

The Evolution of Volcanism in the Tugnui–Khilok Sector of the Western Transbaikalia Rift Area in the Late Mesozoic and Cenozoic

A. A. Vorontsov^a and V. V. Yarmolyuk^b

^a *Vinogradov Institute of Geochemistry, Siberian Division, Russian Academy of Sciences, Favorskogo str., 1A, Irkutsk, 664033, Russia*

^b *Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM), Russian Academy of Sciences, Staromonetnyi per. 35, Moscow, 109017, Russia*

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Abstract—The Late Mesozoic–Cenozoic volcanism of the Tugnui–Khilok sector in the western Transbaikalia rift area is related to the development of the Tugnui, Tsolgin, Margentui, and Khilok grabens and is characterized by a north–south migration of magmatic centers. In these grabens, the igneous associations are composed of high-alkaline rocks: alkaline and subalkaline basalts, tephrites, phonolites, trachytes, trachyrhyolites, comendites and pantellerites, alkaline syenites and alkaline gabbroids. These associations are known to have formed during 10 stages: Late Jurassic (150–158 Ma), Late Jurassic–Early Cretaceous (139–147 Ma), the beginning of the Early Cretaceous (133–145 Ma), mid–Early Cretaceous (115–134 Ma), the end of the Early Cretaceous (104–114 Ma), the end of the Early–beginning of Late Cretaceous (99–102 Ma), Late Cretaceous (72–90 Ma), Eocene (38–48 Ma), Early Oligocene (30–35 Ma), and Late Oligocene (25–27 Ma). The composition of igneous associations was changing in such a way that the relative amount of salic rocks gradually decreased (occasionally even disappeared completely) in the later developmental stages. As well, the content of SiO₂ in basic rocks also decreased with increasing Nb and Ta contents, and depletion occurred in the lithophylic elements Rb, K, Ba, Sr, and in light rare-earths relative to heavy ones. The geochemical and isotope-geochemical parameters of basaltoids change through time, probably due to successive changes in the mantle sources of magmatism. During Mesozoic time, the source composition was consistent, with OIB–EM-II sources enriched in radiogenic strontium, but since the second half of the Cretaceous, the isotope composition began to be modified toward moderately depleted sources of the OIB–PREMA type.

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INTRODUCTION

In central Asia a series of independent intraplate volcanic areas with characteristic long-term and multi-stage development formed in the Late Mesozoic and Cenozoic [12, 24–26, 28]. The igneous history of these areas clearly demonstrates evolutionary tendencies, which are expressed, first of all, in regular variations in the composition of igneous associations and volcanic activity changes through time. The western Transbaikalia area is a typical example. Within its limits, bursts of volcanic activity took place in a regular manner from the Late Jurassic to the Late Cenozoic inclusive, thus attesting to a permanent presence of intraplate magmatic activity at the base of the area. The patterns of structure and development of the area were considered in general in [4, 6, 7, 13, 18, 25, 26]. Several structural sectors are recognized: the western (Dzhida), the central (Tugnui–Khilok and Il’kino–Kizhinga), and the eastern (Uda–Vitim). These sectors correspond to the larger grabens and differ between themselves in their histories of magmatism and volcanic ejecta composition. Both large bursts of magmatism affecting several

sectors simultaneously in the same manner and less important bursts, confined to one or two sectors, have been identified [12, 25].

Based on geochronologic, petrographic, petro-geochemical and isotope studies, this paper considers the evolution of structure and magmatism and its sources, as well as the geodynamic nature of the area from the example of its central, Tugnui–Khilok sector (TKhS). This sector has the longest continuous evolution of magmatism (from Late Jurassic to Late Oligocene inclusive), and in recent years has been thoroughly studied by modern geological, geochronologic and petrologic methods. The materials for this paper were collected in the course of detailed field work with the active participation of V.G. Ivanov (1947–2003). His data is widely used here and we devote this work to his memory.

THE GEOLOGICAL SETTING

The Tugnui–Khilok sector of the western Transbaikalia volcanic area involves the Tugnui, Tsolgin,

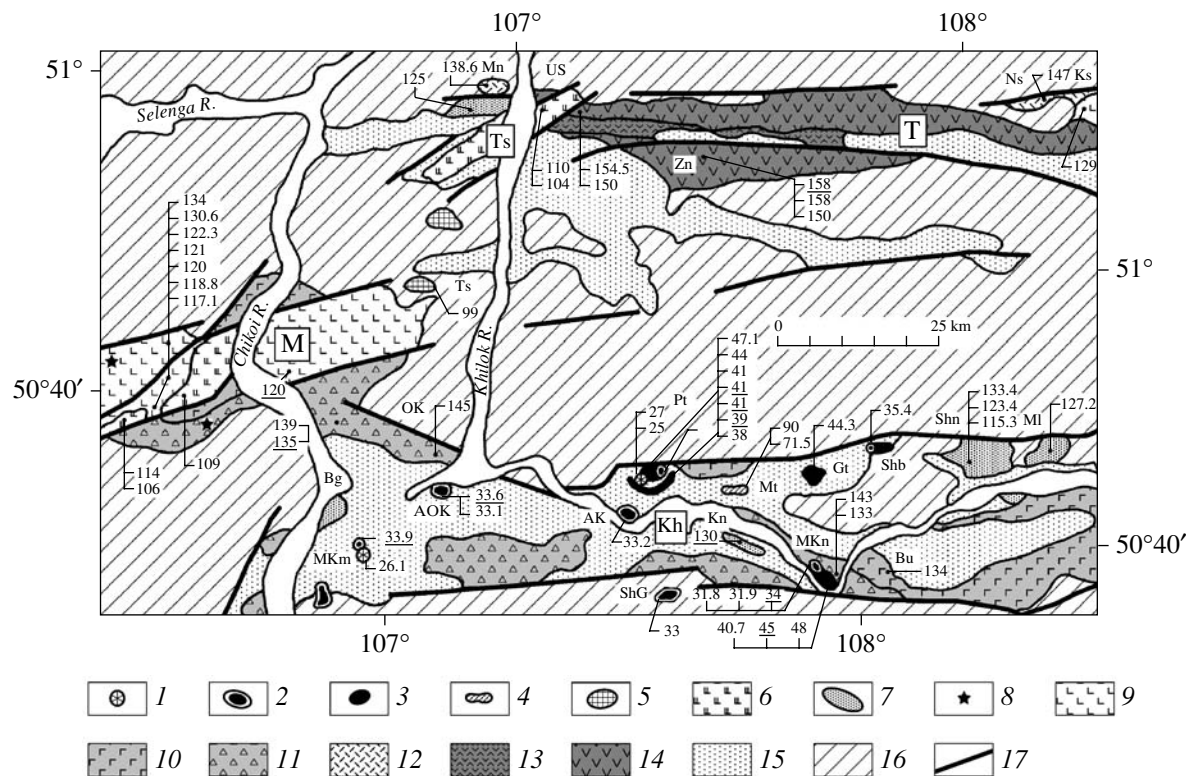


Fig. 1. Distribution of the Late Mesozoic–Cenozoic igneous rock associations within the Tugnui–Khilok sector of the western Transbaikalia rift area. (1–15) Igneous rock associations: (1) Late Oligocene (25–27 Ma), basanite–tephrite association of central volcanoes; (2) Early Oligocene (30–35 Ma), tephrite association of extrusions; (3) Eocene (34–48 Ma), tephrites, basanites, subalkaline basalts and melanephelinites; (4) Late Cretaceous (72–90 Ma), subalkaline basalts; (5) end of Early–beginning of Late Cretaceous (99–102 Ma), tephrites and trachybasalts; (6) end of Early Cretaceous (104–114 Ma), shield volcanoes of tephrites and trachybasalts; (7–9) mid-Early Cretaceous (115–134 Ma): (7) tephrite–phonolite, (8) nepheline–syenite, (9) tephrite–trachybasalt; (10–11) beginning of Early Cretaceous (131–145 Ma): (10) subalkaline olivine basalts, (11) basaltic hyaloclastites; (12) end of Late Jurassic–beginning of Early Cretaceous (138–147 Ma): trachydacite–trachyrhyolite–pantellerite; (13–14) Late Jurassic (150–158 Ma): (13) trachyte–trachyrhyodacite, (14) trachybasalt–trachyandesite–basalt; (15) Late Mesozoic and Cenozoic sedimentary fill of grabens; (16) pre-Late Mesozoic basement; (17) faults. Dots show the sampling sites and numerals the age of igneous rock associations in Ma. Underlined numerals (Ma) are taken from publications. Letters in squares designate the grabens: T Tugnui, Ts Tsolgin, M Margentui, and Kh Khilok. Letters show volcanoes and volcanic fields: Pt Petropavlovskii, MKn Malyi Kumyn, AOK Ambon (Okino–Klyuchi), AK Ambon (Kiret’), Bg Beregovoe, MKn Malyi Kunalei, Kn Kunalei, ShG Shara–Gorkhon, Shb Shibertui, Gt Gutai, Mt Motninskoe, Ts Tsaram, US Ust’-Sukharinskoe, Ks Kusotinskoe, Ns Novospasskoe, Mn Monostoi, Shn Shanaginskoe, Mt Maletinskoe, OK Okino–Klyuchi, Bu Buiscoe, and Zn Zandin.

Margentui and Khilok grabens composed of different-aged igneous associations (Fig. 1).

The **Tugnui graben** extends nearly east–west for more than 140 km from the lower reaches of the Khilok River in the west to the upper reaches of the Tugnui River in the east, with a width of about 35–40 km. The Tsagan-Daban Range forms its northern side and the southern side is the Zaganskii Range, with both sides being composed of Precambrian and Paleozoic rocks that were metamorphosed in the Late Mesozoic. These rocks are considered as Cordilleran type metamorphic cores related to rifting [22]. The graben is largely composed of Late Jurassic and Cretaceous volcanic and sedimentary rocks, the most frequent among these being those of the Ichetui Formation (J_{3ic}). Alongside the dominating subalkali basalts, occasional members and lenses of lavas and tuffs of trachytes, trachydacites,

trachyrhyodacites with some alkaline trachyrhyodacites and pantellerites can be found [8–10, 14]. In addition to the Ichetui Formation rocks, the western part of the graben contains small fields of Early Cretaceous trachyrhyolite strata consisting of comendites and pantellerites of Monostoi Volcano, and trachybasalt strata of mid-Early Cretaceous composed of subalkali basalts.

The **Margentui graben** extends northeast for 70–80 km from the mouth of the Dzhida River in the west to the catchment area of the Chikoi and Khilok rivers. Its width is 20–30 km. On the northwest and southeast the graben is bounded by large normal faults separating it from the Borgoi and Zaganskii horst-like uplifts. The graben is filled with gently dipping Early Cretaceous (the Khilok Formation) and Late Cretaceous trachybasalt flows covering a total area of more than 1000 km².

In addition, there are small stocks of porphyritic syenites and nepheline porphyritic syenites, as well as basalt dykes penetrating through the Early Cretaceous volcanic strata.

The **Khilok graben** trends nearly east–west like the Tugnui graben for more than 150 km and is 20–30 km wide. On the north it is bounded by the large Zaganskii Range uplift and on the south by the Malakhanskii Range composed of Precambrian and Paleozoic rocks. The graben is filled with Cretaceous and Cenozoic rocks, but rocks of the Early Cretaceous Khilok Formation are the most frequent, occurring almost continuously for the entire length of the graben as thick series of lava flows. Since the Late Cretaceous, magmatic activity sharply decreased, but continued until the latest Oligocene with a decreasing number of eruptions.

The **Tsolgin graben** is a narrow (about 7 km wide) northeast trending trough situated at an acute angle to the major orographic features of the area, including the abovementioned grabens. Some fragments of it have been identified in the left-bank portion of the Margentui graben and in the area where the Tugnui graben and the Khilok River intersect. The lower part of the graben succession consists of conglomerates and gravelstones of variable thickness, the upper section consists of basalt lavas dating back to the second half of the Early Cretaceous. This graben cuts across lava fields in the Margentui and Tugnui grabens and unlike these has no horst uplifts on its shoulders.

STAGES OF VOLCANISM FORMATION AND CORRESPONDING IGNEOUS ASSOCIATIONS

The stages of development of the central sector of the western Transbaikalia rift area are the time intervals during which volcanic associations and accompanying subvolcanic rocks formed. Volcanic phenomena of different ages are usually separated by unconformities, members of terrigenous rocks, or differ in structure and position as well as in the composition of the constituent rocks.

Geochronological data. In addition to geological relationships, the age differences of various volcanic associations in the TKhS are supported by geochronological data (Table 1) showing systematic differences in the isotope composition of the rocks. Table 1 primarily summarizes our data, but materials from other workers are also used [2, 3, 8, 9, 16, 20, 21], none, however, without field ties to specific volcanic associations. At the same time, results for altered rocks have been excluded from this analysis, in particular, the large data set [10] which seems to characterize zeolitized rocks with high L.O.I. values (~5%).

Our determinations of K–Ar and Rb–Sr isotope ages were carried out in the laboratories of isotope geochemistry at IGEM of the RAS and the Siberian Branch of the Institute of Geochemistry of the RAS. The reliability of these determinations was checked by their consistency

with the geological ages obtained from paleontological data or based on geological relationships between different volcanic series, as well as by the consistency of dates relevant to different localities of the same volcanic sequence.

The range of age values within the age group of volcanic associations is 19 Myr for the group of mid-Early Cretaceous rocks. When the precision of measurements is taken into account, this interval can be reduced to 11 Myr. In other volcanic groups, this interval is not usually above 10 Myr, and when the precision of measurements is taken into account these intervals may be only half this large. This suggests that the duration of separate volcanic events varied from a few Myr to 10 Myr.

Based on the magmatism characteristics in the area (composition, associations, geological relationships, and dating results) we recognized 10 volcanism stages (Fig. 2): Late Jurassic (150–158 Ma), Late Jurassic–Early Cretaceous (139–147 Ma), the beginning of the Early Cretaceous (133–145 Ma), Early Cretaceous (115–134 Ma), the end of the Early Cretaceous (104–114 Ma), the end of the Early–beginning of the Late Cretaceous (99–102 Ma), Late Cretaceous (72–90 Ma), Eocene (38–48 Ma), Early Oligocene (30–35 Ma), and Late Oligocene (25–27 Ma).

The **Late Jurassic stage** is represented by thick (up to 2000–2500 m) volcanic sequences consisting of contrasting combinations of basic and alkaline–salic rocks: trachybasalts and trachyandesite–basalts with trachytes, trachydacites and trachyrhyodacites. In the western Transbaikalia rift area, igneous rocks of this stage are traditionally classified as belonging to the Ichetui Formation [15]. Rocks of different compositions are usually separated in a rock sequence, forming isolated series of flow units. Basic rocks compose up to 90% of these associations and form lava plateaus. Trachybasalts dominate the basic rock units; plagiophyres are the most common, though pyroxene–plagioclase and olivine varieties also occur. The salic members of the associations are lavas, baked and regular tuffs consisting of trachytes and trachydacites, and less frequently of alkaline trachyrhyodacites and pantellerites. They compose thick units confined to the upper levels of an association, in addition to dykes and stocks.

