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Kimberlites and Related Rocks of the Arkhangel'sk Diamondiferous Province and Adjacent Areas: A Comparative Petrogeochemical Analysis

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Abstract—The formational and metallogenic affiliation of the alkaline ultramafic rocks of the Arkhangel'sk diamondiferous province and the adjacent areas of the northern East European platform were analyzed using recent concepts on the structure of the formational and metallogenic family of kimberlites and related rocks, petrogeochemical criteria, and discriminant diagrams based on reference associations. It was shown that the alkaline ultramafic magmatism of the Arkhangel'sk province belongs to various formations, which is typical of the provinces of ancient craton margins. In addition to diamondiferous kimberlites, the area hosts abundant low-grade diamondiferous kimpicrites and alpicrites, which are typically associated with rare-metal carbonatites. Significant petrogeochemical differences were detected between the diamondiferous kimberlites of the Arkhangel'sk province and the kimberlites of the classic Central Yakutian diamondiferous province. This allowed us to consider the rocks of the Arkhangel'sk province as a specific geochemical type of diamondiferous kimberlites.

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The reliable identification of potentially diamondiferous magmatic rocks and their discrimination from petrographically similar nondiamondiferous rocks showing different metallogenic characteristics are of special importance for territories with inferred or recently revealed diamond potential. Among such territories are the Arkhangel'sk diamondiferous province and adjacent areas of the northern East European platform, where alkaline ultrabasic rocks of diverse metallogenic types are very widespread.

At the same time, in addition to the traditional problem of the identification of diamondiferous rocks, the discovery of the Arkhangel'sk diamondiferous province posed new specific questions. First, the Arkhangel'sk kimberlites appeared to be significantly different from the classic kimberlites of the Central Yakutian province. In particular, the Arkhangel'sk kimberlites contain insignificant amounts of diamond-associated minerals, pyrope and picroilmenite, and have distinctive geochemical and Sr–Nd isotopic characteristics [1, 2].

Second, the available data suggest a compositional heterogeneity of the diamondiferous kimberlites of the Arkhangel'sk province: the rocks of the recently discovered Grib pipe (Verkhotina field) are significantly different from the kimberlites of the Lomonosov deposit (Zolotitsa field) and probably belong to a separate petrochemical series [3, 4]. This indicates that the group of diamondiferous kimberlites is probably heterogeneous and can be subdivided into diverse petrochemical, geochemical, and metallogenic types.

Third, the Arkhangel'sk province is presumably a rare example of a complex and heterogeneous magmatic province where alkaline ultrabasic rocks of similar petrographic compositions but different genetic associations and metallogenic potentials occur within a relatively small area.

These problems arose recently and are still being discussed. It is obvious that their solution is not restricted to this particular province but has a general significance. We hope that the analysis of the metalogenic and formation characteristics of the ultrabasic magmatic rocks of the Arkhangel'sk province and adjacent areas of the northern East European platform will provide important information for a successful solution of these problems. The analysis is based on the concept of magmatic formations advanced by F.Yu. Levinson–Lessing and developed by Yu.A. Kuznetsov. Magmatic formations are natural rock associations, which have common petrochemical and mineral compositions and metallogenic characteristics and are related to definite types of geologic structures.

The analysis was conducted using recent classifications of the kimberlite family and related rocks [5] and petrochemical and geochemical discriminant diagrams [6], which were constructed on the basis of classic or reference occurrences of major formational and metallogenic rock types. The family of kimberlites and related rocks is traditionally subdivided into two formational communities (subfamilies). One of them includes traditional formational types of cratonic alkaline ultrabasic magmatism: diamondiferous kimberlites, picrite–alnoite rocks associating with rare-metal carbonatite complexes (alpicrites), and a wide class of alkaline picrites transitional between the former two formations and having no distinct metallogenic character (kimpicrites). The other group includes diamondiferous olivine lamproites, orangeites, and rarer majhgawanites [7].

In order to obtain more representative regional and formational characteristics of alkaline ultrabasic rocks and increase the reliability of results, the diverse magmatism of the Arkhangel'sk province was considered together with occurrences of kimberlite-related rocks in the adjacent areas of the northern East European platform. The most known among them are the following:

(1) dikes and diatremes of picrites, alnoites, and olivine melilitites associating with the Caledonian formation of ultrabasic alkaline rocks and carbonatites in Turiy Mys, Kandaguba, and Kandalaksha Archipelago, as well as in the massifs of the Karelia–Kola carbonatite province (Kovdor and Vuorijarvi) and surrounding rocks [8–10];

(2) dikes and diatremes of kimberlites, picrites, and olivine melilitites recently described at the Tersky coast of the White Sea (southern Kola Peninsula) [11];

(3) diatremes and dikes of olivine melilitites of the Nenok Complex, Onega Peninsula [12];

(4) diverse alkaline ultrabasic rocks of the Middle Timan, including picrites of the Chetlas Complex [13] and kimberlites from the diatremes of the Vol'sk–Vym Range [14];

(5) dikes and pipes of olivine lamproites in the vicinity of Kostamuksha, Karelia [15–17].

Representative analyses of kimberlites and related rocks from the aforementioned territories of the northern East European platform are shown in Table 1. In addition to these analyses, a large body of data from the literature was used to construct discriminant diagrams (sources are given in figure captions).

The affiliation of some occurrences to particular magmatic formations is unambiguous. However, similar to the Arkhangel'sk province, the interpretation of some complexes is dubious, which complicates the assessment of their diamond and rare-metal potential.

It is convenient to begin our analysis from the kimberlites and related rocks of the areas of the northern East European platform adjacent to the Arkhangel'sk kimberlite province. This makes it possible to test the proposed approaches by the example of well-studied magmatic rocks before addressing the more difficult situation in the recently discovered Arkhangel'sk diamondiferous province.

The Kandalaksha Archipelago, Kandaguba, Turiy Mys, and Tersky coast of the White Sea are extremely abundant in alkaline dikes and eruption breccia bodies. The most common are thin dikes (no more than 0.3–0.4 m, occasionally up to 1–3 m thick). Most dikes have well-developed chill zones and crystallized central parts, especially distinct in thick bodies. The dikes exhibit a diverse composition and consist of monchiquite, alnoite, nephelinite, melanephelinite, melilitite, olivine melilitite, damkjernite, picrite, and other rocks described in detail elsewhere [8–10]. According to A.G. Bulakh, their absolute age is 363–365 Ma.

The rocks correspond to differentiated series. The earliest melanocratic members include picrites, phlogopite–pyroxene picrites, olivine melilitites, and alnoites, which compose the group of kimberlite-related rocks of interest. The later magmatic events produced nephelinites and other alkaline rocks. Compositionally similar dike series were found near and within the Kovdor, Vuorijarvi, and other alkaline massifs of ultrabasic rocks and carbonatites.

Most of the dikes and explosion bodies of the area are now ascribed to the vein series of the formation of ultrabasic alkaline rocks and carbonatites. However, there was a period when picrite and damkjernite breccias in the Kandalaksha Archipelago [20] were considered as prospecting criteria for kimberlite pipes and diamonds.

The vein and explosion bodies of kimberlite-related rocks affiliate with the alkaline ultrabasic carbonatite formational–metallogenic type and mark the Kandalaksha (Belomorian) graben, a Riphean rift structure activated in the Paleozoic.

Kimberlite occurrences were recently found in the Ermakov area of the Tersky coast on the eastern flank of the area considered [11]. To the west toward Turiy Mys, they are changed by olivine melilitites and then by diverse alkaline dikes of the Turiy Group. The Nenok Complex of olivine melilitites of the Onega Peninsula on the southern coast of the White Sea [12] is presumably the western termination of this dike series; the Arkhangel'sk kimberlite province is located farther to the east.

In the discriminant diagrams of SiO_2/MgO–$MgO/\Sigma FeO$ (Fig. 1a), $(Al_2O_3 + Na_2O + K_2O)$–$MgO/\Sigma FeO$ (Fig. 1b), and $MgO/\Sigma FeO$–TiO_2 (Fig. 1c), almost all the aforementioned rocks marking the Kandalaksha graben are plotted in the alpicrite field. The only exception is the rocks from the Ermakov area of the Tersky coast, which were described as kimberlites [11]. They are situated in the northern flank of the Arkhangel'sk diamondiferous province and fall within the field of weakly diamondiferous kimpicrites. The significant extent of the alpicrite field along the $Al_2O_3 + Na_2O + K_2O$ and SiO_2/MgO axes suggests that the alpicrites include a differentiated series, which is represented by alkaline picrites, phlogopite–pyroxene picrites, olivine melilitites, and alnoites near the field of kimberlite

Table 1. Representative analyses of ultramafic alkaline rocks from the Arkhangel'sk diamondiferous province and adjacent areas (weight of trace elements in ppm)

Component	1	2	3	4	5	6	7	8	9	10	11
SiO_2	42.6	41.9	42.2	39.2	41.65	44.4	40.31	39.55	39.02	40.42	38.18
TiO_2	0.82	0.88	0.63	0.9	1	1.3	1.15	1.05	1.05	0.87	0.71
Al_2O_3	3.19	3.27	3.05	1.8	4.61	4.8	1.51	2.02	2.17	1.32	1.59
Fe_2O_3	3.9	4.2	3.81	4.1	9.16	5.63	3.13	4.55	4.80	4.05	3.65
Cr_2O_3	–	–	–	–	–	0.17	–	–	–	–	0.14
FeO	2.7	2.86	3.22	3.53	–	2.49	4.20	3.13	2.86	3.40	3.72
MnO	0.15	0.15	0.13	0.17	0.21	0.16	0.14	0.10	0.11	0.15	0.11
MgO	27.83	28.15	29.3	33.3	18.65	21.88	33.07	33.00	33.49	34.63	36.78
CaO	3.85	3.73	4	5.2	9.4	5.67	2.49	3.00	3.01	1.10	1.72
Na_2O	1.51	1.12	1.44	0.44	1.09	1.43	0.17	0.42	0.18	0.08	0.06
K_2O	0.5	1.47	0.34	1.56	0.98	1.76	0.41	0.38	0.45	0.08	0.14
P_2O_5	0.52	0.36	0.34	0.58	0.71	0.96	0.11	0.18	0.24	0.08	0.11
SO_3	–	–	–	–	–	–	–	–	–	–	0.09
H_2O	7.56	7.9	8.34	6.7	–	7.12	12.43	–	–	–	–
CO_2	0.52	1.39	0.44	1.28	–	1.21	1.10	–	–	–	–
L.O.I.	3.32	2.94	2.13	0.70	11.48	–	–	12.76	13.09	12.80	13.72
F	0.12	0.14	0.11	0.27	–	–	–	–	–	–	–
Total	99.09	100.46	99.49	99.73	98.94	98.98	100.27	100.14	100.47	99.98	100.72
Cr	903	839	835	1254	1556	–	1100	–	–	880	–
Ni	944	978	1071	1075	817	–	1450	–	–	1771	–
Co	64	68	76	86	–	–	70	–	–	88.64	–
Sc	11	10	9	10	19.1	–	–	–	–	–	–
V	84	84	73	73	101	–	63	–	–	155	–
Rb	16	41	14	39	27.9	–	20	16.36	20.44	12.39	–
Cs	0.3	0.3	0.5	0.6	–	–	0.7	0.35	0.83	0.13	–
Ba	695	1386	730	662	622	–	–	–	–	–	–
Sr	307	367	453	476	651	–	179	135	98	543	–
Li	51	37	40	17.6	–	–	–	–	–	–	–
Ta	2.1	2.4	1.5	2.5	–	–	–	–	–	–	–
Nb	29	36	20	31	70	–	38	27.79	36.91	73.53	–
Hf	3.6	4.6	2.7	2.5	–	–	–	–	–	–	–
Zr	113	136	85	76	119	–	59.5	34.94	38.76	67.64	–
Y	16	19	15	16	14.6	–	5	4.01	4.32	6.64	–
Th	5	6.3	3.6	3.7	5	–	–	–	–	–	–
U	0.5	0.6	0.4	0.1	–	–	–	–	–	–	–
La	40.2	40.6	22.5	34.5	–	–	–	–	–	–	–
Ce	62.8	72.6	40.4	55.9	–	–	–	–	–	–	–
Nd	25	39	27	27	–	–	–	–	–	–	–
Sm	4.4	5.2	2.9	3.7	–	–	–	–	–	–	–
Eu	1.1	1.5	0.8	1.1	–	–	–	–	–	–	–
Tb	0.6	0.5	0.5	0.4	–	–	–	–	–	–	–
Yb	0.9	1.1	0.9	0.9	–	–	–	–	–	–	–
Lu	0.12	0.12	0.16	0.12	–	–	–	–	–	–	–

