

## Late Mesozoic Carbonatites of Western Transbaikalia: Isotopic–Geochemical Characteristics and Sources

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**Abstract**—Carbonatites in the western Transbaikalia rift area have a mid-Early Cretaceous age (130–120 Ma) and comprise lavas, tuffs, dikes, and veins, which are commonly associated with alkaline and subalkaline gabbroids and syenites. Compared to the basalts, which predominate in the volcanic area, the rocks of these carbonatite associations have higher concentrations of Ba, Pb, LREE, and Sr at much lower contents of Nb and Ta. The oxygen and carbon isotopic composition of the carbonatites (their varieties not affected by secondary processes have  $\delta^{18}\text{O}$  from 6.0 to 10.7‰ and  $\delta^{13}\text{C}$  from  $-4.1$  to  $-6.5$ ‰) is generally consistent with the mantle genesis of the rocks. The Sr and Nd isotopic composition of rocks from the carbonatite associations varies from  $(^{87}\text{Sr}/^{86}\text{Sr})_0 = 0.7052$  at  $\epsilon_{\text{Nd}} = -1.6$  for tephrites to  $(^{87}\text{Sr}/^{86}\text{Sr})_0 = 0.7059$  at  $\epsilon_{\text{Nd}} = -6.4$  for carbonatites from large bodies. These variations seem to have been produced by the mixing of two isotopically heterogeneous sources. A model is proposed for the genesis of the carbonatite associations that takes into account their trace-element and isotopic characteristics. It is hypothesized that mantle metasomatism under the effect of fluids, whose composition was similar to that of the carbonatites, resulted in the enrichment of LREE, Sr, Ba, and Pb in the mantle source and brought about the derivation of the carbonatite phases proper. The melting of this mantle gave rise to carbonatite, silicate–carbonate, and silicate (alkaline gabbroid) melts, whose further evolution and interaction led to the origin of a wide spectrum of rocks of the carbonatite association in western Transbaikalia.

### INTRODUCTION

The area of western Transbaikalia was determined to include a number of occurrences of Late Mesozoic carbonatites: Khalyuta, Oshurkovo, Toreiskoe, Yuzhnoe, and Arshanskoe (Fig. 1). Previously, all of them were considered to be skarns, hydrothermal veins, weathering crusts on hydrothermally altered limestone xenoliths, and, later, metasomatic “carbonatites.” The researches started in 1996 established the carbonatite nature of the rocks and made it possible to assay their geological links with coeval magmatic rocks (Yarmolyuk *et al.*, 1997; Nikiforov *et al.*, 1998; Ripp *et al.*, 1998; Nikiforov *et al.*, 2000; Ripp *et al.*, 2000). The carbonatites were determined to have been produced in mid-Early Cretaceous time (at ca. 120 Ma) and be controlled by structures of the Late Mesozoic–Cenozoic western Transbaikalia rift (volcanic) area. However, some problems concerning the sources of carbonatite magmatism and their relations with other magmatic sources in the rift area remain unsettled. We consider these issues based on data on the O, C, Nd, and Sr isotopic compositions and trace-element compositions of the carbonatites and related endogenous silicate rocks. We also touch upon the problem of the mechanisms that produced these rocks.

### GEOLOGY OF CARBONATITE OCCURRENCES IN WESTERN TRANSBAIKALIA

Late Mesozoic carbonatites in western Transbaikalia are spatially restricted to a large (200 by 1000 km) rift zone (volcanic area; Nikiforov *et al.*, 2000). The rocks crop out over areas ranging from a few hundred square meters to a few square kilometers and comprise volcanic products, such as lava flows, dikes, and veins, which are usually associated with subalkaline and alkaline silicate rocks, composing common magmatic association with them, which will be referred to as carbonatite associations. The geologic structures of the carbonatites were described elsewhere (Yarmolyuk *et al.*, 1997; Nikiforov *et al.*, 2000; Ripp *et al.*, 2000), and, hence, below we only briefly describe the occurrences for which Sr and Nd isotopic analyses were conducted.

**The Khalyuta carbonatite complex** 25 km west of the town of Ulan-Ude, in the flank of the Uda graben, has an area of 8 km<sup>2</sup> in the middle reaches of the Khalyuta River. The complex comprises morphologically diverse carbonatite bodies with variable geologic settings. The complex was actively studied by P.I. Radchenko, E.S. Gol'dberg, K.B. Bulnaev, G.S. Ripp, and others. The Rb–Sr age of the complex is  $119 \pm 10$  Ma (Bulnaev and Posokhov, 1995). The carbonatites of the Khalyuta Complex comprise volcanic and subvolcanic

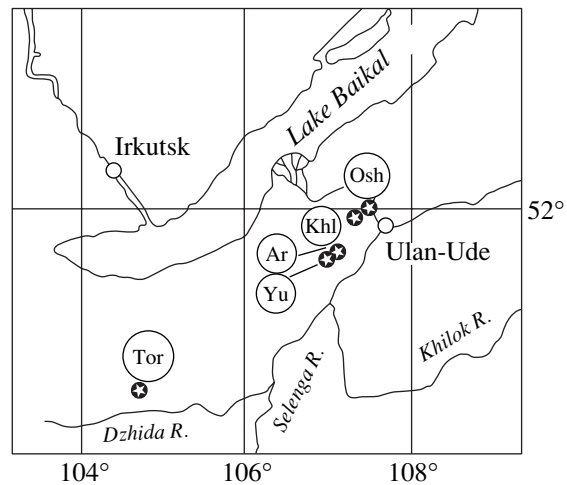
varieties (Yarmolyuk *et al.*, 1997; Nikiforov *et al.*, 2000), and the complex also contains subvolcanic bodies of alkaline gabbroids and syenites.

**The volcanic carbonatites** compose tuff and lava sheets, whose apparent thicknesses vary from a few to a few dozen meters. The volcanic carbonatites are banded, lenticular-banded, or agglomerated rock, whose volcanic nature follows from, first, the conformable position of the carbonatites on a weathering crust of the pre-Mesozoic basement and, second, from the intercalations of the carbonatite lavas and tuffs with beds of terrigenous sandy or sandy-clayey material (Fig. 2). Although none of the rocks shows any traces of metasomatic alterations, Bulnaev (1985, 1995, 1996) suggested that these carbonatites are of metasomatic genesis.

**The subvolcanic carbonatites** are veins and dikes of relatively small sizes (no more than a few meters thick and a few dozen meters long). Subvolcanic carbonatites were found, along with shonkinites and syenites in a composite dike (Yarmolyuk *et al.*, 1997). They have cutting contacts with the wall-rock granites and are often banded, with the banding conformable with the contact surfaces. The banding is defined by variations in the relative contents of minerals of the carbonatites and/or their grain sizes. The mineralogy of the rocks is similar to that of volcanic carbonatites.

The dominant mineral of the Khalyuta carbonatites is calcite. Other widespread minerals are strontianite and barite. The volumetrically subordinate minerals are barite-celestine, magnetite, apatite, phlogopite, orthite, zircon, pyrochlore, and monazite. Along with calcitic carbonatites, the complex contains more rare dolomitic carbonatites, which contain, in addition to dolomite, barite, apatite, and magnetite. The barite is characterized by a peculiar inner "reticulate" structure, which is typical of this mineral in all carbonatites in western Transbaikalia (Nikiforov *et al.*, 2000). The carbonatites contain mineral assemblages of two main stages. The earlier of them (magmatic stage proper) was characterized by the origin of dolomitic and "light" calcitic carbonatites, which compose the bulk of rocks in the complex. The apatite from carbonatites of this type was determined to contain recrystallized melt inclusions (Nikiforov *et al.*, 2000). The later, late-magmatic-post-magmatic, stage was inseparably connected with the earlier one and was responsible for the virtually full transformation of the dolomitic carbonatites into "brown" calcitic carbonatites, decomposition of the "barite-celestine," formation of barite with the aforementioned reticulate structure, overprinting of newly-formed minerals (strontianite, aragonite, and late calcite) on the preexisting rocks, and the development of hydrothermal strontianite-calcite-barite veinlets. Additionally, the carbonatites were locally silicified by younger processes.

