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Mantle(?) Xenoliths in the Carbonatites of Northern Transbaikalia

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Abstract—The composition and nature of high-Cr minerals in lithic clasts from the carbonatites of the Veseloe occurrence, northern Transbaikalia, were considered. In order to determine their source, the Cr-bearing phases were compared with chromite, magnetite, and rutile from ultrabasic rocks, mantle xenoliths, and eclogites. It was suggested that the xenoclasts studied were formed at great depths, whereas the carbonatites were directly derived from the mantle rather than formed by the crustal differentiation of a silicate–carbonate melt.

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INTRODUCTION

There are presently several models for the origin and evolution of carbonatite melt. The model of its derivation directly from the mantle is justified mainly by theoretical and experimental data, whereas natural evidence in support of this model is scanty and, in some cases, ambiguous. Of great importance are mantle xenoliths found in carbonatites, although some of them could be entrained at the upper crustal levels. In particular, such an origin was established for high-Cr xenoliths from the Badou carbonatite diatremes and dikes (China) developed within a kimberlite field [1].

Mantle xenoliths were found only in extrusive carbonatites (15 of 40 occurrences) [2]. They contain Cr-spinel as the major typomorphic mineral, as well as olivine, magnetite, rutile, phlogopite, garnet, pyroxenes, ilmenite, and K-richterite. Many of these minerals have high Cr contents.

Intrusive carbonatites do not bear mantle xenoliths, and only a few show high Cr content. The investigation of one of them, the Chernigov carbonatite occurrence with Cr-bearing magnetite, resulted in distinguishing a specific type of linear carbonatites, which were supposedly derived directly from the mantle [3, 4]. The rocks of the Veseloe area with Cr-spinel and Cr-rich minerals offer another rare example of such intrusive carbonatites and are, therefore, an important object for petrogenetic studies.

METHODS

The composition of minerals and the character of their intergrowths in the carbonatites were studied on MAR-3 and Cameca SX50 electron microprobes and two electron microscopes, LEO-1430 equipped with an energy-dispersive system Jnca Energy-300 and Probe SEM-Jeol125900LV Analytical SEM with cathodoluminescence. The studies were conducted at the Geological Institute, Siberian Division, Russian Academy of Sciences, and at the Mineralogical Department of the Natural History Museum in London. The measurements were performed at an accelerating voltage of 15–20 kV, a beam current of 20–40 nA, a counting time of 20 s, and a beam diameter of 2–3 μm. Minerals were analyzed in several points to obtain a more reliable analysis. The precursor minerals of phases with exsolution lamellae were identified on the electron microscope by rastering the electron beam over certain areas. Central, intermediate, and marginal parts of aggregates were analyzed separately. The minerals mentioned in the paper were also analyzed on the microprobes and electron microscopes.

GEOLOGICAL OVERVIEW

The Veseloe carbonatite occurrence with clasts of supposedly mantle origin is situated in northern Transbaikalia. It includes beforsite dikes and is confined to a rift zone among Riphean schists. This zone is extended along the western boundary of the northern Muya block, which is composed of Precambrian metamorphic rocks. The axis of the zone is tracked by closely spaced dikes of subalkaline gabbroids and lenslike bodies of talc–carbonate rocks.

The carbonatites, basic rocks, talc–carbonate rocks, and host schists were metamorphosed under greenschist facies conditions (epidote–muscovite–chlorite and biotite–chlorite subfacies) at 550 ± 14 Ma (Rb–Sr isochron age). The presence of phengite with high silica content (3.30–3.45 a.f.u.) in all the rocks indicates high-pressure metamorphism (more than 7 kbar).

During the metamorphism, the gabbroids were transformed into amphibole–epidote–chlorite–plagioclase rocks with subordinate biotite, titanite, and apatite. The talc–carbonate rocks were formed in two stages. At the early stage, the primary rocks were replaced by magnesite with talc, quartz, dolomite, and chromite. Subsequent metamorphism was responsible for the formation of Cr-bearing phengite, chlorite, actinolite, phlogopite, and new generations of talc and quartz. The mineral composition of the rocks corresponds to a listwaenite. They are strongly schistose, boudined, and preserved at the contact as lenses embedded in the mica–quartz–feldspar aggregate of the host schists with indications of protrusion processes. Their chemical composition (37–42 wt % SiO_2 and 20–30 wt % MgO) corresponds to ultramafic rocks with low alkali, Al_2O_3, and TiO_2 contents.

In all of the talc–carbonate rocks, finely disseminated chromite was observed in magnesite, talc, quartz, and dolomite. In addition, chromite is also present in carbonate veinlets occurring in the talc–carbonate rocks. Relict low-Fe olivine occurs occasionally in the rocks.