Table 1. (Contd.)

Component	12	13	14	15	16	17	18	19	20	21	22
SiO_2	37.03	37.4	34.0	33.1	35.1	34.5	34.43	41.68	37.77	36.48	36.62
TiO_2	0.88	3.12	2.38	2.44	1.85	3.14	2.67	3.11	3.14	1.84	4.49
Al_2O_3	2.36	3.95	4.3	4.1	2.65	1.8	3.74	6.77	6.01	2.76	8
Fe_2O_3	4.54	8.42	9.72	8.6	6.89	9.16	11.78	11.59	9.14	7.58	15.54
Cr_2O_3	0.15	–	–	2.51	–	–	–	–	–	–	–
FeO	3.02	3.18	1.69	0.2	2.28	1.64	–	0.64	2.91	0.94	1.39
MnO	0.1	0.21	0.21	27.01	0.24	0.41	0.22	0.14	0.14	0.24	0.14
MgO	35.63	25.18	27.37	3.99	27.5	29.5	30.8	20.33	17.59	28.51	19.49
CaO	1.39	3.68	4.19	0.27	4.56	3.74	1.8	4	7.51	5.05	3.11
Na_2O	0.05	0.34	0.22	1.44	0.23	0.2	0.29	0.24	0.42	0.11	1.11
K_2O	0.26	1.59	1.38	2.6	0.21	0.42	1.38	0.46	1.4	0.47	0.64
P_2O_5	0.26	1.24	2.4	–	0.58	0.44	0.9	0.84	0.55	0.34	0.98
SO_3	0.09	–	–	–	–	–	–	–	–	–	–
H_2O	–	7.24	11.27	9.6	7.85	9.82	–	n.d.	n.d.	n.d.	n.d.
CO_2	–	3.8	1.1	1.45	4.95	2.68	–	n.d.	n.d.	n.d.	0.5
L.O.I.	13.54	1.29	–	1.66	5.15	2.03	11.31	8.83	11.33	14.79	7.64
F	–	0.16	0.26	0.4	0.24	0	–	n.d.	n.d.	n.d.	–
Total	99.30	100.8	100.49	99.37	100.3	99.48	99.32	98.63	97.91	99.11	99.65
Cr	–	1590	1347	1403	1424	1715	1231	–	–	–	–
Ni	–	1115	858	819	864	1267	1221	–	–	–	–
Co	–	87	69	74	56	110		–	–	–	–
Sc	–	22	n.d.	n.d.	18	17	21.5	–	–	–	–
V	–	112	241	286	150	134	112	–	–	–	–
Rb	–	42	61	40	8	20	76.6	–	–	–	–
Cs	–	0.56	0.66	0.6	0.28	0.47	–	–	–	–	–
Ba	–	1232	1291	1704	1817	1072	1360	–	–	–	–
Sr	–	367	488	930	242	181	1039	–	–	–	–
Li	–	134.7	39.3	31	88	51.1	–	–	–	–	–
Ta	–	12.6	n.d.	n.d.	10.6	10.3	–	–	–	–	–
Nb	–	127	121	n.d.	106	84	210	–	–	–	–
Hf	–	3.6	n.d.	n.d.	4.5	3.6	–	–	–	–	–
Zr	–	124	232	n.d.	155	133	119	–	–	–	–
Y	–	18	24	n.d.	14	14	12.6	–	–	–	–
Th	–	13.5	n.d.	n.d.	15.4	8.2	13.9	–	–	–	–
U	–	5.9	n.d.	n.d.	3.8	2.7	–	–	–	–	–
La	–	145.8	n.d.	n.d.	88.2	79	–	–	–	–	–
Ce	–	243.1	n.d.	n.d.	140.1	116.8	–	–	–	–	–
Nd	–	140	n.d.	n.d.	76	55	–	–	–	–	–
Sm	–	18.7	n.d.	n.d.	10.2	5.7	–	–	–	–	–
Eu	–	2.7	n.d.	n.d.	2.6	1.7	–	–	–	–	–
Tb	–	0.7	n.d.	n.d.	0.8	0.6	–	–	–	–	–
Yb	–	5.2	n.d.	n.d.	2.2	3.9	–	–	–	–	–
Lu	–	0.09	n.d.	n.d.	0.01	0.01	–	–	–	–	–

Table 1. (Contd.)

Component	23	24	25	26	27	28	29	30	31	32	33
SiO_2	37.35	27.33	43.56	44.75	42.06	42.88	38.4	43	42.4	43.6	45.83
TiO_2	4.58	1.07	4.23	1.81	0.77	1	0.92	1.3	0.74	0.59	0.87
Al_2O_3	6.65	4.03	5.41	4.8	4.81	5.95	5.92	8.7	6.28	4.5	5.21
Fe_2O_3	13.17	8.05	11.91	3.29	5.81	6.59	8.16	7.2	3.49	4.36	8.07
Cr_2O_3	–	–	–	–	–	–	–	–	–	–	–
FeO	1.2	2.05	–	3.65	n.d.	1.57	0.74	4.21	3.3	3.41	n.d.
MnO	0.17	0.2	0.1	0.08	0.15	0.12	0.1	0.21	0.19	0.16	0.17
MgO	17.21	18.9	22.21	22.98	19.57	16.16	21.25	16.4	22.73	23.1	18.92
CaO	4.35	12.91	2.73	4.83	5.95	8.42	7.18	5.8	9.09	7.2	4.56
Na_2O	0.26	0.38	0.39	0.14	0.68	1.15	0.65	1.39	1.91	1.35	2.41
K_2O	0.5	0.48	1.4	0.84	1.81	1.52	0.85	1.58	1.34	0.91	1.42
P_2O_5	1	0.69	0.69	0.33	0.84	1.18	1.31	1.02	n.d.	n.d.	0.5
SO_3	<0.02	0.1	–	–	–	–	–	0.09	–	–	–
H_2O	8.14	4.69	–	n.d.	n.d.	n.d.	n.d.	7.05	5.74	5.5	n.d.
CO_2	1.19	16.73	–	2.41	n.d.	n.d.	n.d.	1.09	0.33	0.51	n.d.
L.O.I.	–	–	6.5	9.16	19.2	12.12	13.96	–	1.98	3.72	11.63
F	–	–	–	–	n.d.	n.d.	n.d.	–	0.05	0.11	n.d.
Total	95.77	97.61	99.13	99.07	101.65	98.66	99.44	99.04	99.57	99.02	99.59
Cr			2729	–	609	–	–	–	716	870	690
Ni	660	470	1277	–	n.d.	–	–	–	787	878	n.d.
Co	–	–		–	41	–	–	–	42	68	54
Sc	–	–	16.9	–	15	–	–	–	18	15	15
V	–	–	224	–	n.d.	–	–	–	156	101	n.d.
Rb	–	–	78.6	–	32	–	–	–	25	18	32
Cs	–	–	–	–	n.d.	–	–	–	0.57	0.66	n.d.
Ba	–	–	744	–	1317	–	–	–	251	188	1317
Sr	–	–	185	–	411	–	–	–	331	252	411
Li	–	–	–	–	n.d.	–	–	–	7.4	6.5	n.d.
Ta	–	–	–	–	2	–	–	–	0.5	0.6	2
Nb	–	–	198	–	32	–	–	–	13	11	31
Hf	–	–	–	–	3.5	–	–	–	2.3	2.2	2.7
Zr	–	–	208	–	118	–	–	–	73	69	95
Y	–	–	31.9	–	17	–	–	–	16	14	19
Th	–	–	18.1	–	4.6	–	–	–	2.1	1.8	4.6
U	–	–	–	–	0.05	–	–	–	0.3	0.1	0.05
La	–	–	–	–	37.4	–	–	–	10.4	8.3	37.4
Ce	–	–	–	–	56.9	–	–	–	21.1	19.4	56.9
Nd	–	–	–	–	29	–	–	–	10	9	29
Sm	–	–	–	–	4.88	–	–	–	2.3	2	4.88
Eu	–	–	–	–	1.19	–	–	–	0.8	0.6	1.19
Tb	–	–	–	–	0.38	–	–	–	0.3	0.3	0.38
Yb	–	–	–	–	1.5	–	–	–	1.3	1	1.5
Lu	–	–	–	–	0.27	–	–	–	0.24	0.2	0.27

Table 1. (Contd.)

