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Conditions of Early Paleozoic Basaltic and Picritic Magmatism in West Siberia

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Abstract—Geological, petrological, isotope-geochemical (^{40}Ar/^{39}Ar analysis, petrochemical data, and geochemistry of trace elements and REE), and mineralogical researches testify that the formation of the early Paleozoic basalt and picrite complexes of the West Siberian Plate basement was related to the development of the Cambrian subduction zone of the Paleo-Asian Ocean. Using the compositions of clinopyroxenes and amphiboles (and also programs of computational modeling), we have established the *P–T* conditions of formation of early Paleozoic picrite complexes. Crystallization of clinopyroxenes began at significant depths (25–20 km) and at high temperatures (1300–1275 °C). Olivine might have formed at elevated pressures (8–7 kbar) and temperatures of 1540–1490 °C. Amphiboles formed, most likely, at 6.1–4.5 kbar and much lower temperatures, 1105–1060 °C. Petrochemical analysis and data on trace elements and REE in the rocks of the studied early Paleozoic complexes in West Siberia testify to their intricate formation involving magmatic systems with basalt (island arc and back-arc basins), picrite, and shoshonite (and also WPB type) melt characteristics. Taking into account the similar geochemical characteristics of the early Paleozoic basaltoids and picrites of the West Siberian Plate basement and the Kamchatka volcanics, we suggest that a considerable part of the studied ancient complexes formed by the model implying (as in the case of the Sredinnyi Ridge in Kamchatka) the action of enriched magmatic systems during the development of a destructive window ("slab-window") under rupture of subducted plate on the background of common island arc magmatism.

Keywords: basalt and picrite complexes; West Siberian Plate basement; ^{40}Ar/^{39}Ar analysis; petrochemistry and geochemistry; *P–T* parameters of magmatism; clinopyroxene; amphibole

INTRODUCTION

Two main basalt associations exist in the West Siberian plate basement. There is a particular interest to a series of Permian-Triassic rocks (Al'mukhamedov et al., 1998; Bochkarev et al., 2003; Medvedev et al., 2003; Reichow et al., 2005; Saraev et al., 2009; Simonov et al., 2010; Ivanov et al., 2016), formation of which caused by widespread events of plateau-basalt magmatism in West Siberia and on the Siberian Platform. Ancient basalts associations have remained underexplored (e.g., Kontorovich et al., 1999; Saraev and Ponomarchuk, 2005; Simonov et al., 2014; Ivanov et al., 2016), and the publications on Paleozoic picrite basalt complexes in the West Siberia basement are scarce (Kuzovatov at al., 1988, 1995; Simonov et al., 2018, 2019).

Paleozoic picritic basalt complexes in the West Siberian plate have motivated investigations, but their genesis is still a mystery especially for paleogeodynamic settings of formation of these associations and their connection with the development of paleo-oceanic structures. Many questions arise on the onset of formation time, crystallization conditions, and characteristics of magmatic systems that give way to the formation of Paleozoic mafic and ultramafic volcanic rocks of the West Siberian basement.

The paper focuses on the paleogeodynamic settings, formation period, and physicochemical characteristics of the study rocks crystallization. For this purpose, mafic and ultramafic rock samples from the Chkalov (70 km below the Tym River estuary) and Vezdekhodnaya (Ket and Tym rivers interfluve) area well core of the Middle Ob (southeastern sector of West Siberia) have been examined. We used an

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integrated geological and petrological, petrochemical, isotopic-geochemical, and mineralogical study of core samples and a comparative analysis of the obtained results with data on standard objects in the present-day territories, providing the detailed consideration of the processes and time of development of magmatic systems when Paleozoic associations of the West Siberian Plate basement have begun to form.

Since the previous publications (e.g., Kontorovich et al., 1999; Saraev et al., 2004; Saraev and Ponomarchuk, 2005; Simonov et al., 2014, 2019) established a connection between the formation of the study complexes and development of active paleo-oceanic margin, we compared the complexes with contemporary systems in the western sector of Pacific Ocean. The authors have their own data on the magmatism of these systems (Simonov et al., 2002, 2004; Dobretsov et al., 2016, 2017, 2019).

METHODS

Thin sections have been studied for all the Chkalov and Vezdekhodnaya samples. Compositions of rocks and minerals were determined at the Analitical Center for multi-elemental and isotope research SB RAS (Novosibirsk) and at the V.S. Sobolev Institute of Geology and Mineralogy SB RAS. Tables 1–5 demonstrate the original analyses obtained by the authors.

Petrochemical compositions were determined by X-ray fluorescence on a Thermo Electron Corporation ARL-9900-XP spectrometer. National standard for rock samples (MU – 1, ST – 1A, etc.) was used for testing. Ranges of the contents described (wt.%) are as follows: Na_2O – 0.04–15; MgO – 0.05–45; Al_2O_3 – 0.01–30; SiO_2 – 0.01–100; P_2O_5 – 0.01–2; K_2O – 0.01–10; CaO – 0.01–40; TiO_2 – 0.01–2; MnO – 0.01–2; Fe_2O_3 – 0.01–20; BaO – 0.005–0.5; and LOI – 0.2–30.

Trace element and REE contents were determined by ICP-MS (inductively coupled plasma mass spectrometry) on a Finnigan Element mass spectrometer. Detection limits for most REE and trace elements are from 0.01 to 0.06 ppm, for Eu, Ho, and Lu – 0.003 ppm, and 0.09–0.22 ppm for HFSE.

Clinopyroxene and amphibole compositions were analyzed on a Camebax-Micro X-ray microanalyser. Collision cell exit potential was 20 kV, absorbed electron current was 40 nA, probe diameter was 2–3 µm, and calculating time was 10 s on each analytical line. Detection limits (wt.%) of the components are: SiO_2 – 0.007, TiO_2 – 0.032, Al_2O_3 – 0.011, FeO – 0.019, MnO – 0.034, MgO – 0.011, CaO – 0.008, Na_2O – 0.017, K_2O – 0.009, Cl – 0.017, P_2O_5 – 0.011. Orthoclase (OR), albite (AB), diopside (DI), garnet (O-145), and basalt glass (GL) served as the standard samples.

The ages of the rocks were determined by the $^{40}Ar/^{39}Ar$ method at the V.S. Sobolev Institute of Geology and Mineralogy following the method in (Travin et al., 2009). The stepwise heating experiments were conducted in a quartz reactor with an external heating furnace. Idle test procedure for ^{40}Ar (10 min at 1200 °C) did not exceed $5 \cdot 10^{-10}$ nsm^3. The isotopic composition of argon was determined on the Micromass Noble gas 5400 mass spectrometer (England) and on the GV-Instruments Argus multicollector mass spectrometer (England). Measurement errors correspond to an interval of ± 1σ.

We used the results on rock and mineral composition obtained by other researchers (GEOROC geochemical rock

Table 1. Representative analyses of porphyric picrites of the Chkalov area, West Siberia

Sample	C-11-15	C-11-16	C-11-17	C-11-18	C-11-19
SiO_2	41.00	39.36	37.80	36.40	39.92
TiO_2	0.79	0.90	0.99	0.64	0.73
Al_2O_3	6.90	8.78	9.00	6.19	6.93
Fe_2O_3	15.38	15.92	16.32	13.37	15.41
MnO	0.15	0.16	0.16	0.20	0.15
MgO	24.14	22.42	22.26	21.86	24.97
CaO	2.56	3.17	3.33	8.02	2.37
Na_2O	0.61	0.77	0.71	0.44	0.50
K_2O	0.17	0.15	0.11	0.09	0.12
P_2O_5	0.09	0.10	0.10	0.08	0.08
Cr_2O_3	0.22	0.20	0.21	0.19	0.21
NiO	0.12	0.11	0.12	0.09	0.12
LOI	6.94	7.41	7.87	11.93	7.54
Total	99.08	99.44	99.00	99.51	99.05
Rb	2.9	2.2	2.2	1.79	2.9
Sr	148	307	248	265	134
Y	10.0	9.7	10.5	9.5	8.9
Zr	40	39	47	33	35
Nb	6.1	6.2	7.3	4.8	5.3
Cs	0.67	0.71	1.05	0.60	0.67
Ba	69	104	89	204	78
La	4.5	5.0	5.2	5.1	4.3
Ce	9.8	10.3	11.3	10.2	8.8
Pr	1.36	1.39	1.53	1.33	1.16
Nd	5.6	5.7	6.3	5.5	5.0
Sm	1.50	1.63	1.66	1.44	1.38
Eu	0.49	0.55	0.58	0.51	0.43
Gd	1.82	1.83	1.80	1.75	1.63
Tb	0.31	0.30	0.30	0.29	0.27
Dy	1.85	1.79	1.91	1.67	1.64
Ho	0.38	0.37	0.36	0.33	0.33
Er	1.00	1.01	1.05	0.87	0.81
Tm	0.15	0.15	0.15	0.12	0.12
Yb	0.95	0.95	0.93	0.75	0.72
Lu	0.14	0.13	0.13	0.11	0.11
Hf	1.00	1.07	1.19	0.94	0.86
Ta	0.36	0.39	0.42	0.30	0.36
Th	0.63	0.63	0.82	0.53	0.56
U	0.20	0.20	0.23	0.13	0.16

Note. Well 11. Major chemical components in wt.%. Trace elements in ppm. This and other tables represent the original analyses made by the authors.

Table 2. Representative analyses of basalt complex rocks of the Chkalov area, West Siberia

Sample	C-7-3	C-7-4	C-7-6	3046	3061	3075	3122
SiO_2	43.49	48.50	46.26	57.86	44.99	54.27	54.09
TiO_2	3.77	3.34	3.59	1.05	4.26	1.77	2.12
Al_2O_3	11.59	15.37	14.96	15.28	15.06	16.51	14.65
Fe_2O_3	21.02	14.29	14.59	9.87	16.11	10.77	11.84
MnO	0.42	0.15	0.20	0.15	0.18	0.21	0.25
MgO	3.10	2.68	5.00	2.32	3.66	3.36	3.16
CaO	3.32	3.03	5.60	2.85	5.46	3.01	3.04
Na_2O	2.73	3.78	3.84	2.85	3.01	5.62	3.96
K_2O	1.95	2.83	1.85	3.27	3.48	2.02	2.94
P_2O_5	1.86	0.35	0.52	0.22	0.78	0.62	0.73
LOI	6.11	5.03	2.95	4.27	3.33	2.09	3.45
Total	99.36	99.35	99.34	99.99	100.33	100.25	100.21
Rb	42	56	35	61	72	38	81
Sr	133	229	539	276	216	532	157
Y	63	35	38	36	87	74	88
Zr	526	522	381	336	921	752	846
Nb	80	77	51	49	160	125	149
Cs	1.01	0.93	0.45	0.42	0.27	0.22	0.43
Ba	354	584	575	753	835	436	495
La	69	35	39	37	102	95	105
Ce	158	77	83	78	207	198	211
Pr	23	10.5	11.4	11	27	27	29
Nd	92	40	44	46	104	103	109
Sm	19.8	8.4	9.5	9.9	21.3	20.6	22.1
Eu	5.5	2.6	3.0	3.3	7.0	6.3	5.3
Gd	17.6	7.6	9.2	9.4	19.1	17.9	20.2
Tb	2.6	1.2	1.5	1.3	2.9	2.6	3.0
Dy	12.5	6.4	7.6	6.7	15.4	13.5	16.3
Ho	2.3	1.3	1.4	1.2	2.9	2.5	3.0
Er	5.9	3.7	3.6	3.1	7.9	6.6	7.8
Tm	0.78	0.60	0.51	0.42	1.12	0.90	1.09
Yb	4.5	3.7	2.9	2.5	6.7	5.0	6.2
Lu	0.68	0.56	0.46	0.37	0.98	0.69	0.93
Hf	12.0	11.7	8.7	7.2	18.7	15.3	17.6
Ta	5.5	5.1	3.6	2.6	8.1	6.2	7.7
Th	6.3	6.6	5.1	3.0	8.1	5.9	7.6
U	2.3	1.08	1.44	1.36	1.50	2.32	2.03

Note. Well 7. Major chemical components in wt.%. Trace elements in ppm.

database) for a reasonable conclusion. A modern (2018) WinPLtb program based on the composition ratio of clinopyroxene and melt from which it crystallizes (Clinopyroxe-Liquid Thermobarometry) (Yavuz and Yildirim, 2018) was applied to explore the physicochemical characteristics of the melts. The melt composition was estimated involving an analysis of porphyric picrite in which clinopyroxene was investigated.