The carbonatites form several thin submeridional dikes traced over 600–1000 m. Their U–Pb zircon age is 593 ± 3.5 Ma (Center of Isotopic Research, Karpinskii All-Russia Research Institute of Geology, analyst A. Larionov). The carbonatites are composed of the typomorphic mineral assemblages of such rocks, and their geochemical and isotopic parameters are similar to those of typical carbonatites [5, 6]. These fine-grained rocks show a distinct banding parallel to the contact formed by aligned grains and mineral aggregates. The rock is composed of Fe-rich dolomite (70–85%), apatite (10–20%), and calcite (5–15%). Magnetite, phlogopite, K-richterite, riebeckite, rutile, zircon, and monazite occur as accessory minerals. The chemical compositions of the rocks plot in the field of magnesiocarbonatite with high P and low Nb contents. The rocks are enriched in LREE and have no Eu anomaly.

The oxygen and carbon isotopic compositions of dolomite and calcite ($\delta^{18}O$ of 8–10‰ SMOW and $\delta^{13}C$ of –2‰ PDB) and oxygen isotopic compositions of magnetite and apatite ($\delta^{18}O$ of 2.5 and 5.2‰ SMOW, respectively) are in general similar to those of carbonatitic minerals, and the initial $^{87}Sr/^{86}Sr$ ratios (0.7038) are identical to those of the Late Riphean mantle.

The crystallization temperature of carbonatites was determined by mineral geothermometers and from a study of inclusions in minerals and indicates their magmatic origin. The crystallization began at a temperature of more than 920°C, which was estimated from the homogenization of melt inclusions in the earliest minerals (apatite and zircon). About 20% of crystals remained unmolten in the inclusions at this temperature. The crystallization temperature of an intermediate phase was estimated by the magnetite–ilmenite geothermometer as 750–800°C, and that of the final phase estimated from the Mg# of calcite is 600–650°C. Calcite is one of the latest minerals. It fills interstices between dolomite and apatite and contains dolomite lamellae formed by exsolution from the solid solution.

CHROMIUM-BEARING PHASES IN CARBONATITES

The contents of Ti, Cr, and Ni in the Veseloe carbonatites are 2–3 times higher than the average values for carbonatite after [7] (113 ppm Cr, 128 ppm Ni, and 0.44 wt % TiO_2). This is caused by several reasons. First, the carbonatites contain xenoclasts with high-Cr minerals. The clasts are small (up to 3–5 mm) variably disintegrated aggregates scattered over a calcite–apatite–dolomite matrix and containing Cr-spinel, magnetite, rutile, ilmenite, and titanite. Most of these minerals have high Cr contents. In addition, Cr also occurs in carbonatite-related riebeckite, richterite, and rutile. Part of Cr is incorporated in phengite, chlorite, and actinolite, which were formed during postcarbonatite metamorphism. The contents and variations of Cr in the minerals from the aforementioned assemblages are given in Table 1.

Two types of clasts were distinguished. One type includes rutile–magnetite symplectites with inclusions of ilmenite, titanite, rutile, and crystal clasts of magnetite. The other type involves disintegrated rutile-dominated aggregates consisting of crystal clasts with trails of broken grains.

The magnetite–rutile symplectites (Fig. 1) look like exsolution lamellae. The composition of the precursor mineral was determined on the electron microscope by rastering over various areas of such aggregates (Fig. 2) and corresponds to Cr-bearing ilmenite (Table 2). The magnetite of these intergrowths contains from tenths to 3.75 wt % Cr_2O_3, and the Cr_2O_3 content of rutile averages 0.7 wt % (Table 1). The xenoclasts are rimmed by titanite formed through their interaction with carbonatite (Figs. 2, 3). Newly formed titanite also occurs in the magnetite–rutile matrix. Its average Cr_2O_3 content is 0.32 wt %.

The magnetite–rutile aggregates contain randomly distributed ilmenite grains and heterogeneous magnetite clasts (Figs. 1, 3), which contain from a few to 16–18 wt % Cr_2O_3. The Cr content decreases from core to rim to 2–3 wt %. The Zn content is usually tenths percent (up to 1.3 wt %). The rutile associating with magnetite clasts is also chromium-rich (2.08 wt % Cr_2O_3 on average) and contains 0.95–2.30 wt % Nb_2O_5.

The magnetite clasts contain corroded grains of Zn-bearing (6–7 wt % ZnO) chromite (Fig. 4). The mineral is classed as ferrochromite and shows low Al_2O_3, low Mg#, and an elevated TiO_2 content (Table 3).

Table 1. Cr_2O_3 contents in minerals from the carbonatites of the Veseloe area, wt %

Analyzed material	Mineral	Number of analyses	Content from–to (average)
Xenoliths with magnetite–rutile symplectites	Magnetite	16	0.33–3.74 (1.17)
	Rutile	17	0.27–1.10 (0.70)
	Ilmenite	7	0.00–1.33 (0.55)
	Titanite	21	0.00–1.38 (0.32)
Magnetite clasts	Chromite	7	41.80–50.21 (45.75)
	Magnetite	10	2.02–18.27
Rutile clasts	Rutile	7	0.99–2.74 (1.62)
Phenocrysts in carbonatite matrix	Rutile	63	0.20–1.32 (0.83)
	Richterite	4	0.08–0.18 (0.11)
Postcarbonatite metamorphic minerals	Actinolite	4	0.12–0.29 (0.18)
	Phengit	18	0.00–5.83
	Chlorite	16	0.00–6.15

Note: Average contents were not calculated for minerals with high Cr variations.

