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GEOCHEMISTRY

New Data on the Composition of Tagamites of the Popigai Astrobleme

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Abstract—New data on the composition of tagamites (impact melt rocks) of the Popigai atsrobleme (Siberia) are presented. The preliminary results support the following major conclusions: (1) the matrix of the studied tagamites is crystallized and is composed of identified minerals; (2) the degree of the matrix crystallization and the amount of inclusions in tagamites can vary significantly; (3) tagamites are identical to the intracrater gneisses of the Popigai astrobleme by the REE contents and are distinct from them by significantly lower SiO_2 and higher Al_2O_3, FeO, MgO, and CaO contents; (4) the Popigai tagamites and intracrater gneisses are enriched in Ni (on average) in comparison with gneisses of the Khapchan Group; and (5) the various (often sufficient) degrees of crystallization of tagamites indicate the duration of the cooling of the melt, when diamonds could possibly have been dissolved.

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The Popigai crater, 100 km in diameter, is located in the northeastern part of the Anabar Shield of the Siberian Platform. It was formed 35.7 Ma ago as a result of large impact event [1–3]. The astrobleme target includes the Archean crystalline rocks of the Upper Anabar and Khapchan groups of the Anabar Shield, which are overlapped by Upper Proterozoic, Paleozoic, and Mesozoic sedimentary, mostly, carbonate and terrigenous rocks [2–4]. Impactites of the Popigai crater include various breccias (klippen, megabreccia, bottom impact breccia or turbulent flow breccia), suevites, and tagamites [5].

Impact metamorphosed gneisses and impactites of the Popigai crater (first, tagamites) contain numerous impact diamonds, which were formed as a result of the solid-phase transition of graphite of primary gneisses under impact compression [2]. The tagamites of the Popigai astrobleme are rather well characterized in [2, 5, 6]; however, they were mostly studied more than ten years ago. In recent years, tagamites have again attracted the attention of researchers due to the possibility of the industrial exploration of impact diamonds, the contents of which in the tagamites of the Skal'noe deposit is 23 k/t, on average (in local blocks, 100 k/t). This required detailed study of tagamites using modern analytical methods. In this work, we present the preliminary results of complex study of ten tagamite samples from the southern, eastern, and southeastern parts of the atsrobleme. The data on mineral composition, the contents of major and trace elements of tagamites, and the chemical composition of minerals are presented, as are comparative data on the contents of major and trace elements of five samples of the intracrater gneisses of the Popigai astrobleme.

The tagamites were studied at the Analytical Center of the Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences (IGM SB RAS, Novosibirsk). Silicate analysis for 15 major oxides was carried out on an ARL-9900-XP X-ray fluorescent spectrometer. The contents of 32 trace elements were analyzed on a high resolution ELEMENT (Finnigan Mat, Germany) ICP mass-spectrometer with a U-5000AT pulverizer ultrasound following the method elaborated in the IGM SB RAS [7]. The mineral composition was determined using X-ray diffractometry on an automatic piston DRON-4 diffractometer equipped with a graphite monochromator (CuK_2 radiation, voltage of 40 kV, current of 24 mA). The detection limit of the mineral is 1 vol %. The composition of rock-forming minerals was analyzed on a MIRA 3 LMU (Tescan Ltd.) SEM equipped with an INCA Energy 450 XMax-80 EDS (Oxford Instruments Ltd.) using an accelerating voltage of 20 kV, electron beam current of 1.5 nA, lifetime of spectrum accumulation of 20 s, and an impulse processing time with an analog–digital transformer of 20 μs (Process Time 4) [8].

The tagamites are massive aphanitic rocks, which are composed of fragments of rocks and minerals embedded in the dark matrix. Studied tagamites are light gray, gray, and dark gray, locally, saturated black (samples PK-105, PK-59, PK-419/3). In four samples (PK-64, PK-107/2, PK-108/2, PK-424/1), the matrix is locally brown, probably because of alteration