A number of thermobarometers (Mercier, 1980; Perchuk, 1980; Lindnsley and Dixon, 1983) was used for determining the crystallization conditions of clinopyroxenes. Amphibole thermobarometers (Ridolfi and Renzulli, 2012) were employed in calculating the pressure and temperature of final stages of magmatic processes. Earlier amphibole barometers (e.g., Johnson and Rutherford, 1989; Schmidt, 1992) have found to be quite adequate according to the comparative analysis.

The *P–T* crystallization characteristics of minerals obtained by various thermobarometers were compared with each other and tested matching the material on reference objects and results of application of computational modeling programs. It should be noted that the ratios of clinopy-

Table 3. Representative analyses of basalt complex rocks of the Vezdekhodnaya area, West Siberia

Sample	Вз-3-1a	Вз-3-1b	Вз-3-9	Вз-3-11	Вз-4-5	Вз-4-7	Вз-4-8
SiO_2	47.82	46.98	44.32	43.90	49.63	47.96	42.79
TiO_2	1.12	1.13	1.31	1.32	1.29	2.81	2.41
Al_2O_3	17.51	17.95	16.78	16.66	17.05	14.24	14.24
Fe_2O_3	9.80	10.71	11.21	11.38	8.97	14.89	15.57
MnO	0.15	0.18	0.11	0.12	0.14	0.23	0.27
MgO	5.87	6.87	8.27	8.27	5.96	5.68	7.98
CaO	11.38	9.16	7.80	8.53	8.72	7.04	9.99
Na_2O	3.06	3.36	2.38	2.58	3.51	4.01	2.41
K_2O	0.15	0.31	2.10	1.90	1.07	1.30	0.10
P_2O_5	0.21	0.21	0.22	0.23	0.26	0.41	0.21
LOI	3.21	3.37	5.56	5.24	3.73	2.28	4.00
Total	100.28	100.23	100.05	100.13	100.32	100.84	99.96
Rb	1.3	3.1	23	17	25	28	2.3
Sr	651	747	646	643	170	321	249
Y	21	20	22	21	24	44	44
Zr	61	58	78	80	130	169	146
Nb	2.9	2.8	5.5	5.1	6.3	3.9	4.2
Cs	0.14	0.47	1.2	0.90	0.62	1.49	0.18
Ba	57	91	315	286	183	210	25
La	13	13	13	13	13.5	10.3	5.0
Ce	27	26	28	28	29	27	15.5
Pr	3.7	3.5	3.9	4.0	3.9	4.6	2.9
Nd	16	15	16	16	17.1	22	14.8
Sm	3.7	3.8	4.1	3.7	3.9	5.9	4.7
Eu	1.3	1.2	1.3	1.3	1.21	1.80	1.64
Gd	3.8	3.7	4.1	3.9	4.3	7.3	6.3
Tb	0.57	0.54	0.63	0.60	0.64	1.21	1.12
Dy	3.3	3.1	3.5	3.2	3.8	7.2	6.9
Ho	0.60	0.63	0.72	0.60	0.75	1.39	1.43
Er	1.6	1.6	1.9	1.7	2.1	4.0	4.1
Tm	0.25	0.24	0.27	0.24	0.33	0.62	0.63
Yb	1.5	1.4	1.7	1.5	2.0	3.5	4.0
Lu	0.23	0.22	0.26	0.23	0.29	0.53	0.59
Hf	1.5	1.5	1.9	1.8	4.6	5.3	5.4
Ta	0.12	0.12	0.24	0.21	0.35	0.24	0.27
Th	1.3	1.3	1.7	1.1	3.3	1.36	0.86
U	0.39	0.36	0.43	0.36	0.46	0.19	0.081

Note. Samples Vz-3-1a–Vz-3-11, Vezdekhodnaya well 3; Vz-4-5–Vz-4-8, Vezdekhodnaya well 4. Major chemical components in wt.%. Trace elements in ppm.

roxene-melt compositions (Yavuz and Yildirim, 2018) were used for the estimation of *P–T* conditions of porphyric picrite crystallization rather than monomineral thermobarometers. In addition, the results of the WinPLtb method (Yavuz and Yildirim, 2018) were verified by other programs (PETROLOG (Danyushevsky and Plechov, 2011), COMAGMAT (Ariskin and Barmina, 2000, 2004), and PLUTON (Lavrenchuk, 2004)), which showed that clinopyroxene and olivine may crystallize from a melt similar in composition to that of the studied porphyric picrite and confirmed the obtained material on the *P–T* characteristics of magmatic systems.

GEOLOGICAL PATTERNS OF THE SOUTEASTERN WEST SIBERIA

The most important results were obtained from the study of the Chkalov and Vezdekhodnaya mafic and ultramafic rock samples (southeastern West Siberia) (Fig. 1).

Chkalov area is located at the boundary of Alexandrovsk arch and Ust-Tym valley. The region belongs to the zone between Koltogorsk-Urengoi and Ust-Tym graben-rifts (after (Surkov and Zhero, 1981)) having a complex structure with fragmented geological formations and altered sedimentary-volcanogenic sequence. Sedimentary rocks are

Table 4. Representative analyses in wt.% of clinopyroxenes from porphyric picrites of the well 11 (Chkalov area)

No	Analysis	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total	Mg#
1	1-1	48.50	1.58	5.12	0.48	6.45	0.11	14.64	22.01	0.49	0.00	99.37	80.18
2	1-2	48.58	1.73	5.00	0.46	6.54	0.12	13.85	22.17	0.47	0.00	98.92	79.05
3	1-3	48.41	1.70	4.98	0.46	6.68	0.11	13.63	22.33	0.47	0.00	98.78	78.43
4	1-4	48.62	1.68	4.98	0.51	6.49	0.08	13.90	22.01	0.45	0.01	98.72	79.24
5	1-5	48.03	1.78	5.27	0.50	6.64	0.10	13.45	21.92	0.44	0.00	98.14	78.31
6	1-6	48.99	1.77	5.10	0.49	6.55	0.09	14.15	22.05	0.47	0.00	99.65	79.38
7	1-7	48.04	1.72	5.01	0.47	6.70	0.11	14.09	21.81	0.46	0.00	98.42	78.94
8	1-8	48.11	1.82	5.29	0.54	6.57	0.11	13.46	22.19	0.41	0.00	98.50	78.50
9	1-9	47.28	1.82	5.06	0.62	6.60	0.11	13.44	21.95	0.41	0.00	97.28	78.40
10	1-10	48.18	1.87	5.43	0.51	6.68	0.11	13.32	22.12	0.42	0.00	98.64	78.04
11	1-11	48.54	2.05	5.38	0.38	6.73	0.11	13.76	21.92	0.49	0.00	99.36	78.46
12	1-12	47.81	2.01	5.24	0.38	7.03	0.11	13.78	21.23	0.49	0.00	98.09	77.74
13	1-13	47.41	2.14	5.33	0.40	6.68	0.11	13.25	22.06	0.50	0.00	97.87	77.95
14	1-14	48.54	1.76	4.98	0.46	6.74	0.09	14.20	21.17	0.51	0.00	98.44	78.97
15	1-16	48.22	1.67	4.91	0.57	6.49	0.14	13.67	22.07	0.44	0.00	98.18	78.96
16	1-17	47.89	1.83	5.36	0.58	6.48	0.09	13.44	22.14	0.44	0.00	98.26	78.71
17	1-18	48.43	1.73	4.95	0.50	6.45	0.12	13.71	21.82	0.50	0.00	98.21	79.11
18	1-19	48.24	1.74	4.90	0.50	6.49	0.09	13.81	21.91	0.46	0.00	98.15	79.13
19	1-20	47.78	1.70	4.86	0.54	6.46	0.11	13.76	22.07	0.45	0.00	97.74	79.15

Note. Clinopyroxene phenocrysts from porphyric picrites. Sample C-11-15. Mg# = Mg·100/(Mg + Fe).

Table 5. Representative analyses in wt.% of amphiboles from porphyric picrites of the well 11 (Chkalov area)

No.	Analysis	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total	Al^{iv}	*T*, °C	*P*, kbar
1	1-1	42.13	4.54	11.05	0.02	9.63	0.10	14.58	11.18	3.64	0.32	97.19	1.81	1074	5.3
2	1-4	41.02	4.88	11.51	0.02	9.95	0.12	14.26	11.30	3.32	0.34	96.72	1.94	1073	5.2
3	1-7	41.33	4.63	11.36	0.08	9.66	0.12	14.39	11.15	3.79	0.32	96.83	1.89	1110	6.7
4	2-2	43.54	4.79	8.78	0.16	10.21	0.13	15.02	10.76	3.89	0.40	97.69	1.52	1105	4.9
5	2-4	42.57	4.86	9.81	0.06	10.42	0.10	14.57	11.03	3.89	0.38	97.68	1.70	1091	4.9
6	2-5	43.09	4.80	8.91	0.14	10.07	0.14	14.75	10.66	3.85	0.42	96.83	1.55	1106	5.1
7	2-6	43.20	4.64	9.23	0.08	9.93	0.10	15.22	10.89	3.81	0.37	97.47	1.59	1087	4.6
8	2-9	43.18	4.55	8.99	0.17	9.98	0.12	15.10	10.73	3.85	0.35	97.03	1.56	1104	5.1
9	4-1	42.11	4.40	10.32	0.06	10.52	0.11	14.43	11.14	3.92	0.35	97.36	1.78	1090	5.6
10	4-2	41.93	4.50	10.43	0.15	10.76	0.11	14.20	11.09	3.62	0.34	97.14	1.80	1086	5.3
11	4-4	41.47	4.81	10.92	0.06	11.13	0.13	13.85	11.22	3.43	0.35	97.36	1.88	1069	4.7
12	4-5	42.03	4.21	10.05	0.02	11.31	0.16	14.14	11.26	3.11	0.33	96.61	1.76	1020	3.5
13	4-6	43.78	4.27	7.98	0.04	10.54	0.13	15.19	10.31	4.06	0.43	96.72	1.39	1091	4.9
14	4-7	43.42	4.43	8.53	0.03	10.86	0.12	14.60	10.44	3.89	0.45	96.79	1.49	1074	4.5
15	4-8	44.02	4.44	8.20	0.12	10.78	0.13	14.97	10.29	3.99	0.47	97.40	1.42	1097	5.1
16	5-1	41.28	4.68	11.20	0.03	10.70	0.14	14.06	11.23	3.51	0.34	97.16	1.91	1078	5.3
17	5-2	41.39	4.79	11.25	0.02	11.11	0.08	13.85	11.26	3.44	0.37	97.57	1.90	1058	4.7
18	5-3	40.95	5.34	11.24	0.04	10.94	0.12	13.75	11.28	3.30	0.37	97.33	1.95	1074	4.5
19	5-5	41.48	4.77	11.40	0.02	10.66	0.12	13.59	11.38	3.48	0.37	97.26	1.86	1059	4.9
20	5-6	41.11	4.95	11.43	0.01	11.01	0.14	14.00	11.38	3.42	0.38	97.83	1.96	1074	5.0
21	5-7	42.01	4.44	10.17	0.05	11.04	0.10	14.20	11.35	2.93	0.33	96.61	1.77	1008	3.1
22	5-9	40.90	4.95	11.31	0.03	10.91	0.13	13.75	11.25	3.42	0.36	97.00	1.94	1074	5.0
23	5	41.00	4.67	11.53	0.01	10.45	0.10	14.00	11.44	3.70	0.33	97.22	1.93	1080	5.6
24	7	41.58	4.59	10.96	0.03	10.79	0.13	14.70	11.41	3.31	0.33	97.84	1.89	1064	4.5
25	8	40.89	4.86	11.71	0.03	10.75	0.15	14.23	11.36	3.39	0.35	97.70	2.01	1087	5.7

Note. Amphibole phenocrysts from porphyric picrites. Sample C-11-15. Al^{IV} is the aluminum in tetradic coordination. *T* and *P* are parameters of the amphibole crystallization calculated by thermobarometer of (Ridolfi and Renzulli, 2012).