**The subvolcanic silicate rocks** occur in strongly subordinate amounts in the Khalyuta Complex. They

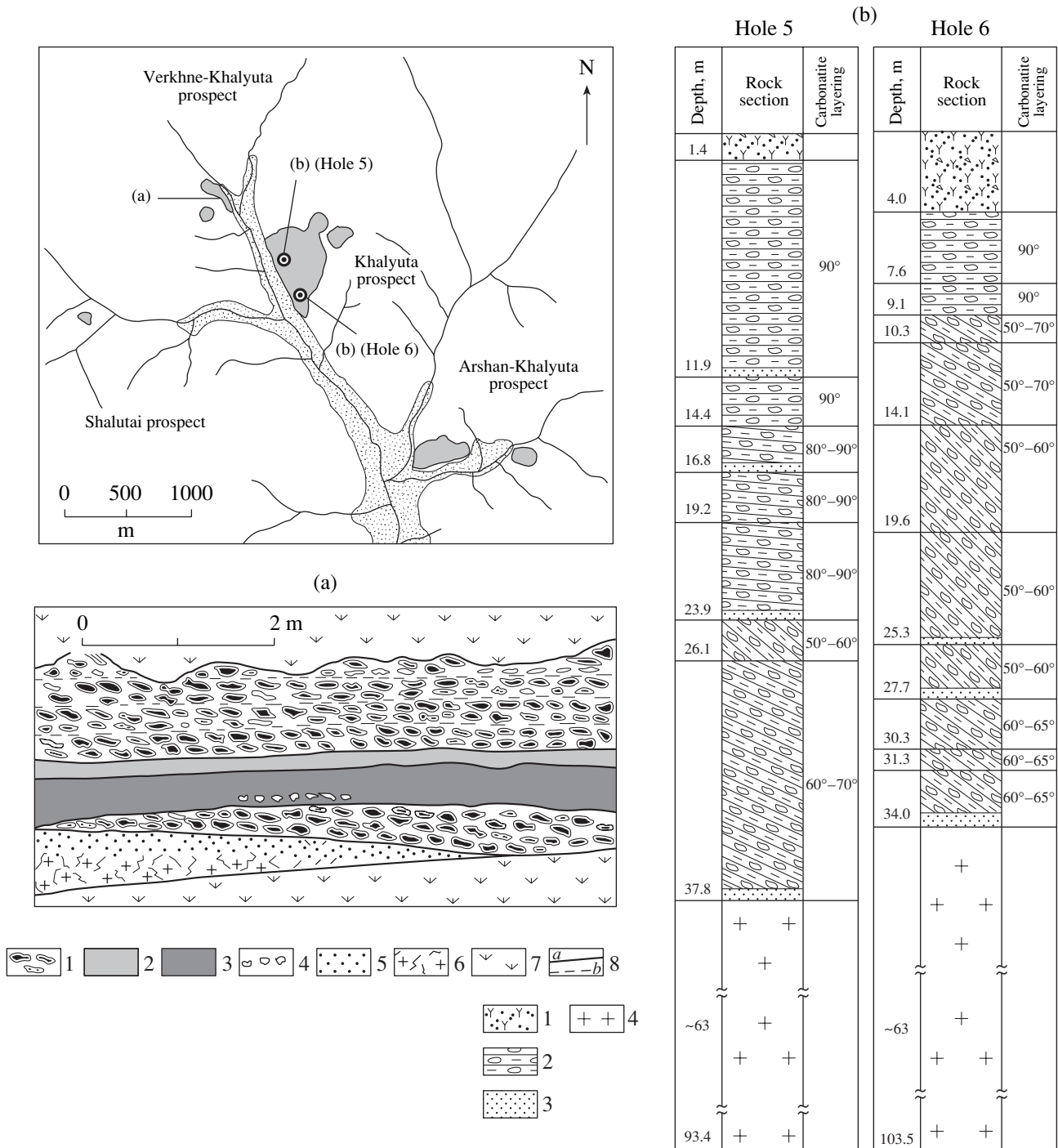


**Fig. 1.** Distribution of the Late Mesozoic carbonatite complexes and occurrences in western Transbaikalia.

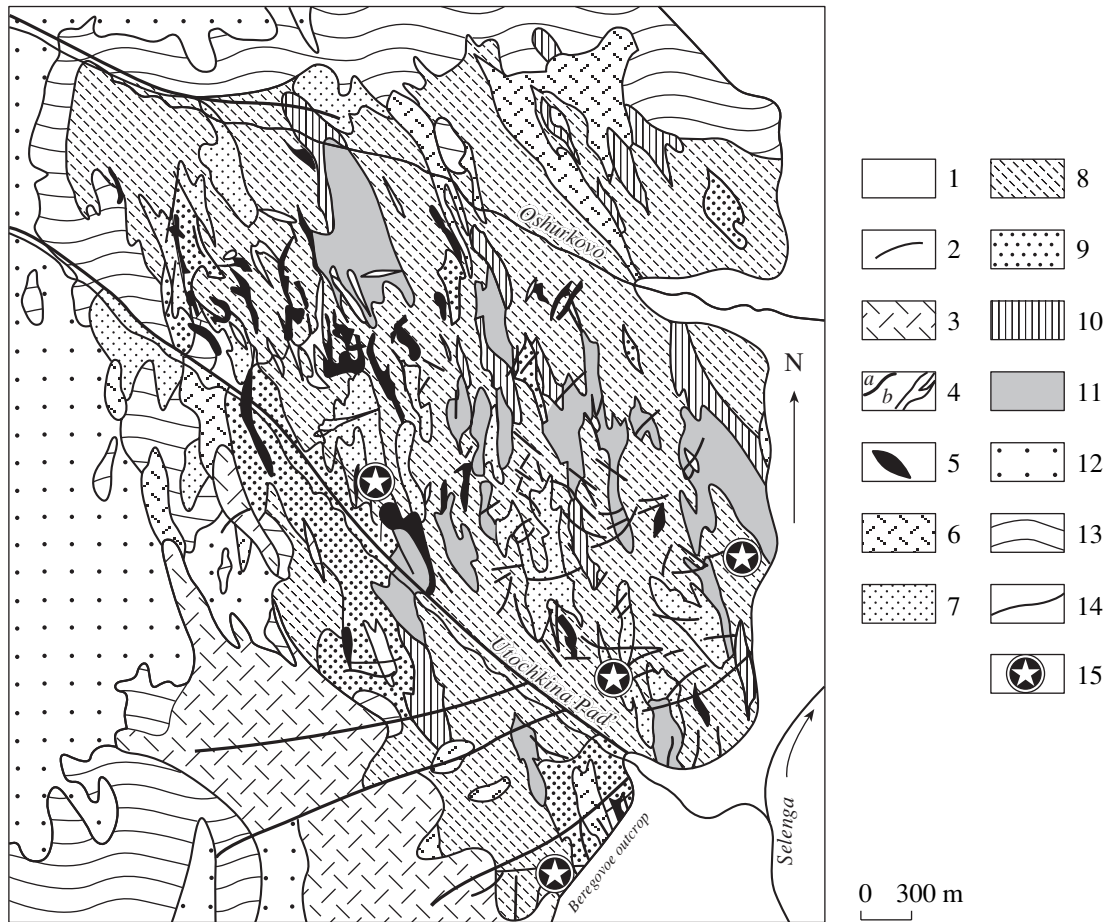
Khl—Khalyuta carbonatite complex, Osh—Oshurkovo occurrence, Ar—Arshan occurrence, Yu—Yuzhnoe occurrence, Tor—Toreiskoe occurrence.

compose rare dike-shaped bodies, no more than a few meters thick. Their rocks vary from leucocratic shonkinite to alkaline syenite. Mineralogically, the shonkinites and syenites are quite similar and differ only by the proportions of rock-forming minerals (potassic feldspar, albite, aegirine-diopside, and hastingsite). The accessory minerals are phlogopite, apatite, richterite, sphene, zircon, and orthite. In addition to minerals usually present in silicate rocks, the Khalyuta shonkinites and syenites contain up to 20 vol % interstitial calcite and celestine. Silicate rock-forming minerals, calcite, and celestine compose closely interlocked aggregates and mutual inclusions without traces of reaction relationships, a fact testifying to their concurrent crystallization.

**The Oshurkovo gabbro-syenite rock complex** (Fig. 3) is located 10 km northwest of Ulan-Ude, in the wall of the Uda graben. The complex has an outcrop area of approximately 14 km<sup>2</sup>. Subalkaline gabbroids and syenites of the complex compose the Oshurkovo Massif, which was studied by G.V. Andreev, I.V. Gordienko, S.V. Kostromin, F.L. Smirnov, B.A. Litvinovskii, and other researchers. According to data of Litvinovskii *et al.* (1998), the Oshurkovo Massif has a mid-Early Cretaceous age (~120 Ma) and was produced in two stages: (1) the development of a differentiated rock series from melanocratic gabbro to syenite, which account for the bulk of the massif, and (2) the formation of small bodies of alkali feldspar syenites. We determined that the massif contains carbonatite bodies in the form of single, relatively thin veins, which were formed after the gabbroids and syenites. The Oshurkovo Complex contains numerous dikes of aplites, granites, and granitic pegmatites, which were



**Fig. 2.** Distribution of relict blocks of the eroded carbonatite volcanic sheet of the Khalyuta Complex (gray fields) and their sections. (a) Cross section through the carbonatite of the Verkhne-Khalyuta prospect (wall of road cut): (1) carbonatite agglomerates; (2) clayey fine-grained sand; (3) sorted coarse-grained arkose; (4) fragments of quartz vein; (5) unsorted coarse-grained arkose; (6) granitoid grus; (7) slope soil; (8) (a) layer boundaries and (b) layering. (b) Profile along core drilling holes at the Khalyuta prospect (prepared with the use of E.S. Gol'dberg's materials): (1) eluvial and deluvial deposits (fragments of carbonatites, gneissose granites, and quartz syenites in a sandy-clayey matrix); (2) calcitic carbonatites (line slopes indicate the orientation of banding); (3) thin layers of terrigenous sandy material, often with carbonatite fragments; (4) granites and quartz syenites (the intensity of weathering decreases with increasing depth).



**Fig. 3.** Schematic geological map of the Oshurkovo Complex (modified after Litvinovskii *et al.*, 1998).

(1) Modern alluvial deposits; (2) dikes and veins of granite pegmatites and aplites; (3–11) rocks of the Oshurkovo Massif: (3) alkaline-feldspar syenites, (4) dikes of (a) alkaline microgabbro and (b) syenites, (5) large subconformable dikes of medium- to fine-grained alkaline gabbro, (6) early-stage syenites, (7) medium-grained mesocratic and leucocratic alkaline gabbro, (8) same, coarse-grained, (9) same, very coarse-grained, (10) medium-grained melanocratic alkaline gabbro, (11) same, coarse-grained; (12) host gneiss-granites; (13) host gneisses; (14) main faults; (15) exposed carbonatite veins.

produced by paligenetic partial melts derived from the country rocks of the massif.

The carbonatite veins are relatively thin, from 2–3 to 60 cm, and their contacts with the host rocks are sharp, crosscut. The rocks have fluidal structures, and most of their mafic minerals and host-rock xenoliths tend to cluster near the footwalls of the veins, a fact pointing to their gravitation-controlled arrangement in the carbonatite-forming medium. The disturbance of the continuity of these xenoliths and their breakup into fragments that are pulled apart and scattered along the vein indicate that this medium mechanically affected xenoliths.

The dominant mineral of the carbonatites is milk-white calcite, some varieties also contain significant amounts of reticulate barite, phlogopite, magnetite, and subordinate amounts of orthite and sphene. The carbonatites are significantly altered by secondary low-temperature silification.

The age relations of the carbonatites and alkaline gabbroids are determined by the fact that both rock types are cut by veins of leucocratic pegmatites. The granitoids and alkaline gabbroids have similar Rb–Sr isochron ages (~120 Ma; Litvinovskii *et al.*, 1998), and the mineral Rb–Sr isochron age of the carbonatites is  $118 \pm 11$  Ma (Ripp *et al.*, 2000).

**The Arshan carbonatite occurrence** is located in the wall of the Ubukun–Orongoi graben, 35 km southwest of Ulan-Ude, and is restricted to a relatively gently dipping tectonic zone, which corresponds to the fault boundary of a Mesozoic rift depression. The host rocks are mylonitized, cataclazed, and extensively silicified granosyenites and diorites, whose age was provisionally assessed as Late Proterozoic.

