

Two Types of Magma Sources of Rare-Metal Alkali Granites

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Abstract—The geological setting, age, and magma sources of rare-metal ores at the Khalzanburgetdei deposit in western Mongolia and the Khan Bogd occurrence in southern Mongolia are considered. The Khalzanburgetdei deposit, 392 Ma in age, is situated in the Lake Zone of the Early Caledonides of the Central Asian Foldbelt at a branch of a triple junction of grabens. The Khan Bogd occurrence, about 290 Ma in age, is located in the South Mongolian Hercynian Zone and related to a continental rift conjugated in space and time with Hercynian island-arc systems. To estimate features of rare-metal magma sources, the Nd and O isotopic compositions were used, as well as ratios of incompatible elements (Nb–U, Nb–Zr, La–Yb, Th–Ta, and Ce–Pb). Since the granitic magma was commonly saturated with these elements, their ratios may be used for estimation of magma source compositions, trends of magma fractionation, and accumulation of rare-metal minerals. A mixture of an OIB source and crustal material (Caledonian ophiolitic and island-arc complexes) served as a source of rare-metal granitic rocks of the Khalzanburgetdei deposit, while the Khan Bogd occurrence was related to a source of subduction-related basic rocks, probably, with participation of the depleted and enriched mantle and continental crust.

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INTRODUCTION

Alkali granites often contain economic Nb, Zr, REE, Be, Li, and other rare-metal ore mineralization (Kovalenko, 1977). The primary deposits of this type were discovered in the Soviet Union in the 1940s–1950s; placers related to rare-metal granites were known earlier from Nigeria. In the 1950s–1960s, such granites were termed *apogranites* (Beus et al., 1962) or *granites with accessory tantaloniobates* (Pavlenko et al., 1960). The Aryska (Kovalenko and Popolitov, 1970; Kostitsyn et al., 1998) and Ulug-Tanzek deposits in Tuva, the Katugin deposit in the northern Transbaikalian region (Apel'tsin et al., 1967), and a number of deposits in northern Canada (Sinclair et al., 1992) serve as examples of rare-metal deposits. Similar deposits and occurrences were discovered in the Mongolian rare-metal province (Kovalenko et al., 1971, 1973, 1985, 1995, 2004b, 2004c, 2006a), including the Khalzanburgetdei Nb–Zr–REE deposit, discovered in 1984 in northwestern Mongolia, and rare-metal occurrences in the large Khan Bogd alkali granite pluton in southern Mongolia (Kovalenko et al., 1973; Vladykin et al., 1981). These deposits and occurrences were described

in detail in the cited publications; new isotopic and geochemical data were reported by Kovalenko et al. (2004b, 2004c, 2006b). In this paper, we briefly summarize the available information and focus our main attention on interpretation of magma sources of alkali granites based on isotopic (Nd, O) and geochemical data (ICP MS results). The analytical methods used were characterized by Kovalenko et al. (2003b, 2003c).

The rare-metal deposits and occurrences considered in this paper have not been chosen arbitrarily. Despite a certain compositional similarity (as of rare-metal alkali granites as a whole), it turned out that the magmas and related ores at the Khalzanburgetdei deposit and Khan Bogd occurrences were derived from different sources.

BRIEF GEOLOGICAL AND GEOCHRONOLOGICAL CHARACTERIZATION OF THE KHALZANBURGETDEI DEPOSIT AND THE KHAN BOGD OCCURRENCE OF RARE-METAL ALKALI GRANITES

The Khalzanburgetdei group of alkali granite plutons and the rare-metal deposit of the same name are situated in the Lake Zone of western Mongolia 45 km

northeast of the town of Kobdo and localized in the regional fault zone that separates the Caledonian tectonic units of the Mongolian Altai from the Early Caledonides of the Lake Zone (Fig. 1). Ophiolitic complexes and various granitoids crossed by a near-latitudinal dike swarm are country rocks. The results of U–Pb and Ar–Ar timing demonstrate the multistage magmatic history of this region (Kovalenko et al., 2004c). The ophiolitic basement of the Early Caledonides was formed 570–520 Ma ago, whereas island-arc complexes cut through by alkali granites are dated at 546 Ma. The collisional stage concluded with emplacement of tonalites and granodiorites 495 Ma ago. Granitic plutons were formed 465 ± 11 , 441 ± 2 , and 355 ± 1 Ma ago. The alkali granite plutons, including that at the Khalzanburgetdei deposit, consist of several intrusive phases. The Khalzanburgetdei pluton comprises the following sequence of intrusive phases (from older to younger): (1) nordmarkite and coeval dolerite; (2) alkali granite and coeval dolerite; (3) ekerite, fine-grained alkali granite, and pegmatites; (4) pantellerite; (5) rare-metal alkali granite; (6) dikes of alkaline basic rocks and leucosyenite (?); and (7) miarolitic rare-metal alkali granite. The ore-bearing rocks (phases 5 and 7) contain Nb, Zr, REE, Y, U, Th, and Be minerals of economic interest (Kovalenko et al., 2004c). The U–Pb zircon ages of the rocks are as follows: 392 ± 2 Ma (alkali granite of phase 2), 391 ± 1 Ma (syenite of phase 6), and 395 ± 1 Ma (quartz–zircon–allanite–epidote ore from the Tsakhir site (Kovalenko et al., 2004c)). The internal structure of the Khalzanburgetdei pluton and the location of the deposit bearing the same name are shown in Fig. 1.

The Khalzanburgetdei group of alkali granite plutons is controlled by a near-meridional extension zone that is traced by large faults and a dike swarm that extends immediately to the east of the alkali granite plutons. This extension zone corresponds to the southern branch of a triple junction of grabens (Kovalenko et al., 2004c) within the Altai–Sayan intraplate region at the southwestern margin of the Early–Middle Paleozoic Siberian paleocontinent.

One of the world's largest, the Khan Bogd alkali granite pluton ($>1500 \text{ km}^2$) is exposed in the southern Gobi desert (Kovalenko et al., 2006b) at the Late Paleozoic active continental margin of the Siberian paleocontinent. The country rocks comprise Devonian island-arc associations, Carboniferous calc-alkaline lavas of various alkalinity, granitoids of the differentiated complex of the marginal igneous complex, and a bimodal basalt–comendite–alkali granite association related to the rifting superimposed on the active margin (Fig. 2). The localization of the Khan Bogd pluton is controlled by the intersection of the near-latitudinal Gobi–Tien Shan Rift Zone and a large oblique fault. The pluton is composed of two ring bodies and has sharp intrusive contacts with the country island-arc vol-

canics and tectonic contacts with the bimodal sequence. The internal ring structure is especially pronounced in the western body, where it is emphasized by ring dikes and roof pendants. According to gravity measurements, the pluton is a sheetlike body (laccolith) and its bottom plunges stepwise to the northwest (Durante et al., 1976). Its internal structure is simpler than that of the Khalzanburgetdei pluton. The sequence of intrusive phases (from older to younger) comprises (1) light gray to pink coarse- to medium-grained elpidite-bearing alkali granite of the main intrusive phase (MIP), which occupies the greater part of the western body and a part of the eastern body; (2) dikes of fine-grained ekerite, porphyritic ekerite, and layered alkali granitic rocks composed of alternating ekerite, pegmatoid alkali granite, and pegmatites of the western body, which accentuate its ring structure; (3) lilac fine- to medium-grained alkali granites (as usual, aegerine or arfvedsonite–aegirine, often miarolitic varieties) with accessory zircon, which dominate in the eastern body; (4) dikes of dark blue or dark green microgranular to vitreous pantellerites; (5) dikes of fine-grained porphyritic alkali leucogranite in the northern part of the eastern body; and (6) dikes of red microgranular granosyenite and monzonite, which make up a system of dike-shaped bodies that extends in the near-latitudinal direction. Rare-metal alkali granite and related pegmatites are associated with ring dikes of phase (2). The areas enriched in rare-metal ekerite dikes and pegmatites, which are shown in Fig. 3, were characterized by Vladyskin et al. (1981). The rare-metal granites contain elpidite; armstrongite, discovered here; and unusual exsolved Nb, Zr, Ti, and REE silicates (*Minerals...*, 2006).

The following geochronological data are available for the pluton and country rocks (Kovalenko et al., 2006b). MIP alkali granite and rare-metal pegmatites of phase 2 are dated at 290 ± 2 Ma (U–Pb zircon age), 283 ± 4 and 285 ± 7 Ma (Ar/Ar age of amphibole and polyolithionite), and 287 ± 3 Ma (Rb–Sr isochron age). The same Rb–Sr isochron age was established for the bimodal basalt–comendite sequence in the southern framework of the pluton. The U–Pb zircon age of 290 ± 2 Ma characterizes a large monzonite–granosyenite pluton located 30 km southwest of the Khan Bogd pluton. Older igneous rocks comprise the Devonian island-arc association, dated at >362 Ma, and the overlying Carboniferous rocks of the differentiated complex of the active margin, which occur at immediate contacts of the pluton and in roof pendants therein; these rocks are 348–330 Ma in age (Khashgerel et al., 2006). The isotopic ages are consistent with estimates based on plant remains (Durante et al., 1976). The island-arc associations and the complexes of the active margin are close to each other not only in age but also in geochemistry and isotopic characteristics and may be regarded as a group of subduction-related rocks.