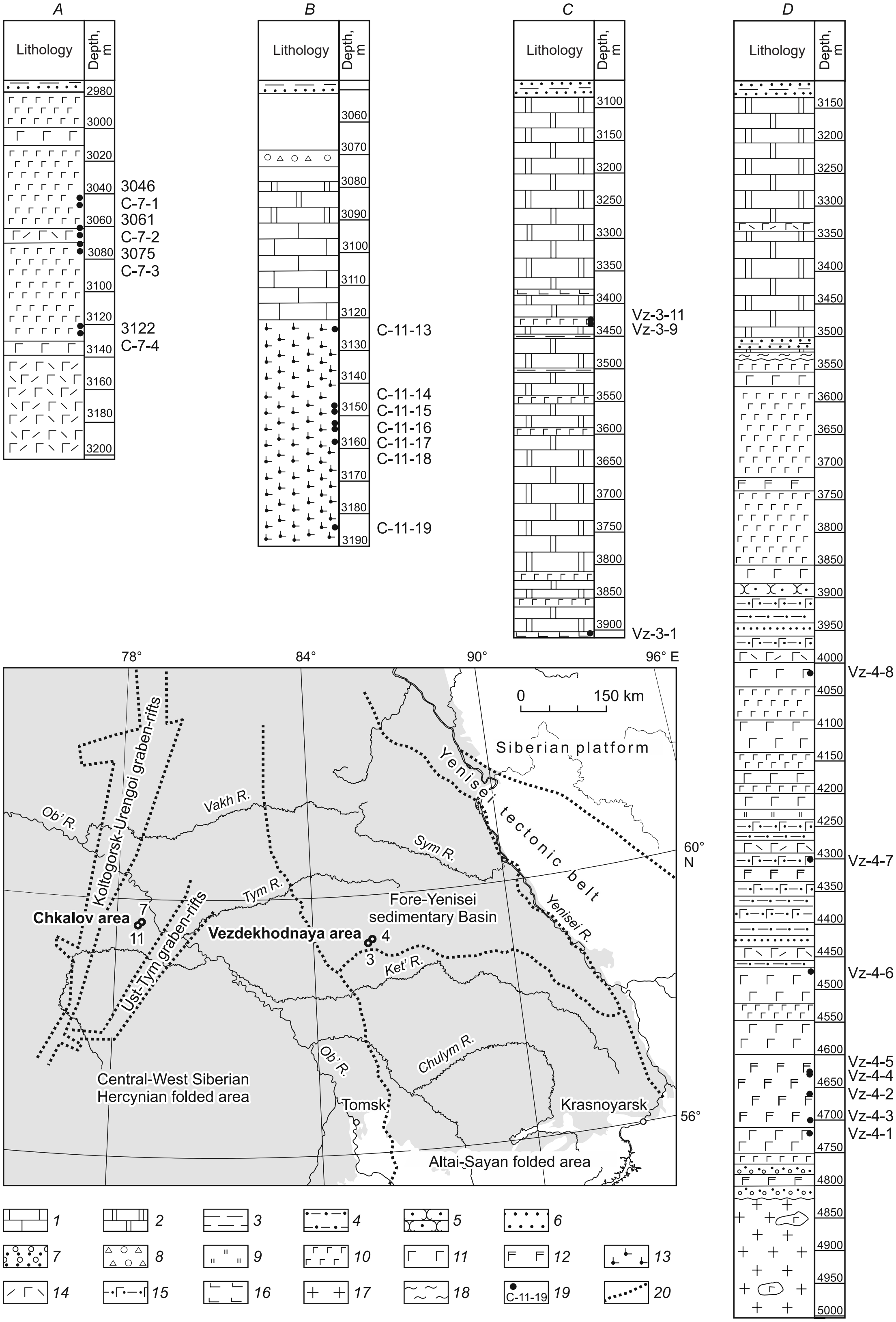

Fig. 1. Scheme of location and geological sections of Chkalov-7 (*A*), Chkalov-11 (*B*), Vezdekhodnaya-3 (*C*), and Vezdekhodnaya-4 (*D*) wells. *1*, limestones; *2*, dolomites; *3*, mudstones; *4*, siltstones; *5*, quartzitic siltstones; *6*, volcanic graywacke; *7*, arcose sandstones; *8*, breccia-conglomerate; *9*, silicites; *10*, basalts; *11*, igneous dolerites; *12*, subintrusive dolerites; *13*, porphyric picrites; *14*, tuffs; *15*, tuffites; *16*, spessartites; *17*, granodiorites; *18*, weathering crust on basaltoids; *19*, sample number; *20*, boundaries of the main tectonic zones in the West Siberian Plate basement and adjacent areas.

Silurian-Devonian in age (Kuzovatov et al., 1988, 1995). Recent paleontological data indicate ancient Vendian-Cambrian carbonate sediments in some wells of the Chkalov area (Koveshnikov et al., 2014a,b).

In the pre-Jurassic interval (2977–3203.5 m), *the Chkalov well-7* was drilled through basic volcanic rocks (Fig. 1*A*). Several members are recognized in the well section.

Grey-green basalt tufts were found in the 3138.1–3203.5 m interval. Microdolerites, dolerites, and basalts with tuff intercalations were discovered in the 3071.7–3138.1 m interval. The 3010.0–3071.7 m interval is characterized by vitric dark grey basalts with porphyric isolations of feldspar and intercalations of microdolerites and tuffs. The 2996–3010 m interval is dominated by altered dolerites and microdolerites. Tectonized and delaminated grey-green basalts with dolerite and tuff intercalations are present in the 2977–2996 m interval.

Ultrabasic rocks were studied in *the Chkalov well-11* section. The well (Fig. 1*B*) penetrates the following Paleozoic units (bottom-top): picrite (more than 60 m in thickness), dark grey and black fine-grained limestone (35 m); black fine-grained dolomite with intercalations of carbonaceous silicites and siliceous dolomites (about 15 m). They are overlain by a redeposited Mesozoic weathering crust dominated by silicite fragments in breccia-conglomerate.

Vezdekhodnaya area (Fig. 1) is located to 400 km east of the Chkalov area in the southeastern West Siberian Plate at the southwest of the pre-Jurassic Fore-Yenisei sedimentary Basin (Kontorovich et al., 1999, 2006). The region (Filippov and Saraev, 2015) likely belongs to the northward continuation of the Kuznetsk-Alatau volcanic zone (Volkov, 1986). In the early Paleozoic (Cambrian-Ordovician), this zone was within the active margin of the Siberian continent, and area of wells in the early Cambrian were located within the back-arc basin (Kontorovich et al., 1999; Saraev and Ponomarchuk, 2005).

In the pre-Jurassic interval (3086.8–3913.0 m), *the Vezdekhodnaya-3 well* (Fig. 1*C*) was drilled through dolomites, which are compared with the carbonate unit in the Cambrian section of the Vezdekhodnaya-4 well. Basalt layers occur in the 3408–3418 and 3852–3861.5 m intervals in the carbonate section of the Vezdekhodnaya-3 well, being slightly younger than the Vezdekhodnaya-4 well basaltoids, which underlie the carbonate thickness. Basalts are grey-green and reddish-brown colour with an intersertal structure containing nodules (up to 5 mm) filled by calcite and chlorite.

There are three complexes in the pre-Jurassic section (3106.4–5005.0 m) of *the Vezdekhodnaya-4 well* (Fig. 1*D*). Granodiorites with dolerite xenoliths are observed at the depths of 4824–5005 m. The ^{40}Ar/^{39}Ar method yielded the granodiorite age of 542 Ma (Saraev and Ponomarchuk, 2005). Granodiorites are overlain by gravelite sandstones (25 m), and overlying basalts have no significant changes.

The superposed complex (3541.5–4824.0 m) includes volcanogenic sedimentary rocks, basic igneous rocks, and dolerites. Basaltoids have an intersertal structure. Nodules are very few. Volcanogenic-terrigenous sediments are represented by tuff and silty distal turbidites. Incomplete turbidite sequences of Bouma type (Bouma, 1962) are most common in the section.

Beds and large dikes consist of dolerites and porphyric dolerites. Silicites are seen among turbidites in the bottom and quartzitic siltstones in the top of the section. The abyssal nature of the complexes is confirmed by the combination of basalt flows, distal turbidites, and silicite intercalations.

Upsection the rocks (3106.4–3541.5 m) consist of carbonate sediments and a terrigenous sequence. The carbonate section part forms dolomites of ribbon and knotted structure with layers of dissolution cavities and relict stromatolite sites.

We selected for investigation the samples of basalt and picrite rocks from the intervals of 3045–3125 m (Chkalov-7 well), 3125–3185 m (Chkalov-11 well), and 3420–3910 m (Vezdekhodnaya-3 well), 4020–4720 m (Vezdekhodnaya-4 well) (Fig. 1). All the samples studied have signs of extensive alteration. The study of thin sections demonstrates active rock transformations and rare primary minerals. For instance, the basalts of Chkalov area (well No. 7) contain a microgranular sussuritized and carbonatized groundmass with sericitized plagioclase phenocrysts.

Ultramafic rocks from the well 11 exhibit further alteration. An examination of the thin sections showed that these rocks are significantly changed porphyric picrites with olivine phenocrysts being fully serpentinized and located in the main fine grained mass of chloritization and serpentinization. Clinopyroxene phenocrysts that largely replaced with chlorites are present. Amphibole single phases occur on pyroxene in individual picrite samples.

The results of thin section study of the Vezdekhodnaya area basalt rocks established almost complete alteration and the primary mineral contours are difficult to trace. Microdolerite and dolerite structures remained only in the individual basalt samples (Vezdekhodnaya-3 and Vezdekhodnaya-4 wells).

AGE OF BASALT AND PICRITE COMPLEXES

We determined the precise formation time of Paleozoic basalt and picrite complexes in the West Siberian Plate basement by the ^{40}Ar/^{39}Ar analysis. ^{40}Ar/^{39}Ar dating of the basalts of the Chkalov-7 well using stepwise heating yielded a primary plateau with an age of 485.6 ± 4.2 Ma (Fig. 2*A*). The same studies of porphyric picrites in the well 11 yielded the maximum age of 494.9 ± 10.5 Ma (Fig. 2*B*) almost matching the results on basalts in this area. It should be noted that in the ^{40}Ar/^{39}Ar ultramafics spectra, stages of about 400 and 220 Ma have been discovered, indicating most likely secondary changes.