The carbonatites occur as a lens-shaped branching body, which is elongated in the fault plane. It was traced for 350 m along the strike and has a thickness from a few dozen centimeters to a few meters. The contacts

between the carbonatite and wall rocks are commonly fairly sharp and are accompanied by zones of extensive outer-contact metasomatic alterations of the host rocks. The carbonatites were determined to contain much xenogenic material, which is present in the form of angular or rounded fragments with sharp outlines, ranging from a few to tens of centimeters. The composition of the xenoliths often does not correspond to that of the wall rocks in immediate contact with the carbonatite veins, a fact suggesting that this material was transported mechanically from elsewhere.

The carbonatites are medium- to fine-grained rocks, often containing phenocrysts, with massive, fluidal, banded, and schistose structures. Near their contacts, the rocks acquire brecciated structures. The ground-mass of the carbonatites consists of calcite, fluorite, phlogopite, barite-celestine, and bastnaesite. Phenocrysts consists of bastnaesite, barite-celestine, and, sometimes, fluorite. The minor mineral is orthite. The bastnaesite was detected in association with parisite, which develops as rims around bastnaesite crystals or fully replaces them. The xenogenic ground-mass minerals are sodic plagioclase, alkaline feldspar, and quartz. Fluorite from the Arshan carbonatite was determined to contain recrystallized melt inclusions (Nikiforov *et al.*, 2000), which testify that the rocks had crystallized from magmatic melt.

Our Sm–Nd isotopic data on fluorite and bastnaesite from the carbonatites (Table 1) cluster along an isochron regression line, which corresponds to an age of 120 Ma. This estimate is close to the earlier dating conducted by Bulnaev and Posokhov (1995) and Ripp *et al.* (2000).

#### COMPOSITION OF ROCKS OF THE CARBONATITE ASSOCIATION

The mineralogical and chemical compositions of the carbonatites and related silicate magmatic rocks were discussed elsewhere (Nikiforov *et al.*, 2000), and below we will touch upon only the most important features of the rocks.

**Carbonatites.** Mineralogically, the carbonatites from western Transbaikalia are dominated by calcite. Iron-bearing dolomite was found only in the carbonatite of the Khalyuta Complex, in which this mineral was identified as dissemination in calcitic carbonatites and in more rare dolomitic carbonatites. We cannot rule out that the dolomitic carbonatites were initially much more widespread in the complex, but the processes of postmagmatic and supergene alterations fully transformed them into “brown” calcitic carbonatites, which are enriched in Fe oxides and hydroxides. In addition to carbonates, the western Transbaikalian carbonatites often contain Ba and Sr sulfates (barite, celestine, and barite-celestine), apatite, fluorite, magnetite, strontianite, fluorite, orthite, and REE fluorcarbonates (bastnaesite and parisite). The magnetite is high in Ti and

bears vermicular ilmenite inclusions, which are typical of exsolution textures of solid solutions.

The evolution of the carbonatites is commonly thought to occur in several stages: magmatic, late magmatic–postmagmatic, epigenetic hydrothermal, and supergene. During the magmatic stage, most minerals crystallized from melt, as follows from the presence of lavas and tuffs and the occurrence of melt inclusions in typomorphic minerals of this stage. This stage was responsible for the crystallization of calcite, dolomite, barite-celestine, apatite, fluorite, bastnaesite, phlogopite, richterite (?), zircon, magnetite, and orthite.

**The late-magmatic–postmagmatic stage** was closely related to the magmatic stage proper and was characterized by transformations in the mineralogical composition of the carbonatites. This process manifested itself most conspicuously in the carbonatites of the Khalyuta carbonatite complex, which is characterized by widespread secondary strontianite mineralization. The strontianite occurs in association with aragonite, calcite, and late barite. During the late magmatic–postmagmatic stage, the dolomitic carbonatites were transformed into calcitic carbonatites, and the barite-celestine was decomposed and replaced by reticulate barite (Nikiforov *et al.*, 2000). It is pertinent to remind that the latter mineral was identified in carbonatites not only from the Khalyuta Complex but also from the Oshurkovo and Yuzhnoe occurrences. Barite-celestine remained stable in the Arshan carbonatites, perhaps, because of the crystallization of the rocks at greater depths.

**The epigenetic hydrothermal stage** was characterized by ubiquitous processes of secondary silification of the carbonatites. It seems to be this stage that was responsible for magnetite replacement by iron hydroxides and the recrystallization and redeposition of some preexisting minerals, as well as the decomposition of mafic minerals with the origin of chlorite. During the “supergene” stage, the predominant process was the leaching of rock-forming minerals and the further oxidation of iron-bearing minerals.

Compared with the average composition of soevite (Wooley and Kempe, 1989), the rocks are higher in Ba (up to 26 wt % BaO), Sr (up to 20–30 wt % SrO), sulfate ion (up to 15 wt %), and, often, Fe (up to 10–15 wt % FeO\*) (Nikiforov *et al.*, 2000). The REE concentrations in the carbonatites of the Khalyuta Complex and the Oshurkovo and Toreiskoe occurrences are approximately 0.3–0.4 wt %, while the carbonatites of the Arshan and Yuzhnoe occurrences contain as much as 5.67 wt % REE<sub>2</sub>O<sub>3</sub>. The variations in the major-oxide concentrations (Fig. 4) testify to the strong differentiation of the rocks.

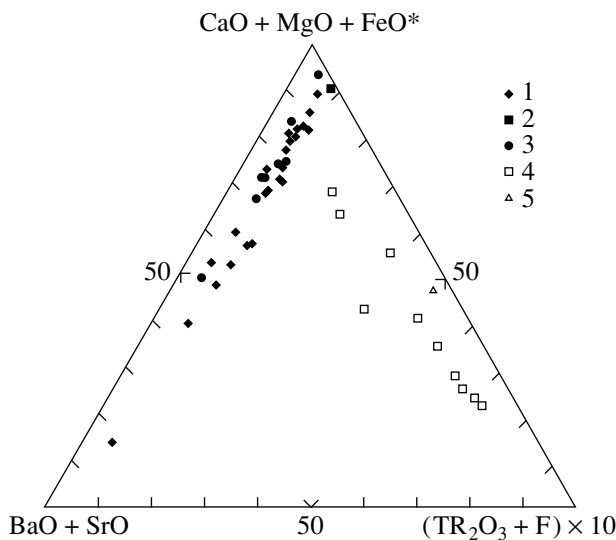
Carbonatites of the western Transbaikalia exhibit similar configurations of their trace-element patterns (Fig. 5a). Compared to basalts of the OIB type, which we utilized as a standard of within-plate magmatism, our rocks are enriched in REE (Ce/Yb = 276–3300), Sr,

**Table 1.** Nd and Sr isotopic compositions of rocks and minerals of mid-Early Cretaceous carbonatite and volcanic associations in western Transbaikalia

Sample number	Rock, mineral	Rb	Sr	<sup>87</sup> Rb/ <sup>86</sup> Sr	<sup>87</sup> Sr/ <sup>86</sup> Sr	Err	ε <sub>Sr</sub> *	Sm	Nd	<sup>147</sup> Sm/ <sup>144</sup> Nd	<sup>143</sup> Nd/ <sup>144</sup> Nd	Err	ε <sub>Nd</sub> *
Rocks of volcanic associations of the mid-Early Cretaceous magmatic stage													
Vi-13/3	Tephrite	43.8	1999	0.0633	0.705238	11	10.9	14.3	99.4	0.08707	0.512482	8	-1.4
Khi-17/3	"	58.6	2172	0.0780	0.705383	13	12.6	12.4	82.4	0.09115	0.512463	9	-1.8
Oshurkovo occurrence													
Osh-1/7	Alkaline pyroxenite	40.1	6010	0.0193	0.705399	18	14.3	33.3	231	0.08709	0.512362	7	-3.7
Osh-2/16	"	27.1	7200	0.0109	0.705409	14	14.6	36.3	235	0.09352	0.512371	6	-3.6
Osh-1/13	Alkaline gabbro	37.6	6430	0.0169	0.705352	17	13.7	27.7	188	0.08924	0.512389	6	-3.2
Osh-1/4	Alkaline syenite	49.6	8900	0.0161	0.705247	15	12.2	14.3	102	0.08533	0.512402	7	-2.9
Osh-2/17	Calcitic carbonatite	8.97	12430	0.0021	0.705216	17	12.1	6.5	44.2	0.08818	0.512419	6	-2.6
Osh-2/2	Calcitic carbonatite			0.0000	0.705393	15	14.7	41.2	331	0.07527	0.512356	6	-3.6
Khaluyuta Complex													
Khl-1/6	Syenite	118	13870	0.0247	0.705819	16	20.1	46.4	303	0.09264	0.512264	8	-5.7
Khl-4/1-si	Pyroxene from shonkinite	1.62	3620	0.00129	0.705807	12	20.5	106	1330	0.04824	0.512300	7	-4.3
Khl-4/1-car	Calcite and celestine from shonkinite	6.30	188400	0.0001	0.705893	13	21.8	5.0	30	0.10333	0.512356	7	-4.1
Khl-4/4-si	Apatite from syenite	0.83	7935	0.0003	0.705706	13	19.1	612.0	4530	0.08164	0.512234	8	-6.1
Khl-4/4-car	Calcite from syenite	10.2	122800	0.00024	0.705839	14	21.0	39.6	275	0.08689	0.512276	6	-5.4
Khl-4/5	Calcitic carbonatite	0.40	40050	0.00003	0.705897	12	21.8	47.6	359	0.08026	0.512222	6	-6.3
Khl-136/1	Dolomitic carbonatite	0.46	38800	0.00003	0.705830	15	20.9	47.8	331	0.08740	0.512241	7	-6.1
Arshan occurrence													
Ar-138/2-f	Fluorite from calcitic carbonatite			0.0000	0.705923	16	22.2	121	703	0.10370	0.512237	6	-6.4
Ar-138/2-b	Bastnaesite from calcitic carbonatite	0.1	22460	0.000013	0.705924	16	22.2	5004	77620	0.03897	0.512186	7	-6.4

Note: The Nd and Sr isotopic analyses were conducted by D.Z. Zhuravlev on a Finnigan MAT-262 multicollector mass spectrometer in static mode, following the conventional technique (Zhuravlev *et al.*, 1983).

\*The ε<sub>Sr</sub> and ε<sub>Nd</sub> values were calculated for an age of 120 Ma.



**Fig. 4.**  $(\text{CaO} + \text{MgO} + \text{FeO}^*) - (\text{BaO} + \text{SrO}) - (\text{REE}_2\text{O}_3 + \text{F}) \times 10$  diagram for the composition of carbonatites in western Transbaikalia.

