0.04	9.5	3.8	193	I
Vezdekhodnaya, 3	3515–3563	82.3	0.73	178	0.08	–	–	5.6	56	I
Vostok, 4	3520–3532	84.2	0.84	237	0.08	0.11	0.2	4.2	52	I
Vostok, 4	4993–5036	209.3	0.76	295	0.10	0.22	4.9	3.4	131	I
Vendian complex										
Vostok, 3	4552–4656	58.7	0.74	185	0.08	0.00	7.8	5.4	173	I
Vostok, 3	4190–4200	69.1	0.71	265	0.07	0.00	7.0	3.8	148	I
Vostok, 3	4956–4962	83.7	0.75	222	0.09	0.00	7.9	4.5	171	I
Vostok, 3	4673–4683	85.4	0.82	267	0.10	0.00	7.0	3.7	165	I
Vostok, 3	4720–4734	89.8	0.82	264	0.07	0.00	6.4	3.8	138	I

Note. Dash means "no data available".

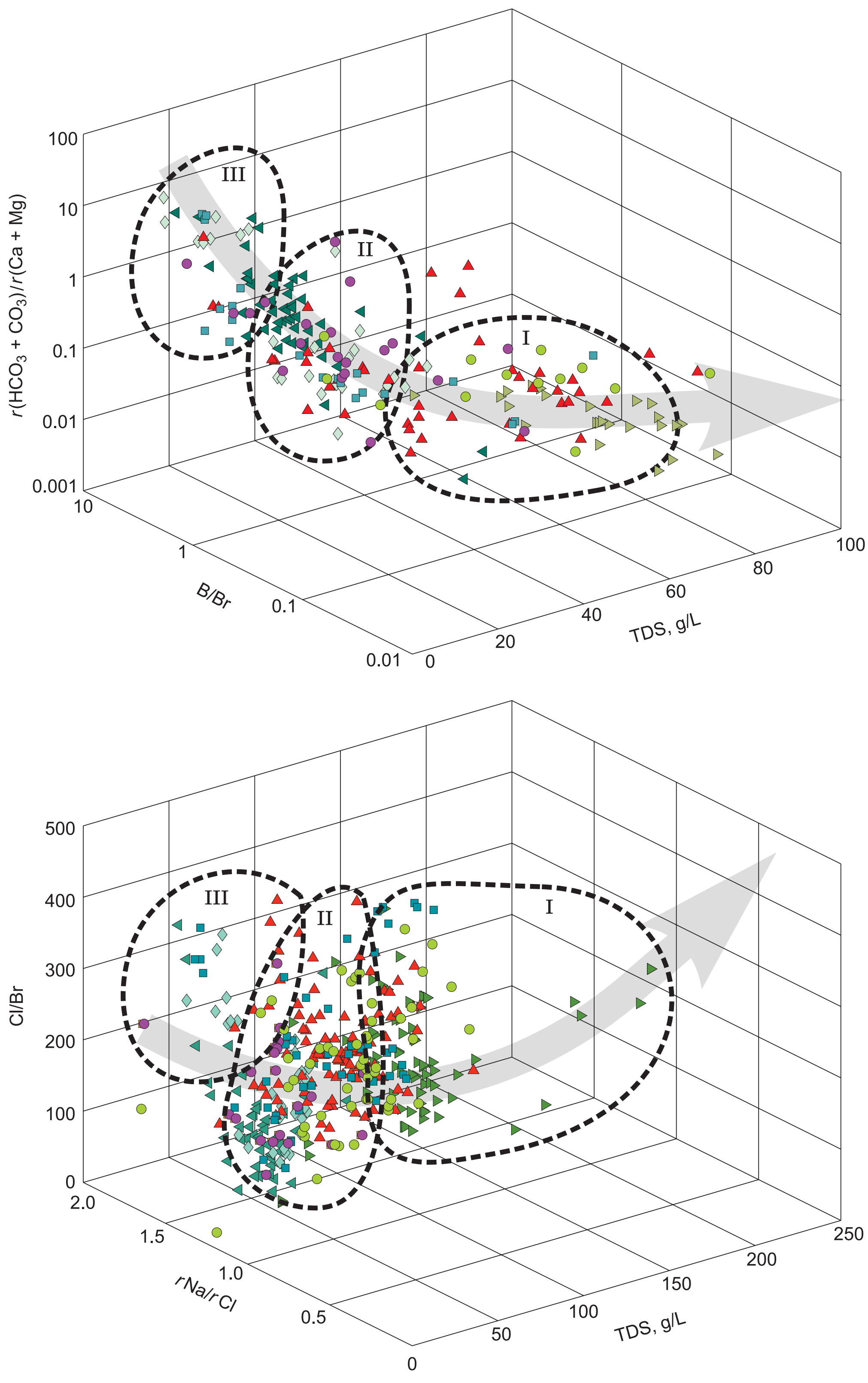

Fig. 3. Genetic groups of groundwater and brines in pre-Jurassic complexes of West Siberia. Aquifer complexes: see Fig. 1. Genetic groups of groundwater and brines: I, sedimentogenic; II, lithogenic (revived) and ancient infiltrogenic; III, condensatogenic. The arrow shows the direction of metamorphization of groundwater and brines.

them: (1) sedimentogenic, (2) lithogenic (revived) and ancient (fossil) infiltrogenic, and (3) condensatogenic.

Among them, condensatogenic waters are marked by the greatest variety of chemical compositions and variation in all genetic coefficients. Apart from low TDS values (within 10 g/L), these are characterized by high saturation with gas (up to 2.0 L/L and more) (Shvartsev and Novikov, 2004; Novikov and Lepokurov, 2005; Novikov, 2017a). Waters of this type were locally encountered in areas