The Ichetui Formation rocks occur only within the Tugnui graben. The development of this graben was compensatory in character: volcanic rocks either lie directly on the weathering crust or are underlain by thin conglomerate beds; interbeds of sedimentary rocks are almost absent, while volcanic rocks are not found outside the graben.

According to K–Ar dating of the Ichetui Formation volcanics, they formed in the interval 150–158 Ma. The Rb–Sr isochronal method gave an age of 158 ± 8 Ma [9]. Generally, radiological data suggest a Late Jurassic age for these igneous associations.

The Stage from the end of the Late Jurassic to the beginning of the Early Cretaceous consists mostly of

Table 1. K–Ar and Rb–Sr datings of volcanic rocks in the Tugnui–Khilok sector of the Late Mesozoic–Cenozoic western Transbaikalia volcanic area

Volcanoes and volcanic fields	Sample	Coordinates of sampling sites		Rock	Age, Ma
		N	E		
Late Oligocene stage (10) <i>Khilok graben</i>					
Petropavlovskii	Khi-14/1	50°41′	107°31′	Basanite	27 ± 1
	Khi-14/2	50°41′	107°31′	Subalkaline basalt	25 ± 0.6
Malyi Kumyn	Khi-7/5	50°29′	106°57′	Subalkaline basalt	26.1 ± 0.7
Early Oligocene stage (9) <i>Khilok graben</i>					
Ambon (Okino–Klyuchi)	Khi-1/1	50°36′	107°0′	Tephrite	33.1 ± 2
	13565			Augitite	33.6 ± 0.8 (B)*
Ambon (Kiret’)	Khi-1/7	50°37′	107°27′	Subalkaline basalt	33.2 ± 0.4
Malyi Kumyn	13562			Olivine basalt	33.9 ± 2.6 (B)*
Malo-Kunalei	Khi-3/20	50°36′	107°21′	Tephrite	31.9 ± 0.4
	Khi-3/21	50°36′	107°21′	Tephrite	31.8 ± 0.8
	3/84			Olivine basalt	34 ± 3 (K)*
Pertopavlovskoe	Khi-12/6	50°41′	107°31′	Melanophelinite	30 ± 1
Shibertui	Khi-15/3	50°47′	107°54′	Basanite	35.4 ± 1.5
Shara–Gorkhon	Khi-18/2	50°31′	107°37′	Basanite	33 ± 1
Eocene stage (8) <i>Khilok graben</i>					
Malo-Kunalei	Khi-3/11	50°36′	107°52′	Melanophelinite	48 ± 2
	Khi-3/16	50°36′	107°50′	Subalkaline basalt	40.7 ± 0.4
	2/84			Olivine basalt	45 ± 3 (K)*
Gutai	Khi-12/2	50°43′	107°46′	Subalkaline basalt	44.3 ± 1
Pertopavlovskoe	Khi-12/5	50°41′	107°29′	Subalkaline basalt	38 ± 1
	Khi-12/7	50°41′	107°29′	Subalkaline basalt	41 ± 1
	Khi-14/4	50°41′	107°29′	Melanophelinite	47.1 ± 1.4
	Khi-14/6	50°41′	107°29′	Melanophelinite	44 ± 1.5
Middle reaches of Khilok R.	13571			Basalt	41.0 ± 2 (B)*
	13/84			Olivine basalt	39 ± 3 (K)*
	13570			Olivine dolerite	41 ± 0.3 (B)*
Cretaceous stage (7) <i>Khilok graben</i>					
Motninskoe	Khi-12/4	50°41′	107°39′	Subalkaline basalt	90 ± 2
	Khi-15/2	50°41′	107°39′	Subalkaline basalt	71.5 ± 2.1
End of Early–beginning of Late Cretaceous stage (6) <i>Tugnui and Margentui grabens</i>					
Tsaram	Khi-13/2	50°49′	106°52′	Tephrite	99 ± 2
Tamchin	13076			Basalt	100.2 ± 0.3 (B, B)*
	Sh-2	50°55′	106°13′	Basalt	101.4 ± 3 (V)*
	GO-4/7	50°55′	106°13′	Basalt	102 ± 3 (V)*
End of Early Cretaceous stage (5) <i>Tsolgin graben (the Tugnui fragment)</i>					
Ust’-Sukharinskoe	Tg-1/11	51°07′	107°06′	Trachybasalt	110 ± 3
	Tg-1/12	51°07′	107°06′	Trachybasalt	104 ± 3

Table 1. (Contd.)

Volcanoes and volcanic fields	Sample	Coordinates of sampling sites		Rock	Age, Ma
		N	E		
Tsolgin graben (the Margentui fragment)					
Margentui	Tszh-3/1	50°41′	106°30′	Trachybasalt	109 ± 6
	Tszh-4/7	50°32′	106°24′	Trachybasalt	114 ± 6
	Mg-5/1	50°34′	106°27′	Trachybasalt	106 ± 3
Mid-Early Cretaceous stage (4)					
Tugnui graben					
Kusotinskoe	Tg-22/26	51°20′	108°18′	Trachybasalt	129 ± 4
Monostoi	Tg-13/30	51°05′	106°49′	Tephrophonolite	125 ± 3
Khilok and Margentui grabens					
Shanaginskoe	Khi-16/4	50°50′	108°10′	Trachybasalt	133.4 ± 4
	Khi-16/7	50°50′	108°10′	Trachybasalt	115.3 ± 3.4
	Khi-17/3	50°45′	108°10′	Trachybasalt	123.4 ± 3.7
Maletinskoe	Khi-17/9	50°45′	108°24′	Trachybasalt	127.2 ± 3.8
Kunalei	Khi-2/3	50°37′	107°43′	Trachybasalt	130 (Ya(a))*
Margentui	Mg-1/3	50°39′	106°24′	Trachybasalt	121 ± 3.6
	Mg-1/8	50°46′	106°24′	Trachybasalt	118.8 ± 3.5
	Mg-1/12	50°46′	106°24′	Trachybasalt	122.3 ± 3.6
	Mg-2/3	50°43′	106°29′	Trachybasalt	134 ± 4
	Mg-2/6	50°39′	106°33′	Trachybasalt	130.6 ± 3.9
	Mg-2/7	50°49′	106°28′	Trachybasalt	117.1 ± 3.5
	Mg-4/4	50°44′	106°41′	Trachybasalt	120 (Ya(a))*
Beginning of Early Cretaceous stage (3)					
Khilok and Margentui grabens					
Okino–Klyuchi	Khi-1/4	50°38′	107°01′	Subalkaline basalt	145 ± 3
Margentui	Khi-8/3	50°40′	106°50′	Subalkaline basalt	139 ± 4
	Mg-4/7	50°40′	106°50′	Subalkaline basalt	135 (Ya(a))*
Malo-Kunalei	Khi-3/3	50°36′	107°48′	Subalkaline basalt	133 ± 5
	Khi-3/12	50°36′	107°48′	Subalkaline basalt	143 ± 6
Buiskoe	Khi-4/3	50°37′	108°02′	Subalkaline basalt	134 ± 5
Late Jurassic–Early Cretaceous stage (2)					
Tugnui graben					
Monostoi	Tg-13/2, 1, 3, 4	51°06′	106°52′	Trachyandesite, pantellerites	138.6 (Ya(b))**
Novospasskoe	Tg-7/10	51°20′	108°12′	Trachyrhyolite	147 ± 2.5
Late Jurassic stage (1)					
Tugnui graben					
Ust’-Sukharinskoe	Tg-2/3	51°07′	107°08′	Quartz trachyte	150 ± 5
	Tg-14/1	51°08′	107°08′	Trachybasalt	154.5 ± 3.7
Zandin	Tg-21/4	51°05′	107°26′	Trachyandesite-basalt	150 ± 3
	Tg-21/10	51°06′	107°24′	Trachyandesite-basalt	158 ± 4
	1–7			Trachybasalts, trachyrhyodacites	158 ± 8 (G)**

Note: The above determinations are due to M.M. Arakelyants, Laboratory of Isotopic Geochemistry, IGM RAS and V.N. Smirnov, Isotope Geochemistry Laboratory, Vinogradov Institute of Geochemistry at the Siberian Division of the RAS.

* Data taken from (letters in parentheses): Ya(a) [25], R [20, 21], B [2], B, B [3], K [16], V [7].

** Rb–Sr isochrones from bulk samples: Ya(b) [28], G [8, 9].

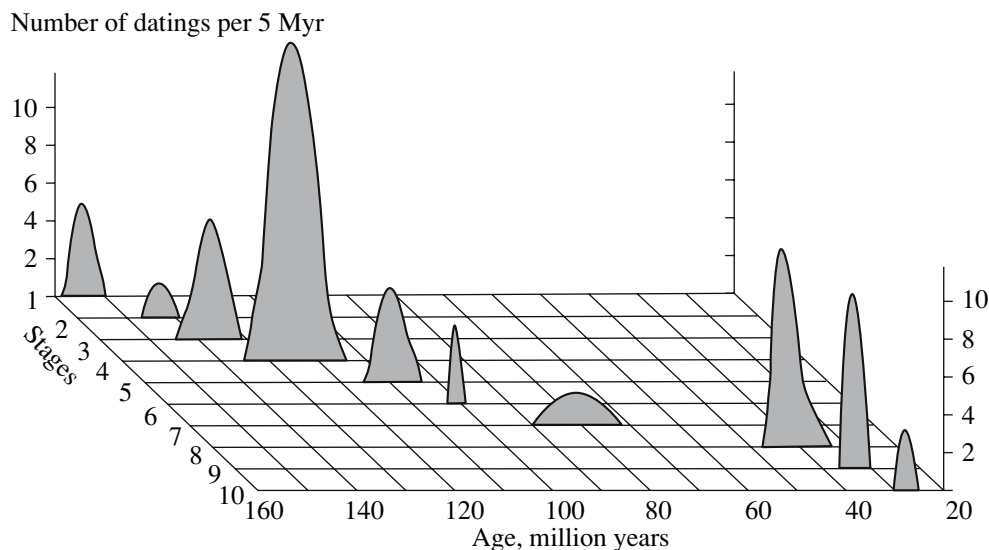


Fig. 2. Block diagram of the distribution of K–Ar ages in volcanic series of different stages in the Tugnui–Khilok sector of the western Transbaikalia rift area (numbers of stages correspond to those shown in parentheses in Table 1).

acid rock associations: trachydacites, trachyrhyolites, and pantellerites. They compose isolated volcanic fields related to the activity of individual stratovolcanoes. The absence of basic volcanic rocks is a peculiar feature of this stage of volcanism (unlike the other grabens of the western Transbaikalia). For example, this type of volcano includes the Monostoi extrusive-dome pantellerite–trachydacite volcano in the west and a series of small volcanic domes forming the Novospassk trachyrhyodacite field in the northeast of the Tugnui graben.

The rocks of this volcanic association are confined to boundary faults of the Tugnui graben. Their age is determined by the unconformable occurrence of lavas on the Late Jurassic volcanic strata. The Rb–Sr isochronal age of the Monostoi volcano is estimated as 139 Ma, and that of the Novospassk trachyrhyodacites as 147 Ma.

The **Stage of the beginning of the Early Cretaceous** is known for the largest eruptions involving the Khilok and Margentui grabens. Plateau basalt series occurring continuously throughout all the grabens accumulated during these events. These strata compose the Khilok Formation consisting of thick series of lavas. The lower levels typically involve thick (up to 500 m) packages of basalt hyaloclastites attesting to underwater eruptions. It should be noted that the formation of this association was related to the major stage of graben development in the western Transbaikalia rift area, which determined the major structural features of all its segments.

Subalkaline olivine basalts with characteristic ovoid jointing absolutely dominate these rocks. Their chemical composition is typically alkaline (6.5% on the average), so that their normative composition contains nepheline (up to 1.5%), while the concentrations of

TiO₂ and MgO are higher than those in the Late Jurassic–beginning of the Early Cretaceous rocks, and the silica content is generally lower.

Their geological age is found from their association with Cretaceous sedimentary strata and a permanent confinement to the lower levels of the Early Cretaceous sequences in the grabens. The K–Ar datings cluster within 133–145 Ma, indicating that they belong to the lower part of the early Cretaceous.

The **mid-Early Cretaceous stage** is known for diversity of volcanic associations conventionally subdivided into subalkaline tephrite–trachybasaltic, alkaline tephrite–phonolitic and nepheline–syenite ones. Magmatic activity was largely concentrated within the Margentui and Khilok grabens.

The tephrite–trachybasaltic association occurs in the Margentui graben. Flat-lying volcanic sequences composed of persistent thin lava flows are typical of this association. Volcanic rocks unconformably (often with conglomerates at their base) overlie the Late Jurassic and earliest Cretaceous volcanic sequences. The associations include bluish-gray tephrites, usually with ball-spotty in color, and olivine-normative trachybasalts.

Rocks of the tephrite–phonolitic association are found in the Tugnui and Khilok grabens as weakly-deformed lava sheets. They are typically highly alkaline: the content of normative nepheline in the tephrites (51% < SiO₂ < 53%) reaches 8%, and in phonolites (53% < SiO₂ < 55%) it is 11%.

The Early Cretaceous affinity of these associations is determined by their permanent confinement to Early Cretaceous strata and by the fact of their occurrence (with conglomerates at the base) above lava series of the beginning of Early Cretaceous in the Khilok graben.

The K–Ar ages of the rocks lie within the interval 115–134 Ma, corresponding to the middle of the Early Cretaceous.

The nepheline–syenite association involves subvolcanic and hypabyssal bodies (dykes and stocks) outcropping in the western part of the Margentui graben. The geological position of this rock group is determined by the cutting of the lower section of tephrite–trachybasaltic series by a zonal stock of nepheline syenite–porphyry. Rocks of the stock's endocontacts are fine-grained, bluish-gray, and their chemistry and mineralogy is consistent with tephrophonolites of the volcanic sequences. The internal parts of the stock are made of fine-grained nepheline syenites with localities of pegmatoid and taxitic texture. According to F.V. Kuznetsova [17], the K–Ar age of the nepheline syenites varies between 110 and 130 Ma, corresponding to the age of tephrite–phonolitic association.

To sum up the data on the mid-Early Cretaceous magmatism, we note the diversity of rock associations. The volcanic activity of this period was due to distinct small shield volcanoes, which is evidenced by the original flat occurrence of lava covers and the spatial isolation of the volcanic fields. The compact distribution of subvolcanic and hypabyssal intrusions suggests the central character of the magmatism.

The **latest Early Cretaceous stage** involved decreasing magmatic activity. The latter was connected with the formation of the narrow northeast-trending Tsolgin graben which traverses the Margentui and Tugnui grabens at oblique angles. Plateau-basalt lava fields distributed within the Tsolgin graben occur unconformably on the volcanics of earlier stages. The K–Ar datings are within 104–114 Ma. The fields consist of thin (up to 80 m) series of flat-lying tephrite and trachybasalt covers.

The **latest Early–earliest Late Cretaceous stage** is represented by isolated small volcanic fields. These include the Tsaram fields situated within the western margin of the Margentui Range, and the Tamchin field situated even farther west, at the boundary of the Dzhida and Tugnui–Khilok sectors of the volcanic area. These volcanics overlie Early Cretaceous deposits and have K–Ar ages between 99 and 102 Ma. The igneous rocks of this stage are tephrites and trachybasalts. The Tamchin field is the largest one and was described earlier as a sill [5]; it consists of lava flow series with a total thickness of more than 100 m.