(1) Khalyuta Complex; (2) Oshurkovo occurrence; (3) Toreiskoe occurrence; (4) Arshan occurrence; (5) Yuzhnoe occurrence. Constructed with the use of data from (Nikiforov *et al.*, 2000).

Ba, Pb, often, Th and U but depleted in Nb, Ta, Rb, Zr, and Hf.

Based on data on the mineralogy, major- and trace-element chemistry of the carbonatites, they can be subdivided into two mineralogical–geochemical groups. The group of *phosphorus–barium–strontium* carbonatites comprises these rocks from the Khalyuta Complex and the Oshurkovo and Toreiskoe occurrences. The carbonatites of this group pervasively contain such rock-forming minerals as apatite and monazite. REE are either contained in trace amounts in rock-forming minerals or compose individual phases (monazite and orthite), whose amounts are insignificant in the bulk-rock composition of the carbonatites. The carbonatites are rich in REE ( $\text{REE}_2\text{O}_3$  up to 0.56 wt %) with the predominance of LREE over HREE ( $\text{Ce}/\text{Yb} = 280\text{--}600$ ) and typically have small Eu maxima. The carbonatites of this group are closely related to alkaline gabbroids and syenites. The other group, *fluorine–REE–barium–strontium* carbonatites, includes rocks of the Arshan and Yuzhnoe occurrences. These carbonatites usually contain widespread F-bearing minerals, such as fluorite and fluorcarbonates of REE (bastnaesite and parisite). Compared with the group-I carbonatites, the F–REE–Ba–Sr carbonatites are much higher in REE ( $\text{TR}_2\text{O}_3$  up to 5.65 wt %) at a significant enrichment in LREE ( $\text{Ce}/\text{Yb} = 1230\text{--}3300$ ). The carbonatites of this group are related to fault zones that bound Early Cretaceous grabens. No silicate igneous rocks accompanying these carbonatites were detected.

**Silicate magmatic rocks of the carbonatite associations.** Chemically, the silicate rocks (alkaline and

subalkaline gabbro, syenites, shonkinites, and teschenites) of the carbonatite associations affiliate with the subalkaline and alkaline petrochemical series and vary in silica concentration from ultramafic to intermediate compositions (Nikiforov *et al.*, 2000). The mafic rocks usually affiliate with the alkaline series, while more silicic varieties are dominated by subalkaline rocks. In accordance with their petrochemical and petrographic characteristics, these compositionally variegated rocks correspond to the differentiation products of mafic melts coeval with the carbonatites.

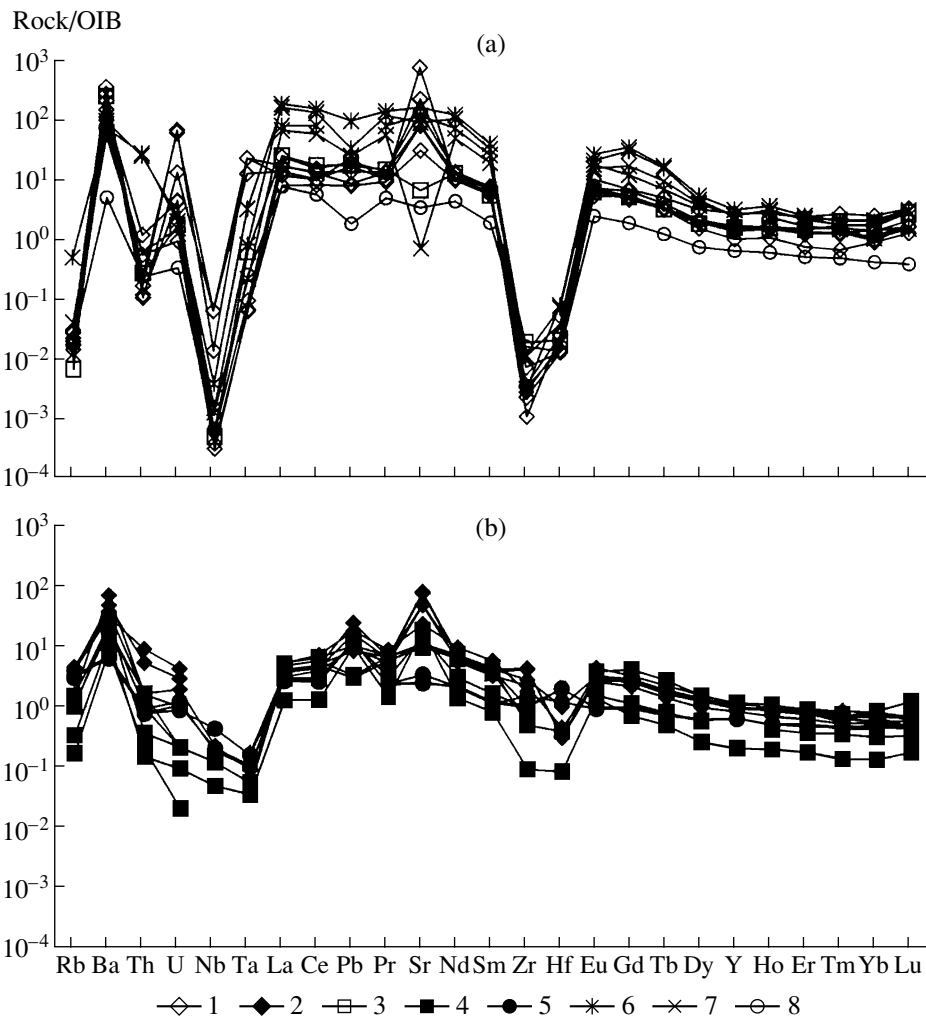
Compared to OIB basalts, silicate rocks of the carbonatite associations are enriched in Ba, Pb, LREE, Sr, Th, and Rb and depleted in Nb and Ta (Fig. 5b). The trace-element composition of the silicate rocks is in good agreement with the composition of the related carbonatites, and this suggests genetic links between them or, at least, the compositional uniformity of their sources.

#### POSITION OF CARBONATITES IN THE EVOLUTION OF RIFT-RELATED MAGMATISM IN WESTERN TRANSBAIKALIA

Late Mesozoic carbonatites in western Transbaikalia occur within a rift zone (volcanic area), which consists of a system of horsts and grabens to which Late Mesozoic–Cenozoic volcanic rocks are restricted. The magmatic evolution of the area occurred in several stages (Yarmolyuk and Ivanov, 2000) and was characterized by alternating pulses of volcanic activity with relatively brief interludes. During the evolution of the rift area, the scale of the magmatic activity varied, as did the styles of eruptions, the composition and diversity of the magmatic products.

The composition of the igneous rocks systematically evolved in the course of the magmatic evolution (Yarmolyuk and Ivanov, 2000). Its early stages ( $J_3\text{--}K_1^1$ ) were characterized by rocks of elevated alkalinity and the presence of both mafic and acid rocks (trachyrhyolites, trachytes, pantellerites, etc.). All rocks of the later stages (Cenozoic) are mafic and have relatively low concentrations of alkalis. The trace-element and Nd and Sr isotopic compositions of the rocks also varied with time. These distinctive features of magmatism in western Transbaikalia, which pertain to long-lasting (tens of million years) evolutionary stages, seem to be explained by processes in the sources of the magmatic melts.

A notable stage occurred in the magmatic evolution of the rift zone in Early Cretaceous time (130–115 Ma) and was responsible for the origin of diverse magmatic associations, including those with carbonatites. This stage also produced the most alkaline of the rocks (tephrites, shonkinites, nepheline syenites, etc.). These rocks and carbonatites are restricted to a specific zone, which structurally coincides with the Gusinozersk



**Fig. 5.** OIB-normalized (Sun and McDonough, 1989) trace-element patterns of (a) carbonatites and (b) related silicate rocks.

(1, 2) Rocks of the Khalyuta Complex: (1) carbonatites, (2) shonkinites and syenites; (3, 4) rocks of the Oshurkovo occurrence: (3) carbonatites, (4) silicate rocks; (5) teschenites from the Murtoi dike; (6–8) carbonatites: (6) Arshan occurrence, (7) Yuzhnoe occurrence, (8) Toreiskoe occurrence. Constructed with the use of data from (Nikiforov *et al.*, 2000).

chain of grabens and their horst surroundings. This zone cuts across the general strike of the rift zone.

The rocks of this stage, including rocks of the carbonatite associations, geochemically notably differ from the younger ( $K_1^3$ – $K_2$ ) and older ( $J_3$ – $K_1^1$ ) mafic volcanics of the rift zone (Table 2, Fig. 6). The latter two groups have similar trace-element compositions and are generally comparable with OIB basalts, differing from them by higher concentrations of Ba, Pb, LREE, Sr, Rb, and Zr at lower concentrations of Nb and Ta. The same anomalies, but pronounced much more strongly, are typical of rocks of the  $K_1^2$  magmatic stage (including carbonatites). The diagram in Fig. 6 demonstrates systematic variations in the trace-element composition of the rocks produced during this stage of alkaline magmatism. For example, the compositional succession from tephrite and phonolite of the volcanic

associations to alkaline and subalkaline gabbroids and syenites of the carbonatite associations and further to carbonatites exhibits a systematic increase in the concentrations of Ba, Pb, LREE, and Sr.