The xenolcasts of rutile aggregates are often composed of broken grains. The rutile contains from 1 to 2.4 wt % Cr_2O_3, more than 1 wt % V_2O_3, and 0.7–1.0 wt % FeO. A typomorphic admixture is Nb_2O_5, reaching up to 5.9 wt % (Table 4). The rutile grains are rimmed by a later Nb-free generation (Fig. 5), which differs in rel-

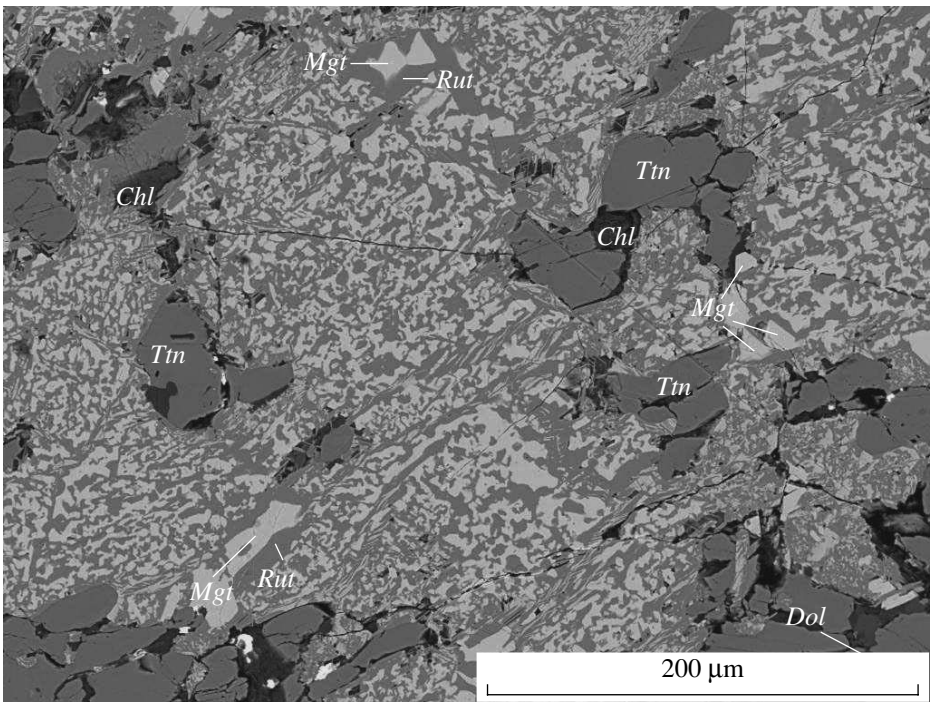

Fig. 1. Back-scattered electron microscope image of a typical xenoclast consisting of rutile–magnetite symplectites and grains of titanite (*Ttn*), phengite, chlorite (*Chl*), and crystal clasts of high-Cr (with chromite) magnetite (*Mgt*). The angular crystal clasts of magnetite are mantled by high-Cr rutile (*Rut*). *Dol* is dolomite and black is phengite and chlorite.