near the water–oil contact (WOC) or gas–water contact (GWC) in most of the studied oil/gas fields (Novoportovskoe, Yagyl-Yakhskoe, Maloichskoe, Severo-Ostaninskoe, and others). They are characterized by the high coefficients of B/Br >0.7 (up to 2.92) and $r(HCO_3 + CO_3)/r(Ca + Mg)$ >1.0 (up to 12.03), whereas coefficients rNa/rCl and Cl/Br range from 0.94 to 1.71 and from 134 to 372, respectively. Lithogenic, or revived (at depths below 4 km), and ancient infiltrogenic waters are distinguished from the previous type by higher salinities (10–35 g/L) and lower values of the above-listed coefficients. Sedimentogenic waters (viewed as indicative of a high-degree hydraulic confinement of subsoil and of the hydrodynamic zone of hindered and grossly hindered water exchange, which largely favor the processes of oil and gas migration and accumulation) are characterized by TDS in excess of 35 g/L, lower (compared to the previous types) values of the rNa/rCl coefficient of groundwater metamorphization (0.52–1.03, averaging 0.87), and Cl/Br varying widely from 81 to 406 (on average, 256). Importantly, their values tend to be even lower in Cambrian brines and, in particular, in Vendian sediments from the Fore-Yenisei basin. Thus, the Vostok-3 well test intervals (from 4552–4656 to 4956–4962 m) showed a decrease in rNa/rCl values from 0.82 to 0.74–0.75, while the Cl/Br values varied between 148 and 267 (Table 3).