The ^{40}Ar/^{39}Ar study of basalts in the Vezdekhodnaya-4 well showed the presence of several distinct stages: 475, 400, and 380 Ma (Fig. 2*C*). Earlier studies of dolerite am-

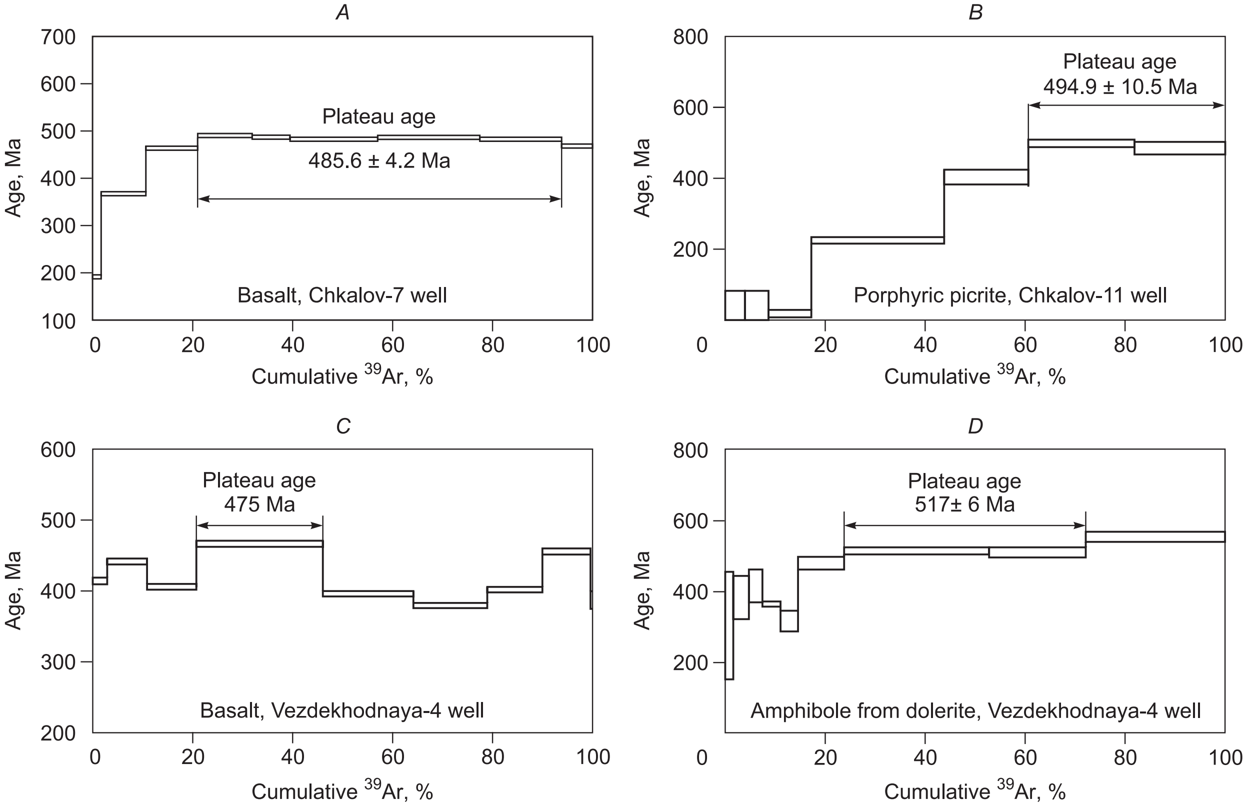

Fig. 2. The ^{40}Ar/^{39}Ar dating results of Paleozoic rocks in the Chkalov and Vezdekhodnaya areas.

phibole in this well yielded a ^{40}Ar/^{39}Ar age of 517 ± 6 Ma (Fig. 2*D*). The isochronous ^{40}Ar/^{39}Ar age was 520 ± 10 Ma (Kontorovich et al., 1999).

The maximum age characteristics of the studied samples from both areas are consistent and indicate the formation of the complexes in the Cambrian period (520–495 Ma). Previous data fall within the stages of secondary change of rocks that is confirmed by the earlier obtained information on the ^{40}Ar/^{39}Ar dating of rocks from the Vezdekhodnaya-4 well showing the age of volcanic rocks of 520 ± 10 Ma on the one hand, and on the other hand, 400 Ma with the onset of chloritization (Kontorovich et al., 1999).

PETROCHEMICAL PATTERNS OF EARLY PALEOZOIC BASALT AND PICRITE COMPLEXES

Samples of porphyric picrites from the Chkalov-11 well (Table 1) and basalt and basaltic andesites from the Chkalov-7, Vezdekhodnaya-3, and Vezdekhodnaya-4 wells (Tables 2 and 3) were used for detailed petrochemical analysis, which showed the influence of secondary processes on the most **basalt and basaltic andesite rocks** of both areas as evidenced by the Na_2O excess (up to 5.6–6.2 wt.%) and LOI (up to 5–6.1 wt.%) contrasted with low CaO contents (up to 1.8–3 wt.%).

The separation to normal alkaline and alkaline rocks was made during petrochemical analysis of basaltoids according to the currently accepted method based on the ratio (Na_2O + K_2O)–SiO_2 (e.g., Bogatikov and Kovalenko, 1987; Bogatikov et al., 2009). Basaltoids were recalculated to anhydrous substance according to (Bogatikov et al., 2009). To distinguish tholeiitic and calc-alkaline rocks, we used the FeO/MgO–SiO_2 (Miyshiro, 1970) ratio, which was chosen due to the presence of a wide silica range in rocks as seen in our basaltoids (from 44 to 58 wt.% SiO_2).

All basalts and basaltic andesites of the Chkalov area were found to be alkaline corresponding to moderately alkaline rocks after the application of the alkali and silica ratio sum. The Vezdekhodnaya area basalts have been divided into two interchangeable groups – alkaline and normal alkaline, with the latter being tholleiites by the FeO/MgO – SiO_2 ratio.

The MgO–SiO_2 diagram displays that the Chkalov area basaltoids have moderate magnesium content and basaltic andesites plot in the field of Kamchatka shoshonites and Uxichan volcano (Sredinnyi Ridge, Kamchatka) igneous rocks. However, the Vezdekhodnaya area basalts with relatively elevated magnesium (up to 12.7 wt.%) belong to olivine basalts and plot close within the field of basalts of the BABB-type (Back-Arc Basin Basalts) of the Woodlark and Lau basins (Pacific Ocean) and of the WPB-type (Within Plate Basalts) of the Sredinnyi Ridge in Kamchatka. In this paper, WPB-type basalts are the rocks reported by A.B. Perepelov (2014) for volcanoes of the Sredinnyi Ridge (Kamchatka) having a crucial role for interpreting the paleogeodynamic

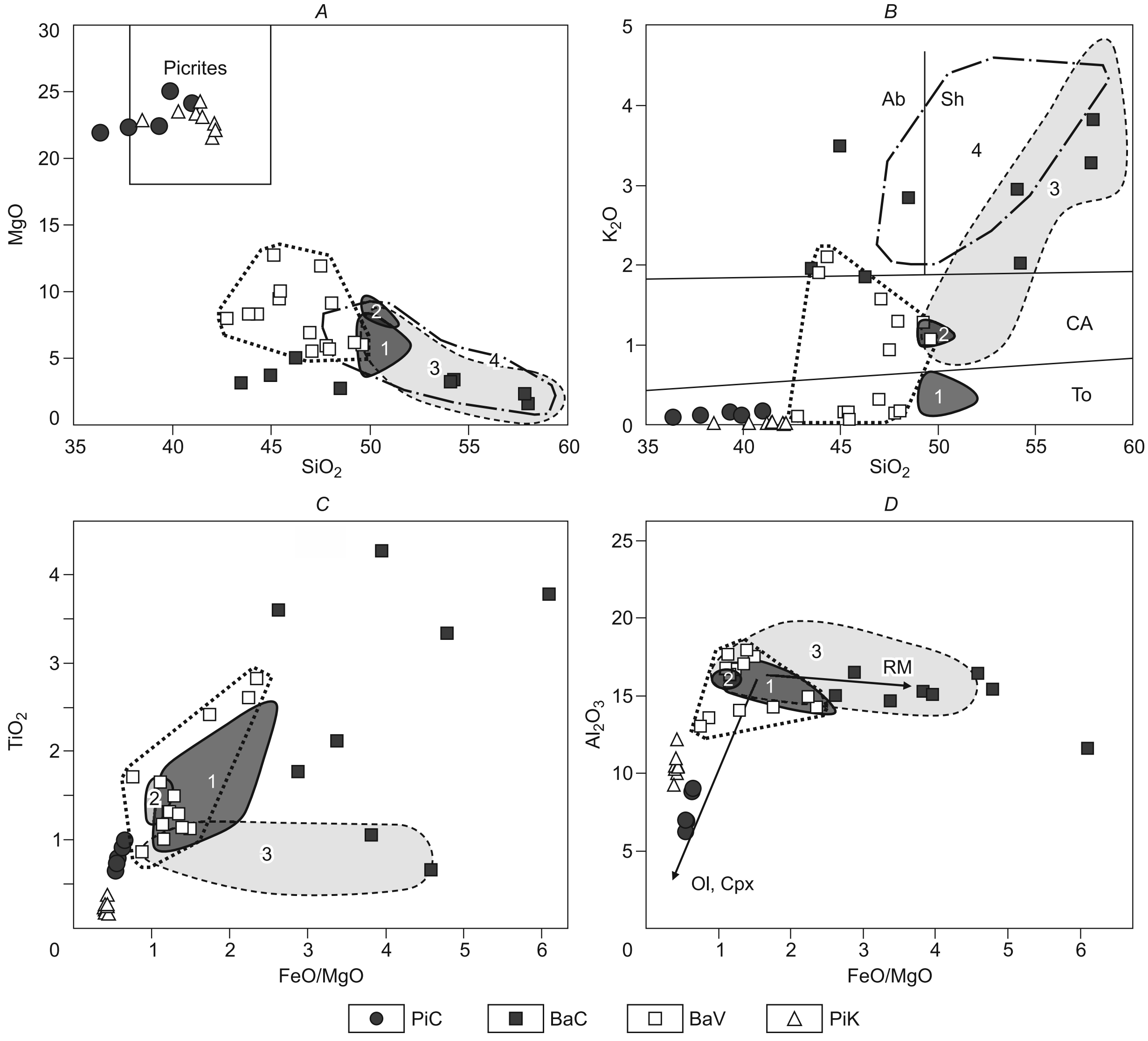

Fig. 3. Petrochemical diagrams (MgO, K_2O–SiO_2 and TiO_2, Al_2O_3–FeO/MgO) (wt.%) for early Paleozoic rocks of the Chkalov and Vezdekhodnaya areas. Chkalov area: PiC, picrites of the well 11; BaC, basalts and basaltic andesites of the well 7. Vezdekhodnaya area: BaV, basalts of the wells 3 and 4. PiK, picrites of the Sredinnyi Ridge, Kamchatka. Rock fields: basalts of the BABB type of the Woodlark and Lau basins (southwestern sector of the Pacific Ocean) (1); basalts of the WPB type of the Sredinnyi Ridge on Kamchatka (2); the Uxichan volcano igneous rocks (3, Sredinnyi Ridge, Kamchatka); Kamchatka shoshonites (4). Rock ranges: absarokites (Ab), shoshonites (Sh), calc-alkaline (CA) and tholeiitic (To) series. Dot line indicates basaltic data on the Vezdekhodnaya area. Trends of olivine (Ol) and pyroxene (Cpx) cumulates and residual melts (RM). The figure is based on original data using information from the publications (Mackenzie and Chappell, 1972; Dril et al., 1997; Lutz, 1980; Zolotukhin et al., 2003; Simonov et al., 2005, 2014, 2016; Bogatikov et al., 2009; Konnikov et al., 2010; Davydova, 2014; Perepelov, 2014; GEOROC http://georoc.mpch-mainz.gwdg.de/georoc/).

settings of the formation of island arc structures in subduction zones.