Component	34	35	36	37	38	39	40	41	42	43	44
SiO_2	26.41	29.48	28.9	29.98	28.42	29.1	32.58	33.73	29.16	25.56	28.34
TiO_2	1.25	1.15	1.16	1.05	1.12	1.13	2	2.24	4.1	3.96	4.14
Al_2O_3	4.55	5.51	5.38	4.53	4.77	4.86	4.41	3.85	4.16	2.64	4.85
Fe_2O_3	8.38*	5.73	7.99	4.92	7.89	7.28	6.42	17.27	2.02	10.91	5.47
Cr_2O_3	–	–	–	–	–	–	–	–	–	–	–
FeO	–	3.16	1.44	3.8	1.44	1.53	5.96	0.98	17.68	6	3.85
MnO	0.21	0.26	0.28	0.28	0.27	0.25	0.2	0.11	0.38	0.56	0.51
MgO	21.17	23.75	24.98	24.24	23.6	24.05	21.61	11.27	13.29	18.54	20.32
CaO	15.99	11.3	11.35	11.44	12.66	12.43	10.51	20.85	19.63	11.48	11.05
Na_2O	0.39	0.18	0.21	0.52	0.24	0.16	1.46	0.28	0.63	3	2.6
K_2O	2.54	2.45	1.77	2.7	1.83	1.75	4.28	4.01	1.75	1.64	2.8
P_2O_5	2.64	1.91	2.82	1.2	2.67	2.2	0.47	–	3.11	0.06	0.17
SO_3	–	–	–	–	–	–	–	–	–	–	–
H_2O	–	–	–	–	–	–	2.3	1.15	–	0.25	0.24
CO_2	–	7.04	5.15	7.7	6.38	6.6	6.2	4.08	3.08	–	–
L.O.I.	15.59	7.45	8.32	7.15	8.42	8.4	0.7	–	–	15.72	15.82
F	–	–	–	–	–	–	0.54	–	–	–	–
Total	99.12	99.37	99.75	99.51	99.71	99.74	99.54	99.82	98.99	100.32	100.16
Cr	–	–	–	–	–	–	–	–	–	–	–
Ni	–	–	–	–	–	–	–	–	–	–	–
Co	–	–	–	–	–	–	–	–	–	–	–
Sc	–	–	–	–	–	–	–	–	–	–	–
V	–	–	–	–	–	–	–	–	–	–	–
Rb	–	96	106	114	110	88	–	–	–	–	–
Cs	–	–	–	–	–	–	–	–	–	–	–
Ba	–	358	671	391	614	438	–	–	–	–	–
Sr	–	1496	2406	1189	2319	1839	–	–	–	–	–
Li	–	–	–	–	–	–	–	–	–	–	–
Ta	–	–	–	–	–	–	–	–	–	–	–
Nb	–	192	191	189	172	186	–	–	–	–	–
Hf	–						–	–	–	–	–
Zr	–	235	262	231	246	263	–	–	–	–	–
Y	–	13	19	14	17	18	–	–	–	–	–
Th	–	–	–	–	–	–	–	–	–	–	–
U	–	–	–	–	–	–	–	–	–	–	–
La	–	–	–	–	–	–	–	–	–	–	–
Ce	–	–	–	–	–	–	–	–	–	–	–
Nd	–	–	–	–	–	–	–	–	–	–	–
Sm	–	–	–	–	–	–	–	–	–	–	–
Eu	–	–	–	–	–	–	–	–	–	–	–
Tb	–	–	–	–	–	–	–	–	–	–	–
Yb	–	–	–	–	–	–	–	–	–	–	–
Lu	–	–	–	–	–	–	–	–	–	–	–

Table 1. (Contd.)

Component	45	46	47	48	49	50	51	52	53	54	55
SiO_2	19.56	36	37.48	34.48	38	38	32.04	39.3	34	30.77	35.5
TiO_2	3.58	3.25	3.1	3.08	3.37	3.83	2.32	3.2	1.6	2.19	2.9
Al_2O_3	3.8	10.4	11	12.01	11.67	10	9.45	8.44	7.8	6.69	7.8
Fe_2O_3	12.78	5.56	7.1	8.72	6.36	6.86	5.02	7.05	4.93	7.78	5.6
Cr_2O_3	–	–	–	–	–	–	–	–	–	–	–
FeO	3.96	6.36	6.66	3.79	5.22	6.01	5.51	6.57	6.46	5.11	7.1
MnO	0.33	0.24	0.24	0.27	0.26	0.26	0.23	0.21	0.26	0.21	0.22
MgO	15.6	6.5	6.51	7.8	5.23	6.39	5.77	12.22	8.92	16.68	15.8
CaO	21.34	15.1	15.62	14.4	13.56	15	19.9	11.9	13.8	17.96	12.8
Na_2O	0.86	5.2	6	2.09	3.4	4.74	5.08	1.66	3.76	0.76	0.27
K_2O	0.81	2.6	2.35	3.36	3	1.6	2.8	0.74	2.46	2	0.98
P_2O_5	7.07	0.62	0.54	–	0.72	0.63	0.5	0.42	1.06	–	0.6
SO_3	–	–	–	–	–	–	–	–	–	–	–
H_2O	1.18	3.78	2.04	3.64	–	0.32	0.2	2.24	0.76	3.88	2.36
CO_2	–	4.2	1	4.57	3.19	1.32	9.96	1.65	9.68	6.2	–
L.O.I.	8.2	–	–	–	4.46	4.32	2.41	4.35	3.92	–	7.6
F	–	0.48	0.3	–	–	–	–	0.15	0.2	–	0.2
Total	99.07	100.29	99.94	98.21	98.44	99.28	101.19	100.1	99.61	100.23	99.73
Cr	–	n.d.	n.d.	n.d.	–	–	–	640	120	–	380
Ni	–	50	48	30	–	–	–	150	74	–	270
Co	–	–	–	–	–	–	–	90	61	–	71
Sc	–	–	–	18	–	–	–	37	25	–	–
V	–	230	195	20	–	–	–	210	400	–	280
Rb	–	80	40	100	–	–	–	–	–	–	–
Cs	–	–	–	–	–	–	–	–	–	–	–
Ba	–	–	–	–	–	–	–	500	2800	–	500
Sr	–	–	–	1510	–	–	–	1700	2600	–	140
Li	–	17	12	41	–	–	–	34	–	–	–
Ta	–	10	11	–	–	–	–	–	–	–	–
Nb	–	105	105	–	–	–	–	63	49	–	119
Hf	–			–	–	–	–	–	–	–	–
Zr	–	460	400	–	–	–	–	350	200	–	290
Y	–	–	–	–	–	–	–	–	–	–	–
Th	–	–	–	–	–	–	–	–	–	–	–
U	–	–	–	–	–	–	–	–	–	–	–
La	–	–	–	–	–	–	–	–	–	–	–
Ce	–	–	–	–	–	–	–	440	–	–	–
Nd	–	–	–	–	–	–	–	–	–	–	–
Sm	–	–	–	–	–	–	–	–	–	–	–
Eu	–	–	–	–	–	–	–	–	–	–	–
Tb	–	–	–	–	–	–	–	–	–	–	–
Yb	–	–	–	–	–	–	–	–	–	–	–
Lu	–	–	–	–	–	–	–	–	–	–	–

Table 1. (Contd.)

Component	56	57	58	59	60	61	62	63	64	65	66
SiO_2	31.66	36.29	40.9	41.18	36.93	36.77	43.32	34.86	39.02	39.38	35.8
TiO_2	2.25	2.27	1.01	0.93	0.83	0.71	0.72	1.82	1.59	1.78	1.53
Al_2O_3	8.41	6.2	9.79	13.28	12.74	12.41	11.45	7.94	10.69	8.68	8.64
Fe_2O_3	6.04	2.85	5.07	7.13	8.19	7.45	4.36	9.07	5.37	8.57	9.74
Cr_2O_3	–	–	–	–	–	–	–	–	–	–	–
FeO	8.19	6	4.39	4.73	1.82	2.26	4.32	4.03	5.47	4.86	3.42
MnO	0.24	0.19	0.32	0.26	0.24	0.28	0.24	0.23	0.21	0.23	0.3
MgO	10.52	12.3	13.21	11.94	14.96	17.61	10.84	15.09	12.28	15.8	19.1
CaO	16.45	12.44	13.05	3.97	10.52	6.35	11.5	17.45	17.02	12.22	11.15
Na_2O	0.56	0.22	3.42	5.08	1.61	1.36	4	0.84	1.7	0.72	0.4
K_2O	1.58	1.32	0.96	1.37	0.66	1.06	0.65	0.6	0.98	1.1	0.84
P_2O_5	0.72	0.48	0.31	0.51	0.62	0.71	0.3	0.41	0.34	0.32	0.25
SO_3	–	–	–	–	–	–	–	–	–	–	–
H_2O	1.12	0.12	5.7	9.77	10.24	11.1	6.88	–	–	–	–
CO_2	–	–	1.78	0.6	0.26	1.67	0.78	0.52	0.22	0.57	1.1
L.O.I.	13.15	19.73	–	–	–	–	–	6.84	4.95	5.56	7.19
F	–	–	–	–	–	–	–	–	–	–	–
Total	100.89	100.41	99.95	100.85	99.65	99.77	100.14	99.7	99.84	99.79	99.46
Cr	480	500	–	–	–	–	–	–	–	–	–
Ni	200	230	–	–	–	–	–	–	–	–	–
Co	66	55	–	–	–	–	–	–	–	–	–
Sc	35	170	–	–	–	–	–	–	–	–	–
V	220	180	–	–	–	–	–	–	–	–	–
Rb	60	66	–	–	–	–	–	–	–	–	–
Cs	–	–	–	–	–	–	–	–	–	–	–
Ba	–	–	–	–	–	–	–	–	–	–	–
Sr	820	320	–	–	–	–	–	–	–	–	–
Li	80	86	–	–	–	–	–	–	–	–	–
Ta	12	11	–	–	–	–	–	–	–	–	–
Nb	220	252	–	–	–	–	–	–	–	–	–
Hf	–		–	–	–	–	–	–	–	–	–
Zr	300	300	–	–	–	–	–	–	–	–	–
Y	–	–	–	–	–	–	–	–	–	–	–
Th	–	–	–	–	–	–	–	–	–	–	–
U	–	–	–	–	–	–	–	–	–	–	–
La	–	–	–	–	–	–	–	–	–	–	–
Ce	–	–	–	–	–	–	–	–	–	–	–
Nd	–	–	–	–	–	–	–	–	–	–	–
Sm	–	–	–	–	–	–	–	–	–	–	–
Eu	–	–	–	–	–	–	–	–	–	–	–
Tb	–	–	–	–	–	–	–	–	–	–	–
Yb	–	–	–	–	–	–	–	–	–	–	–
Lu	–	–	–	–	–	–	–	–	–	–	–

Table 1. (Contd.)