The **Late Cretaceous stage** is known for much less magmatic activity. The Motninskoe lava field in the Khilok graben belongs to this stage. This field occurs on Early Cretaceous conglomerates and volcanics with some scour and a sharp angular unconformity. The rock composition corresponds to quartz–normative subalkaline basalts; they form a series of flat-lying covers with a total thickness of more than 100 m. The K–Ar age of the Motninskoe field basalts has been found to be within the range of 72–90 Ma.

The **Eocene stage**. The magmatism of this stage took place in the Khilok graben only. The relevant rocks are found only in outliers of a lava sheet occurring in near-graben-side localities, with their bases being at approximately the same altitude, 750–800 m a.s.l. The outliers consist of flat-lying covers of basanites, tephrites, subalkaline basalts and melanephelinites, each 8–15 m thick and making a total thickness of more than 80 m. The rocks have higher relative alkalinity (normative nepheline makes up to 11%), a low content of SiO₂ (less than 45% on the average), and high MgO (more than 8.9%). Their compositions in different outcrops are similar, suggesting their former occurrence in a single field that covered at least 450 km². Their geological age is based on their occurrence above Cretaceous and Early Cenozoic strata. The radiologic age corresponds to the interval between 30 and 48 Ma.

The **Early Oligocene stage**. This stage comprises small volcanic massifs within the Khilok graben and on its southern side (Fig. 1). Laccolites, stocks, and extrusive bodies form these fields. On the surface, they appear as dome-like elevations with basement areas up to a few square kilometers and up to 100–200 m high. Fine- and medium-grained basanites dominate, though tephrites, subalkaline basalts, and melanephelinites also occur. On the whole, their composition is close to igneous associations of the Eocene stage, but with a higher relative alkalinity (the content of normative nepheline is as high as 14%).

The radiologic K–Ar ages vary within 30–35 Ma. Some individual extrusions are found above the Eocene basanite–tephrite lava plateau, thus providing evidence of their younger geological age.

The **Late Oligocene stage** comprises small, spatially separated manifestations of volcanism. They include a lava–cinder volcano (Malyi Kumyn Mount) in the Khilok graben. The edifice of the Malyi Kumyn Volcano overlies an Early Oligocene laccolite exposed by erosion. It is composed of basanites and subalkaline olivine basalts, their tuffs and bombs. Its age is estimated as 25–27 Ma. Compared with the Early Oligocene rocks, these differ in having higher concentrations of alumina (13 and 14% respectively), lower contents of total iron (13.8 and 14.8%) and MgO (9 and 7.5%), and lower relative alkalinity (the content of normative nepheline is 9 and 3%, respectively).

The **General regularities of volcanic evolution of the sector**. The data presented here demonstrate that volcanic activity within the Tugnui–Khilok sector of the volcanic area took place in the period from 160 to 25 Ma. The magmatic activity was closely associated with graben formation. The stage character of magmatism is clearly observed, showing a general tendency toward a decreasing amount of volcanic ejecta with time (from the earlier stages to the younger ones). At the same time, activation of volcanic processes took place at different times in different grabens (Fig. 3). Thus, the Late Jurassic burst of magmatism (the igne-

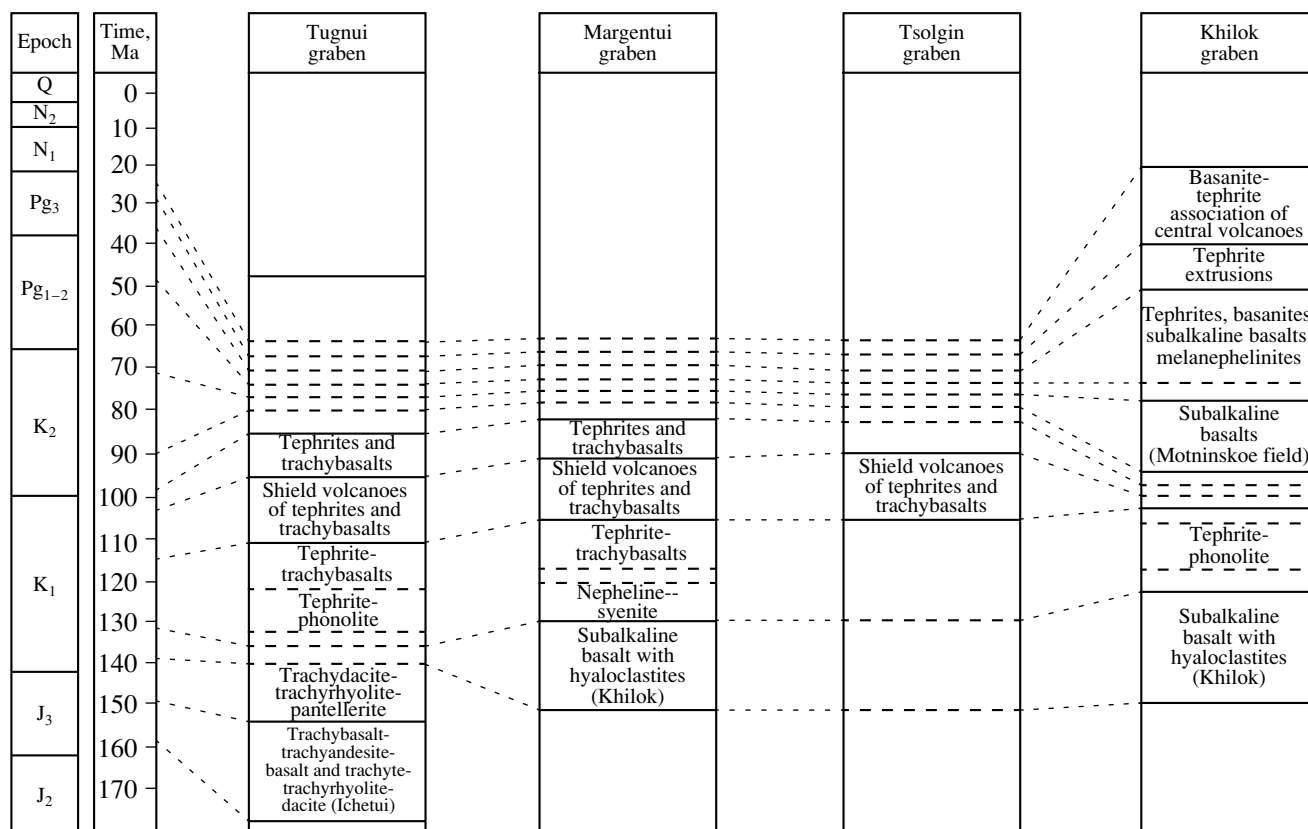


Fig. 3. Correlation of volcanic rock associations in the Tugnui, Tzolgin, Margentui and Khilok grabens of the western Transbaikalia rift area.

ous associations of the Ichetui Formation) took place in the Tugnui graben only; also within its limits, Late Jurassic–Early Cretaceous acid volcanics formed. In the beginning of the Early Cretaceous, the centers of magmatism shifted to the south, into the Margentui and Khilok grabens where the Khilok Formation basalts were erupted. At the end of the Early Cretaceous, in addition to these grabens, the Tzolgin graben was involved in magmatism; later on, however, from about 100 Ma, magmatism was entirely confined to the Khilok graben.

ROCK COMPOSITION IN ASSOCIATIONS OF DIFFERENT AGES

During the evolution of the Tugnui–Khilok sector in the western Transbaikalia rift area, different igneous associations formed, whose composition reflects changes in the environment of magmatism and of its material evolution. The evolutionary character of the magmatism is recorded in the changes in its erupted volumes from stage to stage and in directional changes of igneous association compositions, as well as in the petrographic, petrochemical, geochemical, and isotope–geochemical characteristics of the rocks.

Analytical methods. More than 150 samples were used for our study. Rock chemistry was studied by dif-

ferent methods. At the Institute of Geochemistry in Irkutsk, at the Siberian Division of the RAS, concentrations of petrogenic (major) elements, Ba, Sr, Zr, and Nb were determined by X-ray fluorescent spectroscopy using the technique described in [1]. Rb content was found by the flame photometry method. Other trace elements were studied by neutron–activation instrumental analysis at the United Institute of Geology Geophysics and Mineralogy at the Siberian Branch of the RAS, by the ICP-MS method at the Institute of Precambrian Geology and Geochronology (IGGD) of the RAS and at the Common-use Analytical Center of the Irkutsk Science Center at the Siberian Branch of the RAS.

The composition of minerals was studied at the Institute of Geochemistry at the Siberian Division of the RAS using a Superprobe-733 X-ray microanalyzer manufactured by the Jeol Company.

D.Z. Zhuravlev (IGEM, RAS) studied the isotope composition of Sr and Nd with the help of a Finnigan MAT 262 multichannel mass-spectrometer in the statistical operation mode using the standard technique [11]. Element concentrations were measured with a precision of about 1% relative. Isotope ratios were determined to within (2σ): $^{87}\text{Rb}/^{86}\text{Sr}$ with 0.5% relative and $^{147}\text{Sm}/^{144}\text{Nd}$ with 0.2% relative. Parallel analyses of standard samples gave the following average results: La

Jolla $^{143}\text{Nd}/^{144}\text{Nd} = 0.511840 \pm 15$ ($2\sigma N = 21$) normative to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$; Eimer, Amend $^{87}\text{Sr}/^{86}\text{Sr} = 0.708051 \pm 15$ ($2\sigma N = 8$). The level of idle running did not exceed (in ng) 0.3 for Nd, 0.1 for Sm, 2.0 for Sr, and 0.5 for Rb. The values of $\epsilon_{\text{Nd}}(T)$ are relative to the model vessel CHUR with parameters $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$, $^{147}\text{Sm}/^{144}\text{Sm} = 0.1967$, and $\epsilon_{\text{Sr}}(T)$ is relative to the model vessel UR: $^{87}\text{Sr}/^{86}\text{Sr} = 0.7045$, $^{87}\text{Rb}/^{86}\text{Sr} = 0.0825$ [23].

Petrographic description of rocks. Basaltoids absolutely dominate the different-age igneous associations in the Tugnui-Khilok sector. Special mention should be made of subalkaline (trachybasalts and trachyandesite-basalts) and alkaline (basanites, tephrites, and phonotephrites) varieties. Salic rocks—trachytes, trachyrhyolites, and pantellerites—make up not more than 5–10% of all volcanics. They originated during the initial stages in the evolution of the sector (Late Jurassic and Late Jurassic–Early Cretaceous), and usually combine with basic volcanics to create bimodal associations.

Basic volcanics usually have porphyry texture. The rock-forming minerals are olivine, clinopyroxene, and plagioclase, which occur both in phenocrysts and in groundmass in various proportions. *Olivines* in phenocrysts and groundmass consist of the forsterite-hyalosiderite row (fo_{85-49}). In basanites, olivine is the major phenocryst mineral. *Clinopyroxenes* in their chemistry and optical properties (distinct pleochroism) correspond to the titanite group. Compared with typical titanites, they have a high calcium content (up to 24.8% CaO) and differ from diopside-hedenbergite pyroxenes by higher content of titanium (up to 4.89% TiO_2). *Plagioclases* are mostly labradorite and basic andesine with a small admixture of orthoclase (up to 3.3%). Acid andesine and relatively rare oligoclase may have a much higher presence of the orthoclase component (up to 21%). Albites are found in very few samples of the Late Mesozoic tephrites. Plagioclase phenocrysts are typical of the Mesozoic volcanics and are practically absent from the Late Cenozoic basaltoids. These phenocrysts typically possess direct zonality with variations in basicity from 70 to 45% of anorthite. No zonality is noted in andesine phenocrysts. Recurrent zonality was only found in plagioclase phenocrysts in the Late Mesozoic tephrites.

The groundmass of the most alkaline varieties contains microliths of magnesia biotite, phlogopite, and alkaline feldspar or its rims on plagioclase separations, as well as analcime. Devitrified volcanic glass is found in the interstices between minerals in the groundmass whose content increases in younger (Late Cretaceous and Cenozoic) rocks and those with higher alkalinity. Ore and accessory minerals can also be found in the groundmass. The *ore minerals* occur as titanomagnetites, magnoferrites, and ilmenites. Magnoferrites (up to 5% MgO) are noted only in the Cenozoic basaltoids of higher alkalinity. These have high concentra-

tions of Al_2O_3 (up to 5.5%), Cr_2O_3 (up to 1.3%) and niobium. Titanomagnetites and ilmenites are characteristic both for the Mesozoic and Cenozoic basaltoids.

Secondary alterations are not typical of the rocks studied here and are often of local character. They are more common in Late Jurassic and Early Cretaceous rocks in the form of chloritization and opacitization of glass, serpentinitization and opacitization of olivine and pyroxene, and sericitization of plagioclase.

Salic effusive rocks—trachytes, trachydacite, trachyrhyodacites and pantellerites—have porphyry, more rarely vitreous aphyric textures. The trachytes contain phenocrysts of potassic feldspar with perthite texture, aegirine-augite (sometimes hypersthene), more rarely quartz and zonal pelitized plagioclase (10–30% An), as well as opacitized biotite. The groundmass generally has trachytic texture and consists of fine grains of potassic feldspar, acid plagioclase microliths (10–12% An), and ore minerals. Quartz and brown devitrified volcanic glass occur in small amounts. Sometimes the rock contains prismatic crystals of alkaline amphibole—riebeckite (not more than 2%) and accessory needle-shaped apatite (up to 1%). In phenocrysts of trachydacites and trachyrhyodacites, alkaline feldspar and oligoclase dominate, while quartz and biotite occur in smaller amounts. The groundmass has microfelsitic, microspherulitic texture and consists of micrographic intergrowths of quartz and K–Na feldspar. As a rule, the rocks are of fluid structure formed by alternating subparallel bands of a quartz–feldspar aggregate with different microtextures. The pantellerites are fine-grained aphyric rocks containing quartz and alkaline feldspar grains, and needle-shaped aegirine microliths in a fine-grained groundmass.

The *alkaline nepheline syenites* are medium-grained rocks consisting of alkaline feldspar, nepheline, albite, aegirine, ore and accessory minerals. The latter include apatite, sphene, zircon, and fluorite.