The Chkalov-7 well volcanic rocks with high potassium content (as high as 3.5–3.9 wt.%) plot within the field of absarokites (basalts) and shoshonites (basaltic andesites) by the K_2O–SiO_2 ratio. The Vezdekhodnaya area basalts have two groups. Increased potassium volcanic rocks plot within the WPB-type field of the Sredinnyi Ridge, and low potassium rocks belong to tholeiites (the noted above data by the FeO/MgO–SiO_2 ratio) and are similar to the BABB-type (Fig. 3*B*).

The TiO_2–FeO/MgO diagram shows two groups of the Chkalov area basaltoids. The first have relatively low (associated with the Uxichan igneous rocks) and high (up to 4.3 wt.%) titanium contents (Fig. 3*C*). The second group is characterized by simultaneously increased (up to 3.5 wt.%) potassium as in shoshonite. TiO_2 differences (to 3.5 wt.%) are also observed (Bogatikov, 1983) among the shoshonites from other regions.

Basaltoids from the Chkalov area on the Al_2O_3–FeO/MgO diagram coincide with the trend of residual melts, being in the Uxichan volcanic rock field. The Vezdekhodnaya

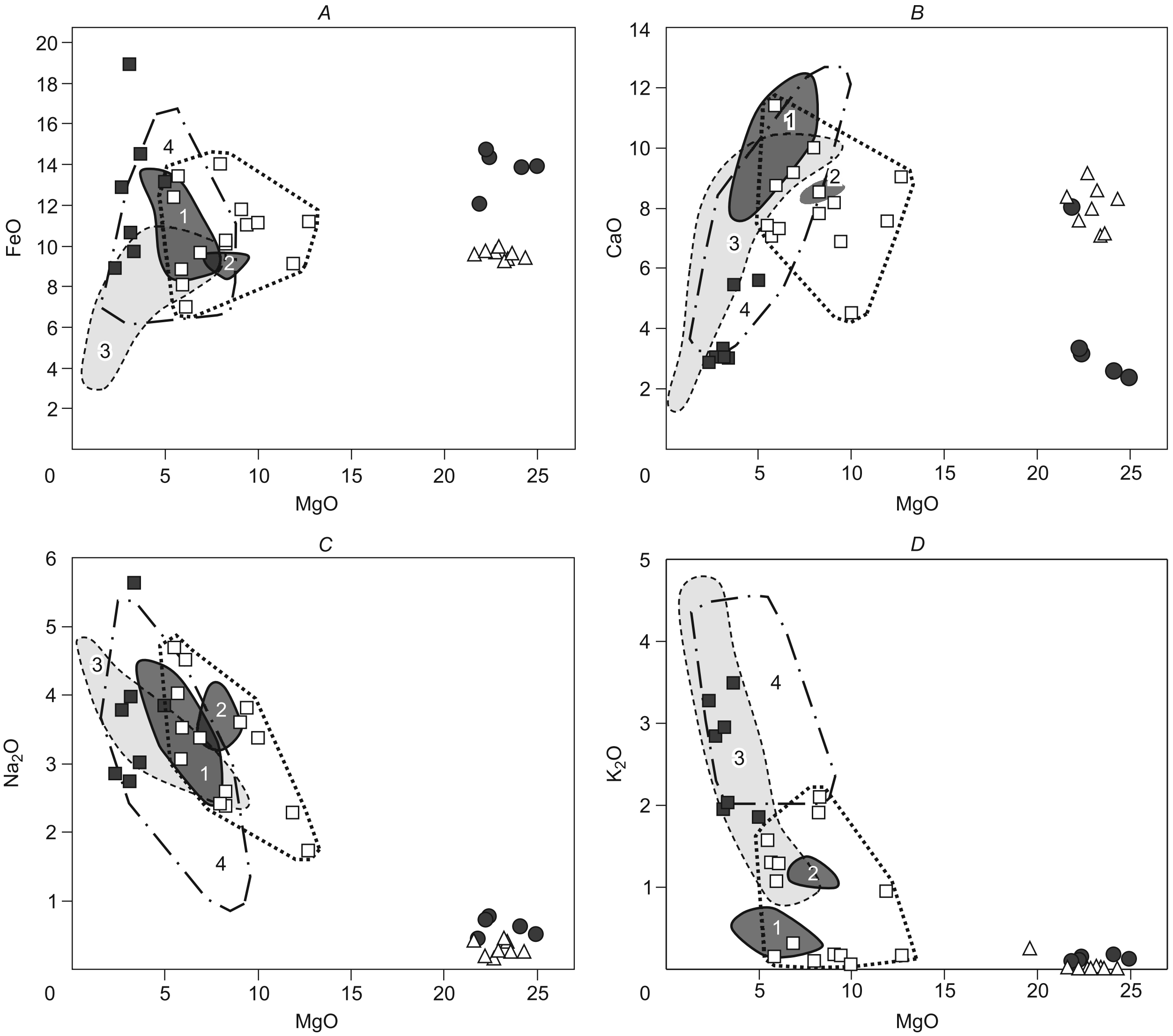

Fig. 4. Correlation of petrochemical components (FeO, CaO, Na_2O, K_2O) and MgO in compositions (wt.%) of early Paleozoic rocks of the Chkalov and Vezdekhodnaya areas. Legend in Fig. 3.

area basalts plot within the trend of olivine and clinopyroxene cumulates and divide into two groups by aluminium content. High Al_2O_3 igneous rocks are associated with the WPB Sredinnyi Ridge basalts (Fig. 3*D*).

The FeO, CaO, Na_2O, K_2O–MgO diagrams demonstrate a sharp difference of basaltoids and picrites in magnesium content (Fig. 4). Unfortunately, we cannot argue whether the transitive rocks from picrites to basaltoids exist in the Chkalov area because the available volume of rock material is limited to samples from the core of single wells.

In the diagrams of chemical components towards MgO, the Chkalov area basalts closely associate with the Uxichan volcanics and Kamchatka shoshonites. At the same time, for the Vezdekhodnaya area, basalts an obvious connection with basalts of BABB type of Woodlark and Lau back-arc basins, and also with basalts of WPB type of Sredinnyi Ridge on Kamchatka is characteristic (Fig. 4). By potassium content, two groups of basalts from the Vezdekhodnaya area are close to the BABB (low-potassium) and WPB (relatively high potassium) types (Fig. 4*D*).

In general, on petrochemical diagrams, basaltoids of the Chkalov area are mainly related to the Uxichan igneous rocks and Kamchatka shoshonites, dividing into two groups. This is clearly seen in the MgO–SiO_2, K_2O–SiO_2, TiO_2–FeO/MgO (Fig. 3) diagrams, and in the FeO–MgO diagram (Fig. 4*A*). Some rocks are characterized by high titanium and iron content at low SiO_2, and in the K_2O–SiO_2 diagram they plot within the field of absarokites. Rocks with relatively low titanium and iron have maximum SiO_2 contents and fall within the shoshonite field (Fig. 3*B*), being closely associated with the Uxichan volcanic rocks locally plotting within their fields (Figs. 3*A*–*C* and 4*A*).

In whole, petrochemical analysis of the Vezdekhodnaya area basalts showed that they considerably differ from shoshonites and less similar to the Uxichan volcanic rocks than those of the Chkalov complex. At the same time, in almost all the diagrams they plot within the fields of basalts of BABB type of Woodlark and Lau back-arc basins, and also of basalts WPB type of Sredinnyi Ridge on Kamchatka (Figs. 3 and 4). In some cases (in the K_2O–MgO diagram), by potassium content, basalts are clearly divided into two groups: associated with BABB and with WPB (Fig. 4*D*).

Petrochemical studies of **ultramafic rocks** of the Chkalov area support the results of thin section examination on the significant impact of secondary processes. This is evidenced by a high LOI up to 12 wt.%. By the (Na_2O+K_2O)–SiO_2 ratio these rocks belong to ultramafic picrite basalts of normal alkalinity, and the FeO/MgO–SiO_2 ratio shows their tholeiitic characteristics. They clearly correspond to picrites given the high levels of MgO (as high as 25–27 wt.%). In the MgO–SiO_2 diagram, compositions of ultramafics fall within the field of picrites and correspond to picrites in the Sredinnyi Ridge on Kamchatka, to which they are close in all petrochemical diagrams (Figs. 3 and 4).

Figure 4 demonstrates that in MgO content porphyric picrites are distinct from basaltoids and therefore there is no evidence on the systematic evolution of melts from picrites to basalts and basaltic andesites. According to the Al_2O_3–FeO/MgO ratio, the points of porphyric picrites plot within the trend of olivine and pyroxene cumulates correlating the data on Kamchatka picrites (Fig. 3*D*).

GEOCHEMICAL CHARACTERISTICS OF EARLY PALEOZOIC BASALT AND PICRITE COMPLEXES

Geochemical investigations showed that the content of trace elements in the rocks from the wells of two areas varies significantly. The Chkalov basaltoids that have high potassium (1.85–3.92 wt.%) and plot within the absarokite and shoshonite fields by the K_2O–SiO_2 ratio (Fig. 3*B*) are characterized by high Ba (354–835 ppm), Nb (49–160 ppm), and Zr (336–921 ppm) contents. In contrast, rocks of the Vezdekhodnaya area have much lower Ba (25–315 ppm), Nb (2.8–6.3 ppm), and Zr (58–169 ppm) contents.

The differences in geochemical patterns of the two studied igneous complexes can be seen in a diagram using trace elements immobile in secondary processes (Y, Zr, and Nb). The Chkalov basaltoids enriched by niobium and zirconium, which are distinct from the more primitive basalts in the Vezdekhodnaya wells, are located in the shoshonite field of modern island arcs and near the recycled slab component (REC in Fig. 5). Compositions of rocks from the Vezdekhodnaya area (with lower Zr and Nb) plot within the fields of the volcanic rocks of Uxichan (Kamchatka) and back-arc basins and associated with the WPB type, being located between the upper depleted mantle (DM) and enriched component (EN). The lowest niobium rocks are mainly in the field of BABB type (Fig. 5).

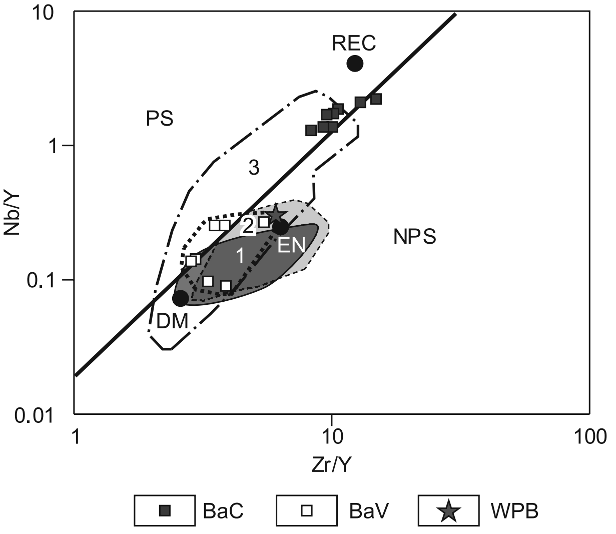

Fig. 5. Nb/Y-Zr/Y diagram for early Paleozoic rocks of the Chkalov and Vezdekhodnaya areas. BaC, basalts and basaltic andesites of the Chkalov-7 well. BaV, basalts from the Vezdekhodnaya-3 and Vezdekhodnaya-4 wells. WPB, the WPB type basalts of the Sredinnyi Ridge on Kamchatka after Perepelov (2014). Rock fields: basalts of the BABB type of the Woodlark and Lau basins (southwestern sector of the Pacific Ocean) (1, plotted after Dril et al. (1997)); the Uxichan volcanics (2, plotted after Davydova (2014)); shoshonites of the modern island arcs (3, including Kamchatka, built on (GEOROC http://georoc.mpch-mainz.gwdg.de/georoc/)). Areas of plume (PS) and non-plume (NPS) magmatism according to (Condie, 2005). DM, upper depleted mantle, EN, enriched component, REC, recycled component according to (Condie, 2005). Dot line indicates basaltic data on the Vezdekhodnaya area. The figure was made using information from (Simonov et al., 2014).