Component	67	68	69	70	71	72	73	74	75	76	77
SiO_2	42.36	39.73	34.18	33.82	38.86	36.62	34.14	38.8	29.35	35.23	41.5
TiO_2	1.61	1.76	2	1.02	1.6	1.2	1.26	1.46	1.73	2.17	2.14
Al_2O_3	12.49	10.24	10.83	6.35	10.48	8.86	8.17	7.33	6.59	7.83	6.15
Fe_2O_3	7.24	11.77*	9.22	7.08	6.41	6	3.74	5.53	6.85	7.17	5.92
Cr_2O_3	–	–	–	–	–	–	–	–	–	–	–
FeO	5.67	–	5.61	3.02	6.48	4.32	5.4	4.07	12.02	4.07	2.35
MnO	0.18	0.2	0.09	0.14	0.32	0.2	0.14	0.24	1.3	0.25	0.15
MgO	10.3	12.32	19.32	22.75	15.77	16.89	18.96	19.74	12.78	17.34	20.36
CaO	11.93	16.1	5.06	11.3	8.75	11.48	11.13	13.36	7.91	7.85	6.2
Na_2O	1.08	1.5	0.33	0.54	0.8	0.1	0.22	0.94	0.08	0.25	0.28
K_2O	1.9	1.19	3	1.3	3.4	2.8	2.8	1.39	0.14	0.8	0.58
P_2O_5	0.29	0.31	0.86	0.79	1.15	1.35	0.55	0.3	0.55	0.72	0.37
SO_3	–	–	0.01	0.12	0.1	0.2	0.23	–	0.1	0.1	–
H_2O	–	–	1.58	1.2	0.55	1.99	0.5	–	2.38	5.29	11.17
CO_2	1.76	–	1.76	4.7	0.84	3.9	8.14	2.32	13.52	4.36	3.54
L.O.I.	5.02	5.87	5.24	5.88	4.16	4.04	4.25	4.24	3.95	5.53	–
F	–	–	–	–	–	–	–	–	–	–	–
Total	101.83	100.99	99.09	100.01	99.67	99.95	99.63	99.72	99.25	98.96	100.71
Cr	–	–	–	–	–	–	–	–	–	–	–
Ni	–	–	–	–	–	–	–	–	–	–	–
Co	–	–	–	–	–	–	–	–	–	–	–
Sc	–	–	–	–	–	–	–	–	–	–	–
V	–	–	–	–	–	–	–	–	–	–	–
Rb	–	–	–	–	–	–	–	–	–	–	–
Cs	–	–	–	–	–	–	–	–	–	–	–
Ba	–	–	–	–	–	–	–	–	–	–	–
Sr	–	–	–	–	–	–	–	–	–	–	–
Li	–	–	–	–	–	–	–	–	–	–	–
Ta	–	–	–	–	–	–	–	–	–	–	–
Nb	–	–	–	–	–	–	–	–	–	–	–
Hf	–	–	–	–	–	–	–	–	–	–	–
Zr	–	–	–	–	–	–	–	–	–	–	–
Y	–	–	–	–	–	–	–	–	–	–	–
Th	–	–	–	–	–	–	–	–	–	–	–
U	–	–	–	–	–	–	–	–	–	–	–
La	–	–	–	–	–	–	–	–	–	–	–
Ce	–	–	–	–	–	–	–	–	–	–	–
Nd	–	–	–	–	–	–	–	–	–	–	–
Sm	–	–	–	–	–	–	–	–	–	–	–
Eu	–	–	–	–	–	–	–	–	–	–	–
Tb	–	–	–	–	–	–	–	–	–	–	–
Yb	–	–	–	–	–	–	–	–	–	–	–
Lu	–	–	–	–	–	–	–	–	–	–	–

Table 1. (Contd.)

Component	78	79	80	81	82	83	84	85	86
SiO_2	34.19	37.39	28.31	40.9	41.21	36.52	35.24	43.69	36.38
TiO_2	2.37	3.02	3.02	2.51	3.37	2.96	2.02	3.92	2.31
Al_2O_3	5.08	5.02	8.04	4.71	5.76	4.95	4.19	6.24	4.71
Fe_2O_3	6.52	6.17	6.31	–	7.72	7.77	14.93	9.00	9.30
Cr_2O_3	–	–	–	–	–	–	–	–	–
FeO	4.12	4.63	4.68	8.71	–	–	–	–	–
MnO	0.19	0.22	0.29	0.14	0.13	0.13	0.09	0.10	0.16
MgO	22.58	24.22	15.84	22.06	19.4	22.36	18.50	17.24	25.49
CaO	6.74	4.05	12.55	6.3	8.81	8.78	8.99	10.86	5.83
Na_2O	0.16	0.11	0.13	0.24	0.17	0.20	0.15	0.25	0.19
K_2O	0.94	1.12	2.06	6.02	3.23	2.31	3.25	3.26	5.60
P_2O_5	0.7	0.57	0.9	0.92	1.82	1.45	1.17	0.95	0.89
SO_3	0.04	–	0.18	–	–	–	–	–	–
H_2O	3.59	10.92	2.59	–	–	–	–	–	–
CO_2	4.41	2.16	9.67	–	–	–	–	–	–
L.O.I.	8.19	–	4.07	7.74	8.67	11.53	10.68	3.84	8.15
F	–	–	–	–	–	–	–	–	–
Total	99.82	99.60	98.64	100.25	100.29	98.96	99.22	99.35	99.02
Cr	–	–	–	1692	1310	1448	1429	613	1501
Ni	–	–	–	1072	–	1030	1030	557	1001
Co	–	–	–	71	69	71	89	48	66
Sc	–	–	–	17.10	22	20.32	14.66	29.26	16.61
V	–	–	–	132	128	185	178	64	141
Rb	–	–	–	240	–	85	120	73	210
Cs	–	–	–	–	–	–	–	–	–
Ba	–	–	–	2200	2100	2046	1373	1295	2372
Sr	–	–	–	1158	1130	1326	505	1283	730
Li	–	–	–	–	–	–	–	–	–
Ta	–	–	–	–	–	18.15	3.85	12.04	–
Nb	–	–	–	124	–	171	106	137	115
Hf	–	–	–	–	–	–	–	–	–
Zr	–	–	–	430	801	770	320	685	370
Y	–	–	–	16.00	18.8	14.00	14.00	19.00	14.00
Th	–	–	–	14	–	12	11	37	10
U	–	–	–	2.7	–	2.7	1.7	3.6	2.2
La	–	–	–	214	267	414	193	417	193
Ce	–	–	–	379	465	677	340	824	340
Nd	–	–	–	–	–	–	–	–	–
Sm	–	–	–	–	–	–	–	–	–
Eu	–	–	–	–	–	–	–	–	–
Tb	–	–	–	–	–	–	–	–	–
Yb	–	–	–	1.13		1.36	1.33	1.42	1.37
Lu	–	–	–	–	–	–	–	–	–

Note: (1–12) Diamondiferous rocks of the Arkhangel'sk province: Zolotitsa field: (1) Karpinsky 2 pipe, (2) Karpinsky 1 pipe, (3) Lomonosov pipe, (4) Pionerskaya pipe, (5) Pomorskaya pipe, (6) Arkhangel'sk pipe; (7–12) Grib pipe, Verkhotina field; (13–39) kimpicrites and alpicrites of the Arkhangel'sk province: (13–25) picrites of the Kepa field: (13) anom. 687, (14, 15) anom. 697, (16) Klyuchevaya, (17) anom. 734, (18) Shocha, (19) anom. 840, (20) anom. 713, (21) anom. 693, (22) Oktyabr'skaya, (23) Pobeda, (24) Yuras, (25) Stepnaya; (26–29) olivine melilitites of the Verkhotina field: (26) anom. 691, (27) Maiskaya, (28) Volch'ya, (29) Verkhotina; (30–33) picrites and olivine melilitites of the Izhmozero field: (30) Aprel'skaya; (31) Izhma, (32) Vesennyaya, (33) Chidviya; (34–39) phlogopite picrites of the Tersky coast (Ermakov area); (40–68) alpicrites from the carbonatite complexes of the Kandalaksha Archipelago, Onega peninsula, and Tersky coast of the White Sea: (40, 41) Kovdor Massif, phlogopite–pyroxene picrite porphyrite; (42–44) Vuorijarvi Massif, phlogopite picrite porphyrite; (45) Sokli Massif (Finland), phlogopite picrite porhyrite; Turiy Mys: (46–48) alnoites, (49–51) melilitites; Kandalaksha islands: (52–54) alnoites, (55–57) alkaline picrite porphyrites; (58–62) Onega peninsula, Nenok field: (58) Karakhta, (59) An-28, (60) An-25, (61) Slavyanka, (62) Kurtyaevo; Tersky coast: (63–68) olivine melilitites; (69–80) ultramafic alkaline rocks of the Middle Timan: (69–74) alkaline picrites of the Chetlas Complex, (75–80) kimberlite-like rocks from the explosion pipes of the Vol'sk–Vym Range: (75–77) Umba pipe, (78, 79) Vodorazdel'naya pipe, (80) Srednenskaya pipe; (81–86) olivine lamproites of the Kostamuksha area. Analyses (1–4), (13–17), (19–22), (26–29), and (31–33) are taken from [1]; (5, 18) after [18]; (6), (23–25), and (30) after E.V. Frantsensson; (35–39) and (63–67) after [11]; (40–48) and (52–57) after [8]; (49–51) after [9]; (58–62) after [12]; (69–74) after [13]; (75–80) after [14, 19]; (7–12), (34), (68), and (81–86) are our data.

*Total iron calculated as Fe_2O_3.