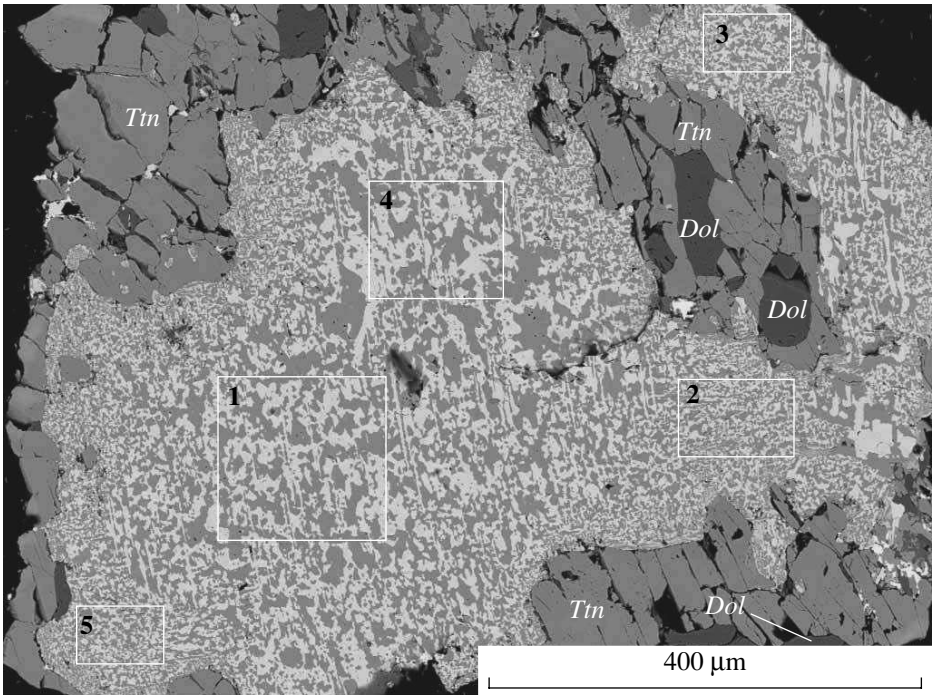

Fig. 2. Back-scattered electron microscope image of a xenoclast of magnetite–rutile symplectites with a titanite (*Ttn*) rim. The dark phase is dolomite (*Dol*). The rectangles show the scanning areas whose compositions are shown in Table 2.

atively low contents of Cr (less than 1 wt % Cr_2O_3), V (0.83 wt % V_2O_3), and Fe (less than 0.1 wt % FeO).

Cr was also found in the minerals that crystallized simultaneously with the carbonatites. Among them is a rutile generation often occurring in the apatite–dolomite matrix. It forms either unevenly distributed disseminations or chains of xenomorphic grains aligned conformably to the carbonatite banding. Rutile is often confined to the interstices between dolomite and apatite and forms a sideronite-like texture. It contains from 0.2 to 1.3 wt % Cr_2O_3 and 0.8–1.0 wt % V_2O_3.

Occasionally, the carbonatites contain short-columnar rutile crystals, which formed during the early crystallization stage. They have induction surfaces of joint growth with apatite and are euhedral relative to dolomite. The rutile contains from 0.6 to 1.25 wt% Cr_2O_3, and the areas of incipient grain growth also accommodate 0.71–1.71 wt % Nb_2O_5. The late crystallization zones do not contain Nb. This fact suggests that Nb-bearing rutile clasts served as crystal nuclei, which continued their growth during carbonatite formation.

The richterite and riebeckite occasionally contain small amounts of Cr (Table 1).

The most part of Cr-bearing phengite, chlorite, and actinolite is confined to xenoliths and was formed during late metamorphism (Fig. 5). The content of Cr_2O_3 is up to 5.8 wt % in the phengite and from tenths to 2–3 wt % in the chlorite. Some chlorite samples contain up to 1.3 wt % NiO.

DISCUSSION

The possibility of formation of dolomitic carbonatite liquids in the mantle has been demonstrated by many researchers [8–13], mainly on the basis of theoretical and experimental data. Mantle xenoliths usually serve as evidence for their deep-seated origin of the host rocks. However, such xenoliths were found only in volcanic carbonatites from some occurrences [14–17]. They contain garnet, phlogopite, Cr-spinel, orthopyroxene, and clinopyroxene. One of the most important features of the minerals is high Cr content. In particular, most minerals in xenoliths from the melilite-bearing carbonatite tuff of southern Italy [16], including orthopyroxene, clinopyroxene, phlogopite, and spinel, are

Table 2. Chemical compositions of precursor minerals (Fig. 2) from xenoclasts with magnetite–rutile sympectites in the carbonatites of the Veseloe area, wt %

Spectrum No.	FeO	TiO_2	Cr_2O_3	Total
1	47.62	52.72	0.72	101.06
2	47.54	52.92	0.78	101.24
3	47.75	51.32	1.02	100.10
4	47.54	51.82	0.71	100.07
5	46.37	53.39	0.67	100.43