The REE distribution plots have a negative slope with a marked enrichment in light lanthanides representing the noted above patterns of Paleozoic magmatic complexes of the West Siberian basement obtained by the petrochemistry and trace element data. The REE spectra of basaltoids of the Chkalov-7 well have a steep slope and two groups. Rocks with the lowest light lanthanide content plot within the shoshonite field of contemporary island arcs, including Kamchatka. Enriched volcanic rocks are similar to the Hawaiian alkaline basalts (Fig. 6*A*), but the situation for basalts of the Vezdekhodnaya wells is more complex. These igneous rocks with the increased TiO_2 content have a flat REE spectra close to the data on the BABB-type basalts, while the spectra with a steady negative slope are for a large portion of other rocks, coincide with the WPB-type basalts of Sredinnyi Ridge on Kamchatka. Principally all the REE data for basalts of the Vezdekhodnaya area plot within the field of Uxichan volcanic rocks (Fig. 6*B*). The REE distribution plots for porphyric picrites of the Chkalov area are located in the field of light lanthanide-enriched picrites of Kamchatka and close to the Hawaiian picrite field (Fig. 6*C*). Thereby the REE data confirm the above-mentioned evidence on petrochemistry and trace elements that Paleozoic magmatism of the Chkalov and Vezdekhodnaya areas has a complex nature.

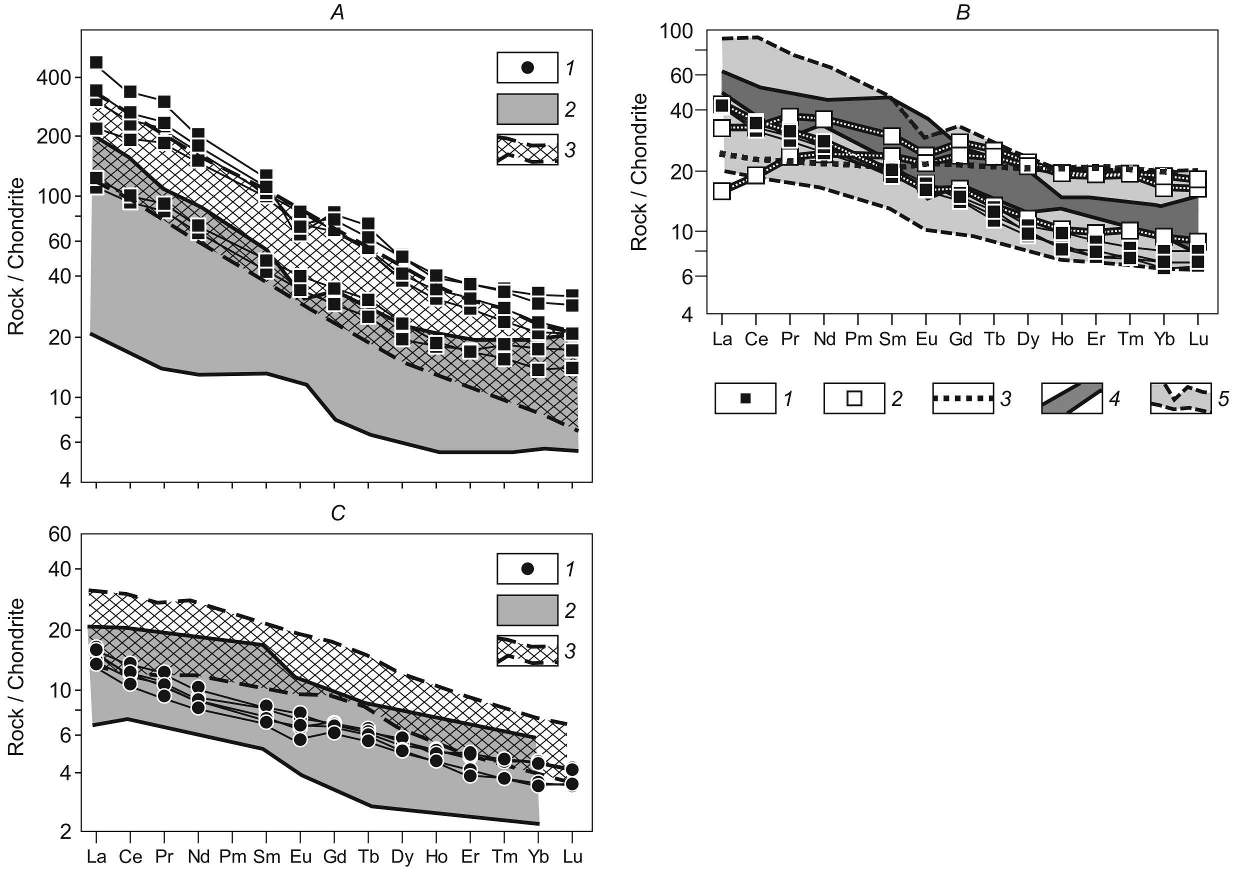

Fig. 6. REE distribution in early Paleozoic rocks of the Chkalov and Vezdekhodnaya areas. A: *1*, basalts and basaltic andesites of the Chkalov-7 well; *2*, shoshonite field of contemporary island arcs, including Kamchatka; *3*, the Hawaiian alkaline basalt field. B: *1* and *2*, basalts from the Vezdekhodnaya-3 (1) and Vezdekhodnaya-4 (2) wells; *3*, upper boundary of the BABB basalt field; *4*, the WPB basalt field of the Sredinnyi Ridge on Kamchatka; *5*, the Uxichan volcanic rock field. C: *1*, porphyric picrites of the Chkalov-11 well; *2*, the field of light lantanide-enriched picrites of Kamchatka; *3*, the Hawaiian picrite field. Element values are normalized to chondrite after (Boynton, 1984). The figure is based on original data using information from (Sharas'kin, 1992; Davydova, 2014; Perepelov, 2014; GEOROC http://georoc.mpch-mainz.gwdg.de/georoc/).

Spider diagrams of the geochemical component distribution normalized to primitive mantle support the data obtained from petrochemistry and geochemistry of trace and REE elements (Figs. 3–6). The Chkalov area basaltoids are similar to those of the Hawaiian (Fig. 7*A*). A portion of basalts in the Vezdekhodnaya area is within the BABB plot. Other igneous rocks are located in the fields of Uxichan volcanics, as well as in the WPB type basalts of Sredinnyi Ridge on Kamchatka (Fig. 7*B*). Interestingly that on basalt plots of the Vezdekhodnaya area (as for the Uxichan volcanics), there are points of distinct minima for Nb and Ta and peaks for Ba, K, and Sr, which is common for the suprasubduction rock series of island arcs (Perepelov, 2014). Porphyric picrites of the Chkalov area are close to the Hawaiian picrite field (Fig. 7*C*). Thereby the data on spider diagrams confirm that plume magmatic systems might have been involved in the formation of Paleozoic complexes of the Chkalov area and also indicate the effect of island arc and back-arc magmatism on formation of the Vezdekhodnaya area basalts.

COMPOSITIONS OF PRIMARY MINERALS OF THE PORPHYRIC PICRITES

The undertaken studies on samples from the wells of the Chkalov and Vezdekhodnaya areas showed that primary clinopyroxenes and amphiboles (Tables 4 and 5) were preserved only in the porphyric picrites. Analysis of picrite clinopyroxene compositions from the Chkalov area indicates that they belong to salites and augites according to the En–Wo–Fs ratio. Due to the high titanium content (up to 2 wt.%), at moderate iron content (FeO 6.5–7 wt.%), the studied pyroxenes correspond to the minerals from oceanic island basalts, including Hawaiian picrite clinopyroxenes. All the study clinopyroxenes correspond to the Hawaiian basalt pyroxenes by the cation ratio (Al–Mg#, Ti–Al, and others).

Almost all the amphiboles turned out to be calcium in composition after examination. In some cases, sodium-calcium amphiboles with Na_B–0.68 are present. The majority of the minerals correspond to kaersutites due to the increased

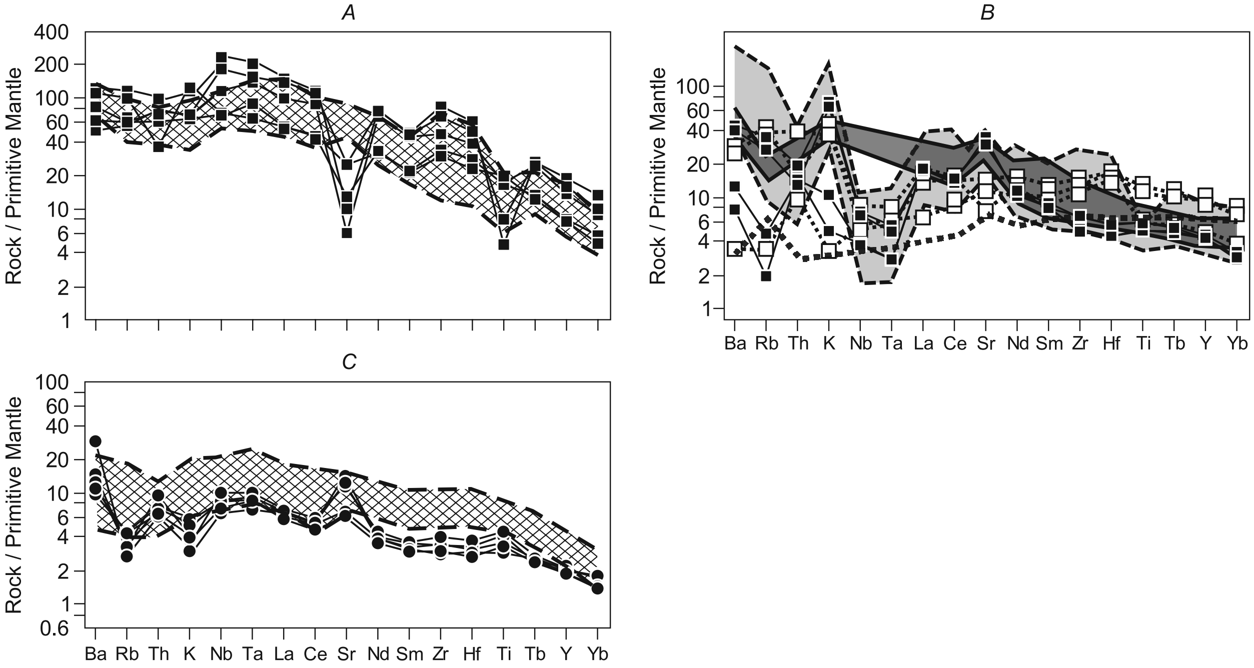

Fig. 7. Spider diagrams for early Paleozoic rocks of the Chkalov and Vezdekhodnaya areas. Legend in Fig. 6. Element values are normalized to primitive mantle according to (McDonough et al., 1992; Rollinson, 1993). The figure is based on original data using information (Sharas'kin, 1992; Sobolev and Nikogosyan, 1994; Davydova, 2014; Perepelov, 2014; GEOROC http://georoc.mpch-mainz.gwdg.de/georoc/).

(4–5 wt.%) titanium content. The K–Al^{IV} ratio demonstrates that the studied amphiboles correspond to minerals from the calc-alkaline rocks.

P–T CHARACTERISTICS OF PORPHYRIC PICRITE CRYSTALLIZATION

We use the study results of the primary mineral composition (clinopyroxenes and amphiboles) to identify the *P–T* parameters of porphyric picrite crystallization in the West Siberian Plate basement. It should be emphasized that the calculations were made with the most advanced (2012–2018) programs (Ridolfi and Renzulli, 2012; Yavuz and Yildirim, 2018), but earlier proven thermobarometers were also applied (e.g., Mercier, 1980; Perchuk, 1980; Lindnsley and Dixon, 1983; Johnson and Rutherford, 1989; Schmidt, 1992). This way gave us an opportunity to perform mutual testing of the used methods and to obtain the most accurate data on *P–T* conditions of the clinopyroxene and amphibole formation.