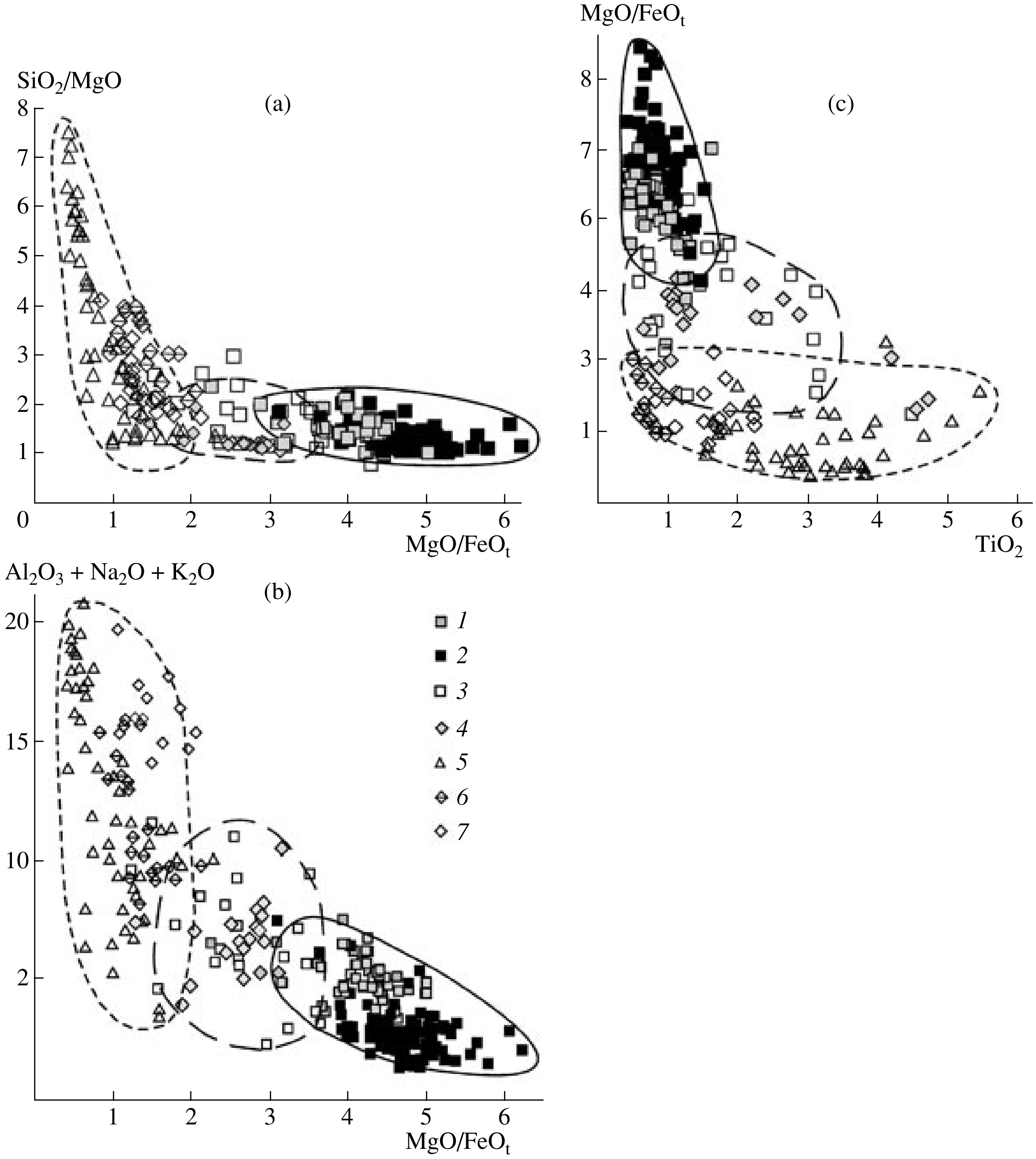

Fig. 1. Fields of kimberlites and related rocks from the Arkhangel'sk province and adjacent areas of the White Sea coast in the diagrams of (a) SiO_2/MgO–MgO/FeO_t, (b) ($Al_2O_3 + Na_2O + K_2O$)–MgO/FeO_t, and (c) MgO/FeO_t–TiO_2. (*1*) Diamondiferous kimberlites of the Zolotitsa field; (*2*) diamondiferous kimberlites of the Grib pipe; (*3*) kimpicrites of the Kepa and Chidviya fields [1]; (*4*) kimpicrites of the Tersky coast, White Sea [11]; *(5)* alpicrites of the Turiy Mys, Kandalaksha Archipelago, Kovdor, and Vuorijarvi massifs [8]; (*6*) alpicrites of the Nenok field, Onega Peninsula [12]; (*7*) alpicrites of the Tersky coast, While Sea [11]. The solid, long-dashed, and short-dashed lines enclose the fields of diamondiferous kimberlites, kimpicrites, and alpicrites, respectively.

compositions and can be continued into the field of olivine melanephelinite and nephelinite.

The Middle Timan alkaline ultrabasic province is located east of the Arkhangel'sk province and comprises alkaline picrites of the Chetlas Complex [13] and kimberlites of the Vol'sk–Vym Range [14]. The Chetlas Complex includes several thousands of phlogopite–pyroxene picrite dikes, which are grouped into about 50 dike swarms in the southeastern part of the Chetlas Kamen region. The complex is dated at 590 Ma, and includes carbonatites and fenites in addition to the picrite dikes. In the discriminant diagrams (Figs. 2a, 2b, 2c), the points of alkaline picrites are grouped mainly in the alpicrite field, and only a few compositions plot in the overlap of the alpicrite and kimpicrite fields.

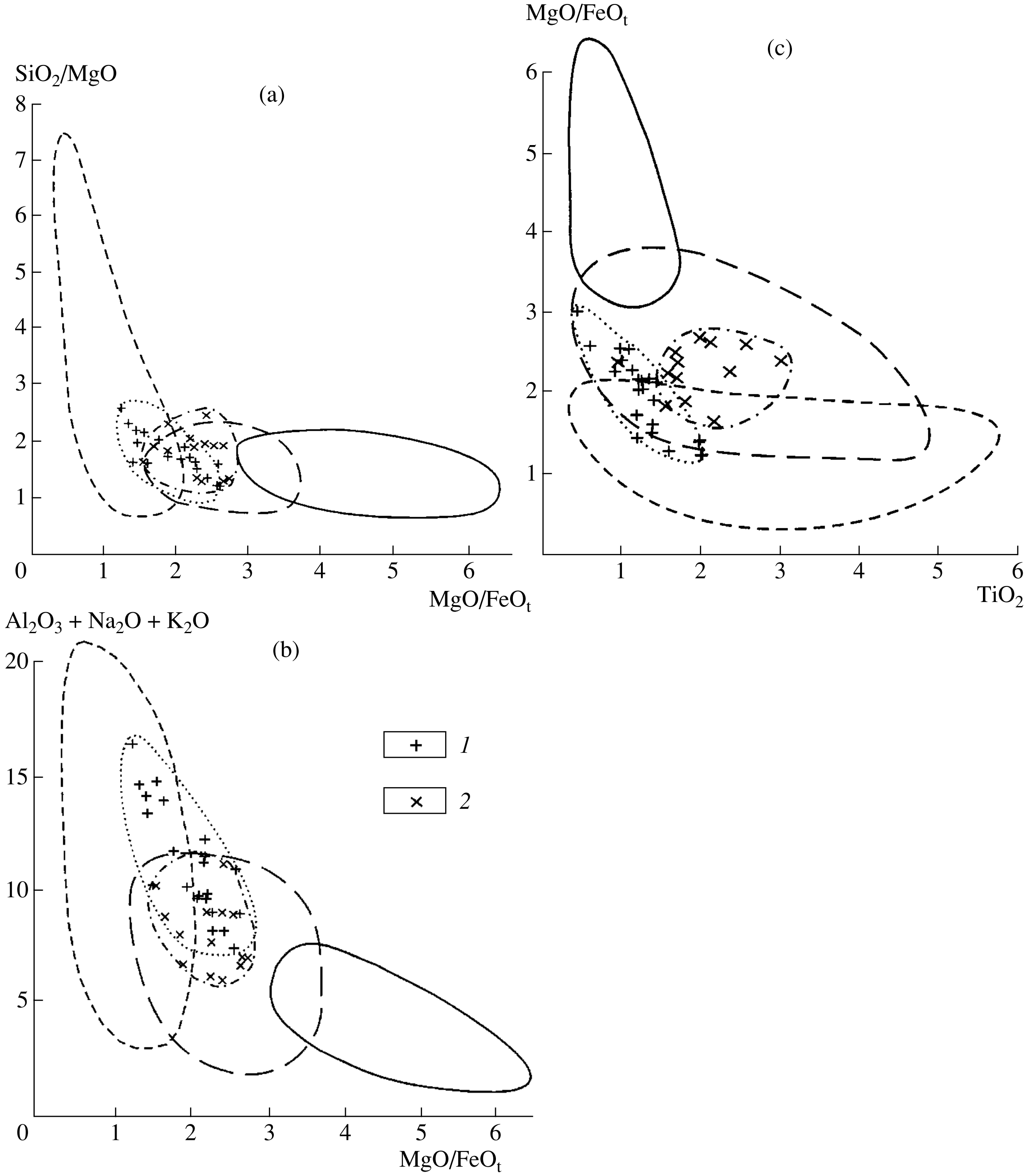

Fig. 2. Rocks of the Middle Timan in the diagrams of (a) SiO_2/MgO–$MgO/\Sigma FeO_t$, (b) ($Al_2O_3 + Na_2O + K_2O$)–MgO/FeO_t, and (c) MgO/FeO_t–TiO_2. The contours of the fields of kimberlites and related rocks of the Arkhangel'sk province and adjacent territories correspond to those in Fig. 1. (*1*) Points of picrites from the Chetlas Complex, the field of which is outlined by the dotted line; (*2*) points of rocks from the explosion pipes of the Vol'sk–Vym Range, the field of which is outlined by a dash–dot line.

The Umba (150 × 160 m), Srednenskaya (60 × 30 m), and Vodorazdel'naya (60 × 60 m) diatremes of the Vol'sk–Vym Range east of Chetlas Kamen are composed of micaceous and mica-poor picrites and olivine melilitites and, according to B.A. Mal'kov, are 490–500 Ma old. In the discriminant diagrams (Fig. 2), these rocks are plotted mainly in the field of nondiamondiferous and weakly diamondiferous kimpicrites and partly in the overlap region between kimpicrites and alpicrites.

These conclusions are, in general, consistent with the fact that the alkaline picrites of the Chetlas Complex are closely associated with carbonatites of the Kos'yu Massif, which is in fact a bulge of a picrite dike. Formational–metallogenic analysis showed that the kimberlite-related rocks of the Middle Timan include both the main formational types of alkaline ultrabasic rocks and transitional varieties. These varieties are important not only for the metallogenic forecasting of magmatic rocks, but also for determining the direction of forecasting and the search for productive magmatic complexes. In particular, the transition from the Chetlas Kamen alpicrites to the kimpicrites of the Vol'sk–Vym Range suggests that the Izhma–Pechera depression located to the east can be a promising area to search for diamondiferous kimberlites.

The analysis of data on the composition of ultrapotassic rocks from Kostamuksha, Karelia, which were initially described as micaceous picrites or micaceous peridotites [15] and then classified as lamproites [16, 17], justify the latter conclusion. The lamproites form a series of submeridional steeply dipping dikes from 0.5–1.0 to 3–4 m thick and up to 400–550 m long, which intersect Late Archean magnetite quartzites and schists. The rocks are Middle Proterozoic in age (1230 Ma), which is typical of many lamproites around the world. Compositionally, the lamproites are subdivided into ultrabasic (phlogopite–olivine and phlogopite–diopside–olivine), basic (olivine–phlogopite–diopside–leucite), and intermediate (leucite-rich) rocks. The phlogopite–olivine rocks are weakly diamondiferous. The minerals of the diamond association are represented by Cr-spinel. The typomorphic minerals of lamproites are K-richterite, high-Ti phlogopite (up to 5.84% TiO_2), and leucite.

The compositional convergence of the lamproite–orangeite and kimberlite–alpicrite subfamilies is expressed in the partial overlap of their compositional fields. Because of this, the use of indicator geochemical and mineralogical features of lamproites is of special importance for the formational classification of the ultrapotassic rocks of Kostamuksha. Some geochemical diagrams supporting their lamproitic nature are shown in Figs. 3 and 4.