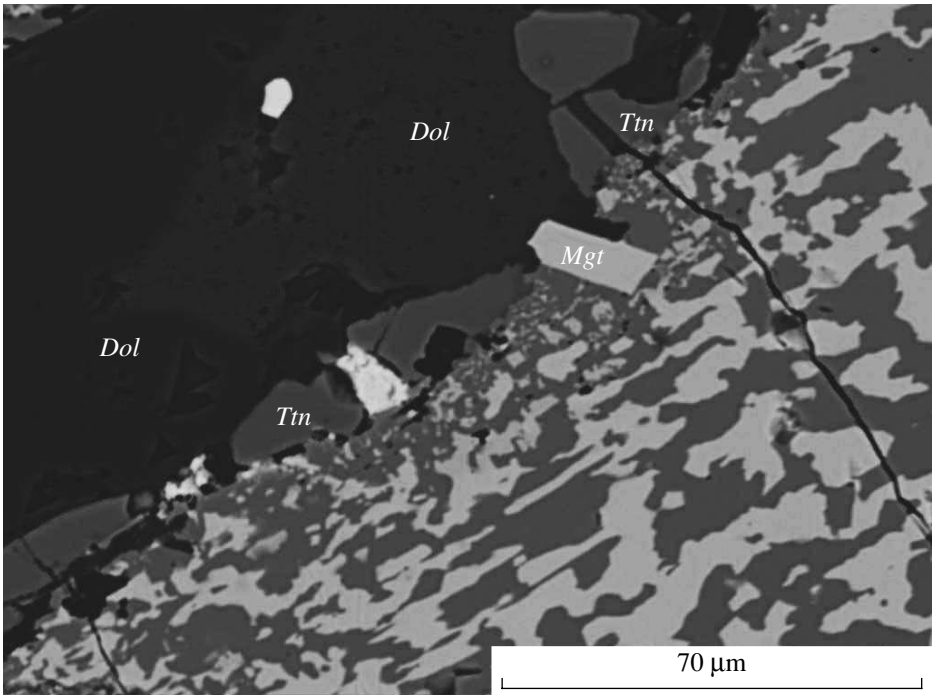

Fig. 3. Back-scattered electron microscope image of the boundary zone between dolomitic carbonatite and a lithic clast composed of sympelctite intergrowth of magnetite (light) and rutile (gray). A titanite (*Ttn*) rim develops along the boundary. The rutile–magnetite aggregate contains a magnetite clast (*Mgt*) with chromite (*Chr*) inclusions.

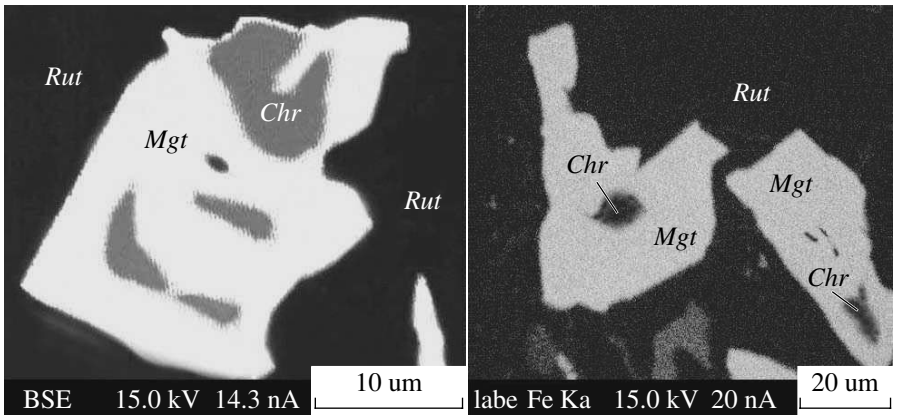

Fig. 4. Back-scattered electron image of chromite (*Chr*) relics in clasts of high-Cr magnetite (*Mgt*). The dark field is Cr-bearing rutile. The image was obtained on the Cameca SX50 electron microprobe.

enriched in Cr. High-Cr pyroxene was found in xenoliths from Tenerife (Canary Islands [15]), and magnetite associating with Cr-spinel in the extrusive carbonatites of the United Arab Emirates contains 0.3 wt % Cr_2O_3 [14].

The composition of inclusions found in the Veseloe carbonatites indicates that the rocks were derived directly from the mantle rather than through the differentiation of a silicate–carbonate melt in a magma chamber. This is emphasized by the occurrence of high-Cr magnetite and rutile, which are most typical of ultramafic rocks. The coexisting ilmenite also has a high Cr content [18]. The absence of typomorphic silicate minerals casts some doubt on this model. However, silicate phases were not found in association with Cr-spinel at some carbonatite occurrences, including Tamazert [17] and Rufunsa [15]. It can be supposed that volcanic carbonatites were rapidly transported to the surface, whereas the carbonatite melts of the Veseloe area interacted with xenoliths for a longer period of time, which resulted in the assimilation of primary silicate phases. This process was responsible for the formation of titan-

Table 3. Chemical compositions of (1–4) magnetite clasts and (5–11) chromite inclusions in them from the carbonatites of the Veseloe area, wt %

Component	1	2	3	4	5	6	7	8	9	10	11
TiO_2	1.22	1.03	0.31	1.76	2.69	1.64	2.68	2.98	1.60	1.35	1.53
$A1_2O_3$	0.18	0.05	0.00	0.20	1.12	0.97	1.06	1.00	1.05	0.72	1.14
Cr_2O_3	13.96	4.58	5.04	16.66	45.62	41.80	46.27	43.03	43.29	50.02	50.21
FeO	77.80	87.85	87.01	74.84	42.43	45.86	41.72	45.79	44.10	43.57	43.44
MgO	–	–	–	–	0.07	0.04	0.08	0.07	0.07	0.06	0.07
V_2O_3	0.19	0.24	0.46	0.25	0.21	0.37	0.22	0.30	0.38	0.00	2.50
ZnO	n.d.	n.d.	n.d.	1.37	6.35	6.15	6.86	6.18	7.11	n.d.	n.d.
Total	94.31	94.07	94.23	95.08	98.81	97.40	99.44	100.04	98.14	98.80	99.76

Note: Totals include SiO_2, MnO, NiO, CoO, and Na_2O, which account for hundredths to a few tenths of a percent.

ite dissemination in the xenoclasts and reaction rims around them (Figs. 2, 3).