The predominance of ancient infiltrogenic waters in the WSAB peripheral areas is associated with the proximity to its margin. This is not the case with the Fore-Yenisei basin. Here, the proximity to the Siberian Platform structures entails changes in the desalinated (salt-free) Cambrian section, so that it is replaced by the saline type. This prompted brine saturation up to 320–330 g/L, achieving the stage of halite precipitation around the Lemok-1 well (Fig. 2) (Novikov and Shvartsev, 2009; Dultsev and Novikov, 2017). The occurrence of lithogenic (revived) groundwater at a depth of 4 km and below is associated with thermodehydration of clay minerals, specifically in the northern, most poorly studied part of the WSAB, where the Triassic volcanogenic–sedimentary rock associations reach more than 1 km in thickness (Kontorovich and Surkov, 2000). In our opinion, this is one of the possible reasons for inversion in the hydrogeochemical zoning in this region (Shvartsev and Novikov, 2004). The established presence of sedimentogenic waters and brines in the southeast of the study area is corroborated by the values of coefficients $(Br/Cl)\cdot 10^{-3}$, rNa/rCl, Cl/Br, Ca/Cl, and $(Sr/Cl)\cdot 10^{-3}$. Condensatogenic waters were revealed in the peripheral zones of hydrocarbon deposits in the Novoportovskoe oil–gas condensate field (gas condensate pool in the oil- and gas-bearing horizon of the contact zone) and the Yagyl-Yakhskoe (oil accumulation in bed M), Maloichskoe (oil accumulations in beds M_0 and M), Nizhne-Tabaganskoe (oil accumulations in M_1 (M_{1-10} beds), and Yuzhno-Tabaganskoe (oil accumulations in M_1^1, M_1^2, and M_1^3 beds) oilfields, etc.

Level of metamorphization of the chemical composition. The previously established genetic groups of groundwater and brines are found to be metamorphosed in different degrees. A comparative analysis of the geochemical signatures of groundwater and brines in the pre-Jurassic Siberian aquifers has shown that, according to coefficients rNa/rCl and $r(HCO_3 + CO_3)/r(Ca + Mg)$, all the studied groundwater is divided into several geochemical groups (Fig. 4). The first group (I) consists of groundwater and weak brines of the Triassic, Carboniferous, Devonian, Silurian, and Ordovician complexes of West Siberia, widespread within igneous and metamorphic formations. These are characterized by TDS up to 50 g/L, high values of coefficients rNa/rCl (up to 1.7) and $r(HCO_3 + CO_3)/r(Ca + Mg)$ (up to 10.0), and low values of coefficient Ca/Cl. Group 2 (II) comprises the brines of the Devonian, Cambrian, and Vendian aquifer complexes studied within the sedimentary (mainly, carbonate) rocks, which are of sodium chloride and sodium–calcium chloride type with salinities in the range from 50.2 to 99.2 g/L. The relationships between different macro- and microcomponents are represented by coefficients rNa/rCl (from 0.5 to 0.94), Ca/Cl (from 0.04 to 0.13), and $r(HCO_3 + CO_3)/r(Ca + Mg)$ (0.01–0.11). This group also includes most of the objects studied within the contact zone between the rocks of the sedimentary cover and the Paleozoic basement (i.e., oil- and gas-bearing horizon of the contact zone), confirming therefore our earlier inferences that the West Siberian groundwater and brines are at the initial stage of metamorphization of their chemical composition (Novikov, 2017a). The integrated index S of metamorphization varies considerably: generally, from 30 to 100 (Table 3).

The Vendian–Cambrian brines of the Fore-Yenisei sedimentary basin exhibit similar characteristics, slightly shifting towards the ultrastrong brines of the Siberian Platform. This is a result of the transitional type of hydrogeologic structure of this region, occupying the interim position between West Siberian and Tunguska artesian basins, which was previously discussed in (Novikov and Shvartsev, 2009; Dultsev and Novikov, 2017; Novikov et al., 2018b; Dultsev, 2019).

Group 3 (III) unites ancient infiltrogenic sodium chloride brines (TDS: 153–312 g/L) formed as a result of rock salt leaching within the Nordvik salt domes area on the Nordvik, South Tigyan, and Il'ya Kozhevnikov structures of the Anabar–Khatanga basin. The values of coefficients amount to 0.90–1.01 for rNa/rCl and up to 0.02 for Ca/Cl; $r(HCO_3 + CO_3)/r(Ca + Mg)$ is from trace amounts to 0.07, while the integrated index S of brine metamorphization is consistently around 0 (Novikov, 2017a; Chernykh and Novikov, 2018).