Petrogeochemical description of rocks. The contents of rock-forming oxides and trace elements in representative rock varieties are given in Table 2. The rock chemistry and, primarily, the variations in their total alkalinity, agree well with their age. The classification diagrams SiO_2 –($\text{Na}_2\text{O} + \text{K}_2\text{O}$) (Figs. 4a–4d) have the composition fields of the Late Jurassic–Early Cretaceous, Late Cretaceous and Cenozoic rocks clearly separated, shifting to an area of less silica and greater alkalinity with younger rocks. These changes are also accompanied by a decreasing amount of salic rocks in igneous associations and increasing alkalinity of the basaltoids. Among the latter, nepheline-normative varieties dominate since the Eocene stage of volcanism. In the salic rocks (syenites, trachytes, trachyrhyodacites, trachyrhyolites–comendites), the SiO_2 content varies in the range of 60–76 wt %. For the basic volcanics, it is within 43–57 wt % and the $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio lies within 1–4. Among these rocks the less silicic and most alka-

Table 2. Composition of igneous rock associations in the Tugnui–Khilok sector. Oxides are in weight percent, trace elements in g/t

Stages	Late Oligocene				Early Oligocene						Eocene			
Rock	Basanite	Subalka- line basalt	Subalka- line basalt	Tephrite	Tephrite	Subalka- line basalt	Tephrite	Tephrite	Melanon- ephelinite	Basanite	Basanite	Melanon- ephelinite	Subalka- line basalt	Subalka- line basalt
Sample	Khi-14/1	Khi-14/2	Khi-7/5	Khi-7/1	Khi-1/1	Khi-1/7	Khi-3/20	Khi-3/21	Khi-12/6	Khi-15/3	Khi-18/2	Khi-3/11	Khi-3/16	Khi-12/2
SiO ₂	44.74	47.04	46.92	43.21	44.47	46.23	45.05	44.57	43.12	43.25	46.87	43.80	45.90	43.05
TiO ₂	2.76	2.65	2.59	2.95	2.77	2.96	3.36	2.60	3.68	3.31	2.61	2.60	2.61	3.17
Al ₂ O ₃	13.19	13.21	13.53	12.48	12.70	14.38	15.69	12.44	11.35	12.98	13.39	12.19	12.96	12.41
Fe ₂ O ₃	13.28	13.70	11.63	13.16	13.03	12.72	12.40	13.73	14.01	14.26	11.57	14.41	13.12	14.25
MnO	0.20	0.16	0.15	0.19	0.17	0.17	0.15	0.18	0.17	0.18	0.15	0.18	0.17	0.17
MgO	9.31	6.84	8.81	9.76	9.50	6.91	3.90	10.37	10.82	7.36	8.53	10.90	9.38	9.54
CaO	9.80	9.79	8.75	10.07	9.21	9.88	9.13	9.71	10.15	8.99	9.03	9.74	9.20	9.22
Na ₂ O	3.02	2.96	3.26	4.55	4.25	3.11	4.00	3.09	3.01	3.40	3.44	2.93	2.91	4.23
K ₂ O	1.54	1.35	1.63	1.29	1.61	1.68	2.37	1.62	1.51	2.12	1.85	1.77	1.59	1.32
P ₂ O ₅	0.71	0.54	0.66	1.18	0.90	0.59	1.57	0.73	0.77	1.07	0.66	0.79	0.67	0.89
L.O.I.	1.53	1.74	2.20	1.02	1.03	1.21	2.44	1.05	1.41	2.96	1.88	1.21	1.23	1.80
Total	100.08	99.98	100.13	99.86	99.64	99.84	100.06	100.09	100.00	99.88	99.98	100.52	99.74	100.05
Rb	28	23	27	15	20	22	43	34	22	35	26	29	24	18
Ba	537	486	490	452	510	430	763	500	580	780	568	510	330	610
Sr	904	723	800	1199	810	620	1358	820	720	1500	1032	1065	700	1040
Zr	241	203	210	390	250	210	345	250	240	390	238	236	230	280
Nb	52.0	32.8	80.3	83.4	60.0	50.0	93.6	—	—	—	81.1	39.7	65.0	74.0
Hf	4.2	3.5	8.5	9.7	—	9.3	5.5	—	—	—	5.8	4.1	—	—
Ta	2.32	1.26	3.03	3.04	—	3.27	4.46	—	—	—	6.13	2.28	—	—
Y	26	21	18	24	—	23	34	—	—	—	20	25	21	—
Th	4.93	3.28	3.37	6.14	—	4.52	7.99	—	—	—	4.70	4.88	—	—
U	1.34	1.00	1.28	2.27	—	1.69	2.41	—	—	—	1.40	1.42	—	—
Pb	3.66	2.83	2.30	0.81	—	3.04	5.61	2.80	3.10	6.00	3.88	3.64	5.20	2.80
La	42.0	28.8	32.3	95.1	—	44.8	73.7	35.2	40.9	—	44.5	45.7	30.0	45.5
Ce	91.9	64.5	68.1	128.6	—	92.6	164.5	70.0	76.7	—	95.2	100.4	100.0	89.7
Pr	10.9	7.9	8.6	15.9	—	11.1	18.1	—	—	—	10.9	11.7	—	—
Nd	44.3	33.2	37.1	64.7	—	47.3	77.0	38.5	39.6	—	47.2	47.8	50.0	48.6
Sm	8.8	7.0	8.0	12.2	—	9.8	14.8	9.8	9.6	—	8.7	9.5	—	12.4
Eu	2.87	2.30	2.37	3.49	—	2.93	4.68	2.75	2.79	—	2.66	3.06	—	3.60
Gd	8.94	7.27	6.50	9.96	—	8.52	14.47	8.50	9.10	—	7.59	9.66	—	11.60
Tb	1.12	0.95	0.94	1.38	—	1.21	1.81	1.10	1.20	—	1.00	1.23	—	1.50
Dy	5.82	5.09	4.93	6.60	—	6.60	8.68	—	—	—	4.92	6.07	—	—
Ho	1.07	0.95	0.66	0.82	—	0.80	1.55	—	—	—	0.83	1.10	—	—
Er	2.48	2.22	1.71	2.08	—	2.09	3.48	—	—	—	2.11	2.50	—	—
Tm	0.33	0.29	0.21	0.25	—	0.28	0.45	—	—	—	0.22	0.34	—	—
Yb	2.20	1.94	1.57	1.78	—	1.94	3.08	1.63	1.46	—	1.40	2.27	2.30	1.67
Lu	0.27	0.23	0.21	0.29	—	0.28	0.36	0.20	0.18	—	0.20	0.27	—	0.20

Table 2. (Contd.)

Stages	Eocene				Late Cretaceous		End of Early- beginning of Late Cretaceous	End of Early Cretaceous				Mid-Early Cretaceous	
	Subalka- line basalt	Subalka- line basalt	Melanon- ephelinite	Melanon- ephelinite	Subalka- line basalt	Subalka- line basalt		Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Tephropho- nolite
Rock	Subalka- line basalt	Subalka- line basalt	Melanon- ephelinite	Melanon- ephelinite	Subalka- line basalt	Subalka- line basalt	Tephrite	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Tephropho- nolite
Sample	Khi-12/5	Khi-12/7	Khi-14/4	Khi-14/6	Khi-12/4	Khi-15/2	Khi-13/2	Tg-1/11	Tg-1/12	Tszh-3/1	Tszh-4/7	Mg-5/1	Tg-13/30
SiO ₂	46.56	46.76	43.55	44.64	50.24	49.85	48.20	49.54	47.67	48.13	48.01	47.03	50.32
TiO ₂	2.61	2.64	3.72	3.79	2.60	2.60	1.99	2.05	1.91	2.00	2.07	2.23	2.46
Al ₂ O ₃	13.11	13.27	12.18	11.64	15.22	15.07	16.06	16.33	15.81	16.05	15.88	15.51	15.41
Fe ₂ O ₃	13.44	13.02	14.04	14.09	11.22	11.17	11.30	9.94	11.67	11.07	11.58	12.66	10.84
MnO	0.18	0.16	0.17	0.18	0.15	0.15	0.17	0.13	0.15	0.17	0.19	0.20	0.16
MgO	7.30	9.66	8.76	7.39	3.76	3.32	5.28	4.20	6.80	4.35	5.11	5.83	4.59
CaO	9.92	9.54	10.67	10.36	7.29	7.57	7.08	6.82	7.78	6.66	6.44	7.00	7.51
Na ₂ O	3.31	3.23	2.93	3.12	3.93	3.41	4.01	4.62	4.07	4.37	4.14	4.38	3.26
K ₂ O	0.82	1.45	2.19	1.25	2.05	1.70	2.62	3.04	1.75	2.97	2.75	2.22	1.42
P ₂ O ₅	0.59	0.52	0.91	0.75	1.56	1.57	1.41	1.55	1.00	1.92	1.79	1.64	1.24
L.O.I.	2.27	0.17	0.86	2.71	1.62	3.23	1.80	1.80	1.31	2.19	1.91	1.10	2.49
Total	100.11	100.42	99.98	99.92	99.64	99.64	99.92	100.02	99.92	99.88	99.87	99.80	99.69
Rb	13	24	51	26	32	24	61	61	28	52	51	33	18
Ba	469	450	780	750	1840	2157	1209	2084	800	2033	1347	1110	1432
Sr	699	690	1184	890	1226	1856	1275	2233	1300	1489	1202	1029	1135
Zr	168	190	316	210	495	422	353	326	223	415	438	364	417
Nb	35.2	—	102.7	—	39.8	30.4	29.7	24.5	14.0	38.4	27.6	30.0	25.1
Hf	3.1	—	5.9	—	9.6	6.5	5.5	4.8	—	7.8	6.6	—	8.3
Ta	1.69	—	6.57	—	1.89	1.15	1.26	0.90	—	1.86	0.90	—	1.34
Y	19	—	25	—	34	34	29	20	—	30	37	—	25
Th	3.52	—	5.48	—	3.08	3.63	3.13	3.47	—	3.55	3.12	—	4.50
U	0.97	—	1.67	—	1.14	1.43	0.86	1.07	—	1.08	0.88	—	1.17
Pb	2.68	1.20	4.29	4.50	18.79	18.44	15.45	19.86	9.80	20.17	18.82	19.00	15.45
La	29.3	—	55.2	—	84.8	86.2	66.4	94.6	—	95.4	85.6	57.3	67.2
Ce	66.6	—	118.9	—	195.2	212.1	153.8	221.5	—	214.2	218.4	131.0	159.2
Pr	8.1	—	13.3	—	22.9	25.2	18.9	23.6	—	23.6	24.2	16.7	18.7
Nd	32.8	—	53.0	—	93.9	99.3	73.7	87.7	—	93.0	93.2	67.9	78.9
Sm	6.8	—	9.5	—	16.6	16.6	12.5	13.3	—	14.5	16.1	12.3	13.2
Eu	2.15	—	3.00	—	4.05	4.06	3.02	3.39	—	3.68	3.49	2.80	3.38
Gd	6.66	—	8.47	—	12.78	14.24	11.04	11.37	—	10.79	13.55	9.40	9.78
Tb	0.86	—	1.09	—	1.61	1.56	1.33	1.20	—	1.31	1.58	1.28	1.22
Dy	4.72	—	5.41	—	7.11	7.78	6.54	4.95	—	5.90	8.19	6.61	5.51
Ho	0.88	—	0.92	—	1.15	1.40	1.26	0.87	—	1.02	1.59	1.22	0.89
Er	2.05	—	2.10	—	2.83	3.27	3.16	1.98	—	2.55	3.93	3.22	2.20
Tm	0.28	—	0.26	—	0.36	0.46	0.45	0.27	—	0.33	0.56	0.46	0.28
Yb	1.79	—	1.47	—	2.37	3.22	3.11	1.91	—	2.17	3.82	2.59	1.72
Lu	0.21	—	0.23	—	0.34	0.40	0.39	0.22	—	0.31	0.47	0.41	0.23

Table 2. (Contd.)

Stages	Mid-Early Cretaceous													
Rock	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyte	Alkaline syenite
Sample	Khi-16/4	Khi-16/7	Khi-17/3	Khi-17/9	Khi-2/3	Mg-1/3	Mg-1/8	Mg-1/12	Mg-2/3	Trachyba- salt	Trachyba- salt	Trachyba- salt	Trachyba- salt	Mg-3/5
SiO ₂	53.42	48.69	50.07	50.01	52.09	48.96	47.76	48.88	48.72	48.49	46.52	48.47	55.16	56.21
TiO ₂	1.69	2.12	2.06	1.91	2.47	2.62	2.23	2.37	2.21	2.42	2.34	2.15	1.32	1.03
Al ₂ O ₃	15.23	15.01	16.42	16.34	15.47	15.33	15.66	15.90	15.75	15.44	15.36	15.80	17.16	16.58
Fe ₂ O ₃	7.44	9.42	9.56	9.17	10.63	11.95	11.97	12.45	11.07	12.64	12.24	11.33	8.08	7.84
MnO	0.10	0.10	0.11	0.11	0.12	0.16	0.19	0.17	0.13	0.19	0.15	0.17	0.08	0.12
MgO	3.30	4.16	3.75	3.66	2.17	4.51	4.47	4.30	4.80	3.27	5.53	4.85	2.34	2.36
CaO	6.12	8.17	6.11	6.85	5.95	6.77	6.89	6.55	6.94	6.40	7.37	6.91	4.88	4.14
Na ₂ O	4.15	3.53	4.70	4.09	4.05	3.75	3.80	4.18	3.67	4.28	3.50	3.98	4.81	5.27
K ₂ O	4.71	4.06	3.24	3.29	4.26	2.08	2.41	2.61	2.38	2.63	2.47	2.71	3.36	4.35
P ₂ O ₅	1.82	1.95	1.39	1.26	1.65	1.44	1.80	1.95	1.47	1.84	1.78	1.63	0.80	0.83
L.O.I.	1.18	1.91	2.16	2.65	0.74	2.04	2.39	0.25	2.45	1.99	2.54	1.51	1.75	0.98
Total	99.16	99.12	99.57	99.34	99.60	99.61	99.57	99.61	99.59	99.59	99.80	99.51	99.75	99.71
Rb	100	62	43	41	78	30	40	45	31	38	28	49	91	156
Ba	3630	3526	2190	2092	1797	1220	1421	1384	1390	1460	1460	1734	1550	1869
Sr	2880	3605	2270	2094	1194	1190	987	1441	1640	1240	2040	1782	823	1073
Zr	340	311	370	653	380	350	457	468	290	430	310	317	386	566
Nb	9.0	31.5	27.7	20.0	26.1	27.0	41.4	24.0	21.0	29.0	21.0	27.2	21.4	27.5
Hf	—	7.5	10.8	9.7	6.0	—	8.8	6.6	—	—	—	4.7	7.6	10.7
Ta	—	1.37	1.18	0.94	1.04	—	2.10	0.80	—	—	—	1.00	1.70	2.20
Y	22	16	18	18	38	—	28	36	—	—	—	29	16	21
Th	—	3.62	3.30	3.41	3.60	—	2.00	2.96	—	—	—	3.86	4.32	7.24
U	—	1.19	1.27	1.57	0.78	—	0.60	0.85	—	—	—	1.14	1.18	2.08
Pb	34.00	21.17	21.00	27.00	21.17	11.00	20.45	19.84	10.00	—	19.00	19.26	20.50	29.68
La	175.0	109.1	156.7	163.9	83.5	—	86.4	88.3	—	—	—	94.3	65.1	95.8
Ce	295.0	225.3	220.5	222.2	207.0	—	212.2	229.4	—	—	—	215.4	138.8	195.4
Pr	—	23.7	23.1	24.3	24.5	—	25.2	26.0	—	—	—	25.2	15.2	19.7
Nd	160.0	87.1	92.1	97.0	96.8	—	103.3	101.1	—	—	—	93.8	59.2	71.2
Sm	—	11.6	13.4	14.3	16.3	—	16.3	16.3	—	—	—	14.7	8.5	9.6
Eu	—	3.14	3.35	3.44	4.09	—	4.20	3.74	—	—	—	3.50	2.38	2.18
Gd	—	8.16	10.17	10.38	14.84	—	11.91	14.54	—	—	—	12.39	6.44	7.59
Tb	—	1.00	1.09	1.12	1.64	—	1.44	1.58	—	—	—	1.33	0.87	0.97
Dy	—	3.69	4.91	4.76	7.85	—	6.30	7.75	—	—	—	6.47	3.63	4.23
Ho	—	0.62	0.59	0.58	1.45	—	1.08	1.44	—	—	—	1.22	0.58	0.74
Er	—	1.58	1.69	1.70	3.53	—	2.57	3.53	—	—	—	2.97	1.49	1.95
Tm	—	0.18	0.20	0.20	0.48	—	0.31	0.49	—	—	—	0.41	0.20	0.27
Yb	1.20	1.07	1.60	1.56	3.40	—	2.08	3.45	—	—	—	2.86	1.27	1.77
Lu	—	0.15	0.24	0.22	0.45	—	0.29	0.45	—	—	—	0.35	0.19	0.28

Table 2. (Contd.)