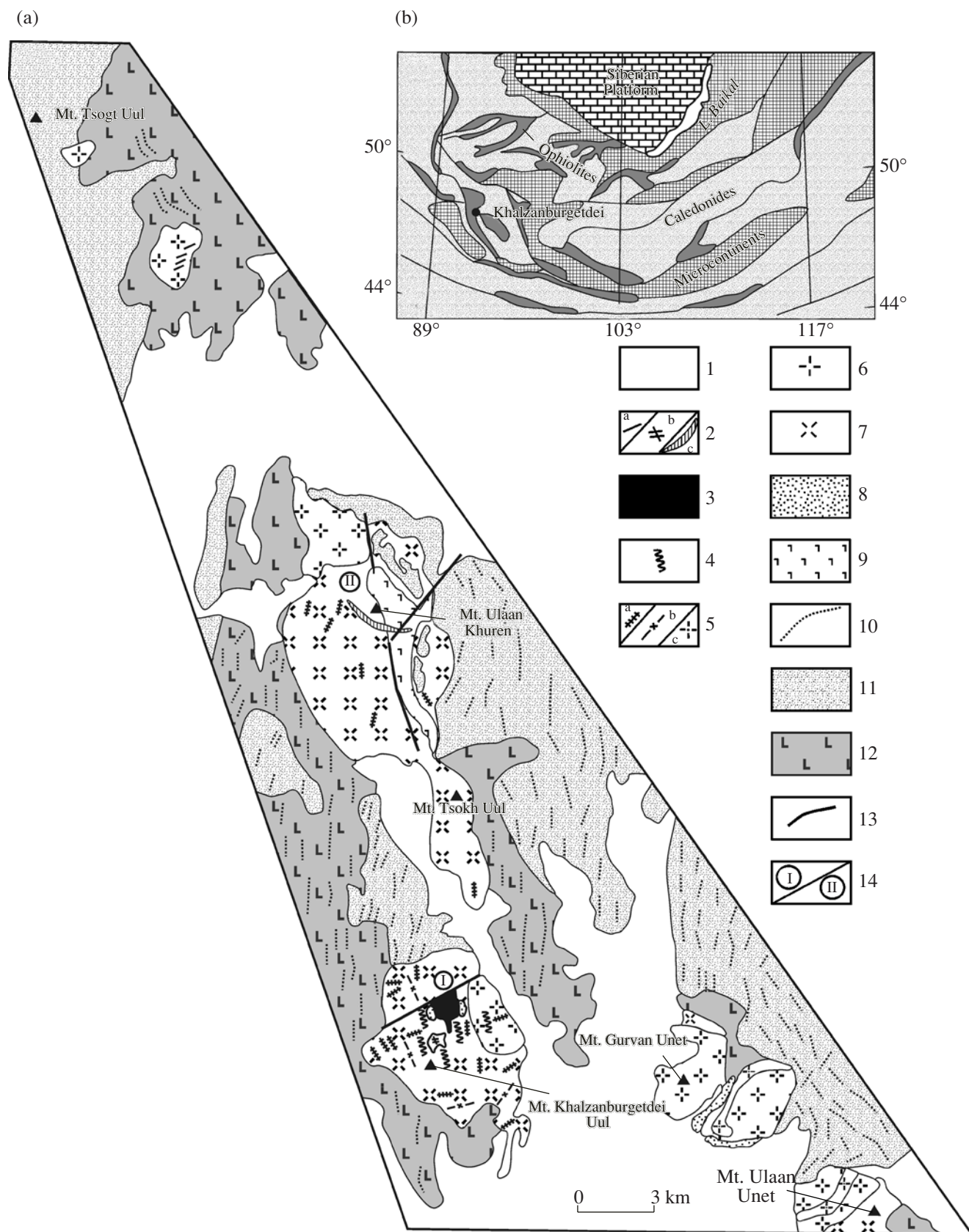


Fig. 1. (a) Geological map of the Khalzanburgetdei group of alkali plutons and their framework and (b) their location in the Caledonides of the Central Asian Foldbelt. (1) Loose sediments; (2a) alkali basalt and (2b) syenite of the sixth (?) phase and (2c) alkali syenite dike of the sixth (?) phase; (3) rare-metal alkali granites of the fifth and seventh phases; (4) pantellerite of the fourth phase; (5a) ekerite, (5b) alkali granitic pegmatites, and (5c) alkali granite of the third phase; (6) alkali granite of the second phase; (7) nor-markite of the first phase; (8) alkali trachydacite, pantellerite, comendite, and alkali granite porphyry of roof pendants (volcanic vents); (9) dolerite and gabbro; (10) basalt, diorite, monzonite, and granite (dikes); (11) normal biotite–amphibole granite; (12) Early Paleozoic ophiolites; (13) faults; (14) Khalzanburgetdei rare-metal deposit (I) and Tsakhir occurrence (II).

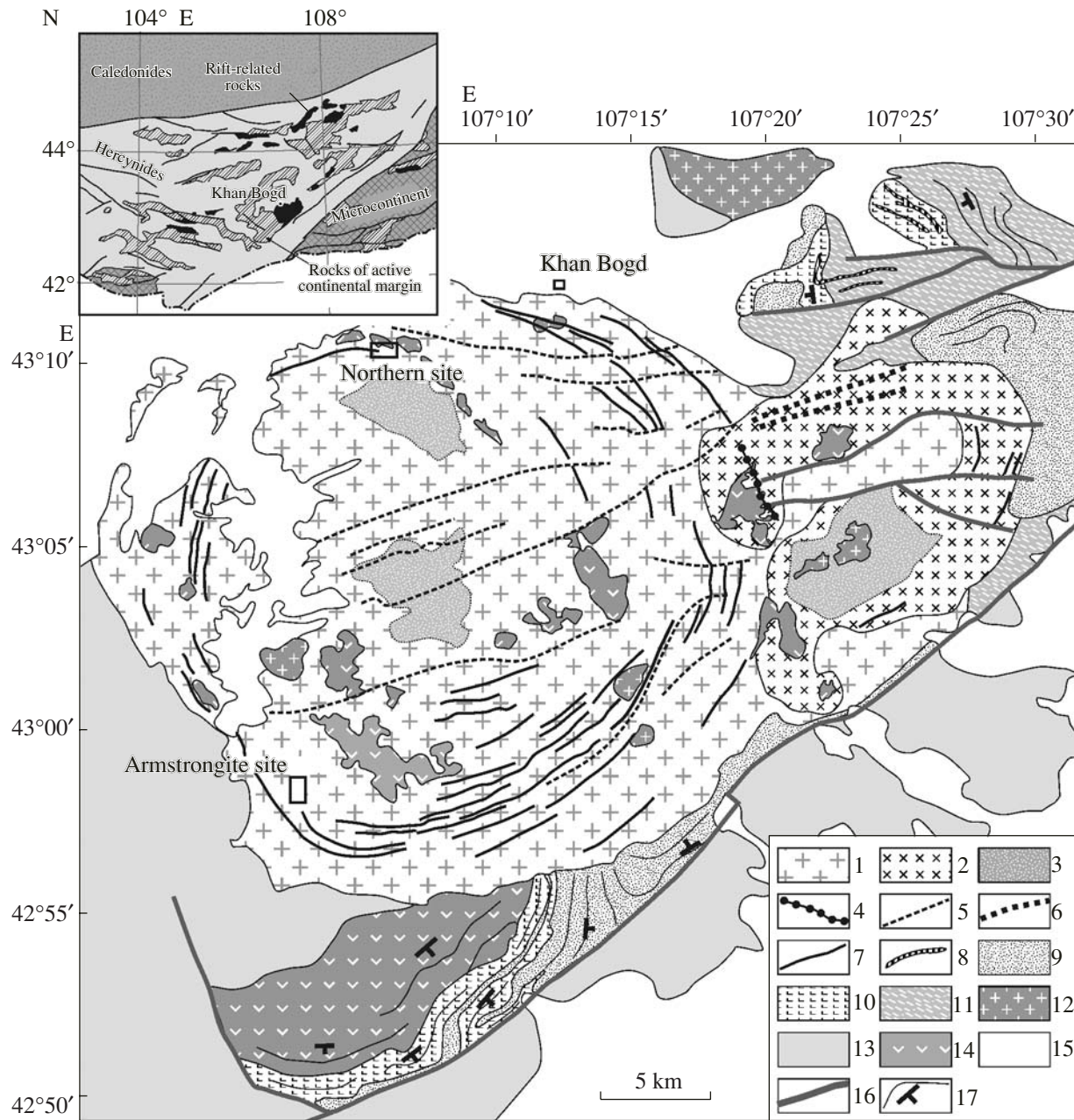


Fig. 2. Geological sketch map of the Khan Bogd alkali granite pluton. (1–7) Plutonic rocks: (1) alkali granite of the main intrusive phase (MIP); (2) fine-grained aegirine granite; (3) porphyritic MIP alkali granite; (4) late pantellerite dikes; (5) microsyenite and micromonzonite dikes; (6) alkali granite porphyry dikes; (7) ekerite, ekerite porphyry, pegmatoid alkali granite, and pegmatite dikes; (8) subvolcanic bodies of various compositions; (9–11) volcanic rocks of the bimodal association: (9) comendite, trachyrhyolite, and tuff and ignimbrite of the same composition; (10) basalt; (11) rocks of the bimodal association, unspecified; (12) biotite and amphibole–biotite granite and granosyenite; (13) pre-Late Paleozoic rocks; (14) rocks of the island-arc association (differentiated complex); (15) Mesozoic and Cenozoic loose sediments; (16) faults; (17) strike and dip of volcanic flows. The inset demonstrates the position of the Khan Bogd pluton and rift-related rock associations in the Late Paleozoic active continental margin of the Siberian paleocontinent.