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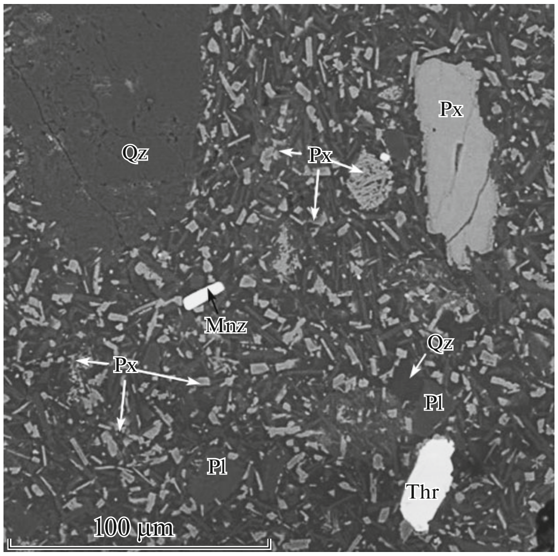

Fig. 1. Petrographic features of tagamites of the Popigai astrobleme (sample PK-105). Oz, quartz; Px, pyroxene; Mnz, monazite; Thr, troilite; Pl, plagioclase.

[5]. The matrix of all tagamites is characterized by a cryptocrystalline texture. The crystallization products of the matrix include orthopyroxene, plagioclase, and potassium feldspar, which form short prismatic crystals less than 30 μm in size (Fig. 1). By the chemical composition, orthopyroxenes include hypersthene (En_{50-67}) and ferrohypersthene (En_{50-67}). Plagioclases are mostly oligoclase–andesine (An_{30-39}) and andesine–labradorite (An_{41-59}) and rarely labradorite–bitownite (An_{64-69}) and bitownite–anorthite (An_{82}). The feldspars are subdivided into high (10.4–14.7 wt % K_2O, 0.5–2.9 wt % Na_2O) and low (2.7–6.8 wt % K_2O, 2.5–4.4 wt % Na_2O) potassium.

Inclusions in tagamites are various rocks of the target (mostly, gneisses) and their minerals. Inclusions in the tagamites make up 2–5 to 25–30%, on average, of the total rock volume, in some samples, up to 60–70%. In one sample, we observe a different percentage of the proportion of the inclusions: from areas almost devoid of them up to 70% of inclusions. In tagamites, the minerals–fragments of the target rocks are characterized by features of impact metamorphism of different stages [9]: systems of linear fractures (0), planar textures (I), reaction rims (II), and transformation into diaplectic (III–IV) and monomineral (IV) glasses. In all samples, we found diaplectic and monomineral glasses, which correspond to quartz (lechatelierite), feldspar, or plagioclase (maskelynite). The schlieren monomineral glass was found in only one sample (PK-59) and corresponds to high-K feldspar (>10 wt % K_2O).

The results of X-ray diffractometry indicate that the tagamites are mostly composed of calcic plagioclase, quartz or potassium feldspar, and, to a lesser extent, cristobalite, tridymite, mica, amphibole, smectite, and chlorite. Amorphous silica was detected only in samples PK-28/2, PK-105, and PK-349. Clino- and orthopyroxene, ilmenite, rutile, zircon, monazite, garnet, apatite, pentlandite, pyrrhotite, troilite, and Cu–Fe sulfide, the modal amount of which is <1 vol %, were found in tagamites under SEM.

The chemical composition of tagamites is relatively homogeneous (table) and is close to some out-of-crater gneisses of the Khapchan and Upper Anabar groups but are clearly distinct from them (Fig. 2): by much lower Na_2O contents from gneisses of the Upper Anabar Group and by the lower SiO_2 and Na_2O and higher MgO contents from granulites of the Khapchan and Upper Anabar groups. The studied tagamites are distinct from the Popigai intracrater gneisses in the much lower SiO_2 and higher Al_2O_3, FeO, MgO, and CaO contents. The LOI value of tagamites and intracrater gneisses is 0.03–2.72 wt % and 0.6–2.2 wt %, respectively.

The trace element content of tagamites is absolutely identical (table). The C1-normalized [10] compositions of the Popigai tagamites and intracrater gneisses are shown in Fig. 3. The trace element distribution of both rock types shows negative Sr, Sm, and Eu anomalies. The tagamites are enriched in LREEs (La_n/Yb_n 8.4–11.8; La_n/Sm_n 4.3–5.0). The HREE spectrum is almost horizontal. Generally, the REE spectrum of tagamites and intracrater gneisses is identical (by La, Ce, Sm, Eu, Tb, Yb, Lu) to that of the out-of-crater gneisses of the Khapchan Group [11]. The Ni, Cr, Cu, and Zn contents of the Popigai tagamites and intracrater gneisses are very close (table). In contrast to gneisses of the Popigai crater, tagamites have higher Sc, V, and Co contents. The tagamites are distinct from gneisses of the Khapchan Group, on average, in the higher Ni (29–51 ppm) contents in contrast to 7–36 ppm Ni for the gneisses.