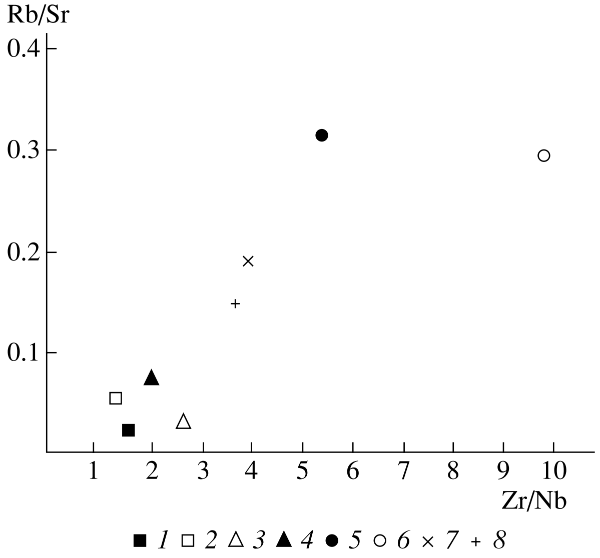

Fig. 3. Diagram of variations in average Zr/Nb and Rb/Sr ratios for the rocks of Kostamuksha, Australian lamproites, and rocks of the kimberlite–alpicrite formational series. (*1*) Diamondiferous kimberlites [6], (*2*) kimpicrites [6], (*3*) alpicrites [6], (*4*) camafugites [6], (*5*) olivine lamproites of Australia, [21], (*6*) leucite lamproites of Australia [21], (*7*) orangeites [22], and (*8*) ultrapotassic rocks of Kostamuskha, our data.

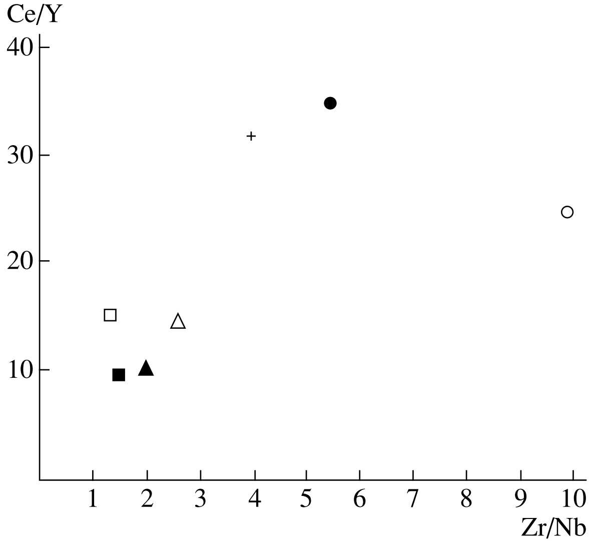

Fig. 4. Diagram of variations in average Zr/Nb and Ce/Y ratios for the rocks of Kostamuksha, Australian lamproites, and rocks of the kimberlite–alpicrite formational series. Symbols are the same as in Fig. 3.

Thus, the examples of the formational–metallogenic analysis of kimberlites and convergent rocks from the areas of the northern East European platform adjacent to the Arkhangel'sk diamondiferous province demonstrated the possibility of obtaining adequate results consistent with geological data. Hence, the proposed technique of formational–metallogenic analysis based on the use of petrochemical and geochemical criteria and relevant discriminant diagrams can be applied to the alkaline ultramafic magmatism of the Arkhangel'sk diamondiferous province.

The distribution of kimberlite and related magmatic occurrences in the Arkhangel'sk diamondiferous province is shown in Fig. 5. A characteristic feature of this province is that diamondiferous kimberlites are much less abundant than nondiamondiferous and weakly diamondiferous alkaline ultrabasic rocks dominated by alkaline picrites and olivine melilitites. The first results of the study of the Arkhangel'sk diamondiferous province highlighted some other features, which were briefly mentioned in the beginning of the paper but deserve more detailed consideration.

Primarily, the diamondiferous kimberlites of the Arkhangel'sk province are anomalous compared to the kimberlites of the classic Central Yakutian province. This is expressed by the insignificant contents of diamond-associated minerals, pyrope and picroilmenite,

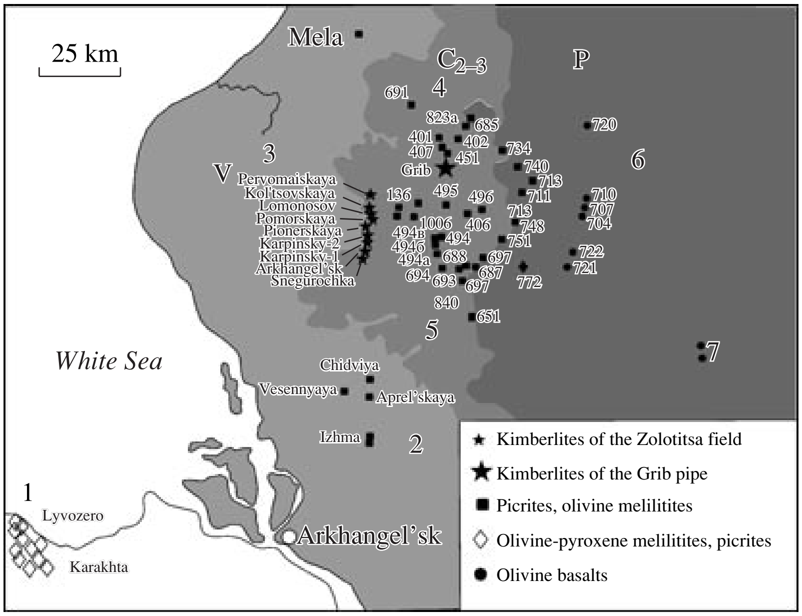

Fig. 5. Distribution of magmatic occurrences in the Arkhangel'sk diamondiferous province (after [1]). (1) Nenok field, (2) Chidviya field, (3) Zolotitsa field, (4) Verkhotina field, (5) Kepa field, (6) Turiy field, and (7) Poltin field. V, Vendian deposits; $C_{2,3}$, Middle–Upper Carboniferous deposits; and P, Permian deposits.

and much lower concentrations of lithophile (Nb, Zr, Ce, and La) and radioactive (U and Th) trace elements. In addition, the Sr and Nd isotope composition of the Arkhangel'sk kimberlites is similar to that of orangeites and lamproites [1, 19], and some geologists argued that this indicates a transitional character for these rocks, which combine the characteristics of group I kimberlites, group II kimberlites, and lamproites [18, 23].

Additional problems are related to the occurrence of two deposits differing in a number of parameters in the Arkhangel'sk province. One of them, the Lomonosov deposit, includes six closely spaced kimberlite pipes of the Zolotitsa field: Arkhangel'sk, Karpinsky 1 and 2, Pionerskaya, Pomorskaya, and Lomonosov. The other deposit is represented by the Grib pipe, which was discovered and explored later and shows a significantly higher diamond content. It is located in the adjacent Verkhotina field, 20 km NW of the Lomonosov deposit.

The observed differences between the kimberlites of these two deposits, in particular, the presence of picroilmenite in the Grib pipe and its nearly complete absence in the Lomonosov pipe, served as a basis for distinguishing two types of economic kimberlite rocks in the Arkhangel'sk diamondiferous province, which were interpreted as derivatives of two different petrochemical series, Mg–Al and Fe–Ti [4].

However, taking into account the constraints imposed by the conditions of generation and ascent of kimberlite melts, in particular, low degrees of partial melting of mantle rocks and extremely high ascent rates of fluidized magmas, the distinguishing of the differentiated series of diamondiferous kimberlites seems to be controversial.

Serious problems were also encountered with the identification of nondiamondiferous kimberlites and weakly diamondiferous alkaline ultramafic rocks, which are predominant in the Arckhangel'sk province and include alkaline picrites and olivine melilitites. These problems concern the formational–metallogenic interpretation of these rocks and their comparison with similar rocks from typical alkaline ultrabasic and kimberlite provinces. In spite of the uncertain formational affinity, these rocks are typically considered kimberlites or kimberlitic rocks and are often combined together with diamondiferous kimberlites into either Mg–Al or Fe–Ti series [4]

Thus, even this brief overview of the problems that have arisen during the initial study of the Arkhangel'sk diamondiferous province indicates a need for the formational–metallogenic examination of the alkaline ultrabasic rocks of this province. First, we performed a general comparison of the alkaline ultrabasic rocks of the northern East European platform, including the Arkhangel'sk province, with the corresponding rocks of the Yakutian diamondiferous megaprovince and adjacent areas of the Siberian platform. For this purpose, we used the approved discriminant diagrams (Fig. 6a, 6b). The field of diamondiferous kimberlites was outlined in these diagrams on the basis of data on the main diamondiferous fields of the Central Yakutian province: Malo-Botuoba, Daldyn, Alakit, and Verkhnyaya Muna. The field of nondiamondiferous and weakly diamondiferous kimpicrites was distinguished using data on the fields of the Anabar–Olenek province: Ukukit, Dyuken, Luchakan, and others. The field of alpicrites was constructed using data on the alkaline–ultramafic rocks of the Chadobets Complex [24], and alnoite–picrites associating with ultrabasic alkaline and carbonatite massifs (Tomtor, Arbarastakh, and others). It can be seen that the fields of kimberlites, kimpicrites, and alpicrites of both provinces are similar in general configuration, indicating the principal resemblance and regular relations of the distinguished formational types.

The SiO_2/MgO–$MgO/\Sigma FeO$ diagram (Fig. 6a) shows a significant overlap of the fields of kimberlites, kimpicrites, and alnoites of the two provinces with a small shift of all the Arkhangel'sk fields toward higher SiO_2/MgO values, which can be related to the regional contamination of the rocks by quartzo–feldspathic crustal material. The (Al_2O_3 + Na_2O + K_2O)–$MgO/\Sigma FeO$ diagram (Fig. 6b) supports the similarity of the two provinces in the general configuration and relative position of kimberlite, kimpicrite, and alpicrite fields but displays a distinct shift of the magmatic rocks of the Arkhangel'sk province toward the (Al_2O_3 + Na_2O + K_2O) axis. This shift is caused by high Na and Al contents in the rocks of the Arkhangel'sk province (Table 2). Indeed, at similar K_2O contents, the K_2O/Na_2O ratio of the magmatic rocks of the northern East European platform is significantly lower than that of the Yakutian rocks.

In addition, the kimberlites of all formational types from the East European platform have higher Al_2O_3 contents (Table 2) than those of the Siberian platform. These differences can be attributed to significant crustal contamination of the alkaline ultrabasic rocks of the northern East European platform or mixing with the material of an ancient subducted crust.