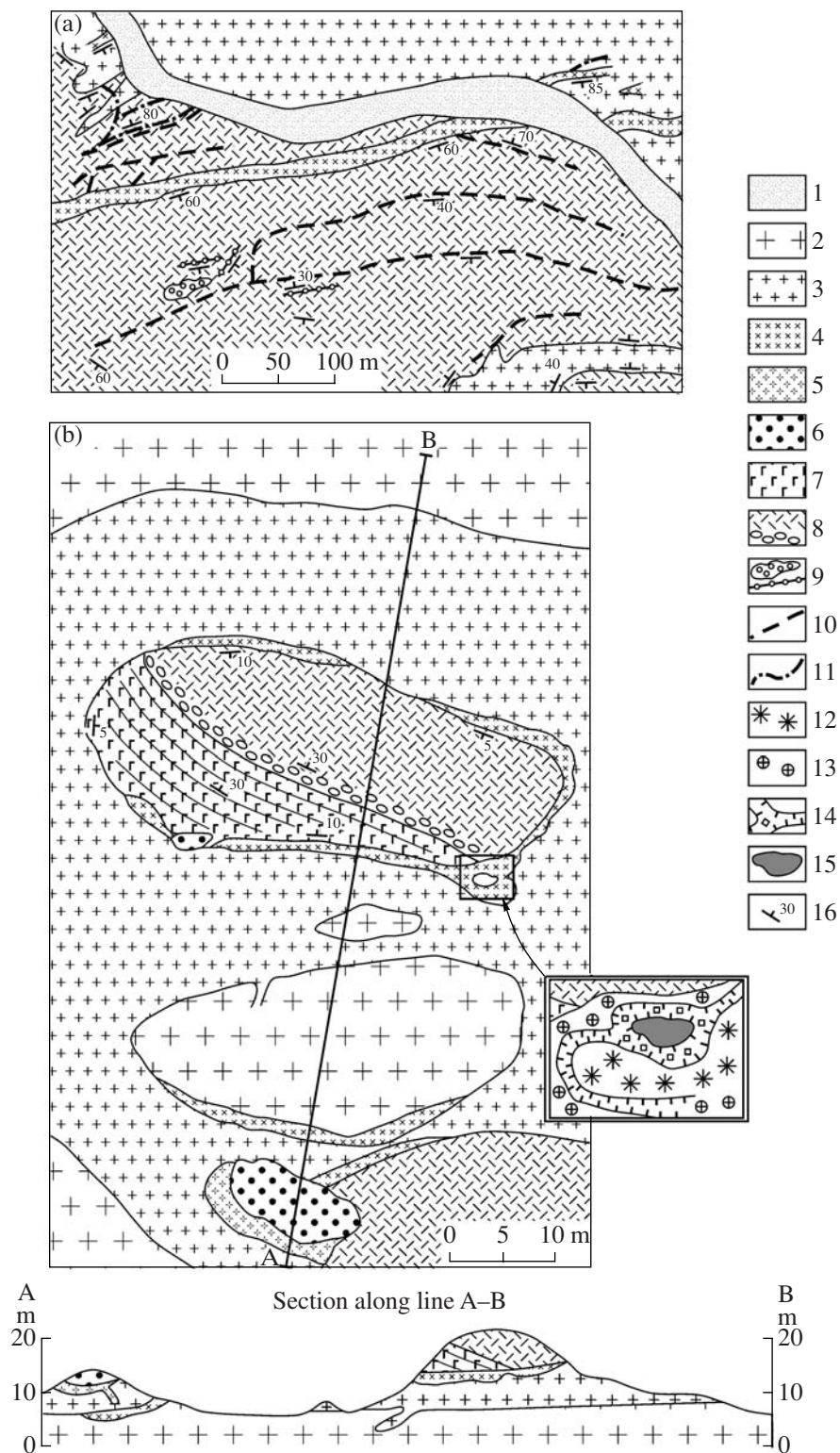


Fig. 3. Geological sketch map of the (a) Northern and (b) Armstrongite sites of rare-metal alkali granites in the Khan Bogd pluton. (1) Loose valley sand; (2) MIP alkali granite; (3) pegmatoid alkali granite of contact zone; (4) layered ekerite and pegmatite bodies; (5) silicified alkali granite; (6) quartz rocks; (7) basic volcanics; (8) dacite, tuffaceous dacitic breccia, rhyolite, and rhyolitic breccia at the base of the rhyolitic sequence; (9) rhyolite dikes; (10) ekerite bodies; (11) alkali granite pegmatites; (12) ekerite with aegerine radiaxial aggregates; (13) fine-grained ekerite; (14) armstrongite-bearing alkali granite pegmatites; (15) zone of anchimonomineralic armstrongite; (16) strike and dip symbols.

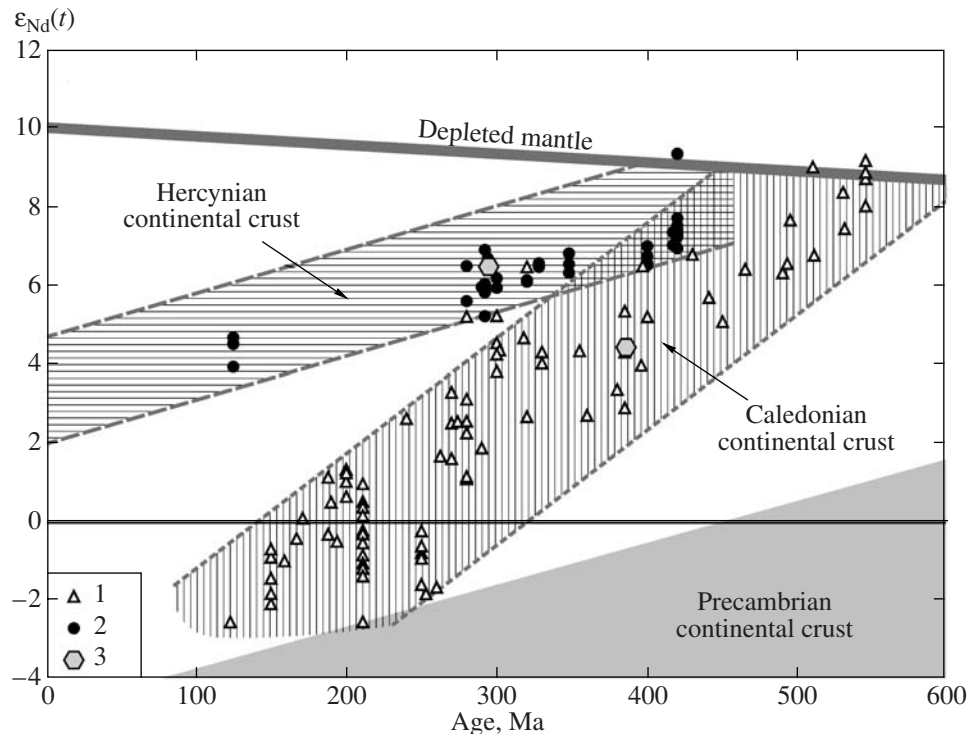


Fig. 4. $\epsilon_{Nd}(t)$ versus age for rocks of the continental crust in the Caledonian and Hercynian tectonic zones of the Central Asian Fold-belt. (1) Rocks of the Caledonian tectonic zone: ophiolitic and island-arc complexes and related granitoids; (2) rocks of the Hercynian tectonic zone: ophiolitic, island-arc, and marginal continental complexes and related granitoids; (3) average isotopic composition of the continental crust in the Caledonides (390 Ma ago) and Hercynides (290 Ma ago), after (Yarmolyuk et al., 2002, 2007; Kovalenko et al., 2004a).

The geodynamic model of the formation of the Khan Bogd pluton suggests collision of the Siberian Craton with the hot spot of the Hercynian ocean or its mid-ocean ridge (Yarmolyuk and Kovalenko, 1991; Kovalenko et al., 2006b). Two variants of geodynamic processes are supposed. According to the first variant, the hot mantle of a plume reworked the subducted lithosphere after the collision of the North Asian paleocontinent with the hot spot, having formed an asthenospheric window that served as a source of rift-related magmatism and the Khan Bogd pluton itself. In terms of the second variant, the emerging hot mantle of the plume flattened the subducted plate; ended island-arc magmatism; and probably created a local convective system in the asthenosphere of the mantle wedge, thus facilitating formation of magma sources related to rifting. The enormous volume of alkali granites and volcanic rocks of the Khan Bogd pluton and its ring structure were caused by a caldera mechanism of magma emplacement and evolution. The primary basic magma should have been many times greater in volume than alkali granites and their volcanic analogues and comparable to moderate-sized flood basalt provinces in this respect.

MAGMA SOURCES OF RARE-METAL ALKALI GRANITES

The approaches used for the estimation of magma sources. Magma sources are estimated most reliably from isotopic data and ratios of incompatible elements. The considered alkali granites are not exceptions in this respect. In our case, the Sm–Nd and O isotopic systems are the most appropriate for realization of this approach because the isotopic composition of REE remains unchanged while the rocks are affected by postmagmatic alteration. These elements are not very mobile in fluids and are abundant in alkali granites and related ores. In addition, the temperature of closure of the Sm–Nd isotopic system is higher than that of the Rb–Sr system, which is less reliable because of high mobility of Rb and Sr in hydrothermal processes and low Sr content in alkali granites and related pegmatites, which are readily subjected to even weak postmagmatic effects (Kovalenko et al., 2004b; Goodenough et al., 2000). Therefore, only the Sm–Nd and O isotopic systems are used in this study.

The ratios of trace elements that are close in incompatibility, i.e., have fairly similar bulk partition coefficients (canonical elements, after (Workman and Hart, 2005)), reflect the same ratios in magma sources of

rare-metal alkali granites most adequately. The relationships between trace element ratios in magmas and their sources as a function of their compatibility and the degree of partial melting or magma fractionation were discussed by Kovalenko et al. (2006a). In particular, it has been shown that trace element pairs with the closest possible incompatibilities are desirable for such residual magmatic systems as rare-metal alkali granites. The close incompatibility must be retained, as a first approximation, through the entire range of fractionation up to the formation of alkali granites at the final stage of magmatic evolution. We chose pairs of trace elements (Nb–U, Nb–Zr, La–Yb, Th–Ta, and Ce–Pb) such that they are steadily gained in the residual melt of fractionating magma irrespective of its composition up to the formation of ore-bearing rare-metal granitic rocks. Precisely these pairs are commonly used for estimation of magma sources and called canonical.

Furthermore, it is important that ratios of these pairs of elements are different in the reference model sources, such as the depleted mantle, a source of MORB; the enriched mantle, a source of OIB; the mantle of a metasomatized mantle wedge, a source of IAB; the continental crust (CC); etc. Hereafter, the abbreviations of products of melting will be used for designation of their sources. In addition to the classical model sources listed above, the components of the Hercynian and Early Caledonian CC (sedimentary and igneous rocks, including granitoids) will be used for comparative purposes in estimation of the sources of the Khan Bogd and Khalzanburgetdei deposits, respectively. The evolutionary trend of Nd isotopic composition $\epsilon_{Nd}(t)$ in the Hercynian and Early Caledonian CC of the Central Asian Foldbelt is shown in Fig. 4 after data reported by Kovalenko et al. (2004a) and Yarmolyuk et al. (2002, 2007). The intraplate $\epsilon_{Nd}(t)$ values of the OIB mantle source were taken from the same publications, where the isotopic evolution of intraplate basaltic rocks is considered in regard to Central Asia. The $\epsilon_{Nd}(t)$ values and trace element contents of suprasubduction basaltic rocks (IAB) correspond to the mean compositions of island-arc and continental margin complexes that are cut through by rare-metal alkali granites.

The aforementioned theoretical requirements for the element pairs are inevitably broken in practice, and a difference in incompatibility always remains, but this difference hardly exerts a substantial effect on the results obtained, as follows from Figs. 5 and 6. The variations in Nb/U, La/Yb, Th/Ta, and Ce/Pb ratios in ores and parental alkali granites remain within narrow limits, thus testifying to their genetic links and derivation from common sources. However, in some cases, the element ratios are scattered and the choice of sources becomes ambiguous (Fig. 6b). For the Khalzanburgetdei deposit, it has been suggested that the rare-metal granites are mixtures of two residual alkali granite magmas related to different sources (Kovalenko

et al., 1995, 2004b, 2004c), so that variations in canonical ratios should indicate the mixed character of magma sources. In addition, the variations in canonical ratios reflect, to a certain degree, the fluctuations caused by variable contents of minerals enriched in rare (ore) elements. The correlations between contents of these elements and Nb as an indicator of magma fractionation are shown in Figs. 7 and 8. The rare-metal alkali granite magma parental for the Khalzanburgetdei deposit is saturated with Zr, Th, LREE, and Pb (Fig. 7), as is also supported by the occurrence of minerals of these elements (Kovalenko et al., 2004c). The Nb, U, and HREE contents are generally below the saturation level; however, the appearance of the respective mineral phases in the most evolved rocks indicates that saturation is achieved in the final residual melts. Similar relationships are established for the Khan Bogd occurrence (Fig. 8). The rocks demonstrate their saturation with Zr, HREE, and Th and remain undersaturated with Nb, U, Pb, and LREE; nevertheless, their contents are close to the saturation level. While magma is becoming saturated, further fractionation leads to a decrease in the Zr/Nb, Th/Ta, and Ce/Pb ratios and to a decrease or an increase in the La/Yb ratio depending on saturation with LREE or HREE at a relatively constant Nb/U ratio. Since rare-metal magmas most likely are close to saturation in Nb, U, La, Ce, and Pb, the crystallization of carrier minerals and concentrators from such magmas and their removal to the region of less evolved magmas is accompanied by an increase in the respective ratios in rocks and ores. For example, at the Khan Bogd occurrence, the Zr/Nb ratio varies from <10 up to 600. Such a high ratio (>50) is unknown in any mantle or crustal sources. The only reasonable explanation is the formation of cumulative rocks with transfer of minerals, e.g., zircon, into the less evolved portion of the magma chamber, for example, containing ~100 ppm Nb (Fig. 6b). It is evident that such high canonical ratios cannot be used for estimation of magma source composition. Even average ratios hardly may be used in this case. The use of slightly undersaturated compositions would be the most correct. In Figs. 7 and 8, the respective ratios are characterized by a positive correlation between elements in canonical ratios, and precisely these elements will be selected for estimation of source compositions for rare-element alkali granitic magmas.