Previously [2, 5], it was shown that tagamites include two major types with (1) an opaque faded chip surface and microcrystalline texture and (2) a glassy and cryptocrystalline texture. Some researchers ascribe these types to the low- and high-temperature varieties, respectively [2]. In [5], it is suggested that the initial water content in the melt is the reason for the different textures and, correspondingly, the degree of glass crystallization. The tagamite texture for low and high water contents is crypto- and microcrystalline, respectively. At this stage of study, it is impossible to ascribe our tagamites to any of the above types because, in spite of macroscopic differences, the matrix of all tagamites is crystallized and hosts identifiable minerals, whereas the degree of crystallization can vary within individual samples.

It has been suggested that the gneisses of the Khapchan Group are the primary rocks for the tagamites [1, 2, 12]. The different trace element contents of these rock types may indicate the amount of matter contrib-

Contents of major (wt %) and trace (ppm) elements of tagamites and gneisses of the Popigai astrombleme

	Tagamites										Gneisses				
No.	64	349	105	108/2	107/2	419/3	39/1	59	424/1	28/2	357/4	13/4	331/3	314/2	325/3
SiO_2	64.4	62.7	63.2	64.4	63.1	64.6	62.7	67.0	64.4	64.8	73.8	73.3	72.6	72.2	70.8
TiO_2	0.7	0.7	0.8	0.7	0.8	0.7	0.8	0.7	0.7	0.7	0.7	0.6	0.6	0.7	0.5
Al_2O_3	14.6	14.4	14.8	14.7	15.3	14.9	15.0	13.9	14.5	14.4	11.4	11.5	12.3	12.9	12.2
FeO	7.2	7.0	7.3	7.1	7.5	7.1	8.3	6.8	7.2	7.3	5.1	4.9	4.9	4.5	7.6
MnO	0.08	0.07	0.08	0.07	0.08	0.08	0.13	0.08	0.09	0.08	0.05	0.05	0.07	0.04	0.05
MgO	3.1	3.7	3.3	3.2	3.1	3.7	3.4	2.9	3.1	3.5	1.5	1.8	1.9	1.4	2.7
CaO	3.5	4.1	3.3	3.6	3.0	3.7	3.5	3.2	3.2	3.6	1.8	1.9	1.2	1.1	0.8
Na_2O	2.0	2.0	2.3	1.8	1.8	2.0	2.1	2.0	1.6	2.1	1.7	1.7	1.4	1.9	1.3
K_2O	2.7	2.7	2.1	2.9	3.0	2.8	2.9	2.8	2.8	2.3	1.8	1.8	4.1	4.0	3.3
P_2O_5	0.11	0.12	0.13	0.13	0.14	0.12	0.12	0.11	0.10	0.10	0.09	0.06	0.17	0.08	0.06
BaO	0.10	0.10	0.10	0.10	0.11	0.10	0.10	0.10	0.10	0.09	0.11	0.06	0.14	0.15	0.09
SO_3	0.13	0.03	0.08	<0.03	0.03	0.04	0.08	0.09	0.03	0.09	<0.03	<0.03	<0.03	<0.03	<0.03
V_2O_5	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.01
CrO_3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.02	0.02	0.02