Stages	Beginning of Early Cretaceous						Late Jurassic–Early Cretaceous						
Rock	Subalka- line basalt	Subalka- line basalt	Subalka- line basalt	Subalka- line basalt	Subalka- line basalt	Subalka- line basalt	Pantellerite	Trachy- andesite	Pantellerite	Pantellerite	Pantellerite	Trachyte	Rhyolite
Sample	Khi-1/4	Khi-8/3	Mg-4/7	Khi-3/3	Khi-3/12	Khi-4/3	Tg-13/1	Tg-13/2	Tg-13/3	Tg-13/4	Tg-7/10	Tg-13/20	Tg-22/14
SiO ₂	50.94	52.03	47.87	49.35	48.46	46.79	71.78	57.52	69.29	71.61	74.11	66.74	69.72
TiO ₂	1.93	1.80	2.60	2.66	3.08	2.35	0.31	1.11	0.47	0.33	0.38	0.65	0.46
Al ₂ O ₃	16.22	17.20	15.33	15.50	15.41	15.83	13.45	17.73	14.38	13.62	11.70	16.00	14.87
Fe ₂ O ₃	10.20	8.54	12.66	11.16	11.63	11.78	3.08	6.96	3.34	3.15	2.76	3.29	2.53
MnO	0.13	0.10	0.16	0.15	0.12	0.15	0.20	0.07	0.17	0.15	0.03	0.16	0.08
MgO	2.91	3.43	4.52	3.97	3.84	6.44	0.19	1.49	0.24	0.19	0.18	0.40	0.05
CaO	6.02	4.93	6.59	6.64	7.00	7.78	0.10	2.88	0.17	0.12	0.62	0.44	0.45
Na ₂ O	4.86	4.75	3.98	3.84	3.49	3.57	5.69	6.03	6.08	5.54	0.86	6.01	4.78
K ₂ O	3.01	3.51	2.30	2.54	2.13	1.80	4.82	3.98	5.43	4.78	8.01	5.56	6.37
P ₂ O ₅	1.61	1.29	1.88	1.52	1.65	1.51	0.03	0.74	0.05	0.04	0.06	0.11	0.06
L.O.I.	2.06	1.99	1.69	2.26	2.76	1.59	0.26	1.19	0.26	0.21	1.15	0.52	0.53
Total	99.89	99.49	99.58	99.59	99.57	99.59	99.91	99.70	99.88	99.74	99.86	99.88	99.90
Rb	44	60	40	40	22	17	308	92	248	252	173	217	209
Ba	1400	1840	1337	1190	1375	1408	30	–	29	–	164	220	109
Sr	1600	1470	1434	940	2003	1722	17	–	17	–	–	92	54
Zr	–	380	409	361	293	373	1312	329	1159	–	433	908	396
Nb	–	–	22.7	29.3	11.6	24.1	94.4	11.0	82.8	–	19.3	46.7	37.1
Hf	–	–	5.8	6.9	7.7	9.1	32.5	–	31.4	–	7.4	16.5	8.8
Ta	–	–	0.74	1.43	1.12	1.16	1.18	1.52	1.12	1.16	1.14	1.08	0.75
Y	–	–	28	17	18	20	85	–	90	–	27	39	30
Th	–	–	3.24	2.29	3.91	2.17	26.35	–	31.43	–	11.89	17.95	13.57
U	–	–	0.87	0.53	1.48	0.94	6.96	–	7.52	–	3.62	5.04	3.13
Pb	23.00	11.00	17.65	18.17	11.79	14.53	45.50	–	38.50	–	39.56	24.39	16.56
La	–	–	86.8	82.9	63.8	112.1	68.8	–	112.5	–	71.1	95.9	91.8
Ce	–	–	229.3	178.7	102.1	167.4	131.8	–	251.5	–	147.6	267.3	217.2
Pr	–	–	24.8	20.0	12.8	19.8	19.9	–	36.8	–	17.1	28.4	24.1
Nd	–	–	96.3	78.2	56.8	81.9	71.2	–	137.7	–	65.0	108.2	93.4
Sm	–	–	15.6	11.4	10.3	12.9	15.5	–	32.2	–	10.2	18.2	14.3
Eu	–	–	3.69	3.12	2.90	3.28	1.43	–	2.81	–	1.61	2.11	1.91
Gd	–	–	13.38	8.21	8.13	9.44	12.83	–	23.68	–	9.54	14.61	11.96
Tb	–	–	1.37	0.98	1.03	1.10	2.43	–	4.22	–	1.12	1.99	1.55
Dy	–	–	6.48	3.72	5.06	5.37	12.83	–	20.96	–	5.66	9.05	7.30
Ho	–	–	1.17	0.63	0.63	0.65	2.85	–	3.53	–	1.03	1.54	1.18
Er	–	–	2.73	1.70	1.84	1.87	7.26	–	8.87	–	2.61	3.84	3.20
Tm	–	–	0.37	0.18	0.25	0.23	1.12	–	1.21	–	0.39	0.49	0.41
Yb	–	–	2.62	1.14	1.81	1.64	6.58	–	6.24	–	2.65	3.38	2.62
Lu	–	–	0.30	0.15	0.28	0.26	1.05	–	1.00	–	0.33	0.47	0.39

Table 2. (Contd.)

Stages		Late Jurassic							
Rock	Quartz trachyte	Trachybasalt	Trachyandesite-basalt	Trachyandesite-basalt	Trachybasalt	Trachybasalt	Trachybasalt	Trachybasalt	Trachyrhyolite
Sample	Tg-2/3	Tg-14/1	Tg-21/4	Tg-21/10	Tg-5/1	Tg-20/8	Tg-20/9	Tg-22/1	
SiO ₂	63.19	54.17	55.36	56.15	49.82	48.16	48.61	70.06	
TiO ₂	0.85	0.90	1.13	1.15	2.18	1.73	2.21	0.52	
Al ₂ O ₃	18.15	18.47	18.98	17.38	16.04	17.30	17.04	15.35	
Fe ₂ O ₃	3.71	8.51	7.08	7.26	9.96	10.59	10.38	1.70	
MnO	0.09	0.13	0.08	0.13	0.17	0.16	0.13	0.02	
MgO	0.55	2.98	1.78	1.85	3.83	6.58	4.07	0.47	
CaO	0.85	7.28	4.55	4.50	6.97	8.18	6.59	0.24	
Na ₂ O	5.61	3.54	5.38	5.98	3.99	3.89	4.43	4.64	
K ₂ O	6.71	1.47	4.16	3.71	2.95	1.44	2.58	6.13	
P ₂ O ₅	0.27	0.28	0.80	0.74	1.55	0.47	1.30	0.06	
L.O.I.	0.09	2.07	0.65	0.96	2.17	1.17	2.24	0.72	
Total	100.07	99.80	99.94	99.80	99.43	99.67	99.58	99.90	
Rb	271	33	96	112	56	22	47	203	
Ba	113	908	1790	1680	1994	654	1896	157	
Sr	42	1781	1250	1301	1920	1339	2473	66	
Zr	1071	127	307	351	332	189	311	739	
Nb	65.9	5.7	11.0	18.7	23.2	8.5	17.2	36.5	
Hf	17.8	2.5	6.3	6.2	5.0	3.9	4.6	14.2	
Ta	2.86	0.30	0.97	1.04	0.91	0.64	0.74	2.46	
Y	65	15	13	12	22	25	21	45	
Th	32.80	4.16	3.43	5.16	3.15	1.11	2.70	15.50	
U	5.29	1.12	1.16	1.44	0.84	0.34	0.74	4.37	
Pb	41.14	9.31	22.42	24.99	19.92	6.21	13.93	34.98	
La	156.7	22.1	72.1	66.9	92.8	21.7	69.6	101.5	
Ce	426.0	51.7	154.2	130.7	217.3	53.3	141.8	246.9	
Pr	51.5	6.3	16.0	14.1	22.9	6.4	16.7	24.8	
Nd	188.5	25.5	59.6	48.9	85.2	29.4	69.7	87.3	
Sm	31.3	5.0	8.1	7.1	13.0	6.1	10.9	13.5	
Eu	2.83	1.40	2.31	1.89	3.42	1.88	2.93	1.58	
Gd	28.75	4.58	5.71	4.95	11.28	5.82	9.92	11.18	
Tb	4.30	0.59	0.70	0.62	1.10	0.83	1.02	1.65	
Dy	15.88	3.27	2.81	2.46	4.89	4.36	4.64	8.93	
Ho	2.93	0.64	0.49	0.41	0.86	0.90	0.83	1.74	
Er	7.25	1.66	1.11	0.99	1.96	2.30	1.94	4.94	
Tm	1.07	0.25	0.15	0.12	0.26	0.31	0.26	0.71	
Yb	7.60	1.66	0.79	0.91	1.84	2.23	1.86	4.99	
Lu	1.10	0.23	0.10	0.11	0.24	0.33	0.23	0.75	

Note: Dash designates absence of data; Fe₂O₃ represents the iron total.

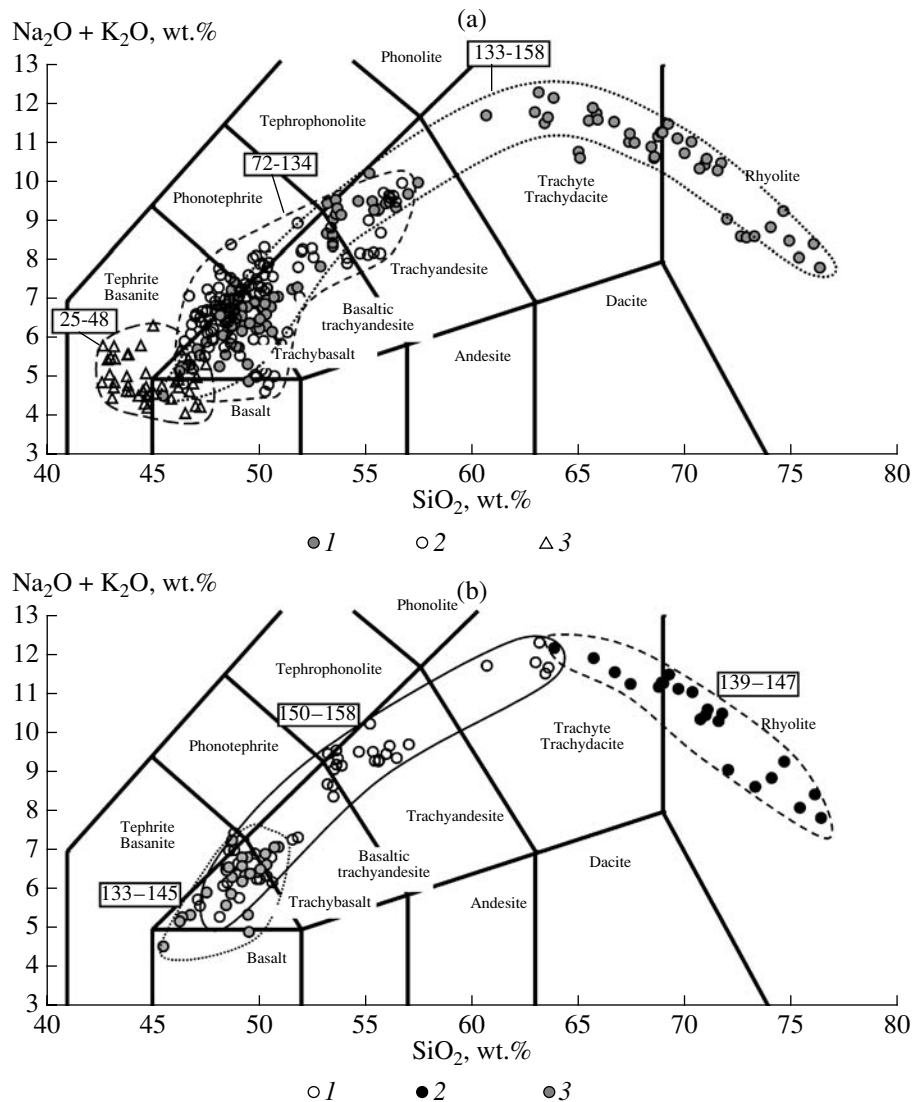


Fig. 4. The SiO_2 vs. $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ diagram (after [34]) for volcanic rocks of the Tugnui-Khilok sector of the western Transbaikalia rift area. Legend for Fig. 4a: (1–3) magmatic stages: (1) 133–158 Ma, (2) 72–134 Ma, (3) 25–48 Ma. Legend for Figs. 4b–4d: (1–10) magmatic stages: (1) Late Jurassic, (2) Late Jurassic–Early Cretaceous, (3) beginning of Early Cretaceous, (4) Early Cretaceous, (5) end of Early Cretaceous, (6) end of Early–beginning of Late Cretaceous, (7) Late Cretaceous, (8) Eocene, (9) Early Oligocene, (10) Late Oligocene.

line are the Cenozoic basalts (43–57 wt % of SiO_2 and a total alkalinity of 4.5–6.5 wt %).