Isotopic compositions of rocks and ores from the Khalzanburgetdei deposit and the Khan Bogd occurrence. Isotopic data on rare-metal alkali granites from the considered plutons are given in the table. Data published by Kovalenko et al. (1995, 2004b) are supplemented in this paper by new determinations of Nd isotopic composition performed at the Institute of Precambrian Geology and Geochronology (IPGG), Russian Academy of Sciences (RAS). All isotopic and geochemical data for rare-metal alkali granites of the Khan Bogd pluton are original. The Nd isotopic com-

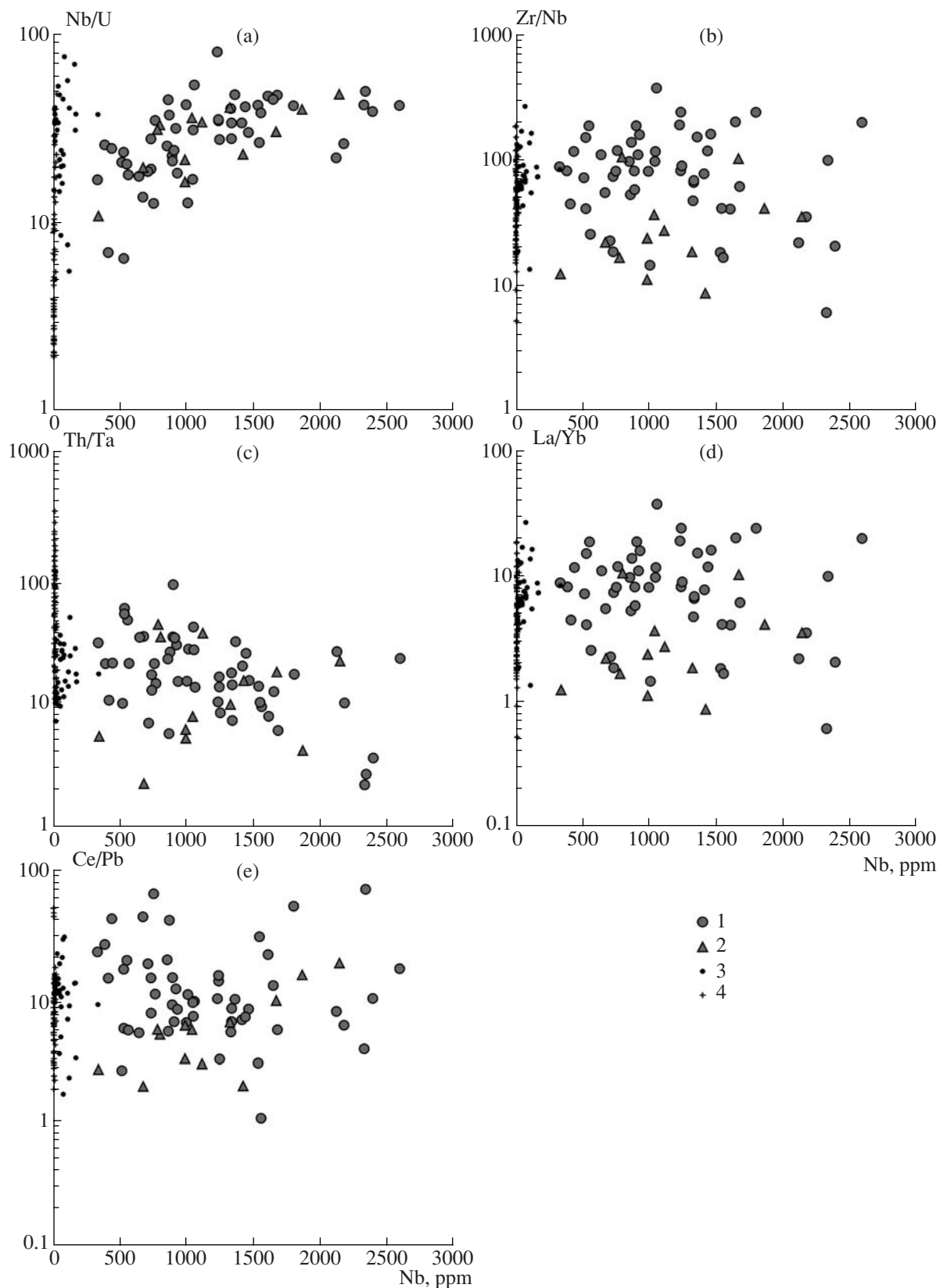


Fig. 5. (a) Nb/U, (b) Zr/Nb, (c) Th/Ta, (d) La/Yb, and (e) Ce/Pb versus Nb content in rare-metal granites and country rocks of the Khalzanburgetdei deposit. (1) Rare-metal alkali granite of the fifth phase; (2) miarolitic rare-metal alkali granite of the seventh phase; (3) intrusive rocks devoid of rare-metal mineralization; (4) country rocks, including ophiolitic and island-arc complexes and related granitoids. See text for explanations.

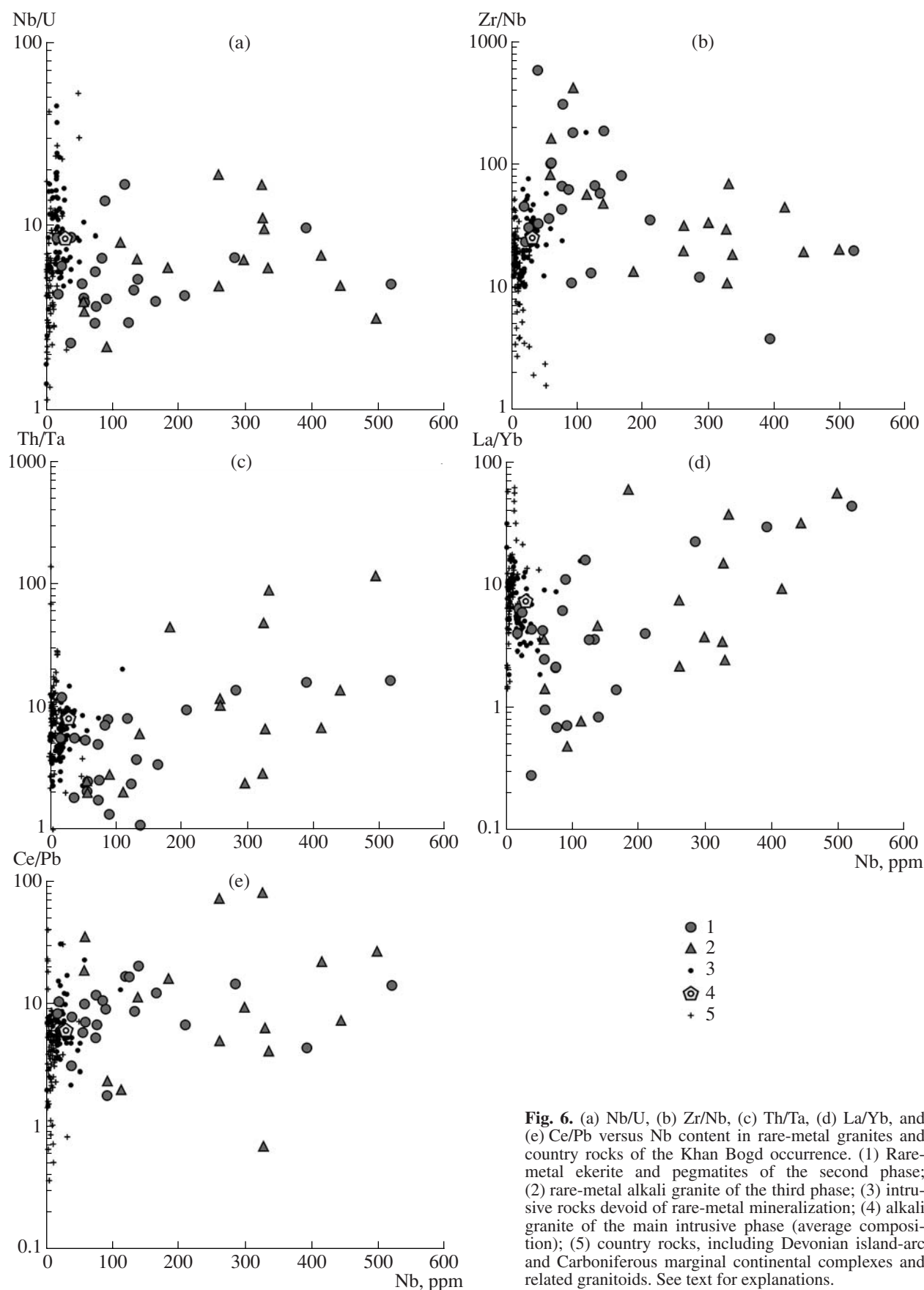


Fig. 6. (a) Nb/U, (b) Zr/Nb, (c) Th/Ta, (d) La/Yb, and (e) Ce/Pb versus Nb content in rare-metal granites and country rocks of the Khan Bogd occurrence. (1) Rare-metal ekerite and pegmatites of the second phase; (2) rare-metal alkali granite of the third phase; (3) intrusive rocks devoid of rare-metal mineralization; (4) alkali granite of the main intrusive phase (average composition); (5) country rocks, including Devonian island-arc and Carboniferous marginal continental complexes and related granitoids. See text for explanations.