The carbonatites, particularly those of the F–REE–Ba–Sr group, are characterized by the highest concentrations of REE, primarily LREE (Fig. 7). The rocks of this age interval display the following tendency in their enrichment in REE: the beginning of the trend corresponds to the tephrites and phonolites of the volcanic associations. Further, as the Ce/Yb ratio and the sum of REE increase, these rocks are followed by alkaline silicate rocks of the carbonatite associations and, then, by the P–Ba–Sr carbonatites and, eventually, by the F–REE–Ba–Sr carbonatites. All of the younger and older magmatic products in the rift area contain REE in amounts not exceeding those in the tephrites and phonolites of mid-Cretaceous volcanic associations. Hence,



**Table 2.** Average concentrations of trace elements (ppm) in rocks from volcanic associations of different ages in western Transbaikalia

Component	Volcanic associations of late J <sub>3</sub> –early K <sub>1</sub> age	Mid-Early Cretaceous volcanic and subvolcanic associations			Volcanic associations of late K <sub>1</sub> –early K <sub>2</sub> age
		alkaline rocks of volcanic associations	alkaline rocks of carbonatite associations	carbonatites	
V	179(9)	135(3)	174(3)	47(4)	205(2)
Pb	15(3)	26(3)	31(14)	71(11)	18(1)
Rb	62(9)	101(3)	67(17)	2(11)	41(7)
Cs	0.22(3)	0.90(3)	0.87(3)	0.07(11)	0.64(1)
Ba	1324(9)	2451(3)	8116(17)	66713(13)	2003(7)
Sr	1096(9)	2140(3)	14495(17)	78347(13)	1214(7)
Ta	1.7(3)	1.2(3)	0.2(9)	0.6(11)	1.7(1)
Nb	40(3)	27(3)	9(6)	15(11)	39(1)
Hf	8.8(3)	7.7(3)	5.9(7)	0.2(11)	6.2(2)
Zr	481(3)	387(3)	412(17)	2(11)	510(1)
Y	36(3)	21(3)	20(9)	44(11)	26(2)
Th	5(3)	11(3)	7(12)	21(11)	5(1)
U	1.0(3)	1.6(3)	1.1(12)	14.8(11)	1.0(1)
La	69(9)	117(5)	117(17)	1722(13)	38(7)
Ce	149(9)	224(5)	293(17)	3055(13)	79(7)
Pr	17(9)	25(5)	41(17)	335(13)	9(7)
Nd	68(9)	90(5)	169(17)	1165(13)	38(7)
Sm	11(9)	13(5)	26(17)	113(13)	7(7)
Eu	2.7(9)	3.3(5)	6.2(17)	26.8(13)	2.0(7)
Gd	8.6(9)	9.2(5)	13.8(17)	67.4(13)	6.2(7)
Tb	1.0(9)	0.9(5)	1.3(17)	5.2(13)	0.8(7)
Dy	5.1(9)	3.9(5)	4.9(17)	12.2(13)	4.4(7)
Ho	0.9(9)	0.6(5)	0.7(17)	1.7(13)	0.8(7)
Er	2.2(9)	1.6(5)	1.5(17)	3.3(13)	2.2(7)
Tm	0.3(9)	0.2(5)	0.2(17)	0.4(13)	0.3(7)
Yb	1.8(9)	1.2(5)	1.0(17)	2.5(13)	1.9(7)
Lu	0.3(9)	0.2(5)	0.1(17)	0.5(13)	0.3(7)

Note: Numbers in parentheses indicate the numbers of analyzed samples.

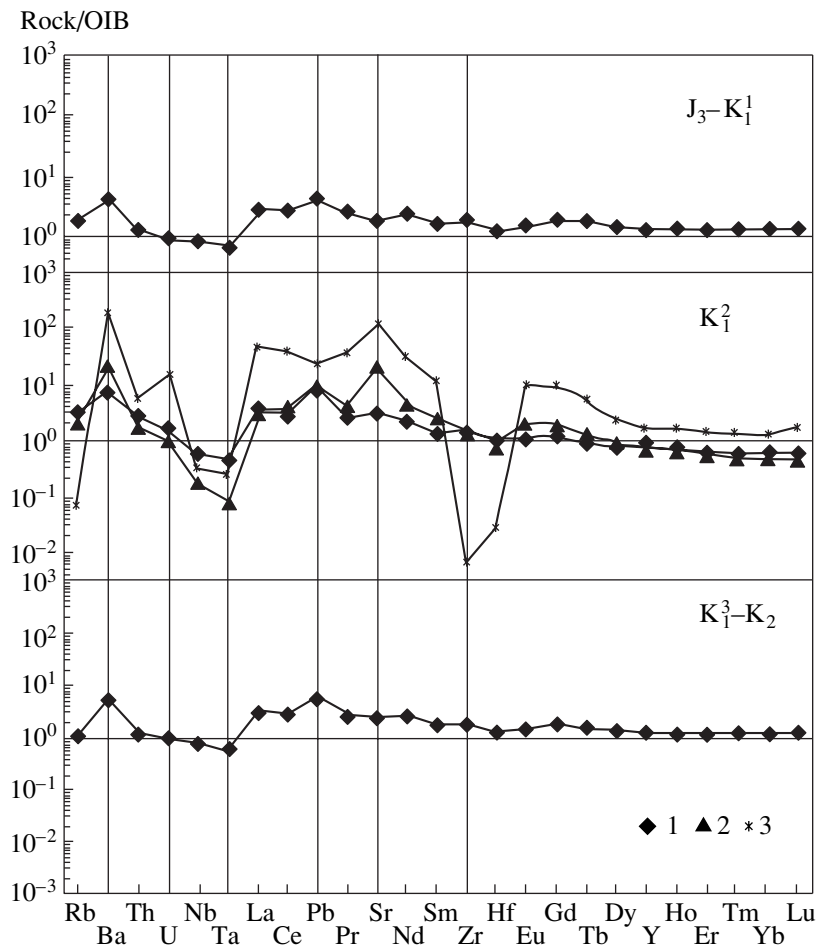
the carbonatites are characterized by the strongest and the most systematic enrichment in LREE relative to rocks of all age groups in the western Transbaikalia volcanic area.

There is no doubt that the systematic differences between the REE compositions of rocks that are otherwise chemically similar but not coeval were determined by the compositions of their sources. Thus, the anomalous composition of the mid-Early Cretaceous alkaline gabbroids (their high alkalinity and high concentrations of several lithophile elements) seems to be explained by the involvement of the most enriched mantle sources in the melting process. The trace-element composition of the carbonatites (Figs. 6, 7) is characterized by extre-

mal values, a fact pointing to relations between these rocks and enriched mantle sources.

#### ISOTOPIC COMPOSITION OF ROCKS OF THE CARBONATITE ASSOCIATION

**Oxygen and carbon isotopic composition of carbonatites.** The O and C isotopic compositions of carbonatites from different occurrences in western Transbaikalia define distinct trends in a  $\delta^{13}\text{C}$ – $\delta^{18}\text{O}$  diagram (Fig. 8). The trends begin near the *Oka box*, which is assumed to represent a standard for carbonatites with a mantle source. The compositions of unaltered (i.e., practically unaffected by postmagmatic processes) carbonatites from different occurrences are similar ( $\delta^{18}\text{O}$



**Fig. 6.** OIB-normalized patterns for the average concentrations of trace elements in rocks of different ages from the western Transbaikalia rift zone.

(1) Rocks of volcanic associations; (2) silicate rocks of carbonatite associations; (3) carbonatites.

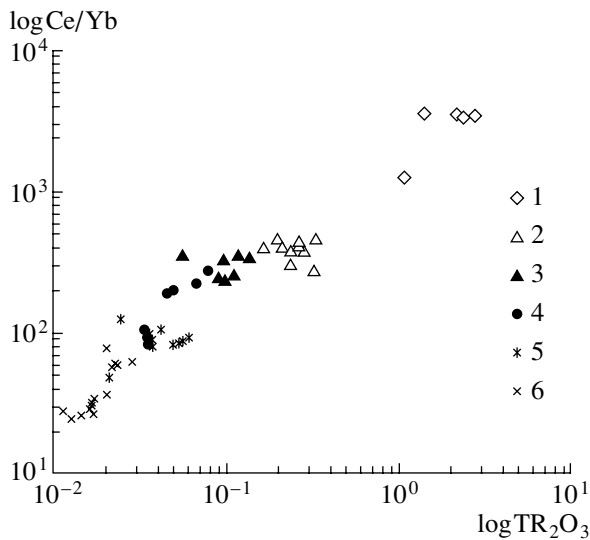
from 6.0 to 10.7‰,  $\delta^{13}\text{C}$  from  $-4.1$  to  $-6.5$ ‰). Analogous characteristics are typical of carbonatites of the magmatic stage and carbonatites from shonkinites and syenites of the Khalyuta Complex; the carbonatites of the Oshurkovo occurrence, which were not affected by later silification; calcite phenocrysts from carbonatites of the Yuzhnoe occurrence; bastnaesite phenocrysts from the Arshan carbonatites; carbonatites of the Toreiskaya vein; and calcite from the teschenites of the Murtoi dike. All of them plot close to the Oka box. This led us to believe that the isotopic compositions of the unaltered carbonatites correspond to the isotopic parameters of the source.

Deviations of the isotopic-composition trends of carbonatites in some occurrences from the region of mantle sources (Fig. 8) suggest the involvement of crustal O and C sources in the carbonatites of western Transbaikalia.

Deviations toward lower  $\delta^{13}\text{C}$  values (of approximately  $-9.5$ ‰) and relatively high  $\delta^{18}\text{O}$  (up to  $\sim 17.4$ ‰) were detected in some volcanic carbonatites and car-

bonates from alkaline silicate rocks of the Khalyuta Complex and carbonatites of the Oshurkovo occurrence. These deviations could be caused by the following processes: (1) interaction of the high-temperature ( $>400^\circ\text{C}$ ) melts of carbonatite with atmospheric  $\text{CO}_2$  and  $\text{H}_2\text{O}$  during the eruptions [analogous explanations of the depletion of the East African volcanic carbonatites in the  $^{13}\text{C}$  isotope were given by Kuleshov (1986) and Keller and Hoefs (1995)]; (2) interaction between the crystalline carbonatites and near-surface low-temperature ( $<50^\circ\text{C}$ ) groundwaters, similar to those from which soil carbonates crystallize (Salomons, 1975).

A trend of carbonatite enrichment in the light oxygen isotope ( $\delta^{18}\text{O}$  from  $+6$  to  $-5$ ‰) at a relatively stable carbon isotopic composition ( $\delta^{13}\text{C}$  from  $-4.8$  to  $-5.7$ ‰) was identified in the calcite and fluorcarbonates from the Arshan occurrence. The O and C isotopic characteristics obtained for the calcite correspond to the isotopic signatures of rocks developing in hydrothermal systems involving atmospheric waters in active volcanic areas (Taran *et al.*, 1987; Hattory and Muehlenbachs,



**Fig. 7.** Correlations between the Ce/Yb ratio and the sum of REE concentrations ( $\text{REE}_2\text{O}_3$ ) in rocks of different ages from the western Transbaikalia volcanic area.

(1–4) Rocks of the mid-Early Cretaceous magmatic stage ( $K_1^2$ ): (1) F–REE–Ba–Sr carbonatite, (2) P–Ba–Sr carbonatites, (3) silicate rocks of carbonatite associations, (4) tephrites of volcanic associations; (5) rocks of the Late Jurassic–Early Cretaceous magmatic stage ( $J_3$ – $K_1^1$ ); (6) rocks of the Early–Late Cretaceous magmatic stage ( $K_1^3$ – $K_2$ ). Prepared with the use of data from (Nikiforov *et al.*, 2000; Yarmolyuk and Ivanov, 2000).