Testing the mineralogical thermobarometers by other methods during a comparative analysis with the study results of reference objects is of great importance. Such activities made for the Kamchatka igneous rock (contemporary subduction zone) showed a good correlation of the material obtained using amphibole barometers with the seismic data on magma chambers beneath volcanoes (Dobretsov et al., 2016, 2019).

For this purpose, amphiboles of the Chkalov area porphyric picrites have been studied with great care and the obtained dataset on their compositions have appeared to be very representative (Table 5). Based on the dataset we applied various mineralogical barometers (Johnson and Rutherford, 1989; Schmidt, 1992) to calculate crystallization pressures of 3–4.4 and 5–6.3 kbar with maximum values coinciding with data on amphiboles from the Sredinnyi Ridge igneous rocks, Kamchatka (Uxichan and Ichinsky volcanoes (Dobretsov et al., 2016, 2019)).

Using the modern programs of (Ridolfi and Renzulli, 2012) following amphibole compositions made it possible to estimate not only pressure, but also the crystallization temperature that resulted in the main (4.5–6.1 kbar, 1060–1105 °C) and rare (3–3.5 kbar, 1005–1020 °C) values. By pressure, these data are quite consistent with the material (obtained on amphiboles) for magmatic systems beneath the Uxichan and Ichinsky volcanoes on Kamchatka (Fig. 8).

Calculations using the WinPLtb program (Clinopyroxe-Liquid Thermobarometry) (Yavuz and Yildirim, 2018), involving the compositions of clinopyroxenes from porphyric picrites, showed that crystallization of clinopyroxenes began at the considerable depths of 25–20 km and high temperatures of 1300–1275 °C. The application of earlier clinopyroxene thermobarometers (Mercier, 1980; Perchuk, 1980; Lindnsley and Dixon, 1983) supports the above mentioned characteristics and exhibits a wide temperature range of 1270–1040 °C of pyroxene crystallization at minimum pres-

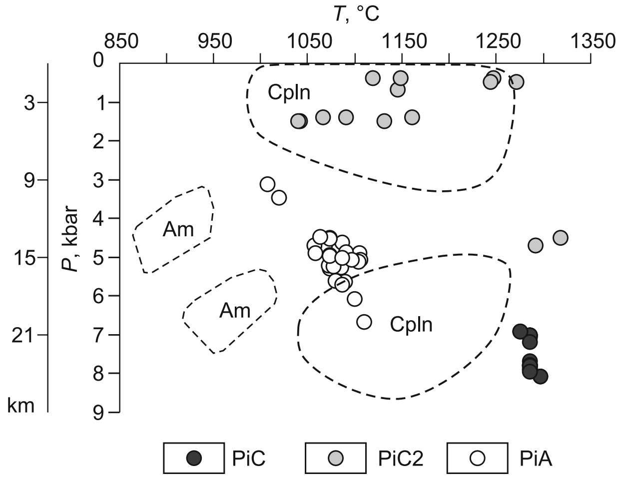

Fig. 8. Crystallization parameters of clinopyroxenes and amphiboles from porphyric picrites of the Chkalov area. Data on the *P–T* parameters of crystallization of clinopyroxenes (PiC, PiC2) and amphiboles (PiA) are calculated using various thermobarometers (PiC – (Yavuz and Yildirim, 2018); PiC2 – (Mercier, 1980; Perchuk, 1980; Lindnsley and Dixon, 1983); PiA – (Ridolfi and Renzulli, 2012)). Data fields on clinopyroxenes and melt inclusions (CpIn) from the Uxichan volcano igneous rocks and on amphiboles (Am) from the Uxichan and Ichinsky volcanoes igneous rocks (Sredinnyi Ridge, Kamchatka). The figure is based on original data using information from (Dobretsov et al., 2019).

sures of 1.5–0.4 kbar, and high temperatures of 1318–1293 °C at moderate pressures of 4.7–4.5 kbar.

The main crystallization interval of clinopyroxenes of porphyric picrites in the Chkalov area at a depth of 25–20 km (8.1–6.9 kbar) and at temperatures of 1300–1275 °C can be distinguished using the WinPLtb program (Yavuz and Yildirim, 2018). These parameters have been tested by other applications: (PETROLOG (Danyushevsky and Plechov, 2011), COMAGMAT (Ariskin and Barmina, 2000, 2004), and PLUTON (Lavrenchuk, 2004)). The following initial characteristics of the magmatic system were used in computational modeling — the composition of porphyric picrite that has undergone minimum alteration. It is a C-11-15 sample (in which clinopyroxenes were studied) in Fig. 3*A* and by SiO_2 41.00 wt.% and MgO 24.14 wt.% falls within the center of the picrite field and corresponds to Kamchatka picrites. The pressure is 7 kbar, water content (presence of the primary amphibole in porphyric picrite indicates influence of H_2O) is 0.6 wt.% (according to the data on melt inclusions in minerals from ultramafic rocks of South Tuva ophiolites formed in ancient transitional ocean-continent zone (Simonov et al., 2009)). The buffer is of the QFM type. PETROLOG computations showed that the liquidus crystallization of clinopyroxene from the picrite melt at a pressure of 7 kbar and at a depth of 21 km occurred in the range of 1325–1315–1275 °C. Using COMAGMAT indicated an augite-melt equilibrium at a temperature of about 1300 °C and at a pressure of 7 kbar, and a picrite composition of the melt. The same temperature results for the augite-melt equilibrium and at the same pressures and magma composition have been obtained in the PLUTON modeling. Thereby the simulation results for all three programs are in good agreement with the data calculated by (Yavuz and Yildirim, 2018) on *P–T* parameters of the clinopyroxene crystallization at a deep depth interval of 8.1–6.9 kbar and 1300–1275 °C.

The olivine of porphyric picrites began to crystallize at the temperatures of 1540–1490 °C by computational modeling with the same programs (PETROLOG, COMAGMAT, PLUTON) under maximum pressures of 8–7 kbar.

We have compared the formation processes of the study rocks of the West Siberian Plate in natural environments with the results of crystallization experiments of picrite melts. Our experiments on high temperature with melt inclusions in Cr-spinels from the ophiolite dunites (Kuznetsk Alatau) showed that when the homogeneous picrite melt is rapidly cooled, idiomorphic olivine crystals form resulting in (after quenching) a synthetic rock almost similar in structure and composition to the Chkalov area porphyric picrites (Fig. 9). Hence,

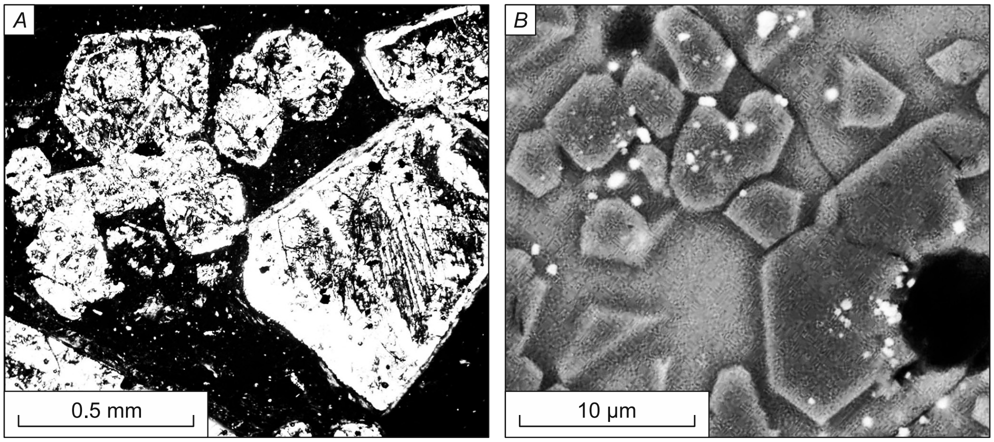

Fig. 9. Cumulate structures with olivine phenocrysts resulted from the rapid crystallization of picritic melts during the formation of porphyric picrites of the Chkalov area in natural environments (*A*) and during our high-temperature experiments with melt inclusions in Cr-spinels from ophiolite dunites of the Kuznetsk Alatau (*B*).

the formation of the considered ultramafics of West Siberia during the crystallization of olivines from rapidly ascending picrite melts has been experimentally verified.

DISCUSSION

A review of the available material showed only few previous publications on Paleozoic basalt and picrite complexes in the West Siberian Plate basement (e.g., Kuzovatov et al., 1988, 1995; Kontorovich et al., 1999; Saraev et al., 2004; Saraev and Ponomarchuk, 2005; Simonov et al., 2014, 2018, 2019; Ivanov et al., 2016). There are several opinions on the formation conditions of Paleozoic picrite basalt associations in West Siberia according to the analysis of the published works.

In the most early works of N.I. Kuzovatov with co-authors (1988, 1995) porphyric picrites have been documented in the southeastern West Siberian Plate similar to those of Maimecha-Kotui (Siberian platform). In general, ultramafic rocks are recognized in the West Siberian Plate basement represented by serpentinites, maimechites, and porphyric picrites, suggesting maimechite magmatism (Siberian platform) genesis of picrite complexes in the West Siberian Plate.

In the article of A.E. Kontorovich with co-authors (1999) an origin of the Paleozoic basalt complexes of the West Siberian Plate (Vezdekhodnaya-4 well) is connected with the development of the Cambrian back-arc basin on the active margin of the Siberian continent. In the work (Simonov et al., 2014) results of petrological-geochemical and isotopic researches confirm the formation of the complexes in the Chkalov and Vezdekhodnaya areas in the geodynamic settings of active margin of the ancient ocean.

In the following publications of V.A. Simonov with co-authors (2018, 2019) noted that the petrochemical analysis testify that Paleozoic porphyric picrites of West Siberia are similar to those of the Castor Guyot (western Pacific Ocean). Data on the trace element geochemistry suggest a plume source for these porphyrites. REE distribution plots in porphyric picrites are close to Hawaiian picrite spectra. Given that the Castor Guyot, whose magmatism is similar to that of Hawaiian Islands, is located near the Izu-Bonin island arc (Pacific Ocean margin) (Simonov et al., 2004), the Paleozoic picrite basalt complex would have been formed in the active margin due to the OIB-type plume magmatism. In addition to that the given age of the West Siberian picrites of 495 Ma, there is no connection with maimechite magmatism of the Siberian platform.

As a whole, after reviewing the available publications we have found that the formation of the study complexes took place due the development of magmatic systems on the active continental margin. The results of isotopic-geochemical and mineralogical investigations obtained in our article are consistent with the noted conclusions.

First of all, the ^{40}Ar/^{39}Ar analysis demonstrated that the maximum age characteristics of the studied rocks from the Chkalov and Vezdekhodnaya areas are consistent indicating the Cambrian time (520–495 Ma) formation of these basalt and picrite complexes. The younger ages (400, 380, and 220 Ma) are most likely linked to the stages of secondary rock alteration. The established difference in the formation period of the study associations of about 25 Ma from the range of 520–495 Ma coincides with the data for the present ocean-continent active zone. For example, in the position of the modern Sredinnyi Ridge on Kamchatka the Central Kamchatka island arc existed during the late Oligocene (28–23 Ma) (Khanchuk and Ivanov, 1999).

On the Vezdekhodnaya area, Paleozoic basalt complexes are closely associated with older granitoids and this region is notable for the modern active ocean-continent zone. In particular, a continental-type crust with granitoids exists beneath a volcanic belt of the Sredinnyi Ridge on Kamchatka (Balesta, 1981) and within its southern end the Paleozoic and Mesozoic granite-metamorphic complexes are overlain by Cenozoic igneous rocks.