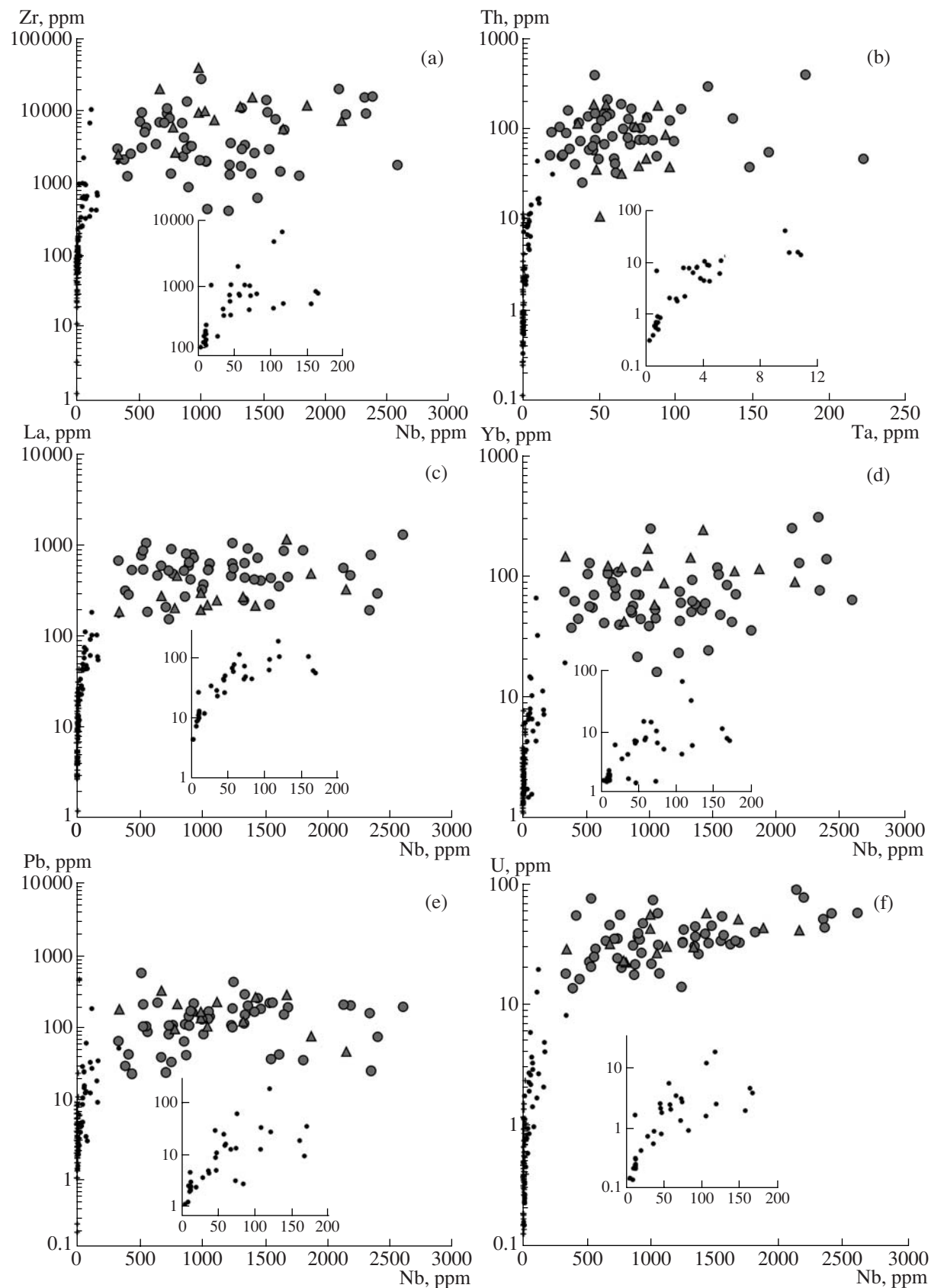


Fig. 7. Variations in Nb, Zr, Th, Ta, La, Yb, Pb, and U contents (incompatible elements) in igneous rocks of the Khalzanburgetdei deposit. See Fig. 5 for legend. The insets show fragments of the diagrams with low contents of the elements typical of parental rocks devoid of rare-metal mineralization. See text for explanations.

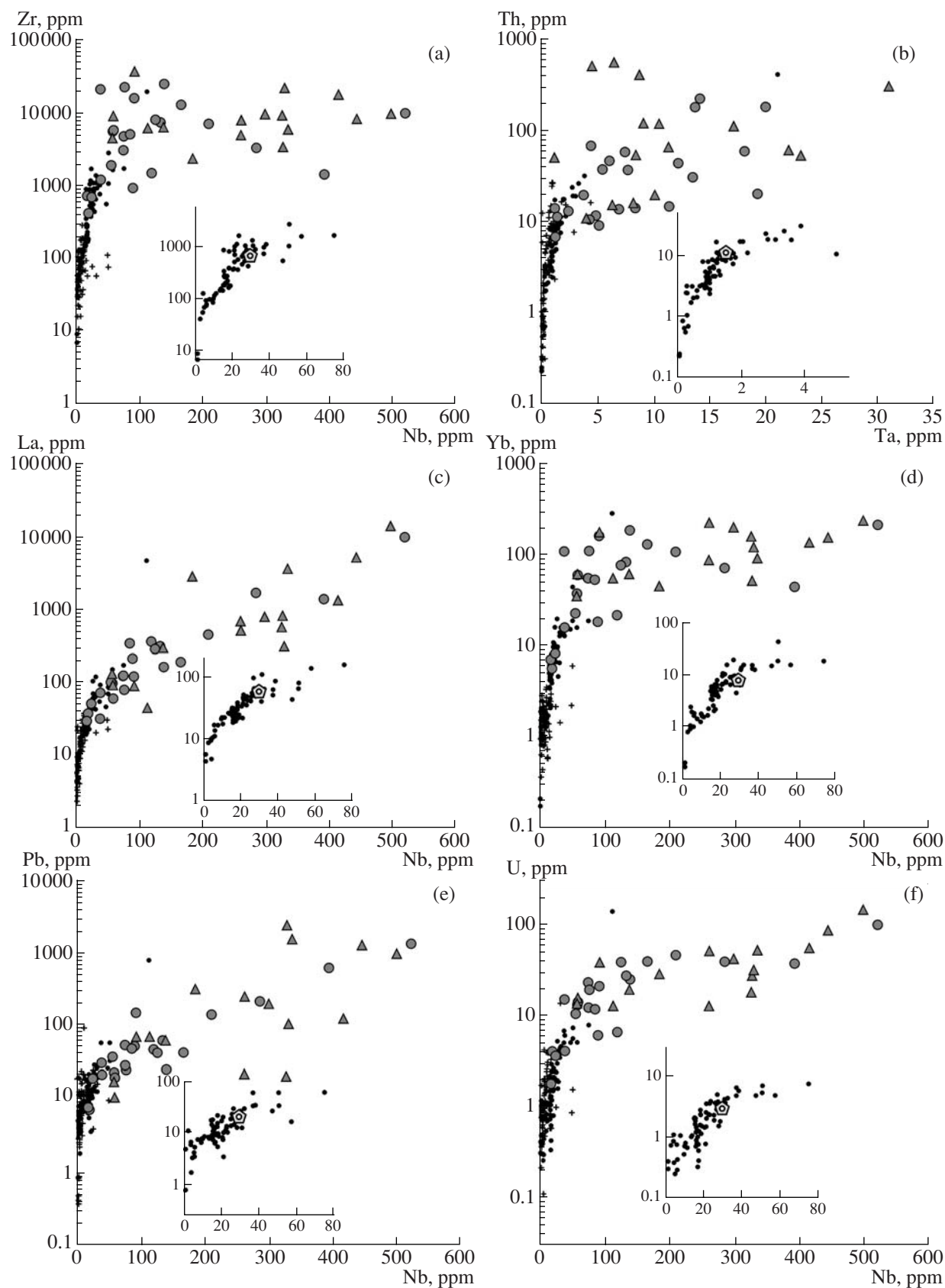


Fig. 8. Variations in Nb, Zr, Th, Ta, La, Yb, Pb, and U contents (incompatible elements) in igneous rocks of the Khan Bogd rare-metal occurrence. See Fig. 6 for legend. The insets show demonstrate fragments of the diagrams with low contents of the elements typical of parental rocks devoid of rare-metal mineralization. See text for explanations.

Neodymium and oxygen isotopic compositions and trace element contents, ppm, in granitic rocks of the Khalzanburgetdei and Khan Bogd plutons

Isotopic parameters and elements	Rare-metal alkali granite of the fifth phase, Khalzanburgetdei group of plutons							
	KhBU-4320	KhBU-4630/1	KhBU-4630/4	C3	D1	F-1	F-6	G-6
$^{147}\text{Sm}/^{144}\text{Nd}$	0.1543	0.1356	0.1697	0.1411	0.1643	0.1618	0.1468	0.1405
$^{143}\text{Nd}/^{144}\text{Nd}$	0.512839	0.512814	0.512792	0.512783	0.512851	0.512852	0.51282	0.512799
$\epsilon_{\text{Nd}}(\text{T})$	6.0	6.5	4.4	5.6	5.8	5.9	6.1	6.0
$\delta^{18}\text{O}, \text{‰}$	7.2							
Li	59	245		54	6.5	10	13	35
Be	21	18		126	22	12	13	8.6
Sc	5.2	1.1		1.0	2.9	0.97	1.7	3.2
Ti	2774	1520		2269	1349	439	3259	11452
V	11	10		0.02	0.74	4.7	0.02	0.02
Cr	16	16		0.71	1.7	3.3	1.2	1.2
Co	0.32	0.58		6.4	0.31	2.0	0.68	34.4
Ni	2.1	2.9		5.4	2.0	0.84	1.5	0.72
Cu	29	3.1		1.8	0.91	0.72	0.91	2.2
Zn	731	658		367	199	235	897	359
Ga	44	41		45	48	56	35	3.8
Rb	438	314		429	442	466	593	516
Sr	388	72		26	15	85	102	237
Y	855	614		691	949	577	1458	1119
Zr	15355	2312		2202	7565	1383	1944	8764
Nb	1530	382		1041	668	1796	2590	14987
Cs	1.4	0.34		0.38	0.49	0.72	0.76	1.3
Ba	64	56		16	59	35	21	105
La	229	325		548	612	909	1352	2313
Ce	673	806		1231	1770	1958	3376	5737
Pr	73	96		136	200	198	354	512
Nd	265	419		382	690	666	1096	1425
Sm	69	97		92	184	165	251	194
Eu	4.4	5.4		5.2	11	11	16	12
Gd	78	101		96	176	148	238	205
Tb	19	17		18	31	27	49	41
Dy	138	96		98	185	122	263	256
Ho	36	20		21	40	24	54	53
Er	118	51		60	113	59	121	159
Tm	20	6.8		9.0	18	7.3	14	28
Yb	124	39		55	110	37	67	179
Lu	18	5.3		6.9	14	4.5	7.1	25
Hf	434	65		57	150	35	37	190
Ta	96	26		55	43	103	184	1094
Pb	234	31		140	41	38	206	1358
Th	131	53		224	145	175	419	183
U	36	15		60	48	42	61	265

Table. (Contd.)