1982). At the same time, the O isotopic composition of the REE fluorcarbonates (Fig. 8, solid circles) varies between the compositions of unaltered carbonates from western Transbaikalia ( $\delta^{18}\text{O}$  from 6.0 to 10.7‰ and  $\delta^{13}\text{C}$  from –4.1 to –6.5‰) and the composition of calcite from the Arshan occurrence (Fig. 8, open circles). In our opinion, this was caused by the later hydrothermal recycling of the carbonatites with the involvement of vadose waters, a process that resulted in the recrystallization of the calcite and the partial replacement of bastnaesite by secondary parisite, as well as a change in the O isotopic composition of the carbonates from values detected in bastnaesite phenocrysts ( $\delta^{18}\text{O} \sim +6\%$ ) to  $\delta^{18}\text{O} \sim -5\%$ , corresponding to the calcite composition.

Deviations in the C and O isotopic composition from the values of  $\delta^{18}\text{O} = 19.5\%$  and  $\delta^{13}\text{C} = -3.7\%$  were also detected in the carbonatites of the Yuzhnoe occurrence. Conceivably, the isotopic composition of the rocks depends on the degree of their supergene alterations, which are widespread in the carbonatites.

The O and C isotopic compositions of carbonatites from western Transbaikalia are characterized by broad variations, which were caused, chiefly, by the processes of secondary alterations. The characteristics of the carbonatites unaltered by postmagmatic processes ( $\delta^{18}\text{O}$

from 6.0 to 10.7‰ and  $\delta^{13}\text{C}$  from –4.1 to –6.5‰) are generally consistent with the concept that the source of these rocks was of mantle nature.

**Neodymium and strontium isotopic composition of the rocks.** The Nd and Sr isotopic compositions of the carbonatites and related alkaline magmatic rocks were examined using the examples of rocks of the Oshurkovo and Khalyuta complexes and the Yuzhnoe occurrence.

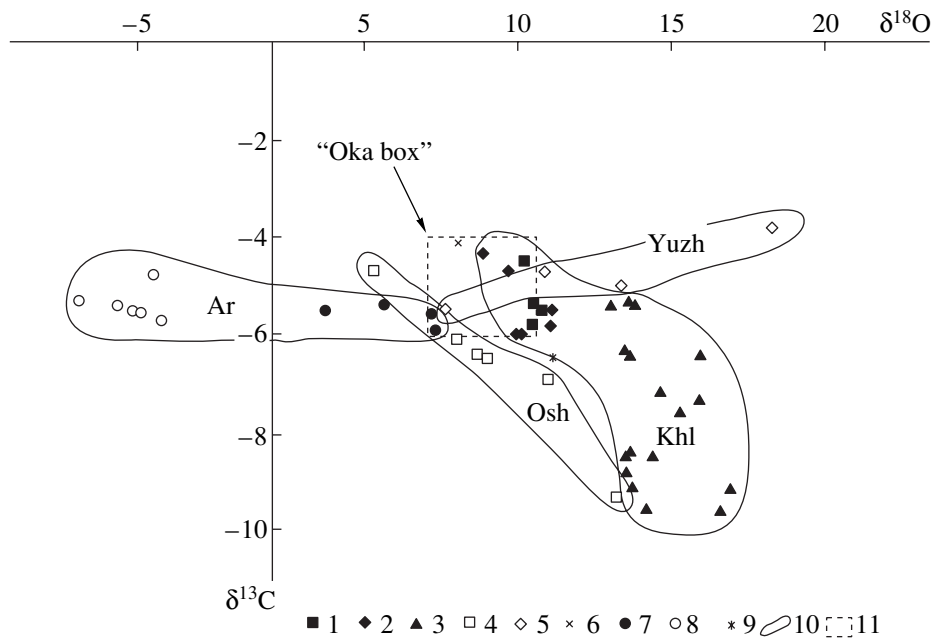
Most isotopic–geochemical data on the *Khalyuta Complex* were obtained for samples from the Shalutai composite dike (Nikiforov *et al.*, 2000) and carbonatite sheets. It is pertinent to remind that the composite dike is made up of carbonatite, shonkinite, and syenite. These rocks consist of >20 vol % calcite and celestine, which occur as equilibrium interlocked aggregates with silicate minerals. We studied samples of carbonatite (Sample Khl-4/5) and shonkinite (Sample Khl-1/6) from the dike and monomineralic fractions of the silicate (pyroxene and apatite) and carbonatite (calcite and celestine) constituents of the shonkinite (Sample Khl-4/1) and syenite (Sample Khl-4/4). To determine the isotopic parameters of carbonatites from the sheets, we selected the least altered dolomitic carbonatites without apparent traces of secondary transformations (Sample Khl-136/1).

The isotopic–geochemical study of the *Oshurkovo Complex* was conducted with the use of carbonatites (Sample Osh-2/2) from the vein of the Beregovoe outcrop, which is the largest and best studied at the occurrence, and the main varieties of the silicate rocks: pyroxenite and melanocratic gabbro (Samples Osh-1/7, Osh-1/13, and Osh-2/16), leucocratic gabbro (Sample Osh-1/4), and syenite (Sample Osh-2/17).

The Nd and Sr isotopic compositions of rocks of the *Arshan occurrence* were examined in monomineralic fractions of fluorite (Sample Ar-138/2-f) and bastnaesite (Sample Ar-138/2-b). No whole-rock samples can be utilized for this purpose, because they contain significant amounts of xenogenic material. Moreover, this approach allowed us to eliminate the effect of secondary alterations, which were identified based on data on the O and C isotopic compositions of the carbonatites.

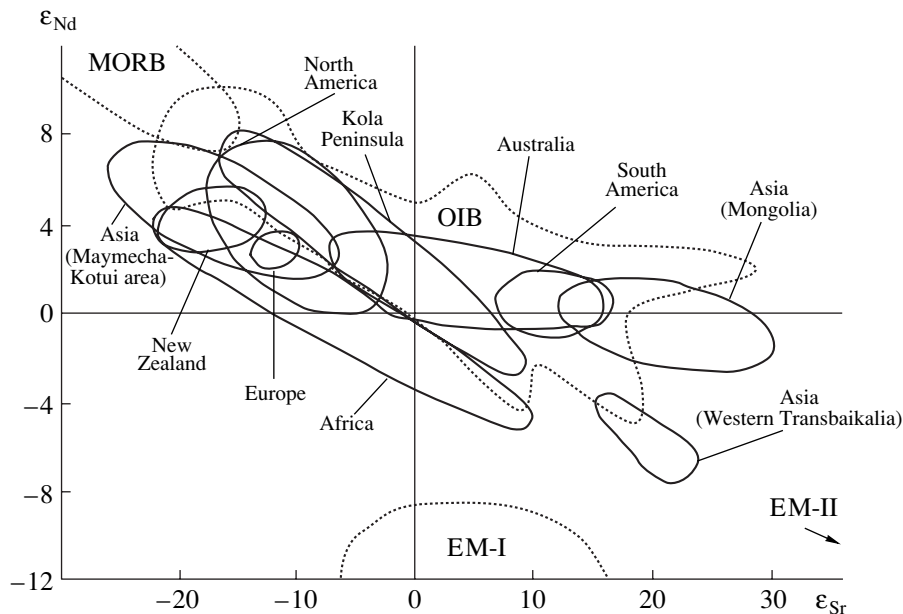
Compared with carbonatites from elsewhere (Fig. 9), the Nd and Sr isotopic compositions of whole-rock and monomineralic samples of carbonatite associations from western Transbaikalia (Table 1) are notably shifted toward the region enriched in radiogenic Sr and depleted in radiogenic Nd and corresponding to enriched mantle sources of the EM-II type (Zindler and Hart, 1986). Similar signatures were also encountered in rocks from other carbonatite complexes in the southern framing of the Siberian Platform: Mushugai and Lulingol (Vladykin, 1987) and in South America (Bell and Blenkinsop, 1989).

The isotopic composition of carbonatites from western Transbaikalia is compatible with the composition of the sources of within-plate magmatism in the rift zone.



**Fig. 8.** Oxygen and carbon isotopic compositions of carbonates from rocks of carbonatite associations (Nikiforov *et al.*, 2000).

Khalyuta volcanic complex: (1) calcite from shonkinites and syenites; (2) calcite and dolomite from mineral assemblages of the early stage; (3) calcite from late mineral assemblages in silicified and supergeneously altered carbonatites; (4) calcite from carbonatites of the Oshurkovo occurrence; (5) calcite from carbonatites of the Yuzhnoe occurrence; (6) calcite from carbonatites of the Toreiskoe occurrence. Arshan occurrence: (7) bastnaesite; (8) calcite; (9) calcite from teschenites of the Murtoi dike; (10) compositional fields of samples from individual localities: Khl—Khalyuta Complex, Ar—Arshan occurrence, Osh—Oshurkovo occurrence, Yuzh—Yuzhnoe occurrence; (11) Oka box (Daines, 1970).

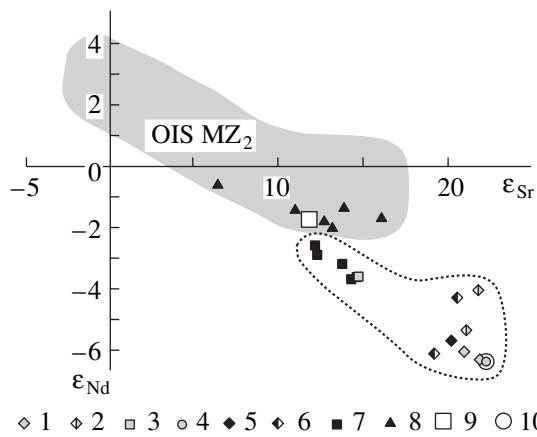


**Fig. 9.** Composition of carbonatites from western Transbaikalia in comparison with the composition of carbonatites from different areas around the world (Bell and Blenkinsop, 1989; Kramm, 1993; Kogarko *et al.*, 1999; Vladykin, 1987).

Dotted contours show the compositional fields of MORB, OIB, EM-I, and EM-II (Zindler and Hart, 1986).