Two aspects are of special importance for the characterization of the diamondiferous rocks of the Arkhangel'sk province: (1) a comparison of kimberlites of the Lomonosov and Grib pipes and validation of their supposed affiliation to different petrochemical types or to differentiated kimberlite series, and (2) their comparison with the diamondiferous kimberlites of the Yakutian Province.

In order to estimate the extent of petrochemical variations of the diamondiferous kimberlites of the Arkhangel'sk province, the data points of the Lomonosov and Grib pipes were shown by different symbols in Fig. 1. In all diagrams, the points corresponding to two deposits and supposedly different types of diamondiferous rocks [2, 3] are grouped into a common field. A shift of the points of the Zolotitsa field relative to the kimberlites of the Grib pipe toward the Al_2O_3 + Na_2O + K_2O apex is presumably related to the more significant crustal contamination of the kimberlites of the Zolotitsa field, and a slight shift of the kimberlites of the Zolotitsa field toward lower magnesian compositions is within the range of typical compositional variability of diamondiferous kimberlites. Note that the wider scatter of the points of the Zolotitsa field in the diagrams (Fig. 1), in particular, the occurrence of some points in the kimpicrite field, indicates a formational heterogeneity even within this comparatively compact field. The points occurring in the kimpicrite field correspond to the rocks of the Pomorskaya pipe, which differs from other pipe of this field by a low diamond content.

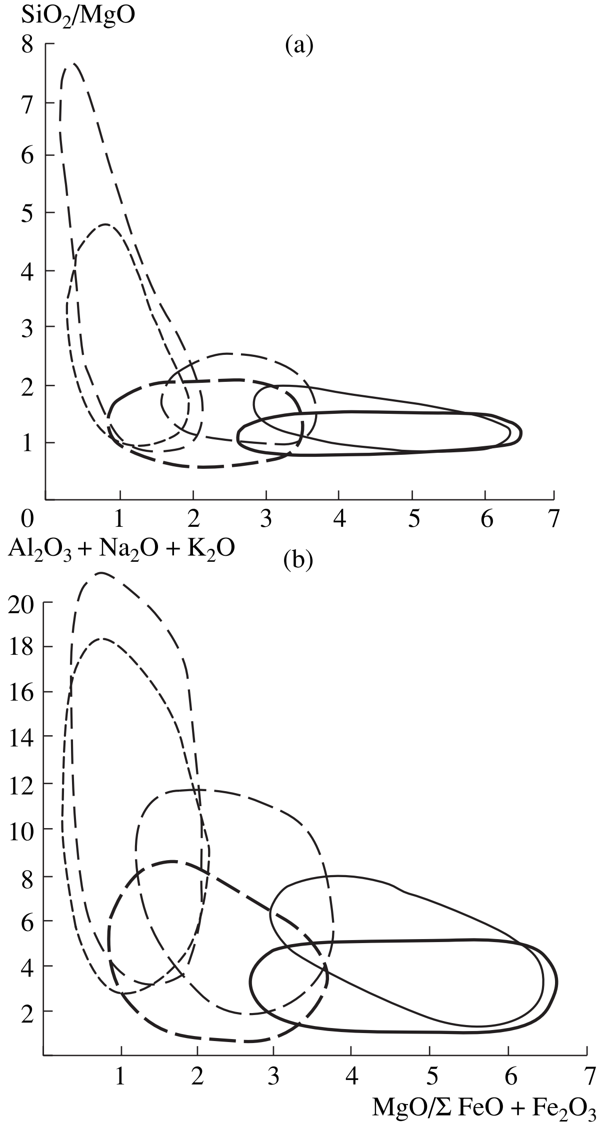

Fig. 6. Relative position of the fields of kimberlites and related rocks of the northern Siberian Platform and northern East European platform in the diagrams of (a) SiO_2/MgO–$MgO/(FeO + Fe_2O_3)$ and (b) (Al_2O_3 + Na_2O + K_2O)–$MgO/(FeO + Fe_2O_3)$. The designation of the fields is the same as in Fig. 1. The fields of rocks from the Siberian Platform are shown by bold lines.

Thus, the real differences between the rocks of the two deposits are restricted mainly to their mineralogical characteristics: the presence of picroilmenite, cli-

Table 2. Average contents of K_2O, Na_2O, and Al_2O_3 (wt %) and K_2O/Na_2O ratio in the alkaline ultramafic rocks of the Arkhangel'sk (AP) and Central Yakutian (YaP) provinces

Rock		Na_2O	K_2O	Al_2O_3	K_2O/Na_2O	$Al_2O_3 + K_2O + Na_2O$
Kimberlites	AP	0.89	1.08	3.22	1.21	5.19
	YaP	0.112	0.54	2.96	4.82	3.61
Kimpicrites	AP	0.59	1.38	4.91	2.34	6.88
	YaP	0.16	1.23	3.88	7.68	5.27
Alpicrites	AP	2.19	1.76	8.02	0.80	11.97
	YaP	1.07	2.21	5.14	2.06	8.42

Table 3. Average contents of trace elements (ppm) and their indicator ratios in the diamondiferous kimberlites of the Arkhangel'sk province, Srednyaya Markha area, and traditional diamondiferous areas of Yakutia

Rock	Nb	Zr	Ce	Y	U	Th	Rb	Zr/Nb	Ce/Y	Th/U	Rb/Nb
Kimberlites of the Zolotitsa field (20)	32	92	53	15.3	0.53	4.39	28	2.9	3.46	8.3	0.88
Kimberlites of the Grib pipe (5)	35.3	47	37	4.48	0.58	2.9	18.4	1.33	8.26	5	0.52
Kimberlites of the Srednyaya Markha area (20)	25	71	42.3	9.2	0.57	1.27	29	2.84	4.6	2.63	1.16
Kimberlites of the Malo-Botuoba, Daldyn, Alakit, and Verkhnyaya Muna fields (123)	117	170	150	16	3.0	11.0	15.0	1.45	9.38	3.7	0.13

Note: In addition to the authors' data, analyses from [1, 8, 25] were used. The number of analyses is shown in parentheses.

nopyroxene, and pyrope and strongly subordinate role of chromite in the Grib pipe, and the predominance of chromite at low contents of Cr-diopside, and garnet and practically complete absence of picroilmenite in the Lomonosov deposits. Therefore, these groups of rocks should be considered as mineral types of kimberlites, whose petrochemical differences are much less significant.

A general petrochemical comparison of the diamondiferous kimberlites of the Arkhangel'sk and Central Yakutian provinces (Figs. 6a, 6b; Table 2) indicated a relative enrichment of the Arkhangel'sk kimberlites in Si, Al, and Na. In addition, the diamondiferous kimberlites of the Arkhangel'sk province are richer in MgO than kimberlites of the Yakutian province (30.98% MgO in an average composition of the Grib pipe kimberlites and 24.21% in the diamondiferous kimberlites of Yakutia). These differences are related mainly to the enrichment of the Yakutian rocks in carbonate material (CO_2 and CaO), which was mostly assimilated from the country rocks decreasing the contents of other major components, MgO and SiO_2. At the same time, the diamondiferous kimberlites of two provinces are weakly contrasting in major component contents and do not show distinct differences. Fundametally different relations were revealed by a comparison of the trace-element systematics of diamondiferous kimberlites from the Arkhangel'sk and Central Yakutian provinces.

Table 3 shows the average contents of trace elements and their indicator ratios in the diamondiferous kimberlites of two deposits of the Arkhangel'sk province and in the kimberlites of traditional diamondiferous areas in Yakutia and the recently discovered Nakyn field of the Srednyaya Markha area. As can be seen from the table, the diamondiferous kimberlites of the Arkhangel'sk province differ from the rocks of typical diamondiferous areas in Yakutia by significantly lower contents of Nb, Zr, Ce, U, and Th and a higher content of Rb. The concentrations of the most rare and radioactive elements in these rocks vary by a factor of more than two, and the geochemical differences are significantly more contrasting compared with the major elements. At the same time, Table 3 suggests the similarity between the diamondiferous kimberlites of the Arkhangel'sk province and the rocks of the Srednyaya Markha area of Yakutia, as well as their difference from the kimberlites of typical diamondiferous areas in the Yakutian province.

The presented data support the distinguishing of a specific geochemical type of diamondiferous kimberlites [1], which occur in various provinces and differ from the rocks of the traditional diamondiferous areas of Yakutia in lower contents of rare and radioactive elements and an elevated content of Rb. This type of kimberlites shows distinctive trace element indicator ratios, such as Zr/Nb, Ce/Y, etc., higher contents of Al, Na (in the rocks of the Zolotitsa field) or K (in the rocks of the