NiO	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	<0.01	<0.01	0.02	<0.01	0.01
LOI	0.96	2.72	1.85	1.46	1.98	1.12	0.81	0.03	1.26	1.22	2.1	2.2	0.7	0.9	0.6
Total	99.6	100.3	99.4	100.2	100.0	100.5	99.8	99.7	99.2	100.4	100.1	100.0	100.1	100.0	100.1
Sc	15.9	15.4	16.7	16.5	16.8	16.4	17.5	14.4	15.6	15.8	12.3	11.9	10.7	13.6	13.4
V	104	82	98	98	101	102	91	94	95	85	72	71	67	80	68
Cr	131	141	146	134	140	135	151	139	136	147	172	203	153	146	124
Co	18.1	15.2	17.1	17.0	18.4	18.3	17.0	16.0	16.2	13.7	12.9	11.3	12.8	11.7	13.6
Ni	51	49	40	42	48	46	51	49	36	29	43	38	39	23	62
Cu	34	39	35	38	41	41	40	36	40	50	66	65	101	158	70
Zn	79	79	77	78	83	89	91	75	74	79	70	57	56	63	72
Rb	67	85	117	71	78	71	81	75	71	76	49	36	122	92	74
Sr	269	234	304	299	296	261	228	268	272	253	184	289	267	224	151
Y	35	30	37	36	38	39	34	31	33	30	26	27	21	23	35
Zr	247	249	255	243	250	277	256	238	228	250	304	245	235	257	179
Nb	10.6	10.3	11.0	10.7	10.9	10.9	11.1	9.8	10.2	10.1	8.9	9.4	7.1	12.1	8.2
Cs	0.48	0.82	0.63	0.19	0.30	0.26	0.49	0.63	0.79	0.56	0.18	0.18	0.36	2.5	0.25
Ba	711	693	751	741	798	700	749	773	696	705	802	463	1121	1205	762
La	45	52	52	51	51	51	54	45	45	46	42	33	47	42	32
Ce	87	99	99	98	99	99	103	87	86	90	84	64	91	84	59
Pr	11.0	11.3	12.7	12.4	12.9	12.6	11.9	10.9	11.4	9.9	10.2	7.5	10.0	9.3	6.8
Nd	38	39	44	42	44	44	40	38	39	34	37	27	33	32	23
Sm	6.5	6.5	7.0	6.7	7.4	7.3	7.0	6.3	6.4	6.3	6.3	4.7	6.2	5.6	5.0
Eu	1.31	1.19	1.42	1.55	1.45	1.44	1.33	1.15	1.29	1.31	1.10	1.44	1.19	1.28	1.13
Gd	5.6	5.9	6.1	6.3	6.5	6.7	6.5	5.1	5.9	5.9	5.2	4.5	4.9	5.1	5.6
Tb	0.95	0.85	1.04	0.99	1.00	1.05	0.96	0.81	0.99	0.94	0.74	0.76	0.76	0.74	0.94
Dy	5.7	5.2	6.0	6.1	6.0	6.3	5.5	4.9	5.5	5.2	4.3	4.5	3.8	4.3	5.7
Ho	1.13	1.02	1.24	1.24	1.19	1.22	1.16	0.99	1.08	1.08	0.91	0.90	0.69	0.88	0.19
Er	3.5	3.2	3.6	3.4	3.6	3.6	3.6	2.9	3.2	3.3	2.6	2.7	2.0	2.5	3.3
Tm	0.56	0.46	0.58	0.58	0.58	0.60	0.54	0.48	0.57	0.51	0.44	0.45	0.31	0.39	0.51
Yb	3.5	3.0	3.8	3.7	3.7	4.0	3.5	3.0	3.6	3.2	3.0	2.8	1.98	2.4	3.1
Lu	0.54	0.44	0.54	0.57	0.55	0.57	0.51	0.48	0.54	0.50	0.43	0.45	0.30	0.37	0.47
Hf	7.4	6.5	7.7	7.2	7.5	8.2	6.8	7.1	7.0	6.3	8.1	6.2	6.3	7.4	5.0
Ta	0.66	0.60	0.65	0.66	0.66	0.69	0.63	0.60	0.66	0.63	0.40	0.54	0.18	0.72	0.48
Th	10.4	14.3	11.9	11.7	11.7	12.7	14.4	11.1	10.5	11.1	11.3	5.1	13.5	7.5	4.1
U	1.49	1.74	1.28	1.43	1.32	1.52	1.76	1.49	1.20	1.46	1.77	0.86	1.25	1.40	0.95