The compositions of rocks of the carbonatite association (Fig. 10) define a trend of data points that emanates from the field of the isotopic compositions of Late

Mesozoic within-plate magmatic rocks (OIS MZ<sub>2</sub>) (Yarmolyuk *et al.*, 1998) and deviates toward higher <sup>87</sup>Sr/<sup>86</sup>Sr ratios (ε<sub>Sr</sub> up to +22) and lower <sup>143</sup>Nd/<sup>144</sup>Nd



**Fig. 10.** Nd and Sr isotopic compositions of rocks of the carbonatite associations.

(1–4) Carbonatites: (1–2) Khalyuta Complex (1—whole-rock samples, 2—carbonatite component of shonkinites and syenites); (3) Oshurkovo Massif; (4) Arshan occurrence. (5–8) Alkaline silicate rocks of the carbonatite associations: (5–6) Khalyuta Complex (5—whole-rock shonkinite samples, 6—silicate component of shonkinites and syenites); (7) Oshurkovo Massif; (8) tephrites of mid-Early Cretaceous volcanic associations. (9, 10) Compositions of inferred sources: (9) tephritic, (10) carbonatitic. The dotted contour shows the compositional field of rocks of the carbonatite associations, OIS MZ<sub>2</sub> is the field of the isotopic compositions of Late Mesozoic within-plate magmatic rocks from the western Transbaikalia volcanic area.

( $\epsilon_{\text{Nd}}$  up to  $-6$ ). The composition points at the base of this trend (corresponding to the Oshurkovo gabbroids) practically coincide with the compositions of the coeval OIS MZ<sub>2</sub> tuffs and phonolites. The points most distant from the OIS MZ<sub>2</sub> field correspond to the composition of carbonatites from *large* bodies in the Arshan and Khalyuta occurrences, with the rocks of the other occurrences plotting in between.

Our researches made it possible to reveal some distinctive features in the isotopic composition of rocks of the carbonatite associations. First of all, it is worth noting the constancy of the Sr isotopic composition [ $(^{87}\text{Sr}/^{86}\text{Sr})_0 = 0.70588$ ] and Nd ( $\epsilon_{\text{Nd}}$  from  $-6.1$  to  $-6.4$ ) of large carbonatite bodies affiliating with different mineralogical–geochemical types in the Arshan occurrence and Khalyuta Complex.

Additionally, it should be noted the similarities between the composition of carbonatites and silicate rocks from different occurrences in western Transbaikalia, a fact testifying to the existing of genetic links between them.

The carbonatite associations display correlations between the isotopic compositions of their rocks occurring in subordinate and dominant amounts. For example, the composition of the Oshurkovo carbonatites, which occur in minor amounts among silicate rocks, is close to the composition of these rocks, showing a tendency of similarities with carbonatites from the Arshan Massif. The carbonatite and silicate rocks from shonk-

inite and syenite dikes in the Khalyuta Complex have isotopic compositions different from those of carbonatites from sheets but approaches the isotopic characteristics of silicate rocks from the Oshurkovo Complex. The isotopic compositions of carbonatites from the sheets are, in turn, close to the compositions of the Arshan carbonatites, in which no silicate rocks were detected as yet.

It is also worth noting the composition of monomineralic fractions from the carbonatite and silicate constituents of the shonkinites and syenites. Their isotopic characteristics testify to the absence of isotopic equilibrium between both the same minerals from different rock varieties and these varieties themselves. There-with, minerals from the carbonatite constituent are systematically enriched in  $^{87}\text{Sr}$  and  $^{143}\text{Nd}$  compared to minerals from the silicate constituent.

The field of the isotopic composition of rocks affiliating with the carbonatite associations extends between two end members, one of which (Fig. 10, large square) corresponds to the composition of alkaline gabbroids of the Oshurkovo Massif and genetically related phonolites and tephrite of the OIS MZ<sub>2</sub> region, and the other (Fig. 10, large circle) corresponds to the composition of the Arshan and Khalyuta carbonatites.

**Model for the binary mixing of carbonatites.** Taking into account the aforementioned distinctive isotopic features of rocks of the carbonatite associations, the variations observed in their isotopic composition can be described based on the mixing model between two isotopically distinct sources. One of the sources of the magmatic melts (Fig. 10, large square) plots within the field of the isotopic compositions of late Mesozoic magmatic rocks from western Transbaikalia, can be paralleled with the source of the early Cretaceous tephrites and phonolites, and will be referred to as the *tephritic source*. Its parameters ( $\epsilon_{\text{Nd}} = -1.6$ ,  $\epsilon_{\text{Sr}} = +11.8$  at Nd and Sr concentrations of 90 and 2000 ppm, respectively) correspond to the average isotopic composition of the tephrites coeval with the carbonatites. The other source (Fig. 10, large circle) will be referred to as *carbonatitic source*, because its most typical derivatives are carbonatites. The isotopic parameters of this source were assumed to be equal to the average composition of carbonatite from the Arshan Massif ( $\epsilon_{\text{Nd}} = -6.4$ ,  $\epsilon_{\text{Sr}} = +22.21$ ), which is most distinct from the composition of rocks of the tephritic source. The Nd and Sr concentrations in the carbonatitic source (400 ppm Nd and 5000 ppm Sr) can be assayed from the average concentrations of these elements in carbonatites from western Transbaikalia.

In plots like  $\epsilon_{\text{Nd}}$  vs.  $\epsilon_{\text{Sr}}$  (Fig. 10), the products of binary mixing compose swarms of regularly distributed data points (mixing hyperboles). In calculating binary mixing models (Faure, 1986), it should be taken into consideration that, at a stable isotopic composition of the initial mixing components, their heterogeneity in terms of Nd and Sr concentrations may result in some

intermediate mixing products that plot on different hyperboles. The further evolution of these mixing products (for example, in the differentiation process) does not affect the isotopic composition of the resultant melts.

The carbonatites from western Transbaikalia, which were produced without any significant involvement of alkaline gabbroid melts (at the Arshan occurrence and the Khalyuta Complex) are characterized by remarkably stable Nd and Sr isotopic compositions, a fact suggesting the isotopic heterogeneity of the sources of their melts. At the same time, these carbonatites are highly evolved rocks, as follows from the existence of two groups of these rocks: one enriched in Sr (P–Ba–Sr group) and the other, in REE (F–REE–Ba–Sr group). This led us to conclude that the carbonatitic source was significantly heterogeneous in terms of Nd and Sr distribution at constant isotopic compositions. Figure 11 shows the mixing hyperboles that describe the distribution of the isotopic compositions of rocks of the carbonatite associations from western Transbaikalia. Most of the intermediate compositions cluster along the hyperbola marked with a heavy line. It corresponds to the mixing of tephrite melts ( $Sr/Nd = 23$ ) with the compositionally most typical (and, perhaps, predominant) derivatives of the carbonatitic source. The Sr/Nd ratio of these rocks was estimated at  $\sim 12$ . The leftmost and rightmost hyperboles in the plot correspond to the uttermost Sr/Nd ratios in the carbonatitic source,  $\sim 460$  and  $\sim 3$  for the leftmost and rightmost hyperboles, respectively.

#### MODEL FOR THE GENESIS OF CARBONATITIC ASSOCIATIONS IN WESTERN TRANSBAIKALIA

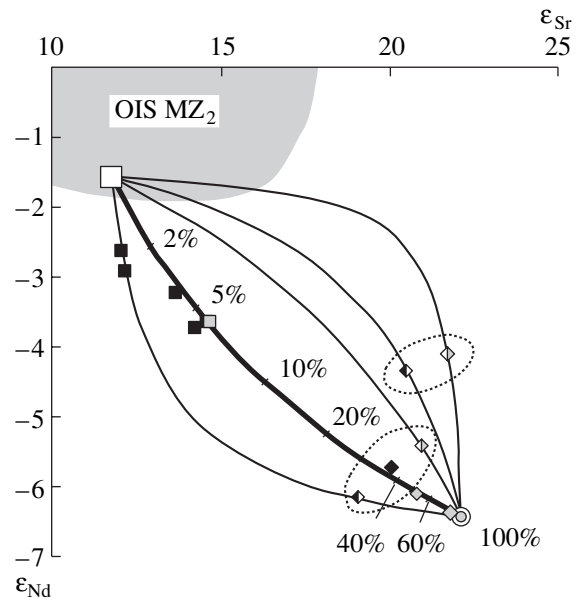
Preparatory to discussing the model for the genesis of the carbonatites and related silicate rocks from western Transbaikalia, it is necessary to emphasize the following important points:

(1) The western Transbaikalian carbonatites are magmatic rocks, as follows from (a) the occurrence of volcanic carbonatites in the Khalyuta Complex; (b) gravitational character of the distribution of xenoliths in veins and their transport along these veins at the Oshurkovo and Arshan occurrences; and (c) the presence of melt inclusions in typomorphic minerals of the carbonatites (apatite at the Khalyuta Complex and fluorite at the Arshan occurrence).

(2) Carbonatites in western Transbaikalia are spatiotemporally interrelated with alkaline silicate rocks, with all rocks of the area produced simultaneously in mid-Early cretaceous time.

(3) The alkaline silicate and carbonatite rocks are characterized by similar distributions of trace elements and similar anomalies at LREE, Ba, Pb, Sr, Nb, Ta, and Zr.

(4) The extremal trace-element composition of the carbonatites compared to the composition of silicate



**Fig. 11.** Variations in the isotopic composition of rocks of the carbonatite associations as a result of mixing between the tephritic and carbonatitic sources of melts.

See Fig. 10 for symbol explanations. The dotted contour shows the carbonatite and silicate constituents of carbonatites (Sample Khl-4/1) and syenites (Sample Khl-4/4). The heavy-line hyperbola shows the calculated contribution of the carbonatitic source to the mixture.

rocks of different ages from western Transbaikalia suggests that the carbonatites characterize an enriched source (with high concentrations of Sr, REE, particularly LREE, Ba, Pb, P,  $CO_2$ , and S).

(5) The O and C isotopic compositions of the carbonatites that were not altered by postmagmatic processes ( $\delta^{18}O$  from 6.0 to 10.7‰,  $\delta^{13}C$  from  $-4.1$  to  $-6.5$ ‰) suggest that the rocks have a mantle source.

(6) The genesis of rocks of the carbonatite associations involved carbonatite proper and alkaline gabbroid melts, as well as the products of their melting in the form of silicate magmatic rocks with a high percentage of incorporated carbonatite material.