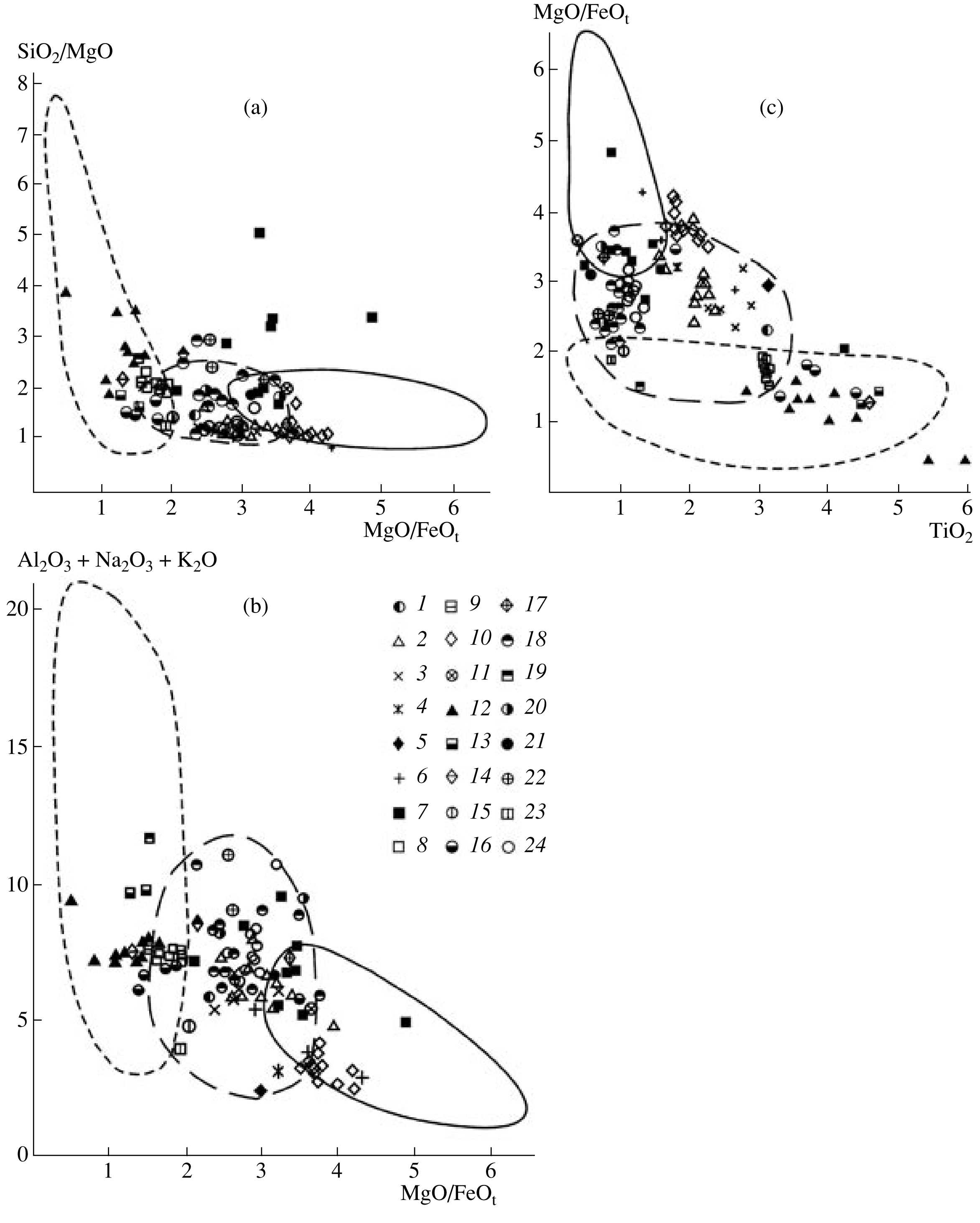

Fig. 7. Rocks composing the pipes and sills of the Kepa, Verkhotina, and Izhmozero fields in the diagrams of (a) SiO_2/MgO–MgO/FeO_t, (b) (Al_2O_3 + Na_2O + K_2O)–MgO/FeO_t, and (c) MgO/FeO_t–TiO_2. The data are from [1, 11, 19] and our results. (*1–15*) Kepa field: (*1*) anom. 687, (*2*) anom. 697, (*3*) Zvezdochka, (*4*) Klyuchevaya, (*5*) anom. 734, (*6*) Shocha, (*7*) anom. 688, (*8*) anom. 840, (*9*) anom. 713, (*10*) anom. 693, (*11*) anom. 772, (*12*) anom. 695, (*13*) Oktyabr'skaya, (*14*) Pobeda, and (*15*) Yuras; (*16–18*) Verkhotina field: (*16*) anom. 691, (*17*) Mai, and (*18*) pipes 401–402; (*19–22*) Izhmozero field: (*19*) Aprel'skaya, (*20*) Izhma, (*21*) Vesennyaya, and (*22*) Chidviya; (*23*) picrites of the Mel'skoe field; (*24*) picrites of the Ermakov area (Tersky coast).

Nakyn field), low concentrations of Ti and almost complete absence of picroilmenite.

These features and the unusual Sr and Nd isotope compositions of the diamondiferous kimberlites of the Arkhangel'sk province [1, 19] suggest that the distinguished geochemical type of kimberlites was derived from a specific mantle source, different from those of the kimberlites of the Yakutian diamondiferous province and typical Group I kimberlites of southern Africa. This question will be discussed in more detail below, and now we will consider the formational–metallogenic characteristics of rocks allied with the diamondiferous kimberlites of the Arkhangel'sk province. For these purposes, the compositions of the Kepa, Verkhotina, Izhmozero, and Mel'skoe fields were plotted in the same discriminant diagrams (Figs. 7a, 7b). The main conclusion is that the diamondiferous pipes of the Zolotitsa field and the Grib pipe of the Verkhotina field are associated with other formational–metallogenic rock types, kimpicrites, alpicrites, and transitional rocks.

In particular, within the Kepa field, the rocks of the anom. 695, Oktyabr'skaya, and Pobeda pipes are classed as alpicrites, the rocks of pipe 840 are transitional from kimpicrite to alpicrite, and the anom. 697 and Zvezdochka pipes are composed of kimpicrites. Among the Kepa field rocks, those from the anom. 722 (Suksoma), anom. 693, and anom. 688 pipes (overlap a region between kimberlites and kimpicrites or in the kimberlite field near this region) lie closest to the field of diamondiferous kimberlitic rocks. The distribution of the compositions of kimberlites from the Stepnaya pipe (anom. 688) in the SiO_2/MgO–MgO/FeO_t diagram (Fig. 7a) testifies to significant contamination by crustal quartz rocks. In the Verkhotina field, alpicrites occur in the anom. 691 pipe, and kimpicrites make up pipes 401 and 402.

The data of [1] suggest that kimpicrites can be subdivided into two geochemical types, similar to those distinguished among diamondiferous kimberlites. In particular, the rocks of some kimpicrite pipes (an. 772, Izhma, and Vesennyaya) are distinguished by very low contents of typical trace and radioactive elements (Nb, Zr, Ce, U, and Th). This allows us to distinguish geochemical types of formational series, which include kimberlites, kimpicrites, and, presumably, alpicrites having common geochemical characteristics, in particular, the presence or absence of negative anomalies of high-field-strength and radioactive elements.

Thus, the magmatism of the Arkhangel'sk province comprises several magmatic formations, which is probably typical of the marginal parts of cratonic areas. The diversity of formational types was observed not only on the scale of the province, but also within individual fields, especially largest of them, such as the Kepa and Verkhotina fields. These fields exhibit irregular shapes, extremely uneven distribution of pipes and sill-like bodies, and formational heterogeneity of magmatic rocks. It is obvious that the more compact and homogeneous clusters, including diamondiferous kimberlites, kimpicrites, and alpicrite rocks, can be distinguished in such fields by future studies.

The polyformational magmatism of the Arkhangel'sk province can be interpreted as a result of unstable dynamically varying magma generation conditions, which are typical of boundary zones between rigid cratonic blocks with low heat flows favorable for the generation of diamondiferous kimberlites and more permeable intracratonic mobile zones and rift structures, which are characterized by a more intense migration of deep-seated fluids, elevated heat flow, and produce magmatic formations of the kimpicrite and alpicrite types.

The boundary position of the province and unstable magma generation conditions resulted in the activation of several mantle levels within a relatively small area: from the deepest zones of diamond stability, which generated kimberlites, through an intermediate pyrope peridotite zone generating transitional kimpicrite magmas, to the shallowest levels dominated by spinel peridotites, which produced alkaline–ultramafic and carbonatite melts.

The presence of two geochemical types of kimberlites and related rocks suggests their derivation either from different mantle sources or under different conditions. Studies of the geochemical and Sr–Nd isotopic systematics of the kimberlites of the Arkhangel'sk province [1, 19] showed that the diamondiferous rocks of the Zolotitsa field display negative anomalies of trace and radioactive elements (Nb, Zr, Ce, U, and Th) and EMI isotopic signatures, which correspond to the slightly enriched lithospheric mantle. The geochemical features of kimberlites of this type indicate that their source was metasomatized by fluids supplied from a paleosubduction zone of supposedly Early Proterozoic age [19]. This conclusion is supported by several facts [26] suggesting that the Early Proterozoic mantle experienced extensive metasomatism, which resulted in mass transfer between the subducted crust and mantle and provided conditions for the appearance of enriched mantle reservoirs.

On the other hand, rocks with ordinary geochemical characteristics and Sr–Nd isotope compositions typical of the weakly differentiated mantle were probably derived from an asthenospheric source. Such rocks can be exemplified by kimpicrites from some pipes of the Kepa field, kimberlites from traditional diamondiferous areas of Yakutia, and Group I kimberlites of southern Africa.

CONCLUSIONS

The formational–metallogenic analysis of the alkaline ultramafic rocks of the Arkhangel'sk diamondiferous province showed that several magmatic formations had developed in this region. It includes the main rock types of the kimberlite–kimpicrite–alpicrite formational family. The diamondiferous kimberlites proper occur in subordinate amounts, whereas weakly diamondiferous kimpicrites and nondiamondiferous alpicrites are more abundant. The Arkhangel'sk province is characterized by the close spatial association of various formational–metallogenic types. In this respect, the Arkhangel'sk province is different from the Central Yakutian province hosting the main fields of diamondiferous kimberlites in Yakutia. The diversity of formational types in the Arkhangel'sk province is similar to that of the Anabar–Olenek province in northern Yakutia.

The Arkhangel'sk province is a good example illustrating the existence of two types of diamondiferous kimberlite provinces: (1) the polyformational type characteristic of the marginal parts of stable ancient cratons and (2) the monoformational type developing in the inner parts of cratons. This demonstrates that petrogeochemical criteria are an efficient tool for the formational–metallogenic analysis of kimberlites and related rocks, especially, in polyformational provinces, where diamond-associated minerals often occur in minor amounts comparable with diamond contents.

The analysis of the available data did not confirm the suggestion that the kimberlites from two diamond deposits of the Arkhangel'sk province belong to different petrochemical series: Al and Fe–Ti. In any case, these so-called "series" have little in common with the differentiated petrographic series but reflect the different histories of contamination during kimberlite magma generation or ascent to the surface. The differences between the kimberlites of two deposits are restricted to mineralogical compositions and some chemical features, which allows us only to distinguish mineral types of kimberlites and suppose a more significant role of the crustal contamination or mixing in the formation of the Zolotitsa kimberlite field.

Our study supported the conclusion that the diamondiferous kimberlites of the Arkhangel'sk province belong to a specific geochemical type of kimberlites, which differs from the Group I kimberlites of southern Africa and kimberlites from the traditional diamondiferous areas of Yakutia [1]. The recently discovered kimberlites of the Nakyn field in the Srednyaya Markha area of the central Yakutian province are probably also of the same geochemical type.

The fact that kimberlites can be subdivided into mineral and geochemical types indicates a significant variability in this formational–metallogenic type of magmatic rocks, which is an important inference for identifying potentially diamondiferous rocks and predicting the diamond potential of new areas.

Since the compositions of various formational types of alkaline ultramafic rocks show a strong convergence, any efficient metallogenic evaluation of an area should be based on the modern classification of this family with clearly distinguishable formational types of kimberlites, kimpicrites, and alpicrites. The proposed formational–metallogenic taxa reflect natural interrelations between the different rock types, as well as between their composition and minerageny. Therefore, they have some advantages over regional classifications based on a purely empirical approach, for examples, subdivision of kimberlites into groups 1, 2, 1A, 1B, etc.

It should be noted that the logic of the metallogenic analysis of magmatic rocks requires the use of the term kimberlite in a narrow sense, restricted to the rocks that contain diamond and associated minerals and show specific petrochemical features. We are not the first to propose such a definition of kimberlites. However, this approach is presently justified and prepared by the progress in mineralogical and petrogeochemcial investigations aimed at more reliable identification of diamondiferous rocks.

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