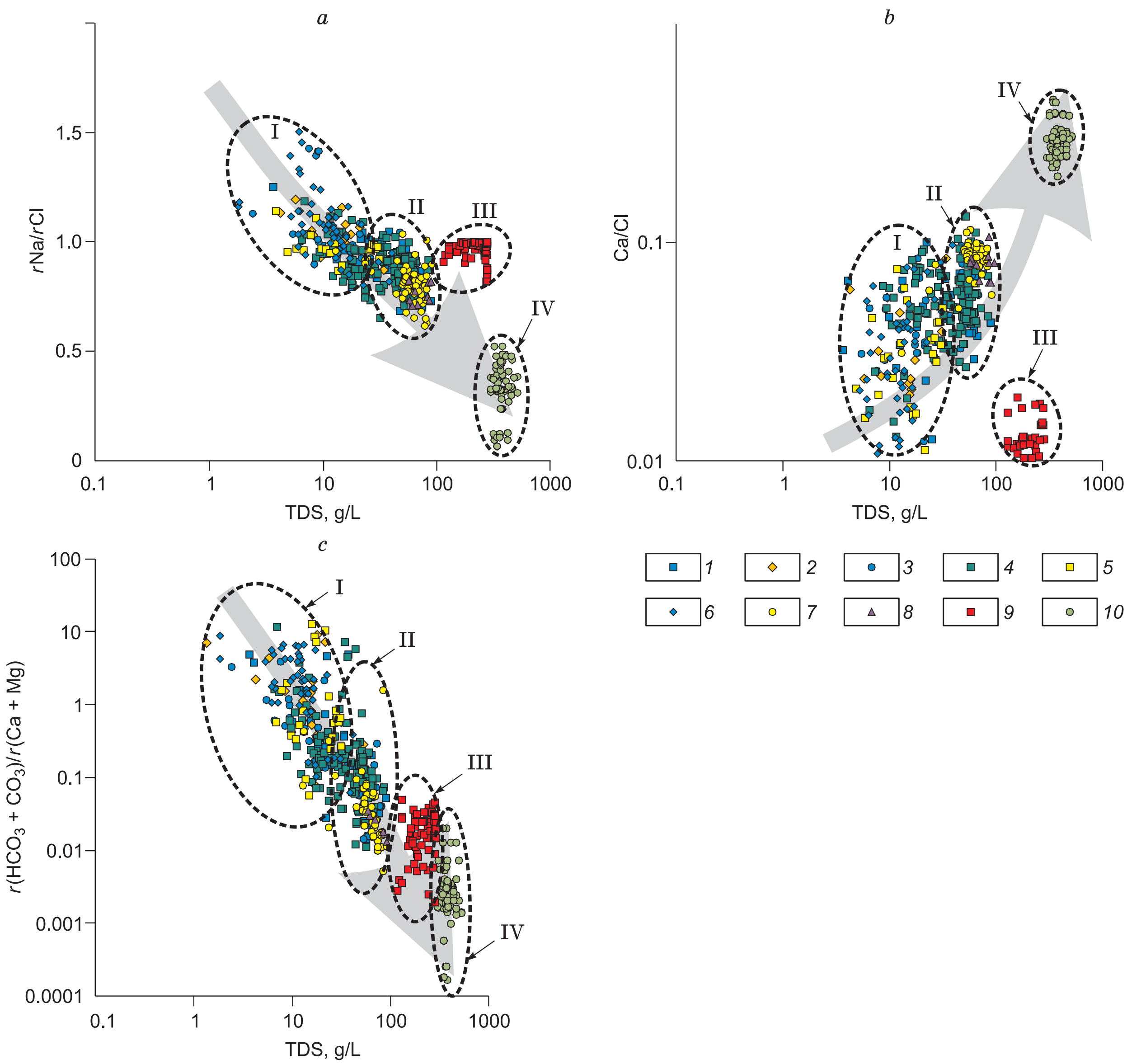

Fig. 4. Coefficients *r*Na/*r*Cl (*a*), Ca/Cl (*b*), and $r(HCO_3 + CO_3)/r(Ca + Mg)$ (*c*) and their relationships with the general salinity of groundwater and brines in pre-Jurassic complexes of West Siberia. Aquifer complex: *1*, oil- and gas-bearing horizon of the contact zone; *2*, Triassic; *3*, Carboniferous; *4*, Devonian; *5*, Silurian; *6*, Ordovician; *7*, Cambrian; *8*, Vendian; *9*, Triassic deposits of salt dome structures in the Anabar–Khatanga basin; *10*, Cambrian deposits of the Siberian Platform border structures. The arrow shows the direction of metamorphization of groundwater and brines. I–IV, geochemical groups.

Finally, Group 4 (IV) includes ultrastrong (TDS from 324 to 563 g/L), predominantly chloride calcium–sodium and calcium brines in the border regions of the Siberian Platform. These are characterized by the following values of "genetic" coefficients: *r*Na/*r*Cl <0.5; Ca/Cl is from 0.22 to 0.47, and $r(HCO_3 + CO_3)/r(Ca + Mg)$ <0.07 (Fig. 4). The level of their metamorphization is the highest with respect to the major coefficients, including *S*, which is over 400.

Thus, the level of metamorphization (catagenetic changes) of the chemical composition of groundwater and brines in the studied Siberian basins tends to increase from the areas of igneous and metamorphic sedimentary formations within the Triassic, Carboniferous, Devonian, Silurian, and Ordovician complexes of the WSAB to the border structures of the Siberian Platform (Baikal anticline, Fore-Sayan–Yenisei syncline, etc.), where ultrastrong chloride calcium–sodium and calcium brines are found. An integrated analysis of coefficients *r*Na/*r*Cl, Ca/Cl, $(Br/Cl)\cdot 10^{-3}$, and $(Sr/Cl)\cdot 10^{-3}$, together with integrated index *S*, justifies the inferences made in (Novikov, 2017a).

CONCLUSIONS