The assimilation also causes the general Cr "contamination" of carbonatites and their minerals, including rutile, riebeckite, and richterite crystallizing simultaneously with the rock. Owing to the high Cr content in the rocks, late metamorphic phengite, chlorite, and actinolite are also enriched in this element.

Noteworthy is the fact that rutiles from the xenoclasts are rich in both Cr and Nb (Table 4). Similar rutiles occur in the matrix of volcanic dolomitic carbonatites with Cr-spinel clasts from Tamazert [17]. Cr-bearing rutile is also a typical mineral of kimberlites, mantle xenoliths in them [19, 20], and eclogites [21]. In the Ti versus Cr + Nb diagram, the compositions of the rutiles fall within the fields of kimberlites and eclogites.

The appearance of chromite and high-Cr phases in the carbonatites of the Veseloe area can also be explained by the entrainment of material from ultrabasic rocks in upper crustal levels. As was mentioned above, the carbonatite bodies are spatially associated with talc–carbonate rocks. The chemistry of these rocks and the presence of chromite in them indicate their primary ultrabasic nature. Owing to carbonation, they were transformed into a magnesite-dominated aggregate with talc, dolomite, and quartz. The oxygen and carbon isotopic compositions of the carbonate minerals are close to those of carbonatites (averaging $\delta^{13}C = -1.03‰$ PDB and $\delta^{18}O = 12.9‰$ SMOW), which suggests a common source of carbon dioxide in these rocks. By contrast, the lack of any significant amounts of Ti in the talc–carbonate rocks and the high Ti content of the xenoliths are more consistent with different sources. The compositions of chromites (Fig. 7) and magnetites also suggest different sources. Our investigations showed that the talc–carbonate rocks contain two types of chromite. One of them includes relict chromite with high contents of Al_2O_3 (up to 10–11 wt %) and MgO (up to 4–5 wt %). The other chromite type

Table 4. Chemical composition of rutile from xenoclasts in the carbonatites of the Veseloe area, wt %

No.	TiO_2	Cr_2O_3	Nb_2O_5	FeO	V_2O_3	Total
1	97.83	0.99	0.57	0.37	–	99.76
2	91.16	2.30	5.75	0.98	–	100.19
3	96.17	1.10	1.79	0.57	–	100.63
4	89.79	2.10	5.66	1.21	1.17	99.93
5	93.33	1.40	3.17	0.94	0.99	99.83
6	92.69	1.55	3.42	0.67	1.18	99.51
7	96.08	1.55	1.43	0.36	n.d.	99.42
8	95.93	2.11	0.95	n.d.	–	101.17
9	92.84	2.90	2.30	0.38	0.93	100.58
10	96.02	2.74	1.75	n.d.	n.d.	101.22
11	98.48	1.36	0.77	0.37	0.10	101.42
12	97.74	0.59	1.07	n.d.	–	99.40
13	96.22	0.90	1.38	0.48	0.72	99.70
14	95.70	0.67	1.63	0.52	0.98	99.50

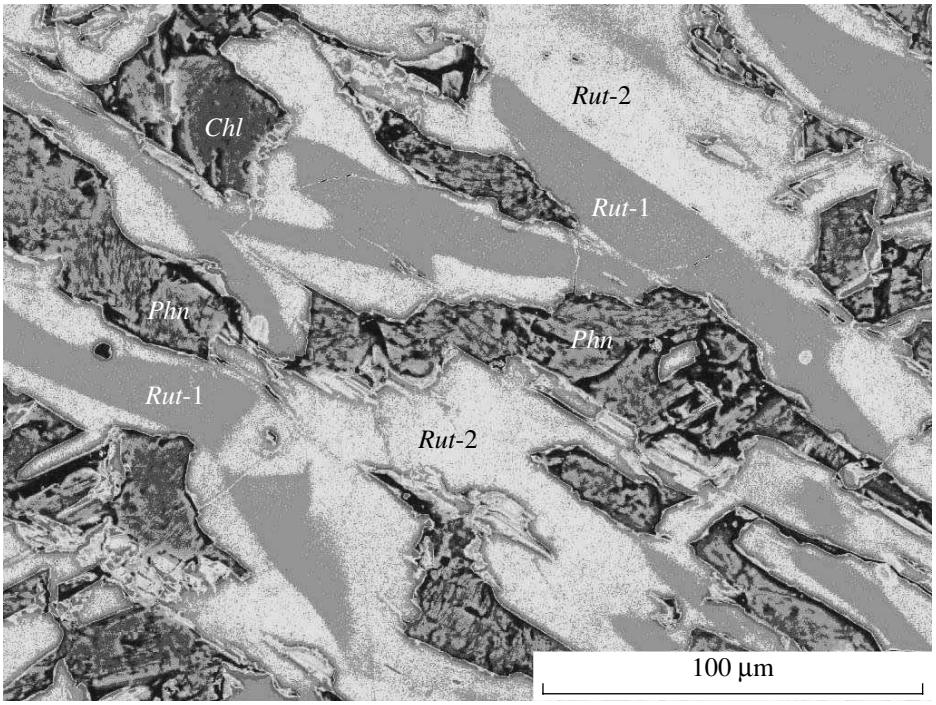

Fig. 5. Back-scattered electron microscope image of a fragment of a xenoclast composed of the aggregates of angular grains of Nb-bearing rutile (*Rut*-1) rimmed by late rutile (*Rut*-2). The interstices between grains are filled with Cr-bearing chlorite (*Chl*) and phengite (*Phn*).