Isotopic parameters and elements	Rare-metal alkali granite of the seventh phase, Khalzanburgetdei group of plutons							
	H-4	I-1	I-3	I-4	KhBU-4535/2	KhBU-4535/3	KhBU-4630/9	KhBU-4766/7
$^{147}\text{Sm}/^{144}\text{Nd}$	0.1745	0.1516	0.1970	0.2425	0.1435	0.1618	0.1486	0.1542
$^{143}\text{Nd}/^{144}\text{Nd}$	0.51287	0.512828	0.512948	0.51301	0.512765	0.512795	0.512792	0.512803
$\varepsilon_{\text{Nd}}(\text{T})$	5.6	6.0	6.0	5.0	5.1	4.8	5.4	5.4
$\delta^{18}\text{O}, \text{‰}$				7.0				6.3
Li	9.4	7.0	2.6	54	29			
Be	23	190	124	25	39			
Sc	7.4	2.5	3.0	3.5	13			
Ti	1241	1387	3275	1583	1473			
V	4.6	0.06	0.02	0.02	10			
Cr	2.7	1.5	1.1	0.98	17			
Co	3.6	2.5	2.6	2.1	1.6			
Ni	1.1	1.7	2.1	1.9	5.5			
Cu	1.9	1.0	1.2	3.4	9.2			
Zn	542	829	501	908	1458			
Ga	45	44	57	35	26			
Rb	285	316	373	598	546			
Sr	696	111	68	463	1440			
Y	685	901	918	365	888			
Zr	21839	6099	7954	10824	42797			
Nb	670	1666	2139	1036	983			
Cs	1.00	0.27	0.25	0.68	0.81			
Ba	108	79	36	96	261			
La	284	1199	335	225	199			
Ce	650	2741	903	588	550			
Pr	68	290	83	59	62			
Nd	255	904	309	203	230			
Sm	59	177	97	45	58			
Eu	6.5	11	6.2	2.6	4.0			
Gd	69	146	105	41	66			
Tb	15	25	23	9	17			
Dy	103	160	152	62	133			
Ho	28	35	36	15	39			
Er	103	103	104	50	141			
Tm	19	18	17	9.1	26			
Yb	128	115	94	61	178			
Lu	20	15	11	8.6	26			
Hf	614	132	193	259	1267			
Ta	50	80	88	48	80			
Pb	345	301	50	110	176			
Th	11	143	191	38	50			
U	34	54	44	28	45			

Table. (Contd.)

Isotopic parameters and elements	Rare-metal ekerite and pegmatites of the second phase of the Khan Bogd pluton							
	KhB-1247	KhB-1248	KhB-1252	KhB-1253	KhB-1376	KhB-1421	KhB-1743	KhB-1750
$^{147}\text{Sm}/^{144}\text{Nd}$	0.2213	0.1612	0.1593	0.1343	0.1524	0.0942	0.0911	0.0976
$^{143}\text{Nd}/^{144}\text{Nd}$	0.5129958	0.5129121	0.512905	0.512873	0.512894	0.5128367	0.51277268	0.5127141
$\varepsilon_{\text{Nd}}(\text{T})$	6.1	6.7	6.6	6.9	6.7	7.7	6.6	5.2
$\delta^{18}\text{O}, \text{‰}$				6.8	0.1			
Li	321	231	246	230	9.0	41	67	6.8
Be	9.5	8.9	15	15	16	14	127	30
Sc	4.5	9.3	2.4	1.0	4.6	0.34	3.8	1.5
Ti	3075	6624	1942	1770	2309	1263	1936	1891
V	14	32	2.4	0.02	75	1.6	23	15
Cr	5.3	0.1	3.8	0.1	1.8	22	0.79	0.1
Co	0.54	0.57	0.93	0.69	1.1	0.60	0.51	0.33
Ni	2.4	2.8	0.60	6.7	4.9	20	3.8	3.2
Cu	3.6	21	7.6	10	21	24	6.9	12
Zn	444	687	349	476	552	327	1217	910
Ga	44	19	33	23	6	35	72	0.01
Rb	38	304	456	294	231	21	29	58
Sr	49	110	18	18	46	9.0	134	31
Y	898	695	390	188	1111	207	4103	571
Zr	22698	17134	5980	2044	7601	1293	10625	1529
Nb	37	91	57	55	209	104	519	391
Cs	17	10	4.4	1.8	2.6	0.74	3.5	0.75
Ba	40	234	60	33	229	16	960	359
La	33	126	101	105	470	299	10279	1445
Ce	106	296	247	239	1048	693	20751	2991
Pr	15	42	35	29	155	84	2204	285
Nd	75	187	159	120	638	342	7422	1134
Sm	25	51	40	27	167	74	802	174
Eu	1.0	1.6	1.6	0.9	6.5	2.2	24	4.7
Gd	41	58	45	25	175	60	718	140
Tb	11	15	8.9	5.2	36	9.6	91	20
Dy	89	112	57	31	223	47	504	97
Ho	26	31	14	6.8	48	9.0	103	19
Er	93	115	42	21	140	24	262	52
Tm	17	22	6.6	3.5	20	3.5	38	7.5
Yb	115	170	40	24	113	21	225	47
Lu	21	30	6.3	3.8	16	2.9	34	7.1
Hf	416	490	110	60	213	27	164	35
Ta	5.1	11	6.9	3.8	20	6.8	14	4.4
Pb	33	161	24	40	152	53	1438	669
Th	9.5	15	14	20	192	55	236	71
U	16	22	14	11	48	6.5	103	39

Table. (Contd.)

Isotopic parameters and elements	Rare-metal ekerite and pegmatites of the second phase of the Khan Bogd pluton			Rare-metal alkali granite of the third phase of the Khan Bogd pluton				
	KhB-1797	KhB-1812	KhB-1818	KhB-1756	KhB-1249	KhB-1433	KhB-1747	KhB-1748
$^{147}\text{Sm}/^{144}\text{Nd}$	0.1806	0.1414	0.0950	0.1872	0.1566	0.1005	0.1903	0.1302
$^{143}\text{Nd}/^{144}\text{Nd}$	0.5129341	0.5128759	0.5127707	0.5129356	0.5128932	0.51278647	0.5129415	0.512845
$\epsilon_{\text{Nd}}(\text{T})$	6.4	6.7	6.4	6.2	6.5	6.5	6.2	6.5
$\delta^{18}\text{O}, \text{‰}$								4.6
Li	326	146	16	46	314	861	116	328
Be	13	12	20	7.7	20	90	8.8	27
Sc	6.2	4.4	2.3	4.3	6.4	2.7	3.0	8.1
Ti	7696	1330	1323	4342	2799	843	2436	3334
V	20	2.4	6.0	3.6	125	17	38	145
Cr	0.79	1.9	2.9	0.82	7.8	2.9	0.56	7.2
Co	0.35	0.35	0.66	0.47	3.20	0.73	0.62	5.8
Ni	1.0	0.27	0.05	8.7	3.2	4.6	0.54	2.6
Cu	13	2.9	2.1	9.4	16	6.3	7.0	14
Zn	275	341	324	414	466	679	207	836
Ga	23	31	0.12	8.5	11	2.7	24	2.4
Rb	511	161	244	99	180	66	307	393
Sr	58	6.5	47	37	50	85	14	68
Y	1326	142	824	401	1813	2928	553	1232
Zr	26845	1292	3535	6605	9926	8856	9735	5287
Nb	138	38	284	112	325	443	58	260
Cs	4.5	2.6	3.2	6.6	1.0	3.5	1.5	1.7
Ba	197	25	189	73	205	628	70	216
La	170	75	1762	47	596	5415	96	717
Ce	559	182	3441	155	1795	10323	402	1733
Pr	65	23	381	15	216	1109	38	170
Nd	293	99	1449	68	649	4038	184	697
Sm	91	24	232	21	168	471	53	156
Eu	3.2	0.7	7.1	0.9	6.4	14	2.0	5.2
Gd	110	23	202	30	181	410	64	139
Tb	25	4.5	32	8.0	38	62	13	27
Dy	176	27	163	61	243	328	90	155
Ho	46	5.7	33	15	58	66	22	32
Er	159	17	90	45	176	184	64	98
Tm	26	2.4	12	8.4	28	26	10	15
Yb	196	17	75	58	168	163	65	93
Lu	34	2.7	10	10	26	23	11	12
Hf	521	24	95	135	180	133	190	89
Ta	19	2.4	14	8.2	22	9.1	10	10
Pb	27	23	232	76	22	1379	11	23
Th	21	14	191	17	64	127	21	125
U	26	4.2	41	13	19	90	16	13

position was determined at the IPGG, while the O isotopic composition was measured at the Far East Geological Institute, RAS. The analytical procedures were described by Kovalenko et al. (1995, 2003b).

The initial Nd isotopic composition in rocks of the Khalzanburgetdei pluton expressed as $\epsilon_{\text{Nd}}(t)$ for 392 Ma varies from +4.4 to +6.5. This range corresponds to the moderately depleted Middle Paleozoic mantle. The relationship between $\epsilon_{\text{Nd}}(t)$ and $1/\text{Nd}$ for all rocks and ores of this pluton is shown in Fig. 9a. The $\epsilon_{\text{Nd}}(t)$ values of rare-metal granites (ores) vary between two end members of Nd isotopic compositions. One end member is characterized by the lowest $\epsilon_{\text{Nd}}(t)$ and corresponds to pantellerite of the fourth phase and syenite of the sixth phase (pantellerite–syenite group). The second end member, with the highest $\epsilon_{\text{Nd}}(t)$, corresponds to ekerite of the third phase (ekerite group). With allowance for the highly evolved character of alkali granites in comparison with any other rocks of this pluton, it may be supposed that the Nd isotopic compositions of rare-metal alkali granites are close to the parental pantellerite–syenite and ekerite groups and their sources, which may be mixtures of OIB-type sources with CC of the Early Caledonides or diverse country ophiolitic rocks in the Lake Zone of western Mongolia. Since the ophiolites include basic rocks once derived from the depleted (MORB) and metasomatized (IAB) mantle (Kovalenko et al., 1996), these sources likewise may formally participate in the formation of rare-metal granites at this deposit, but indirectly, via compositions of ophiolites, i.e., through crustal components of the sources. At the same time, island-arc magmas could not take part in the origination of alkali granites because island-arc magmatism was completed in the Lake Zone more than a hundred million years before the formation of alkali granites and the related rare-metal deposit.