On the diagram of major and trace element distribution relative to SiO_2 (Figs. 5a, 5b), rocks of the Late Jurassic–Early Cretaceous and Cenozoic associations generally follow the overall succession of composition variation. With the increase of SiO_2 content, a clear decrease in the concentrations of MgO , CaO , TiO_2 and an increase of the incompatible elements Zr, Rb, and La are obvious. The concentrations of Al_2O_3 , Ba, and Sr slightly increase with transition from basalts to trachyandesite-basalts and subsequently decrease in trachyrhyolites and comendites. Such a type of dependence between these groups of elements corresponds to their distribution in rock-forming minerals and residual

melts with successive crystallization of olivines, plagioclases, alkaline amphiboles, and K-Na feldspars. Therefore, it attests to a possible relationship of the whole range of compositions to the fractional crystallization of basaltic magma. The diagram also displays the compositions of the lower and upper continental crust, and of the crust as a whole, estimated for the part of Central Asia occupied by China [38]. We assumed these data as a standard of the continental crustal substratum to use in magma generation models. Most probably, crustal contamination was of secondary importance in magmatic processes, which can be inferred from different positions of figurative points for igneous rocks and crust on the diagrams. Compared to the Jurassic and Cretaceous basic rocks, the Cenozoic

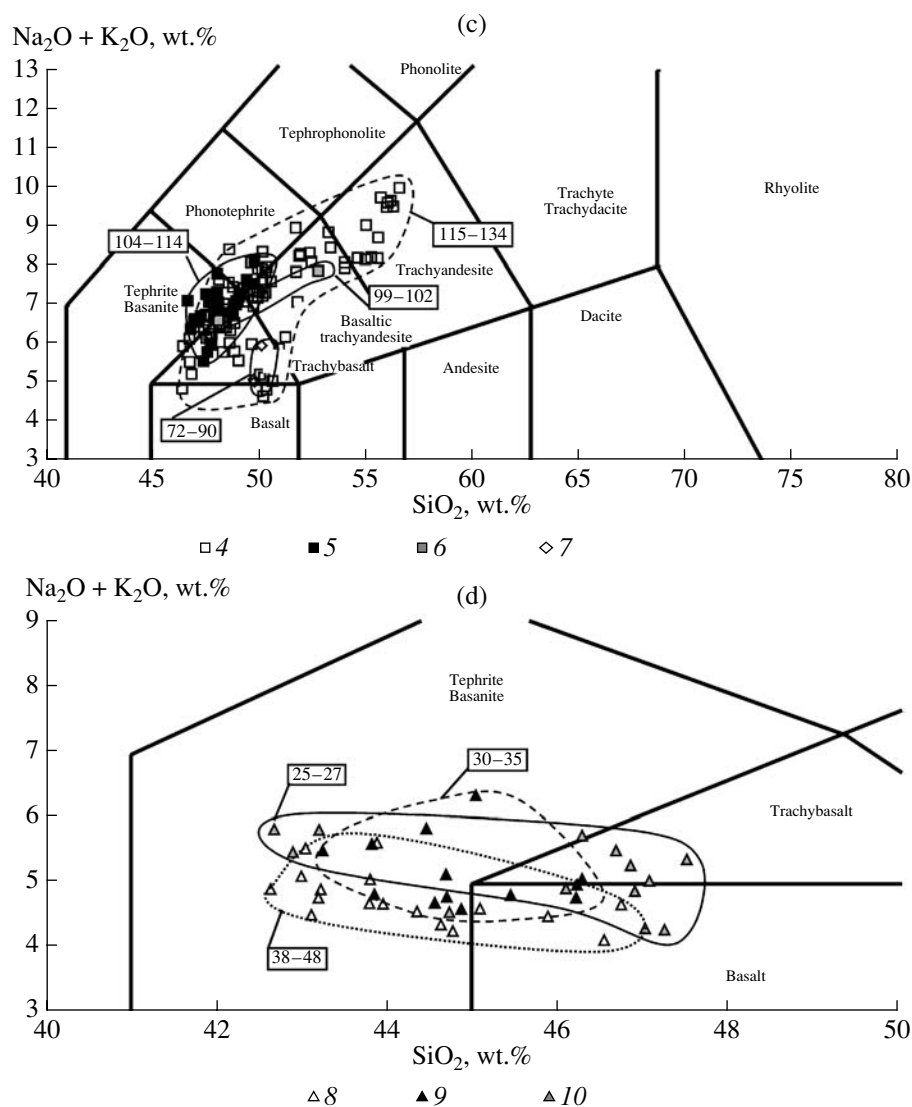


Fig. 4. (Contd.)

basaltoids are rich in MgO , CaO , TiO_2 , and Nb and depleted in Al_2O_3 , P_2O_5 , Ba , Sr , and La . Due to this, in corresponding coordinates the composition fields for the Late Jurassic–Cretaceous and Cenozoic rocks are clearly separated, possibly attesting to differences in their sources. In general, all these rocks show higher concentrations of incompatible elements and in this aspect are close to OIB basalts. This similarity is reflected on the spidergrams of element distributions in the compositions of rocks belonging to different magmatic stages (Fig. 6). We also note that the rock composition depends on rock age. Thus, compared to the OIB and Cenozoic basalts, the Late Jurassic and Early Cretaceous basalts are rich in Rb , K , Ba , Sr , P , Pb , Zr , Hf , and LREE , but also depleted in Nb and Ta . The Nb – Ta minimum, best seen in the Late Jurassic basaltoids of the Ichetui Formation, successively smooths out through geological time up to the Late Cretaceous stage

inclusive, suggesting a gradual change of geochemical characteristics of the melt sources in the interval from 158 to 72 Ma. The composition of the Cenozoic basalts is practically that of OIB basalts, differing from the Late Jurassic and Cretaceous rocks by higher contents of Th , U , Nb , and Ta and a sharp Pb -minimum.

The ratio of incompatible elements, for example, Zr – Rb , (Fig. 7) demonstrates a positive linear dependence and corresponds to their behavior in a differentiated magmatic system. We tried to estimate the composition of magma sources and the influence of crustal contamination on the formation of melts with different SiO_2 content based on ratios of incompatible elements in multicomponent systems, taking into account that these ratios remain constant during fractionation. The Ti/Y – Rb/Ba , Ce/Pb – Nb/U , Th/Ta – La/Yb , and Th/Yb – Ta/Yb diagrams (Fig. 7) usually have the figurative points of basic and salic rocks separated. In general, the

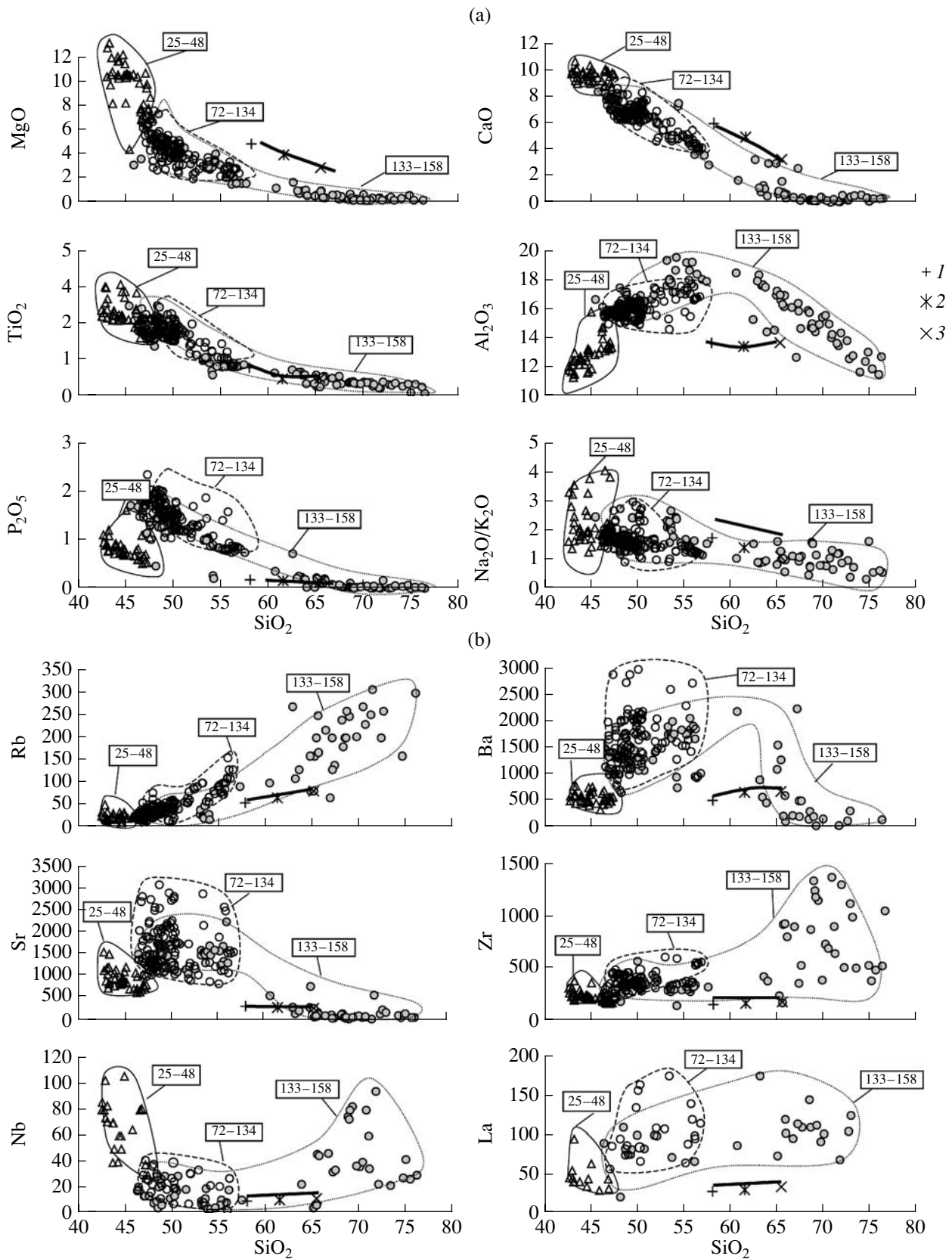


Fig. 5. Variations in major (wt %) and trace (g/t) elements in relation to SiO_2 content in volcanic rocks of the Tugnui-Khilok sector of the western Transbaikalia rift area. (1–3) Average crustal composition of central Asia after [38]. Solid line shows the crustal trend. For symbols, see Fig. 4a.

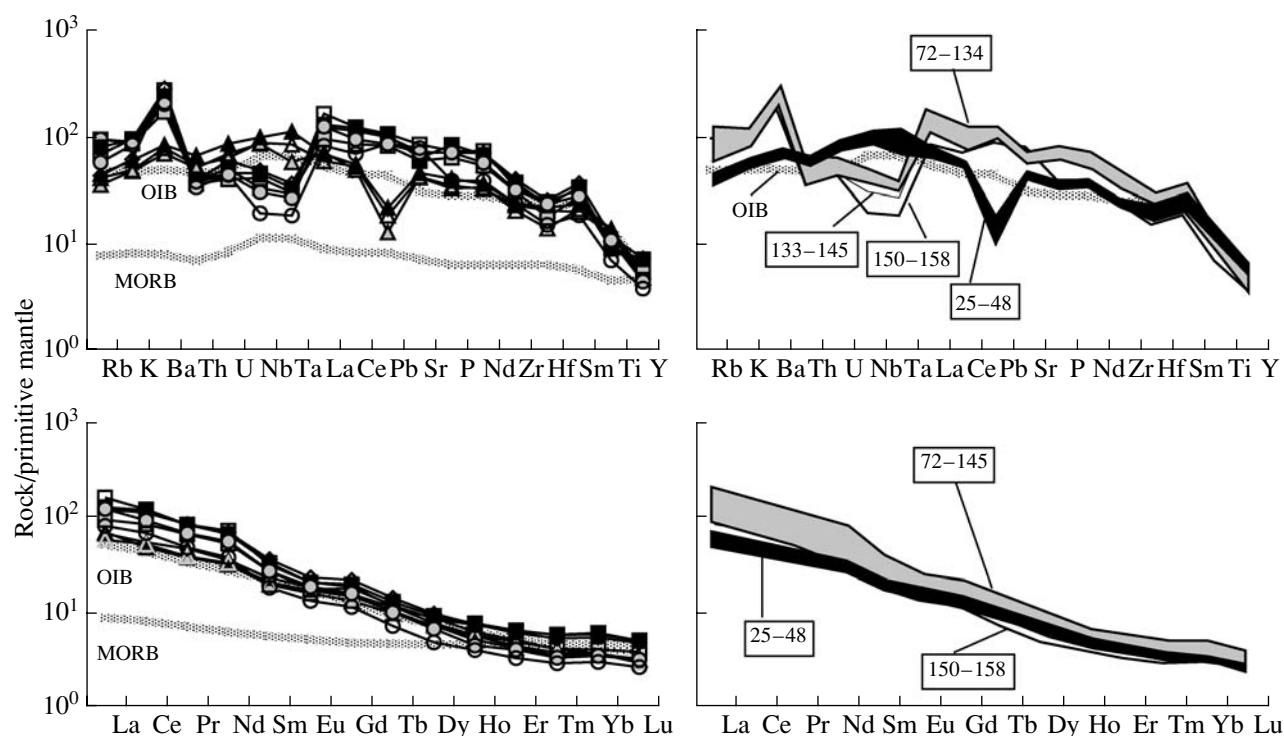


Fig. 6. Plots of the normalized distribution of rare and trace elements in basalts of different stages for the Tugnui–Khilok sector of the western Transbaikalia rift area. Normalization of primitive mantle after [39]. For symbols, see Figs. 4b–4d.

basalt compositions are consistent with the compositions of rocks derived from enriched mantle sources of the OIB, EM-I, and EM-II types. They are also fairly consistent with basalts of the East-African Rift System (Fig. 7, Nb/U–Ce/Pb) and significantly differ from basalts of subduction zones, oceanic plateaus, and mid-oceanic ridges. At the same time, salic rock compositions are displaced toward the average crustal compositions observed in Central Asia. Thus, on the Th/Yb–Ta/Yb diagram, the compositions of acid volcanics associated with basalts of acid volcanics have higher Th/Yb ratios and occur somewhat above the boundary of the trend that reflects variations in the mantle series between N-MORB and intraplate basalts [35]. Since the continental crust is enriched in Th relative to Ta and Yb (a high value of Th/Yb [35]), we suppose that the relative enrichment in Th as determined here may result from a certain effect of crustal contamination on the magma composition.