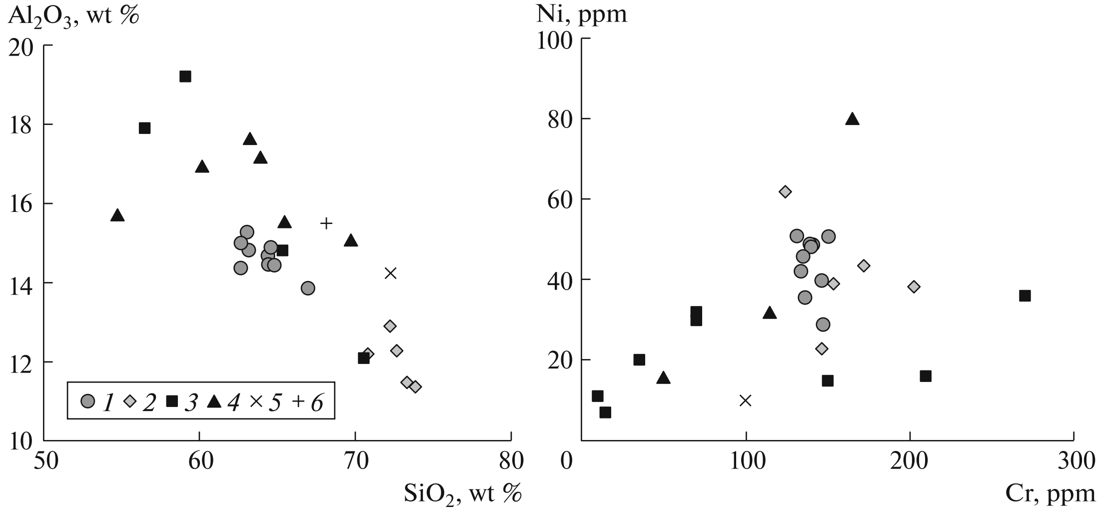

Fig. 2. Distribution of Al_2O_3/SiO_2 and Ni/Cr of tagamites of the Popigai astrobleme. *1*, Tagamite; *2*, intracrater gneiss; *3*, gneiss, Khapchan Group; *4*, gneiss, Upper Anabar Group; *5*, granulite, Khapchan Group; *6*, granulite, Upper Anabar Group. The compositions of rocks of the Khapchan and Upper Anabar groups from [11, 13, 14].

uted during the impact event. The Ni content of tagamites is generally higher than in gneisses of the Khapchan Group; however, there is a zone, the Ni content of which is similar in both rock types. The tagamites are characterized by a positive correlation between the Ni/Sc ratio and Ni, as well as the Popigai intracrater gneisses. The tagamites are enriched in Ni, whereas no Co, Sc, Cu, and Cr enrichment is observed. The Ni enrichment of tagamites can be considered as a possible impactor trace. It is necessary to take into account, that the available geochemical data on gneisses of the Khapchan Group are rather limited both by the amount of the samples studied and by the assemblage of elements analyzed [11, 13, 14]. It is also necessary to consider the high Ni contents in mafic (amphibolite schists, two-pyroxene schists, 50–90 ppm Ni) and ultramafic (amphibolized and serpentinized peridotites and pyroxenites, 1000 ppm Ni) rocks of the Popigai crater, which could also be the source of Ni [5].

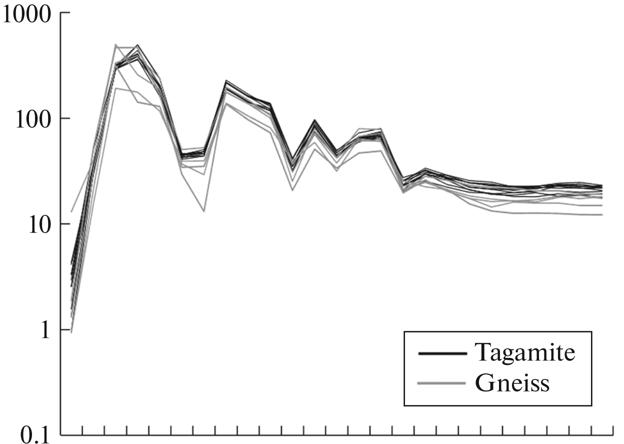

Fig. 3. C1-normalized trace element contents of tagamites and gneisses of the Popigai astrobleme [10].

The results of study of tagamites as the primary rock for the impact diamonds are important from the scientific (impactite genesis) and applied (preservation of diamonds) points of view. The various (often, sufficient) degrees of crystallization of tagamites indicate the duration of the cooling of the melt, during which diamonds possibility had to dissolve [15].

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