was related to metamorphic and metasomatic transformations, which obliterated its primary compositional features. In particular, these chromites have lost Al, Mg, and part of Cr but gained ferric Fe. Their outer zones are usually composed of intermediate chromite–magnetite phases or high-Cr magnetite. Both chromite types differ from chromite from the xenoliths in the carbonatites, which is free of Al and Mg but shows high ZnO (6.5 wt %) and TiO_2 (on average, 2.07 wt %) contents. In contrast to magnetites from the carbonatite-hosted xenoliths, magnetite from the talc–carbonate rock contains, on average, 1.5 wt % NiO and is free of TiO_2.

Chromite from the xenoliths in the carbonatites is sharply different from chromites in most mantle xeno-

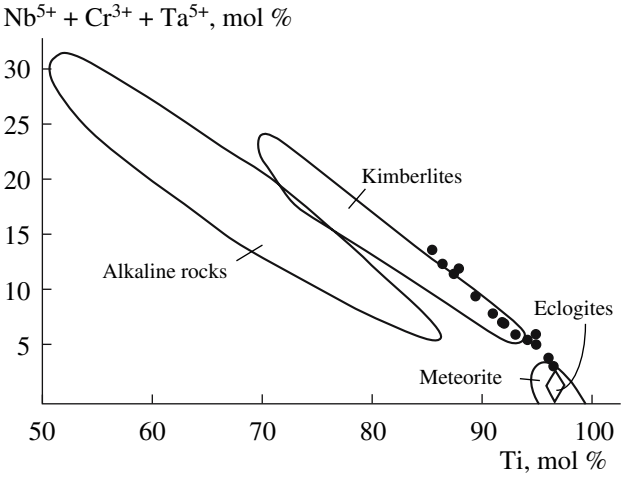

Fig. 6. Diagram of Ti – Nb^{+5} + Cr^{+3} + Ta^{+5} for rutile from xenoclasts in carbonatites at. %. The compositional fields are after [20].

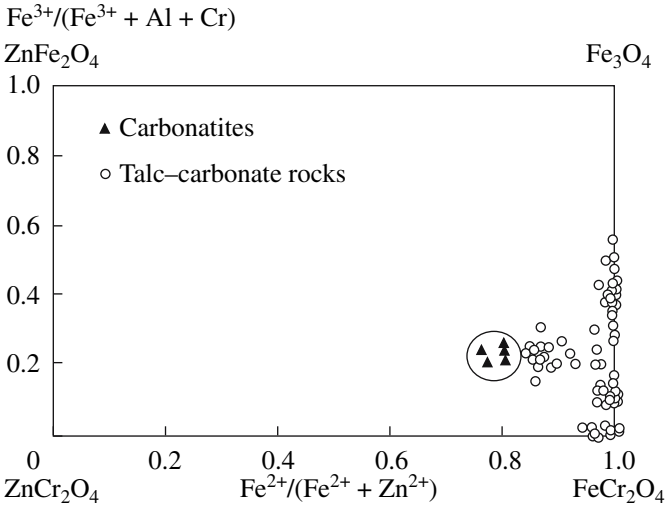

Fig. 7. Compositions of chromite from talc–carbonate rocks and xenoliths in carbonatites.

liths and ultrabasic rocks in extremely low contents of Al_2O_3 and MgO but approaches chromite from some kimberlites in terms of Al_2O_3 content. Similarly, not all chromites from kimberlites have high Ti contents. There is as yet no plausible explanation for these compositional features.

The discovery of Cr-bearing phases in the intrusive carbonatites and the possible direct derivation of their melts from the mantle call for more detailed investigations in the Veseloe area, as well as at the Pogranichnyi occurrence of dolomitic carbonatites in the same region. This occurrence contains graphite and was presumably formed in high-pressure conditions.