A different situation is characteristic of the Khan Bogd alkali granite pluton and associated rare-metal ore occurrence (Fig. 9b). The Nd isotopic composition of rare-metal ekerite and related pegmatites of the second phase is virtually identical to that of the parental ekerite that pertains to the same phase, MIP alkali granite, and country comendite of the bimodal association. These isotopic compositions are close to the average isotopic composition of the CC in the Hercynides of southern Mongolia, represented by Devonian subduction-related island-arc associations and Carboniferous rocks of the active continental margin. As can be seen from Fig. 9b, an OIB–MORB mixture theoretically cannot be ruled out from possible magma sources of rare-metal ekerites and pegmatites of the Khan Bogd occurrence. However, the subsequent consideration (see below) shows that the contribution of these sources was not great. In contrast to the Khalzanburgetdei deposit, subduction-related magmas could have participated in the formation of rare-metal ekerites of the Khan Bogd occurrence and the alkali granite pluton as

Table. (Contd.)

Isotopic parameters and elements	Rare-metal alkali granite of the third phase of the Khan Bogd pluton		
	KhB-1793	KhB-1794	KhB-1805
$^{147}\text{Sm}/^{144}\text{Nd}$	0.1493	0.0850	0.1520
$^{143}\text{Nd}/^{144}\text{Nd}$	0.512907	0.5127584	0.5128953
$\epsilon_{\text{Nd}}(T)$	7.0	6.5	6.7
$\delta^{18}\text{O}, \text{‰}$			
Li	13	383	22
Be	15	352	10
Sc	7.2	3.8	8.7
Ti	2297	1242	2819
V	141	12	2.8
Cr	0.1	0.78	3.1
Co	1.1	0.50	0.59
Ni	3.0	0.84	0.59
Cu	28	10.0	2.4
Zn	613	3602	145
Ga	5.1	2.4	17
Rb	74	54	170
Sr	124	288	34
Y	1215	4786	765
Zr	8522	10419	39931
Nb	260	497	91.3
Cs	4.5	4.9	1.9
Ba	453	1219	64
La	536	14626	93
Ce	1378	28767	183
Pr	178	3081	24
Nd	787	10842	98
Sm	330	1486	23
Eu	11	28	0.9
Gd	309	1218	35
Tb	61	115	8.1
Dy	370	771	66
Ho	78	113	21
Er	245	293	89
Tm	38	42	22
Yb	237	251	187
Lu	36	38	36
Hf	318	113	725
Ta	31	4.5	4.0
Pb	270	1049	76
Th	323	540	11
U	53	152	40

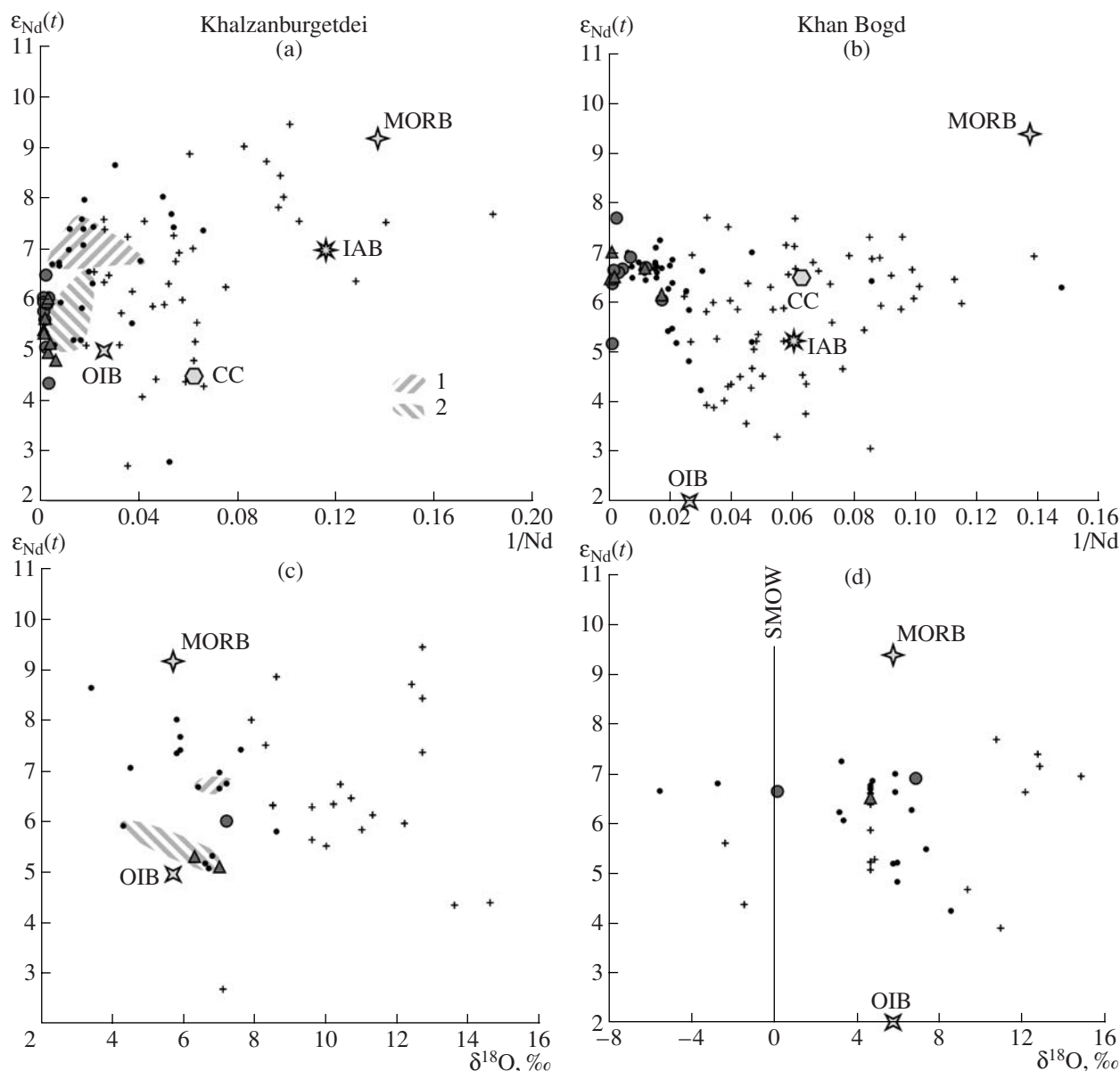


Fig. 9. $\epsilon_{Nd}(t)$ versus (a, b) $1/Nd$ and (c, d) $\delta^{18}O$ in rocks of the Khalzanburgetdei rare-metal deposit and the Khan Bogd occurrence. Fields of parental rocks of the Khalzanburgetdei deposit: (1) ekerite of the third phase and (2) pantellerite–syenite. See Figs. 5 and 6 for other symbols and the text for explanations. Model compositions of mid-ocean ridge basalts (MORB) and ocean island basalts (OIB), derivatives of the depleted and enriched mantle, respectively; average compositions of suprasubduction island-arc basalts (IAB) pertain to the Lake Zone of the Caledonides in western Mongolia (a, c) and the Hercynian island-arc and marginal continental complexes (b, d); CC is the average composition of the continental crust after (Taylor and McLennan, 1985). REE contents in MORB and OIB are given after (Sun and McDonough, 1989). See Figs. 5 and 6 for other symbols and text for explanations.

a whole because the rocks of the continental margin and the bimodal association differ in age only by 30–40 Ma. The development of subduction-related igneous rocks simultaneously with alkali granites cannot be ruled out, and, hence, subduction-related magmatic processes might have participated in the formation of the alkali granite pluton and related rare-metal varieties.

$\delta^{18}O$ in rocks of the Khalzanburgetdei deposit varies from +6 to +8‰ (Kovalenko et al., 2004b). As in the case of the Nd isotopic compositions, the $\delta^{18}O$ values

of rare-metal ore occupy an intermediate position between the oxygen isotopic compositions of the pantellerite–syenite group and ekerite of the third phase (Fig. 9c). The rare-metal alkali granites of the fifth and seventh phases are characterized by $\delta^{18}O$ of +7.2 and +6.3 to +7.0‰, respectively. In general, the rare-metal ore at the deposit and diverse igneous rocks that occur therein differ from country ophiolites by lower $\delta^{18}O$. It should be recalled that the average $\delta^{18}O$ in mantle sources is close to +5.5‰ (Pokrovsky, 2000) and occa-