The isotope composition of Sr and Nd in basalts and the factors that cause variations in igneous rock composition. The origin of rock associations in the Tugnui–Khilok sector is related to the formation and evolution of the mantle sources of the parent melts. This is supported by the fact that among igneous rocks, mantle-derived varieties (subalkaline and alkaline basalts) typical of intraplate magmatic associations dominate. In order to determine the types of mantle sources in different-age basalts, we examined the isotope composition of Sr and Nd (Table 3). The results

show that the ratios $(^{87}\text{Sr}/^{86}\text{Sr})_0$ vary from 0.703733 to 0.705809 and the values $\epsilon\text{Nd}(T)$ from 4.4 to 5.1, though correlation ties between values of isotope ratios remain. On the diagram $(^{87}\text{Sr}/^{86}\text{Sr})_0$ – $\epsilon\text{Nd}(T)$ (Fig. 8), the figurative points are located between the composition fields of mantle sources that are enriched in neodymium and radiogenic strontium, such as EM-II, and the moderately depleted PREMA types. It should be noted that the isotope composition of Sr and Nd for rocks of the associations depends on the time of their origin. For example, the composition fields of the Late Mesozoic and Cenozoic rocks are clearly separated, shifting (with younger age) from the quadrant of sources rich in radiogenic strontium and neodymium to that of moderately depleted sources. In the $(^{87}\text{Sr}/^{86}\text{Sr})_0$ –Sm/Nd coordinates, the Cenozoic basalt compositions are displaced (compared to the Late Mesozoic ones) toward higher Sm/Nd ratios, i.e., silicate melts in magma sources are depleted, as time goes on, in neodymium relative to samarium. Partial melting results in a liquid phase, compared to the solid one, enriched in Nd relative to Sm, which depends on the differences of geochemical properties between these two elements. With the partial removal of the liquid phase from the system and partial melting of the solid residual, subsequent melts will be increasingly depleted in Nd relative to Sm, such that the Sm/Nd ratio will increase in them. This might explain the variation of rock compositions through time. However, isotope data demonstrate significant discrepancies in isotope sources of different-age parent melts. For

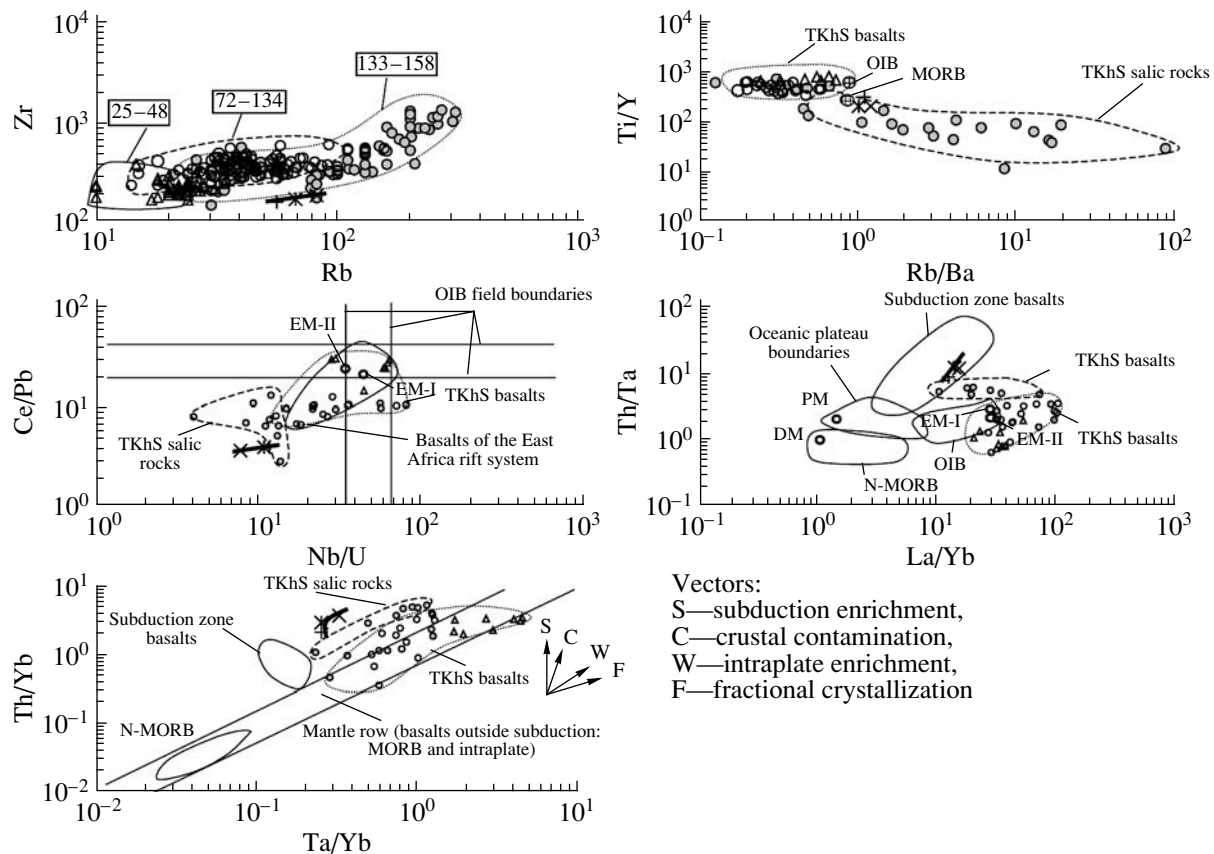


Fig. 7. Distribution of rock compositions for the Tugnui-Khilok sector (TKhS) of the western Transbaikalia rift area plotted in coordinates of incompatible elements and their paired ratios in relation to the average compositions of crust and products of sublithospheric magma generation. Basalt composition fields: East Africa rift system, oceanic plateaus, subduction zones, mid-oceanic ridges (MORB, N-MORB), oceanic islands (OIB). Rock compositions of typical mantle sources: DM depleted mantle, PM primitive mantle, EM-I mantle enriched in neodymium, EM-II mantle enriched in radiogenic Sr. Data are from [29, 30, 32, 37, 40, 41]. For symbols, see Fig. 4a.

example, in the Late Mesozoic stages the composition of basalt sources was largely controlled by an enriched EM-II mantle, while for the Cenozoic basalts moderately depleted PREMA sources are typical.

The changes of sources through time are also evidenced by the fact that the Ta-Nb minimum that was distinct in the Late Jurassic-Early Cretaceous basalts gradually disappeared with time and the Cenozoic rocks have high concentrations of these elements (a Ta-Nb maximum). Low concentrations of Nb and Ta, as well as high concentrations of Pb and Ba, are typical of melts enriched in water that form island-arc series and originate in subduction conditions [31, 33, 36]. The influence of fluid water favors the accumulation of rutile in restite, concentrating Ti, as well as Nb and Ta, thus depleting the melt and the corresponding igneous products of these elements. Therefore, we believe that the Late Mesozoic igneous associations of the Tugnui-Khilok sector, as well as of the entire western Transbaikalia area, and other manifestations of intraplate magmatism in North Asia during Late Paleozoic-Mesozoic time [27], originated from an enriched

hydrated mantle source which formed with the participation of an EM-II mantle. In the course of development of the Late Mesozoic riftogenic magmatism, this source was gradually exhausted, and since the Late Cretaceous, a moderately depleted PREMA mantle was involved in melting. Both geochemical data (time-dependent composition of magmatic melts toward increasing Nb and Ta and decreasing Rb, K, Ba, Sr, P, Pb, Zr, Hf, and TR concentrations) and isotope evidence support the hypothesis. The composition of the Cenozoic basalts is the closest to the PREMA mantle.

CONCLUSIONS

(1) An important feature in the evolution of the central (Tugnui-Khilok) sector of the western Transbaikalia rift area was the continued (for more than 100 Myr) development of the Late Mesozoic-Cenozoic magmatism (as periodically repeated bursts of volcanism) in the same structural conditions. These bursts occurred successively in the Late Jurassic (150–158 Ma), Late Jurassic-beginning of Early Cretaceous (139–147 Ma), the beginning of the Early Cretaceous (133–145 Ma),

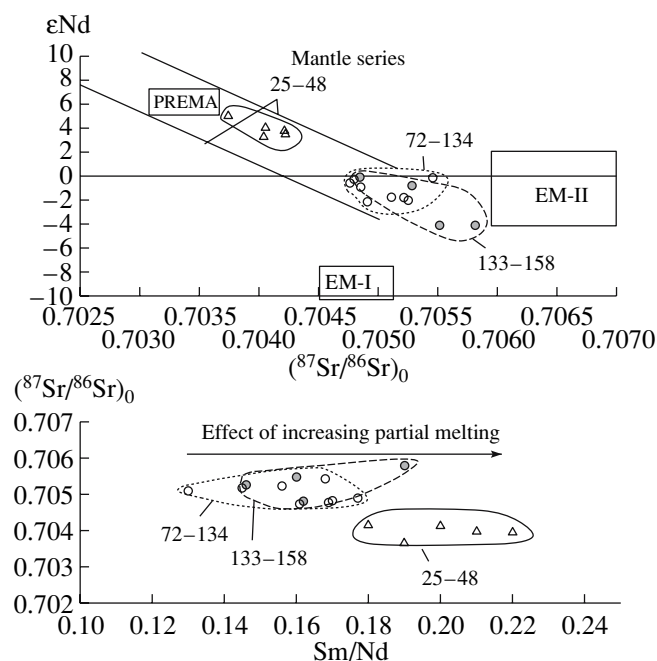


Fig. 8. Isotope composition of volcanic rocks in the Tugnui–Khilok sector of the western Transbaikalia rift area on a $(^{87}Sr/^{86}Sr)_0$ – ϵ_{Nd} diagram and in the coordinates Sm/Nd – $(^{87}Sr/^{86}Sr)_0$ as an indicator of the combined effect of mixing two types of mantle sources and different degrees of partial melting. For symbols, see Fig. 4a.

mid-Early Cretaceous (115–134 Ma), the end of the Early Cretaceous (104–114 Ma the end of the Early–beginning of the Late Cretaceous (99–102 Ma), Late Cretaceous (72–90 Ma), Eocene (38–48 Ma), Early Oligocene (30–35 Ma), and Late Oligocene (25–27 Ma). These impulses of igneous activity resulted in different rock association types. Basaltic and bimodal basalt–trachyte–trachydacite associations dominate, the general feature of these being high alkalinity and high concentrations of rare lithophile elements, which is typical of intraplate magmatism [19].

(2) The geological history of the sector involves the successive evolution of magmatism resulting primarily from a gradual decrease in magmatic productivity from the earlier stages to later ones, and also from the decreasing amounts of salic rocks in the associations until their complete disappearance, with this phenomenon being observed since as early as the second half of the Early Cretaceous. Basic volcanic rocks undoubtedly dominate the associations of all ages, but the most diverse rock composition is typical of the associations in the Late Jurassic and the end of the Jurassic–beginning of the Early Cretaceous. They usually contain intermediate (trachytes) and acid (trachydacites, trachyrhyolites and pantellerites) volcanic rocks, which either form separate sheet packages or irregularly intercalate with basic volcanic rocks. The mid-Early Cretaceous associations are less variegated in composition. In addition to basic subalkaline and alkaline rocks, they

comprise intermediate–basic alkaline volcanic rocks (phonolites, phonotephrites, and nepheline syenites). Since the second half of the Early Cretaceous, the magmatism has appeared to be more homogeneous, and exclusively basic rock associations of high alkalinity were formed since that time.

Another aspect of the evolution of magmatism is registered in the successive reduction of lithophylic elements in rocks through time. This cannot be explained by fractionation of mineral phases from the parent melts or by decreasing partial melting in the magma source without considering a mechanism that could be made responsible for changes in source composition with time. The isotope-geochemical data support such changes. Based on an isotope classification of mantle sources, we determined that in the Late Jurassic–mid-Early Cretaceous the melting substratum was enriched in radiogenic strontium and its characteristics were those of the EM-II mantle. In the Cenozoic, the concentration of radiogenic strontium in the sources decreased and that of neodymium increased, which corresponds to the parameters of moderately depleted PREMA mantle.

Salic rocks in riftogenic igneous associations are characterized by vivid geological relations to basic magmatism. The same relations are expressed in regular trends in the variation of incompatible element concentrations in the basic–intermediate–acid series, therefore suggesting the leading role of fractionation in the formation of these rocks (Fig. 5). For salic rocks, however, features of their variations closer to the crustal composition are also characteristic (Fig. 7). In general, the observed geochemical properties of salic rocks indicate that they formed during fractionation of basaltic magmas involving contamination, most probably in intermediate magma chambers.

It should be noted also that the composition of the igneous associations of the Tugnui–Khilok sector and the direction of their evolution agree well with the evolution of magmatism in the other sectors of the western Transbaikalia rift area. This is primarily expressed in the synchronous manifestation of associations of the same kind and in the similarity of geochemical and isotope rock characteristics [14, 27].

(3) The evolution of magmatism in the area was undoubtedly related to rifting. These processes commenced in the Late Jurassic, when the Tugnui graben formed, and were accompanied by Late Jurassic bimodal eruptions and Late Jurassic–beginning of Early Cretaceous trachydacite–pantellerite eruptions of lavas confined to this graben. In the beginning of the Early Cretaceous, the Margentui–Khilok system of grabens formed to the south and southwest of the Tugnui graben, with these processes generally going on in parallel. From the very beginning, grabens of this system were bounded by large-amplitude faults, leading to formation of deep-water lakes in the resulting troughs. This is shown by considerable thicknesses of hyaloclastites

Table 3. Isotopic composition of strontium and neodymium in igneous rock associations of different ages in the Tugnui–Khilok sector

Sample no.	Rock	Age	Rb (g/t)	Sr (g/t)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_0$	Sm (g/t)	Nd (g/t)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\epsilon_{\text{Nd}}(T)$
Late Oligocene stage												
Khi-14/2	Subalkaline basalt	25	20.7	704	0.0851	0.704235	0.704044	6.3	28.7	0.13291	0.512842	4.2
Khi-7/5	Subalkaline basalt	26.1	37.1	877	0.1224	0.704306	0.704031	7.02	32.80	0.12941	0.512800	3.4
Early Oligocene stage												
Khi-18/2	Basanite	33	29	834	0.1007	0.704440	0.704214	7.13	33.4	0.12908	0.512809	3.6
Khi-3/20	Tephrite	31.9	39.8	1284	0.0898	0.703935	0.703733	14.4	74.5	0.11702	0.512885	5.1
Eocene stage												
Khi-3/11	Melanephelinite	48	25.7	982	0.0757	0.704375	0.704205	8.75	43.4	0.12182	0.512815	3.9
Late Cretaceous stage												
Khi-12/4	Subalkaline basalt	90	25.3	1456	0.0503	0.705019	0.704906	15.4	89.4	0.10382	0.512475	-2.1
End of Early–beginning of Late Cretaceous stage												
Khi-13/2	Tephrite	99	60.89	1275.17	0.1312	0.705090	0.705072	12.45	73.68	0.10171	0.512565	-0.2
End of Early Cretaceous stage												
Tszh-4/7	Trachybasalt	114	46.9	1064	0.1275	0.705136	0.704850	14.3	83.94	0.10298	0.512523	-0.9
Mid-Early Cretaceous stage												
Khi-16/7	Trachybasalt	115.3	60.9	3465	0.0508	0.705221	0.705107	15.9	110.6	0.08665	0.512467	-1.7
Khi-17/3	Trachybasalt	123.4	58.6	2172	0.0780	0.705383	0.705208	12.4	82.4	0.09115	0.512463	-1.8
Khi-2/3	Trachybasalt	130	47.7	1145	0.1205	0.705719	0.705448	15.1	88.4	0.10329	0.512552	-0.1
Mg-1/12	Trachybasalt	122.3	40.3	1314	0.0899	0.704959	0.704757	16.34	97.69	0.10112	0.512533	-0.6
Mg-4/4	Trachybasalt	120	44.3	1733	0.0739	0.705411	0.705245	14	88.7	0.09521	0.512457	-2.0
Beginning of Early Cretaceous stage												
Mg-4/7	Subalkaline basalt	135	37.6	1382	0.0788	0.705014	0.704837	14.8	89.4	0.0997	0.512549	-0.1
Khi-3/3	Subalkaline basalt	133	46.5	1103	0.1219	0.705553	0.705279	15	85.2	0.10661	0.512522	-0.7
Late Jurassic stage												
Tg-14/1	Trachybasalt	154.5	33.19	1780.73	0.0512	0.705820	0.705809	4.97	25.5	0.11731	0.512350	-4.1
Tg-20/8	Trachybasalt	155	22.1	1338.7	0.045373	0.705520	0.705510	6.08	29.39	0.124519	0.512357	-4.1

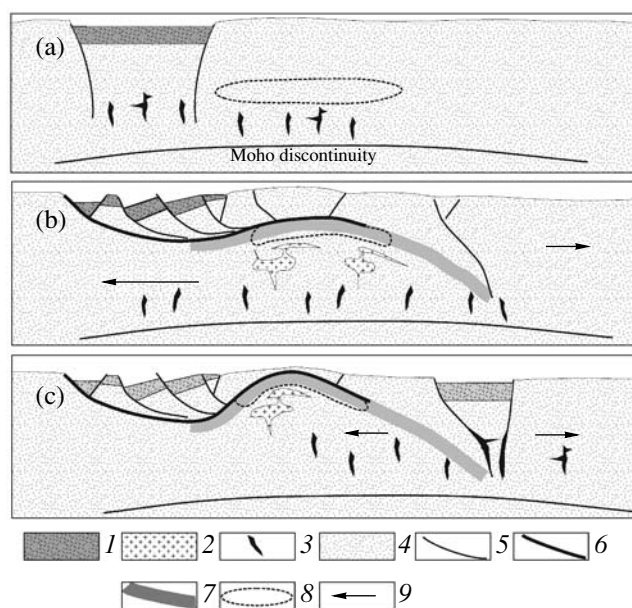


Fig. 9. Evolution model for the Tugnuï–Khilok sector of the rift area (developed with model [22] taken into account). (1) Graben volcanic complexes; (2) magma chambers and chambers of acid magma; (3) channels of rising mantle magma; (4) lithosphere; (5) faults; (6) detachment zone surface; (7) zone of milonites and high-temperature dynamic metamorphic rocks; (8) conventional area of plastic yielding and dynamic metamorphic rocks exposed to the present-day surface; (9) directions of extension

(up to 500 m) which compose the lower horizons of the Khilok Formation. Graben generation was accompanied by the development of Cordilleran type cores along their circumference (as in the Zaganskii Range) that were metamorphosed 150–120 Ma [22]. Based on this evidence, it was concluded that the earlier stages (Late Jurassic, and the beginning and middle of the Early Cretaceous) are similar to the rifting regime characteristic for the Basin and Range Province in North America. According to E.V. Sklyarov [22], this regime was related to large-amplitude stretching above a mantle plume accompanied by generation of deep-seated, low-angle detachment zones. These authors also believe that the final stage of these movements was recorded in the eruption of the Khilok Formation basalts.