Sodium chloride groundwater and brines with TDS up to 330 g/L (background water salinity 40–50 g/L) are the most widespread in the pre-Jurassic sediments of the West Siberian artesian basin. Within the study area, these are dominated by sodium chloride brines with a TDS value of 50–70 g/L, metamorphosed to the extent characteristic of salt-free sediments. The data of comprehensive geological and geophysical studies of pre-Jurassic deposits and results of detailed analysis of hydrogeochemical data allowed assuming the presence of the following three main genetic groups of groundwater and brines within them: (1) sedimentogenic, (2) lithogenic (revived) and ancient infiltrogenic, and (3) condensatogenic. Ancient infiltrogenic waters predominate in the peripheral areas of the basin except for the Fore-Yenisei basin, where the proximity of the Siberian Platform structures is marked by the Cambrian section grading from the salt-free type to saline sediments, prompting the formation of brines achieving the stage of halite precipitation, with TDS as high as 320–330 g/L reported from the Lemok-1 well. Lithogenic (revived) waters commonly occur at a depth of 4 km and below. Here, the processes of thermodehydration of clay minerals are involved, in particular, in the northern, largely underexplored part of the WSAB, where the Triassic volcanic–sedimentary complex has a thickness exceeding 1 km. In our opinion, the combination of these factors is very likely to have caused the inverse hydrogeochemical zonality. Sedimentogenic waters and brines have been established in the southeast of the study area, which is remarkably manifested in coefficients $(Br/Cl)\cdot 10^{-3}$, rNa/rCl, Cl/Br, Ca/Cl, and $(Sr/Cl)\cdot 10^{-3}$. Condensatogenic waters are revealed in the peripheral zones of hydrocarbon deposits in the Novoportovskoe, Yagyl-Yakhskoe, Maloichskoe, Nizhne-Tabaganskoe, Yuzhno-Tabaganskoe, and other fields. A comparative analysis of the geochemical characteristics of groundwater and brines of the pre-Jurassic Siberian complexes have shown that the studied West Siberian brines are presently at the initial stage of metamorphization (catagenetic changes) of the chemical composition.

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