(7) The Sr and Nd isotopic compositions of rocks of the carbonatite associations are heterogeneous and vary according to the mixing law of two isotopically distinct sources: tephritic and carbonatitic.

Taking into account the considerations presented above, we tried to assay the probable evolutionary paths in the genesis of the carbonatite associations. This problem is generally reduced to the elucidation of relationships between the tephritic and carbonatitic sources. Judging from their characteristics, these sources should have been spatially separated but exist simultaneously. The following two scenarios of their interaction are possible.

According to one of them, the activity of the tephritic source can be related to the development of

**Table 3.** Comparison of trace-element and isotopic (Nd and Sr) compositions of carbonatites and crustal carbonate rocks from the Baikal area

Rock	V	Pb	Rb	Cs	Ba	Sr	Ta	Nb	Hf	Zr	Y	Th
Carbonate rocks from the cover of the Tuva–Mongolia microcontinent (2)	1.6	7.6	–	–	74.6	256	–	–	–	9.8	4.5	–
Dolomitic marbles from the western Baikal area (3)	–	–	–	–	17	49	–	–	–	–	–	–
Calclitic marbles from the western Baikal area (3)	–	–	–	–	30	180	–	–	–	–	–	–
Quartz–calcite marbles from the western Baikal area (3)	–	–	–	–	590	790	–	–	–	–	–	–
Marbleized limestones from western Transbaikalia (Sample Khl-2/11)	–	–	2	–	1700	270	–	–	–	–	–	–
Dolomitic limestone from western Transbaikalia (Sample E-1)	<b>17</b>	<b>15</b>	<b>99</b>	<b>8.1</b>	<b>216</b>	<b>455</b>	<b>0.04</b>	<b>0.8</b>	<b>0.2</b>	<b>8.2</b>	<b>4</b>	<b>0.7</b>
Calclitic limestone from western Transbaikalia (Sample E-466)	<b>50</b>	<b>15.3</b>	<b>24.9</b>	<b>0.4</b>	<b>271</b>	<b>748</b>	<b>0.06</b>	<b>1.2</b>	<b>0.2</b>	<b>5.7</b>	<b>17</b>	<b>0.9</b>
Carbonatites from western Transbaikalia	47	71	2.0	0.1	66713	78347	0.62	15.1	0.2	1.8	44	20.6

Table 3. (Contd.)

Rock	U	La	Ce	Nd	Sm	Eu	Gd	Yb	Lu	$(^{87}\text{Sr}/^{86}\text{Sr})_0^*$	$\epsilon_{\text{Nd}}(T)^*$
Carbonate rocks from the cover of the Tuva-Mongolia microcontinent (2)	-	-	-	-	-	-	-	-	-	-	-
Dolomitic marbles from the western Baikal area (3)	-	-	-	-	-	-	-	-	-	-	-
Calclitic marbles from the western Baikal area (3)	-	-	-	-	-	-	-	-	-	-	-
Quartz-calcite marbles from the western Baikal area (3)	-	-	-	-	-	-	-	-	-	-	-
Marbleized limestones from western Transbaikalia (Sample Kh1-2/11)	-	91	175	93	44	20	-	0.5	-	0.7083(1)	-
Dolomitic limestone from western Transbaikalia (Sample E-1)	<b>0.9</b>	<b>7.56</b>	<b>10.7</b>	<b>3.05</b>	<b>0.39</b>	<b>0.14</b>	<b>0.48</b>	<b>0.27</b>	<b>0.03</b>	<b>0.70939</b>	<b>-1.64</b>
Calclitic limestone from western Transbaikalia (Sample E-466)	<b>0.4</b>	<b>33.8</b>	<b>47.5</b>	<b>14</b>	<b>2.19</b>	<b>0.562</b>	<b>2.3</b>	<b>1.16</b>	<b>0.164</b>	-	<b>-4.00</b>
Carbonatites from western Transbaikalia	14.8	1722	3055	1165	113	26.8	67.4	2.5	0.5	0.70539-0.70592	-3.6...-6.4

Note: For comparison, the table lists data on carbonatites from western Transbaikalia. Dashes mean the absence of data; \*parameters were calculated for 120 Ma. Values typed in bold face were obtained by ICP at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences. For carbonates from western Transbaikalia, average values are reported; for isotopic compositions, minimum and maximum values are reported. References: (1) Ripp *et al.*, 2000; (2) Belichenko *et al.*, 1999; (3) Ivanov and Sapozhnikov, 1985.



mantle tephritic melts, which ascended to the surface and *en route* intruded the material of the carbonatitic source. This material melted under the effect of heat from the tephritic magmas and gave rise to carbonatite melts and their interaction products with the silicate magmas. This scenario of relationships between the sources turns to be unrealistic because of the following considerations. Crustal carbonate rocks occurring in western Transbaikalia have isotopic geochemical features ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.7083\text{--}0.7094$ ; Table 3) and trace-element concentrations (REE, Ba, Sr, Pb, Nb, and Ta concentrations tens and hundreds of times lower than in the carbonatites; Table 3) notably different from the analogous features of the carbonatites. Moreover, it is very difficult to explain, within the frameworks of this scenario, the preservation of the carbonatitic source in pre-Early Cretaceous time, when this area was affected by magmatic processes whose scales exceeded that of the mid-Early Cretaceous magmatic activity.

According to the other scenario proposed for the genesis of rocks of the carbonatite associations, it was the products of the carbonatitic source that affected the source of the tephrite magmas. Given the richness of carbonatites in volatile components, such as  $\text{CO}_2$ , S, and P, it can be hypothesized that the carbonatitic source was of fluid nature, and the sources interacted in the mantle according to the following mechanism. A mobile phase (carbonatitic source), which was saturated in volatiles and rich in Ba, LREE, Pb, and Sr, intruded into the mantle source of the tephrites and metasomatized it. Traces of mantle metasomatic processes with the inflow of some components were reported by several researchers (Kovalenko *et al.*, 1987; Batanova *et al.*, 1999; Dawson and Smith, 1977; Kramers *et al.*, 1983; Sweeney *et al.*, 1993; Yaxley *et al.*, 1991; Hauri *et al.*, 1993; Rudnik *et al.*, 1993; Ionov *et al.*, 1993). In mid-Early Cretaceous time, the fluid effect on the material of the tephritic source resulted in the enrichment of this source (and its melting products, such as tephrites and teschenites) in Sr (>1000 ppm), Ba (>1000 ppm), REE (>500 ppm), Pb (>70 ppm), P (up to a few wt %  $\text{P}_2\text{O}_5$ ), and  $\text{CO}_2$ .

The isotopic compositions of rocks of the carbonatite associations indicate that, in addition to geochemical and isotopic–geochemical transformations in the silicate mantle in the zone of metasomatism, there was a brief separation of a carbonate-rich phase, which inherited its isotopic characteristics from the carbonatitic source. This follows from the differences between the isotopic compositions of the carbonatites and silicate rocks of the carbonatite associations. The melting of this mantle with heterogeneous isotopic and phase compositions may have resulted in the appearance of isotopically different melts: silicate (alkaline mafic) and carbonatite. The isotopic composition of the silicate melts could vary depending on the degree of the metasomatic recycling of the mantle source. The carbonatite melts seem to preserve the isotopic signatures of the carbonatitic source. At the same time, it is quite

probable that mixed “silicate–carbonate” magmas could be produced, whose isotopic compositions are characterized by intermediate values. The latter can be exemplified by the rocks of the Oshurkovo Complex.

Hence, it can be hypothesized that the origin of a wide range of rocks of the carbonatite associations in western Transbaikalia was related to the metasomatic alteration of the mantle source under the effect of fluids enriched in  $\text{CO}_2$ , P, S, LREE, Sr, Ba, and Pb and the further derivation, from metasomatized mantle domains, of silicate (alkaline gabbroid), silicate–carbonate, and carbonatite melts.

## CONCLUSIONS

1. The Late Mesozoic carbonatites of western Transbaikalia related to a rift zone were produced in mid-Early Cretaceous time (130–115 Ma), within a local area, whose position in the rift zone was controlled by the Gusinozersk chain of grabens. The carbonatites occur as volcanic sheets, dikes, and veins, are usually associated with subalkaline and alkaline silicate rocks, and compose with them common complexes.

2. The carbonatites are subdivided into two mineralogical–geochemical groups: (1) phosphorus–barium–strontium carbonatites (the Khalyuta volcanic complex and the Oshurkovo and Toreiskoe occurrences) and (2) fluorite–rare earths–barium–strontium carbonatites (the Arshan and Yuzhnoe occurrences). Minerals from the carbonatites of both groups contain melt inclusions, which provide evidence for the magmatic genesis of these rocks.

3. The carbonatites are genetically related to alkaline and subalkaline rocks: shonkinites, teschenites, alkaline gabbro, syenites, and phonolites. They crop within the same fields, have similar trace-element and isotopic–geochemical characteristics, and are coeval rocks, which were derived in mid-Early Cretaceous time.

4. The O and C isotopic compositions of the carbonatites were predominantly determined by a mantle source ( $\delta^{18}\text{O}$  from 6.0 to 10.7‰,  $\delta^{13}\text{C}$  from –4.1 to –6.5‰) with the involvement of a crustal source. The latter is identified in the carbonatites that underwent later transformations.

5. The Sr and Nd isotopic compositions of the carbonatites and related alkaline igneous rocks are characterized by elevated concentrations of radiogenic Sr and relatively low concentrations of radiogenic Nd. The variations in the compositions correspond to mixing trends of two isotopically heterogeneous mantle sources, one of which can be paralleled with the mantle source [ $(^{87}\text{Sr}/^{86}\text{Sr})_0 = 0.7052$ ,  $\epsilon_{\text{Nd}} = -1.6$ ] of the Late Mesozoic mafic rocks of the western Transbaikalia volcanic area, and the other corresponds to “carbonatitic” mantle fluid [ $(^{87}\text{Sr}/^{86}\text{Sr})_0 = 0.7059$ ,  $\epsilon_{\text{Nd}} = -6.4$ ], which was enriched in LREE, Sr, Ba,  $\text{CO}_2$ , P, and S.

6. The compositionally heterogeneous rocks of the carbonatite associations were produced with the involvement of the same process, namely, mantle metasomatism. The melting of the metasomatized mantle was associated with the derivation of both alkaline gabbroid and carbonatite melts and the origin of their mixed varieties. The concurrent participation of these melts in the magmatic processes resulted in a broad range of rocks of the carbonatite associations in western Transbaikalia.

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