The materials in this paper may improve the understanding of this matter. The model here proposed is based on the following facts. A number of large distinct grabens (Ichetui, Khambin, and Tugnuï) filled with volcanic rocks of the Ichetui Formation originated in the western Transbaikalia in the Late Jurassic. Absence of similar igneous products outside these grabens indicates that the magma-supplying channels were directly under the grabens. That contradicts their relation to the low-angle faults assumed in the model of [22]. Expansion of the graben-formation zone to the south in the beginning of the Early Cretaceous was accompanied by

exposition of the metamorphic cores of the Zaganskii Range, the shifting of magmatism centers into the Khilok and Margentui grabens, and the termination of igneous activity in the Tugnuï graben. The later development stages were probably consistent with a regime of ordinary rift zones characterized by normal faulting and steep-dipping volcanic conduits. That is why the structural control of volcanic activity in the Late Cretaceous–Cenozoic history of the area remained constant, with periodic resumption of volcanism taking place exclusively in the Khilok graben.

Based on all these data, we suggest the following model of the rift area development. The series of events began with the appearance of a mantle plume at the base of the region. Extension processes resulted in the formation of distinct grabens, including the Tugnuï graben, where the bimodal volcanic series of the Ichetui Formation accumulated (Fig. 9a). Under the influence of an intense heat flow and possible injections of deep-seated magma in the crustal portions contiguous to the graben, the processes of anatexis and metamorphism took place, creating a volume of higher plasticity. In the extension environment, these fragments of a plastic crust favored the development of a low-angle detachment zone of southeast vergence (Fig. 9b) recorded in milonite zones [22]. The fault surface restricted the supply of mantle melts into the Tugnuï graben and, in its turn, was upwarped by the heated rising crust of the Zaganskii Range. The Khilok graben originated above the steep branch of the fault (Fig. 9c) descending toward the source of the extension, i.e., the plume. This provided conditions for creation of stable volcanic conduits that have persisted throughout subsequent geological history.

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REFERENCES

1. Afonin, V.P., Gunicheva, T.N., and Piskunova, L.F., *Rentgeno-fluorescentnyi analiz* (X-Ray Fluorescent Analysis), Novosibirsk: Nauka, 1984.
2. Bagdasar'yan, G.P., Polyakov, A.I., and Roshchina, I.A., The Age and Chemistry of the Mesozoic–Cenozoic Basaltoids of the Baikal Area, *Geokhimiya*, 1983, no. 1, pp. 102–108.
3. Bazarov, D.-D.B. and Bagdasar'yan, G.P., Major Stages of Manifestation of the Cenozoic Volcanism in the Transbaikalia and Baikal Area, in: *Geologiya, paleovulkanologiya i rel'ef Zabaikal'ya* (Geology, Paleovolcanology and Relief of the Transbaikalia), Ulan-Ude: Buryat. Fil.Sib. Otd. Akad. Nauk SSSR, 1986, pp. 91–101.
4. Bayanov, V.D., The Late Mesozoic Shoshonite–Latite Series of the Dzghida Ore-Bearing Area (the Southwest-

- ern Transbaikalia), *Dokl. Ross. Akad. Nauk*, 1994, vol. 339, no. 3, pp. 374–377.
5. Belov, I.V., *Trakhibazal'tovaya formatsiya Pribaikal'ya*, (Trachybasaltic Rock Association of the Baikal Area), Moscow: Izd. Akad. Nauk SSSR, 1963.
 6. Vorontsov, A.A., Yarmoluyk, V.V., Ivanov, V.G., and Smirnov, V.N., The Late Mesozoic Magmatism of the Borgoi Trough of the Western Baikal Area: Age and Material, *Geol. Geofiz.*, 1997, vol. 38, no. 8, pp. 1305–1314.
 7. Vorontsov, A.A., Yarmoluyk, V.V., Ivanov, V.G., and Nikiforov, A.V., The Late Mesozoic Magmatism of the Dzhida Sector of Western Transbaikalia Rift Area: Formation Stages, Associations, and Sources, *Petrologiya*, 2002, vol. 10, no. 5, pp. 510–531.
 8. Gordienko, I.V. and Klimuk, V.S., Bimodal Volcanism of the Tugnui Rift-Related Trough (Transbaikalia), *Geol. Geofiz.*, 1995, vol. 36, no. 5, pp. 23–37.
 9. Gordienko, I.V., Klimuk, V.S., Ivanov, V.G., and Posokhov, V.F., New Data on the Composition and Age of the Bimodal Volcanic Series in the Tugnui Rift-Related Trough (Transbaikalia), *Dokl. Ross. Akad. Nauk*, 1997, vol. 352, no. 6, pp. 799–803.
 10. Gordienko, I.V., Bayanov, V.D., Klimuk, V.S., et al., Composition and Age ($^{39}\text{Ar}/^{40}\text{Ar}$) of Volcanic Rocks in the Chikoi–Khilok Rift-Related Trough, Transbaikalia, *Geol. Geofiz.*, 1999, vol. 40, no. 4, pp. 583–591.
 11. Zhuravlev, D.Z., Chernyshev, I.V., Agapova, A.A., and Serdyuk, N.I., Precisional Isotopic Analysis of Neodymium in Rocks, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1983, no. 12, pp. 23–40.
 12. Ivanov, V.G., Yarmoluyk, V.V., and Smirnov, V.N., New Data on the Age of Volcanism in the Western Transbaikalia Late Mesozoic–Cenozoic Volcanic Area, *Dokl. Ross. Akad. Nauk*, vol. 345, no. 5, pp. 648–652.
 13. Ivanov, V.G. and Yarmoluyk, V.V., The Early Cretaceous Tephrite–Phonolite Association on the Southern Slope of the Malyi Khamardaban Range, *Dokl. Ross. Akad. Nauk*, 1996, vol. 349, no. 3, pp. 364–367.
 14. Ivanov, V.G., Yarmoluyk, V.V., Antipin, V.S., et al., Intracontinental Magmatism as an Indicator of Processes that Initiated the Formation of the Baikal Rift Zone, *Geol. Geofiz.*, 2000, vol. 41, no. 4, pp. 563–567.
 15. Komarov, Yu.V., *Mezozoiskii vnegeosinklinal'nyi magmatizm Zapadnogo Zabaikal'ya*, (The Mesozoic Extra-Geosynclinal Magmatism of the Western Transbaikalia), Novosibirsk: Nauka, 1972.
 16. Kononova, V.A., Ivanenko, V.V., Karpenko, M.I., et al., New Data on K–Ar Ages of the Cenozoic Continental Basalts of the Baikal Rift System, *Dokl. Akad. Nauk SSSR*, 1988, vol. 303, no. 2, pp. 454–457.
 17. Kuznetsova, F.V., *Nefelinovye sienity obramleniya Borgoisoi vpadiny* (Nepheline Syenites in the Circumference of the Borgoi Trough), Moscow: Nauka, 1975.
 18. Litvinovskii, B.A., Zanzvilevich, A.N., Shadaev, M.G., and Lyapunov, S.M., Conditions of Formation of a Trachybasalt–Trachyrhyolite Bimodal Series: the Malyi Khamardaban Volcano-Tectonic Structure, Transbaikalia, *Petrologiya*, 1996, vol. 4, no. 1, pp. 26–45.
 19. *Magmaticheskie gornye porody. Tom 6. Evolyutsiya magmatizma v istorii Zemli* (Igneous Rocks. Vol. 6. Evolution of Magmatism in Earth's History), Moscow: Nauka, 1987.
 20. Rasskazov, S.V., *Magmatizm Baikalskoi riftovoi sistemy* (Magmatism of the Baikal Rift System), Novosibirsk: Nauka, 1993.
 21. Rasskazov, S.V. and Ivanov, A.V., Episodes and Geodynamic Environment of the Quaternary Volcanism in the Baikal Rift System, *Dokl. Ross. Akad. Nauk*, 1996, vol. 349, no. 6, pp. 804–807.
 22. Sklyarov, E.V., Mazukabzov, A.M., and Mel'nikov, A.I., *Kompleksy metamorficheskikh yader kordil'erskogo tipa* (Complexes of Cordilleran-type Metamorphic Cores), Novosibirsk: Izd. Ross. Akad. Nauk, Sib. Otd., NITs, OIGM, 1997.
 23. G. Faure, *Principles of Isotope Geology*, 2nd Edition, New York: Wiley and Sons, 1986.
 24. Yarmoluyk, V.V., Kovalenko, V.I., and Ivanov, V.G., The Late Mesozoic–Cenozoic Intraplate Volcanic Province of the Eastern Central Asia: The Projection of a Hot Mantle Field, *Geotektonika*, 1995, no. 5, pp. 41–67.
 25. Yarmoluyk, V.V., Ivanov, V.G., and Kovalenko, V.I., Sources of Intraplate Magmatism in the Western Transbaikalia during Late Mesozoic–Cenozoic Time (Based on Geochemical and Isotope–Geochemical Data), *Petrologiya*, 1998, vol. 6, no. 2, pp. 115–138.
 26. Yarmoluyk, V.V. and Ivanov, V.G., Magmatism and Geodynamics of the Western Transbaikalia in the Late Mesozoic and Cenozoic, *Geotektonika*, 2000, no. 2, pp. 43–64.
 27. Yarmoluyk, V.V. and Kovalenko, V.I., Geochemical and Isotopic Parameters of an Anomalous Mantle in North Asia during Late Paleozoic–Early Mesozoic Time (A Study in Basic Intraplate Magmatism), *Dokl. Ross. Akad. Nauk*, 2000, vol. 375, no. 4, pp. 525–530.
 28. Yarmoluyk, V.V., Vorontsov, A.A., Ivanov, V.G., et al., Epochs of Bimodal and Alkaline Granitic Magmatism in the Western Transbaikalia: Geochronologic Data on the Tugnui Trough, *Dokl. Ross. Akad. Nauk*, 2000, vol. 373, no. 1, pp. 78–83.
 29. Davis, G.R. and Macdonald, R., Crustal Influences in Petrogenesis of the Naivvasha Basalt–Comendite Complex: Combined Trace Element and Sr–Nd–Pb Isotope Constraints, *J. Petrol.*, 1987, vol. 28, pp. 1009–1031.
 30. Gamble, J., Woodhead, J., Wright, I., and Smith, I., Basalt and Sediment Geochemistry and Magma Petrogenesis in a Transect from Oceanic Island Arc to Rifted Continental Margin Arc: the Kermadec–Hikurangi Margin, SW Pacific, *J. Petrol.*, 1996, vol. 37, pp. 1523–1546.
 31. Hawkesworth, C.J., Callaghan, K., Hergt, J.M., and McDermott, F., Trace Element Fractionation Processes in the Generation of Island Arc Basalts, *Phil. Trans. R. Soc. London, Ser. A*, 1993, vol. 342, pp. 179–191.
 32. Hofman, A.W., Jochum, K.P., Seufert, M., and White, W.M., Nb and Pb in Oceanic Basalts: New Constraints on Mantle Evolution, *Earth Planet. Sci. Lett.*, 1986, vol. 79, pp. 33–45.
 33. Kelemen, P.B., Shimizu, N., and Dunn, T., Relative Depletion in Niobium in Some Arc Magmas and the Continental Crust: Partitioning of K, Nb, La, and Ce During Melt/Rock Reaction in the Upper Mantle, *Earth Planet. Sci. Lett.*, 1993, vol. 120, pp. 111–134.

34. Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., and Zanettin, B., Chemical Classification of Volcanic Rocks Based on the Total Alkali–Silica Diagram, *J. Petrol.*, Oxford, 1986, vol. 27, pp. 745–750.
35. Pearce, J.A., The Role of Subcontinental Lithosphere in Magma Genesis at Destructive Plate Margins, in *Continental Basalt and Mantle Xenolith*, Hawkesworth, C.J. and Norry, H.J., Eds., Nantwich: Shiva, 1983, pp. 230–249.
36. Ryerson, F.J. and Watson, E.B., Rutile Saturation in Magmas: Implications for Ti–Nb–Ta Depletion in Island-Arc Basalts, *Earth Planet. Sci. Lett.*, 1987, vol. 86, pp. 225–239.
37. Rogers, N., Macdonald, R., Fitton, J.R., et al., Two Mantle Plumes Beneath the East African Rift System: Sr, Nd and Pb Isotope Evidence from Kenya Rift Basalt, *Earth Planet. Sci. Lett.*, 2000, vol. 176, pp. 387–400.
38. Shan Gao, Ting-Chuan Luo, Ben-Ren Zhang, et al., Chemical Composition of the Continental Crust as Revealed by Studies in East China, *Geochim. Cosmochim. Acta*, 1998, vol. 62, no. 11, pp. 1959–1975.
39. Sun, S.S. and McDonough, W.F., Chemical and Isotopic Systematics of Ocean Basalts: Implications for Mantle Composition and Processes, Magmatism in the Ocean Basins, *Geol. Soc. Spec. Publ.*, 1989, no. 42, pp. 313–345.
40. Tomlinson, K.Y. and Condie, K.C., Archean Mantle Plumes: Evidence from Greenstone Belt Geochemistry, in *Mantle Plumes: Their Identification through Time*, Spec. Paper 352, Colorado, 2001, pp. 341–358.
41. Weaver, B.L., The Origin of Oceanic Basalts End-Member Compositions: Trace Element and Isotopic Constraints, *Earth Planet. Sci. Lett.* 1991, vol. 104, pp. 381–397.