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REFERENCES

1. A. Goto and H. Fujimaki, and T. Morikiyo, "Geochemical and Lithological Characteristics of Badou Carbonatite Pipe, Shandong China," in *Proceedings of 13th Goldschmidt Conference, Kurashiki, Japan, 2003* Geochim. Cosmochim. Acta. **67**, 124 (2003).
2. A. R. Woolley and A. A. Church, "Extrusive Carbonatites: A Brief Review," Lithos. **84**, 1–14 (2005).
3. Yu. A. Bagdasarov, "Geochemical Features of Magnetites from Carbonatites and Other Rocks of the Chernigov Zone, Azov Area," Dokl. Akad. Nauk SSSR **252** (1), 208–212 (1982).
4. Yu. A. Bagdasarov, "Chromium Geochemistry in the Rocks of the Carbonatite Complexes," Geol. Rudn. Mestorozhd., No. 6, 85–89 (1981).
5. G. S. Ripp, M. V. Badmatsyrenov, A. G. Doroshkeyich, and I. A. Isbrodin, "Mineral Composition and Geochemical Characteristic of the Veseloe Carbonatites (Northern Transbaikalia, Russia)," in *Proceedings of the International Workshop on Deep-Seated Magmatism, Its Sources and Their Relation to Plume Processes, Irkutsk–Ulan Ude, Russia, 2004*, (Irkutsk and Ulan-Ude, 2004), pp. 257–273.
6. G. S. Ripp, M. V. Badmatsyrenov, A. G. Doroshkevich, and I. A. Izbrodin, "New Carbonatite-Bearing Area in Northern Transbaikalia," Petrologiya **13**, 538–547 (2005) [Petrology **13**, 489–498 (2005)].
7. A. R. Woolley and R. C. Kemp, "Carbonatites: Nomenclature, Average Chemical Composition, and Element Distribution," in *Carbonatites: Genesis and Evolution* (Unwin Hyman, London, 1989), pp. 1–14.
8. I. D. Ryabchikov, G. Brey, L. N. Kogarko, and V. K. Bulatov, "Partial Melting of Carbonated Peridotite at 50 kbar," Geokhimiya, No. 1, 3–9 (1989).
9. I. D. Ryabchikov, "Processes of Mantle Magma Formation," in *Evolution of Magmatism in the Earth History* (Nauka, Moscow, 1987), pp. 349–371 [in Russian].
10. L. N. Kogarko, G. Kurat, and T. Ntaflos, "Carbonate Metasomatism of the Oceanic Mantle beneath Fernando de Noronha, Brazil," in *Proceedings of Conference on Deep-Seated Magmatism, Its Sources and Their Relation to Plume Processes, Irkutsk–Ulan-Ude, Russia, 2004*, (Irkutsk and Ulan-Ude, 2004), pp. 29–47 [in Russian].
11. R. E. Harmer and J. Gittins, "The Origin of Dolomitic Carbonatites: Field and Experimental Constraints," J. Afr. Earth Sci. **25**, 5–28 (1997).
12. D. K. Bailey, "Carbonate Melt from the Mantle in the Volcanoes of South-East Zambia," Nature **338**, 415–418 (1989).
13. A. R. Wooley, "Igneous Silicate Rocks Associated Carbonatites: Their Diversity, Relative Abundances and Implications for Carbonatite Genesis," Period. Mineral. **72**, 9–17 (2003).
14. A. R. Wooley, W. C. Barr, V. K. Din, et al., "Extrusive Carbonatites from the Uyaynah Area, United Arab Emirates," J. Petrol. **32**, 1143–1167 (1991).
15. E. R. Neumann, E. Wulff-Pedersen, N. J. Pearson, and E. A. Spenser, "Mantle Xenoliths from Tenerife (Canary Islands): Evidence for Reactions between Mantle Peridotites and Silicic Carbonatite Melts Including Ca Metasomatism," J. Petrol. **43**, 825–857 (2002).
16. A. P. Jones, T. Kostoula, F. Stoppa, and A. R. Woolley, "Petrography and Mineral Chemistry of Mantle Xenoliths in a Carbonate-Rich Melilitic Tuff from Mt. Vulture Volcano, Southern Italy," Mineral. Mag. **64**, 593–613 (2000).
17. S. Mourtada, M. J. Le Bas, C. Pin, "Petrogenese des magmes carbonatites du complexe de Tamazert (Haut Atlas marocain)," Earth Planet. Sci. **325**, 559–564 (1997).
18. Yu. A. Bagdasarov and I. P. Ilunin, "Coexisting Ilmenites and Ti-Magnetites of Kimberlite Groundmass," Dokl. Akad. Nauk SSSR **290**, 945–948 (1986).
19. S. E. Haggerty, "Metasomatic Mineral Titanates in Upper Mantle Xenoliths," in *Mantle xenoliths*, Ed. by P. H. Nixon (Wiley, Chichester, 1987), pp. 670–691.
20. S. E. Haggerty, "Oxide Mineralogy of the Upper Mantle," in *Oxide Minerals: Petrologic and Magnetic Significance* Mineral. Soc. Am. Rev. Mineral. **25**, 355–416 (1991).
21. N. V. Sobolev, Yu. G. Lavrent'ev, and L. V. Usov, "On Trace Elements in Rutile from Eclogites," Geol. Geofiz., No. 11, 108–112 (1972).