Petrochemical studies showed that picrites and basaltoids of the Chkalov area have similar composition to the island arc rocks of the Sredinnyi Ridge on Kamchatka. Moreover, basaltoid volcanic rocks exhibit a significant similarity with shoshonite series rocks. In the Vezdekhodnaya area, magmatic complexes have another formation path because they are close to the BABB type basalts of Woodlark and Lau back-arc basins (Pacific Ocean), and also to WPB type basalts of the Sredinnyi Ridge on Kamchatka. As a whole, the studied Paleozoic complexes of West Siberia have features of island-arc type systems coincident with the characteristics of present-day volcanic bodies located, in particular, on Kamchatka and having shoshonites and picrites in addition to basaltoids. Petrochemical data on the Vezdekhodnaya area basalts show the development of the enriched magmas of the WPB type of the Sredinnyi Ridge on Kamchatka and BABB type melts of the back-arc basins in the transition zone of ocean-continent.

Geochemical studies show that the obtained data on trace and REE elements generally confirm the petrochemical material on the complex nature of Paleozoic magmatism in West Siberia, including magmatic systems with characteristics of basalt (island arc and back-arc basins), picrite, and shoshonite melts. Signs of magma involvement with some plume characteristics have been noticed in the Chkalov area, while in the Vezdekhodnaya area, all the trace and REE element plots (Figs. 5, 6, and 7) represent the characteristics of island arc and back-arc basalts, with a certain involvement of the WPB type melts of the Sredinnyi Ridge on Kamchatka.

If we divide the study complexes by origin, the majority of basaltoids of the Chkalov area, whose compositions are closely related to the data on the Uxichan volcanics (Kamchatka), can be generally attributed to island arc (subducted) complexes with shoshonites. While some samples possess certain signatures of plume magmatism. Due to the close connection with Kamchatka picrites, the Chkalov area porphyric picrites are most likely belong to island arc systems, but with some plume characteristics. The Vezdekhodnaya area rocks have the characteristics of island arc and back-arc basalts with a certain involvement of melts like the WPB type of the Sredinnyi Ridge on Kamchatka.

Not only petrochemical and geochemical data indicate a complex nature of the considered Paleozoic picrite basalt magmatism in the West Siberian plate, but also the compositions of primary minerals (clinopyroxene) in the Chkalov area picrites and REE data show that plume melts may have been involved.

In general, petrochemical, isotope-geochemical, and mineralogical studies indicate the formation of early Paleozoic basalt and picrite complexes in the West Siberian Plate basement principally in the Cambrian period (520–495 Ma) in the ancient active transition ocean-continent zone, which is close to present-day systems with island arcs and back-arc basins (Pacific Ocean).

The paleogeodynamic settings of formation of the described complexes in West Siberia appear to be related to the development of complex subduction zone with various magmatic systems of the Paleo-Asian Ocean. Data on the Chkalov area samples reflect an island arc development of the paleosubduction zone, and the Vezdekhodnaya area materials include a record both on the island arc and back-arc basin. Since the studied basaltoids of the Chkalov area generally correspond to the island arc complexes of Kamchatka, and some basalts of the Vezdekhodnaya area in petrochemistry and geochemistry of trace and REE elements are similar to the WPB type igneous rocks of the Sredinnyi Ridge (Kamchatka), it is possible that the magmatic systems like of the Kamchatka WPB type (of asthenospheric origin) (Perepelov, 2014) have participated in the formation of the West Siberian Plate Paleozoic complexes.

The study results are supported by reconstruction of paleogeographical situation and volcanism manifestation (Filippov and Saraev, 2015; Saraev, 2015) indicating that basalt complexes of the Vezdekhodnaya area formed in the active back-arc basin on the Paleo-Asian Ocean margin. Basaltoids, tuffs, and tufaceous turbidites (Vezdekhodnaya-4 well) exist in the bottom of the section. A carbonate unit locally covered by deep-sea basalt (Vezdekhodnaya-3 well) and tuff layers can be seen in the section top. Eastward the Vezdekhodnaya-4 well, a passive part of the back-arc basin is located, where carbonates dominate in the sediments (Saraev, 2015).

Recent investigations have resulted in new data on the conditions of formation of carbonate-volcanic sedimentary complexes of the Chkalov and Vezdekhodnaya areas. It should be noted that in the Chkalov area pre-Jurassic sediments penetrated by the Chkalov-11 well are composed of fine-grained carbon limestone and dolomitized limestone which, in some places, have graded bedding and intercalated with black carbon silicites. The composition and structure of this rock association indicate a relatively abyssal origin and can be compared to the Cambrian Kuonamian complex and its age equivalent represented by the Paiduga suite on the Fore-Yenisei basin margin, where the fine-grained carbonate material was associated with breaking of an isolated reef system located at the upper boundary of continental slope. The above mentioned patterns suggest that there is no sense in the comparison of silica carbonate-volcanic complex of the Chkalov area with guyot formations, where close spatial connection of carbonate sediments with volcanic edifices may occur, but in quite different sedimentation settings. Composition of sedimentary-volcanic complex in the Vezdekhodnaya area dominated by distal tephra turbidites and silicites that alternate with flood basalt also exhibits their abyssal nature in the settings of the active back-arc basin margin. The model of formation of the Chkalov area picrites linked to the development of a guyot cannot be applied to the detailed study of carbonate-sedimentary complexes, since we proposed it using the data only on magmatic rocks (Simonov et al., 2019).

Identifying the conditions of formation of the Chkalov area porphyric picrites yielded important data by using the clinopyroxene and amphibole compositions and computational modeling. In particular, calculations in the modern WinPLtb program (Yavuz and Yildirim, 2018) tested by modeling with the application of well-known programs (PETROLOG (Danyushevsky and Plechov, 2011), COMAGMAT (Ariskin and Barmina, 2000, 2004), and PLUTON (Lavrenchuk, 2004)) provided determination of *P*–*T* parameters of the clinopyroxene crystallization under maximal conditions of 8.1–6.9 kbar and 1300–1275 °C. Simulations in the same programs (PETROLOG, COMAGMAT, PLUTON) at maximum pressures of 8–7 kbar demonstrated that the olivine of porphyric picrites crystallized at the temperatures of 1540–1490 °C.

Applying the present-day programs (Ridolfi and Renzulli, 2012) it was found that amphiboles of porphyric picrites crystallized mainly in a range of 6.1–4.5 kbar that in fact coincides with the data of 4.7–4.5 kbar on clinopyroxenes established by a number of thermobarometers (Mercier, 1980; Perchuk, 1980). Using the same thermobarometers updates the above mentioned characteristics showing the clinopyroxene capability to crystallize at minimum pressures of 1.5–0.4 kbar.

In general, computational modeling with the application of a whole set of thermobarometers and programs suggests that the main crystallization of olivines and clinopyroxenes from the studied porphyric picrites in the West Siberian Plate basement has taken place in a deep interval of 25–20 km. Amphiboles formed further upward at the 18–12 km depths.

Comparative analysis of *P*–*T* characteristics of the Chkalov area magmatism with the existing materials on modern structures showed that the obtained results on conditions of the development of the Paleozoic magmatic systems in West Siberia are quite consistent with the data on amphiboles, clinopyroxenes, and melt inclusions from the Uxichan volcanics (Kamchatka), and with the seismic exploration results of the location of magma chambers beneath other Kamchatka volcanoes (Dobretsov et al., 2016, 2019). Thereby, the comparison with reference objects in contemporary island arc systems suggests that the mineral crystallization intervals established in the present research could exist during the formation of the study Paleozoic (paleo-island arc in origin according the study results) complexes.

According to the carried out studies and identified similarity of petrochemical and geochemical characteristics of the early Paleozoic complexes of the West Siberian basement with the features of igneous rocks of the Sredinnyi Ridge on Kamchatka, we can assume that the geodynamic conditions of formation were similar too, that is to say, in both cases magmatic systems operated in the formation of a "slab-window" according to (Flower et al., 1998; Davydova, 2014; Perepelov, 2014) at the subducted plate rupture process.

It is necessary to note that the geodynamic model with a slab window and asthenosphere plume was proposed earlier to explain the patterns of development of magmatic systems of the Sredinnyi Ridge on Kamchatka (Perepelov, 2014). Particularly, A.B. Perepelov in his doctoral thesis on the Kamchatka Cenozoic magmatism (2014 a, p. 304) reported that "in the volcanic belt of the Sredinnyi Ridge K-Na alkaline-basalt magmatism forms close in origin with the matter upwelling of the West Kamchatka asthenosphere plume ... Conditions for the activation of plume magma generation were the formation of a slab-window in the subducted … oceanic lithosphere plate".

CONCLUSIONS

1. ^{40}Ar/^{39}Ar analysis revealed that the maximum age characteristics of the studied early Paleozoic rocks from the Chkalov and Vezdekhodnaya areas are consistent, suggesting the Cambrian age of basalt and picrite complexes in the range of 520–495 Ma.

2. Petrochemical analysis and data on trace and REE elements, and compositions on primary minerals (clinopyroxene) in the rocks of the early Paleozoic basalt and picrite complexes of the West Siberian Plate demonstrate nature complexity of their formation, involving magmatic systems with basalt (island arc and back-arc basins), picrite and shoshonite (and also the WPB type) melt characteristics. The most close contemporary situation is observed in the region of the Sredinnyi Ridge on Kamchatka, where not only similar island arc basaltoids are expanded, but picrites (Konnikov et al., 2010), shoshonites, WPB type basalts, and marginal sea sediments (Perepelov, 2014) are presented.

3. In general, investigations have shown that the formation of early Paleozoic basalt and picrite complexes of West Siberia associated with the development of a complex Cambrian subduction zone of the Paleo-Asian Ocean, whose fragments are represented on two examined polygons, have their distinctive peculiarities. Particularly, data on the samples from the Chkalov area wells reflect mainly an island arc stage of paleosubduction structure development with some participation of a plume (recycled – REC) component, and the Vezdekhodnaya area samples have a record of magmatic systems of the island arc and back-arc basins with probable influence of the WPB type melt with participation of an enriched (EN) component.

4. The structure and composition analysis of sedimentary-volcanic complexes of the Chkalov and Vezdekhodnaya areas revealed their deep-sea genesis typical for the active margin of a back-arc basin or the lower part of a continental (or island arc) slope, which confirms our study results of Paleozoic volcanic rocks of West Siberia.

5. New data obtained on the Chkalov area confirm and update the earlier conclusions of the authors (Kontorovich et al., 1999; Saraev et al., 2004; Saraev and Ponomarchuk, 2005) on the formation Paleozoic basalts of the Vezdekhodnaya area in the active margin of a back-arc basin in the early Cambrian. The island arc system migrated generally westward from the Siberian platform. The early Paleozoic section on the Chkalov area can be attributed to an isolated fragment of this island arc.

6. Using the compositions of clinopyroxenes and amphiboles supported by the computational modeling allowed identifying *P–T* parameters of the formation of Paleozoic picrite complexes. Clinopyroxene crystallized at greater depths of 25–20 km and high temperatures of 1300–1275 °C. Olivine formation might have occurred under the conditions of increased 8–7 kbar pressures at temperatures of 1540–1490 °C. Amphiboles most likely formed at 6.1–4.5 kbar and significantly lower temperatures of 1105–1060 °C.

7. Similarity in geochemical characteristics of Paleozoic basaltoids and picrites of the West Siberian basement with the Kamchatka volcanics suggests that geodynamic conditions of their formation were approximately the same. We can therefore assume that a majority of the studied Paleozoic complexes formed according to a model (as in the case of the Sredinnyi Ridge on Kamchatka (Perepelov, 2014)) of operating enriched magmatic systems in a "slab-window" during rupture of subducted plate in the presence of common island arc magmatism.

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