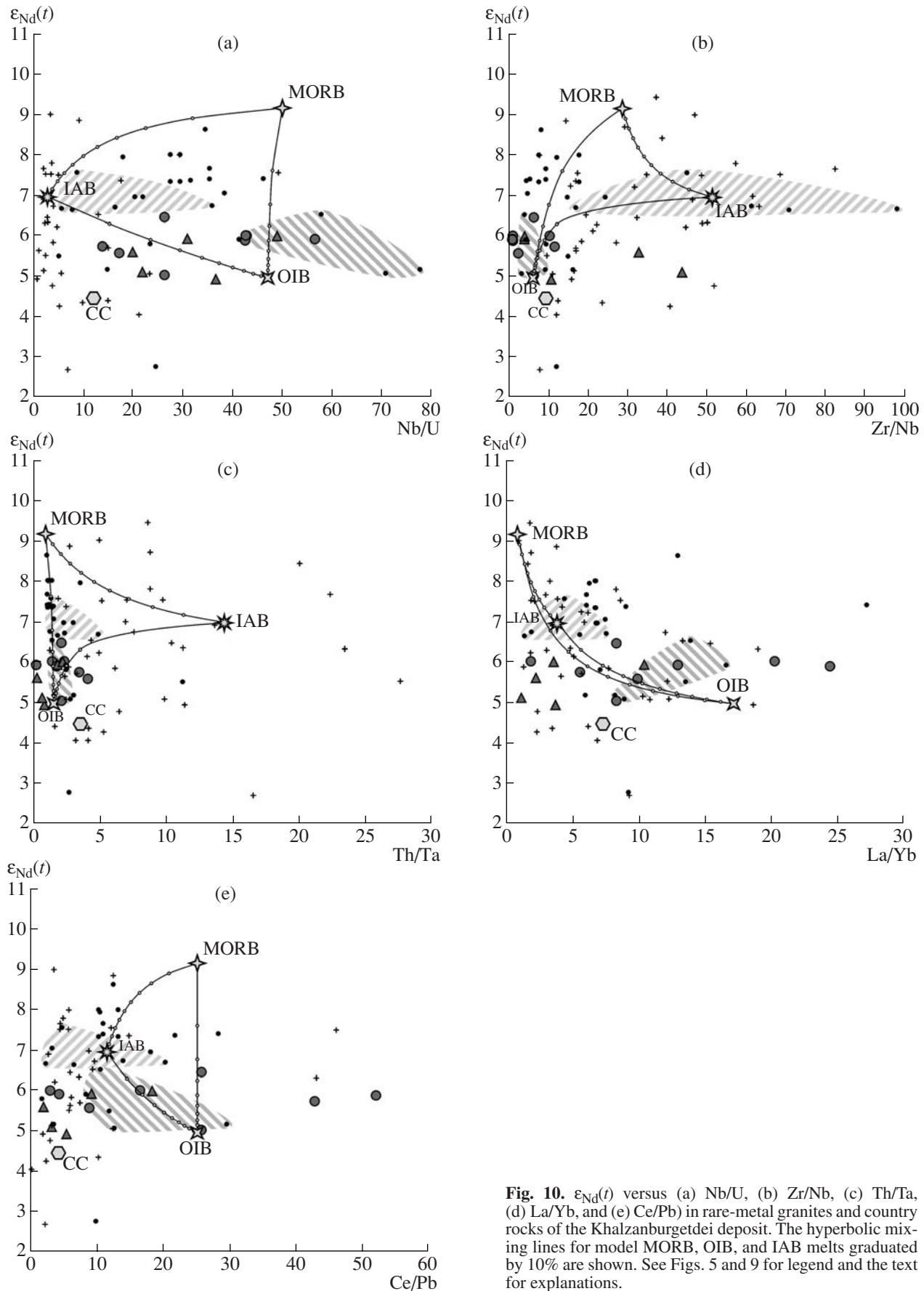


Fig. 10. $\epsilon_{Nd}(t)$ versus (a) Nb/U, (b) Zr/Nb, (c) Th/Ta, (d) La/Yb, and (e) Ce/Pb in rare-metal granites and country rocks of the Khalzanburgetdei deposit. The hyperbolic mixing lines for model MORB, OIB, and IAB melts graduated by 10% are shown. See Figs. 5 and 9 for legend and the text for explanations.

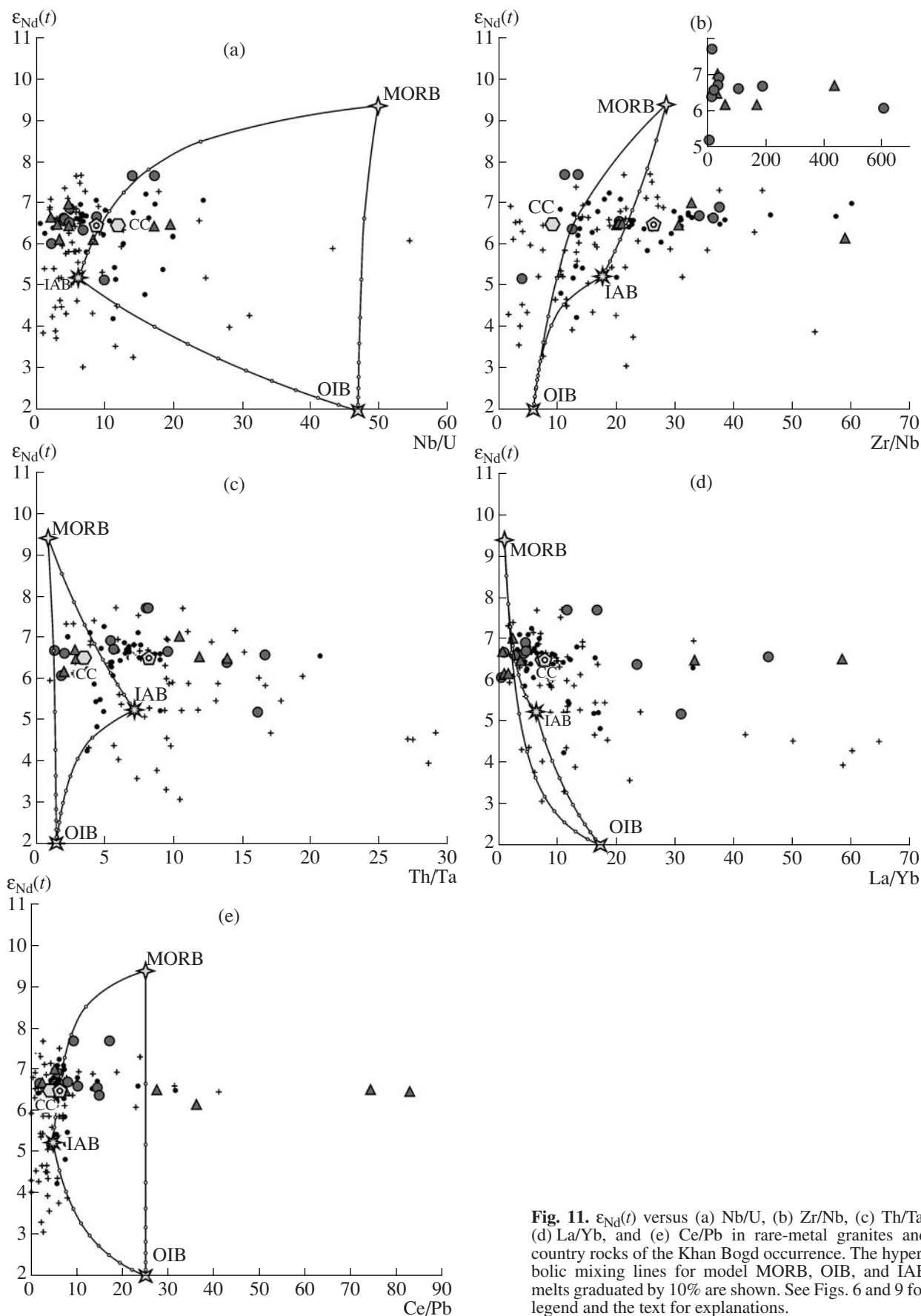


Fig. 11. $\epsilon_{\text{Nd}}(t)$ versus (a) Nb/U, (b) Zr/Nb, (c) Th/Ta, (d) La/Yb, and (e) Ce/Pb in rare-metal granites and country rocks of the Khan Bogd occurrence. The hyperbolic mixing lines for model MORB, OIB, and IAB melts graduated by 10% are shown. See Figs. 6 and 9 for legend and the text for explanations.

sionally decreases to +4.0‰. The rare-metal granites and pantellerites, obviously mantle-derived and close to the OIB source in Nd isotopic composition, demonstrate a higher level of $\delta^{18}\text{O}$. Thus, it may be assumed that components of country ophiolites with markedly higher $\delta^{18}\text{O}$ than in the mantle and rare-metal granites (ores) might have contributed to their source.

The $\delta^{18}\text{O}$ value of rocks from the Khan Bogd occurrence commonly varies from +3.1 to +7.3‰, i.e., is close to the mantle level (Fig. 9d). The same is true for the rocks of the differentiated complex of the active continental margin, where $\delta^{18}\text{O}$ is +4.6 to +4.8‰. One rare-metal ekerite sample from the fifth phase with $\delta^{18}\text{O} = 0.1\text{‰}$ falls in the field of hydrothermally altered rocks. Thus, the oxygen composition does not come into conflict with the suggestion on a subduction-related, depleted, or enriched mantle magma source of alkali granites at the Khan Bogd ore occurrence.

Relationship between $\epsilon_{\text{Nd}}(t)$ and incompatible element ratios. The distribution of trace elements in rare-metal igneous rocks of the Khalzanburgetdei group of plutons and the Khan Bogd ore occurrence is presented in the table. The relationships between the ratios of the aforementioned trace elements and $\epsilon_{\text{Nd}}(t)$ for the Khalzanburgetdei deposit are shown in Fig. 10a. In the Nb/U– $\epsilon_{\text{Nd}}(t)$ diagram, the data points of rocks, including rare-metal granites, are plotted along a near-horizontal line at a relatively constant $\epsilon_{\text{Nd}}(t)$ at a Nb/U ratio varying from 10 to 60. As was mentioned above, rare-metal alkali granite magma is generally undersaturated in U and Nb minerals. Therefore, the above-mentioned variation is caused by variable source composition rather than by magma fractionation. Taking into account the Nd isotopic composition, a source of intraplate OIB-type basalts is identified first for the parental pantellerite–syenite group of rocks. Another probable source is composed of the country island-arc complexes (IAB) derived from the metasomatized material of the mantle wedge. It is hardly accidental that the average Nb/U ratio of ~30 in the rare-metal ores of the fifth and seventh phases falls between the compositions of sources of pantellerite (Nb/U = 57) and ekerite (Nb/U = 14) or between the average compositions of OIB and country ophiolites (Nb/U = 2.8). The data points of rare-metal granitic magma occupy approximately the same position in the diagrams Zr/Nb– $\epsilon_{\text{Nd}}(t)$, Th/Ta– $\epsilon_{\text{Nd}}(t)$, La/Yb– $\epsilon_{\text{Nd}}(t)$, and Ce/Pb– $\epsilon_{\text{Nd}}(t)$ (Figs. 10b–10e, respectively). The compositions of rare-metal magmas do not spread beyond the range of average compositions of parental magmas of pantellerite–syenite and ekerite for Zr/Nb, Th/Ta, and practically La/Yb, indicating that magma fractionation even with participation of carrier minerals of the above elements exerts only a weak effect on the compositional variation of rare-metal magmas and ores. This process probably was more important in regard to the Ce/Pb ratio

because Ce and Pb contents reach saturation levels and their ratio extends beyond the limits of the pantellerite–syenite and ekerite fields. Thus, the presented diagrams indicate that the rare-metal granitic rocks of the Khalzanburgetdei deposit were derived from residual melts of the pantellerite–syenite and ekerite groups. The country island-arc complexes or their metasomatized mantle source and an enriched mantle similar to the source of intraplate OIB-type basalts were sources of these melts.

Quite different relationships are shown in Fig. 11 for the Khan Bogd ore occurrence. As can be seen from all the diagrams, many data points of rare-metal ekerites and pegmatites are plotted near the average compositions of subduction-related basic rocks localized in island arcs and at the active continental margin and the average composition of the Hercynian CC of the Central Asian Foldbelt with a small admixture of depleted material. This is especially characteristic of the Nb/U ratio (Fig. 11a) because the Nb and U contents in rare-metal granites of this ore occurrence are commonly undersaturated (Fig. 8) and the Nb/U ratio is controlled by the source composition rather than by the fractionation of Nb and U minerals. The average Nb/U ratio in rare-metal ekerites and pegmatites, equal to 5.8, is close to that in MIP alkali granite (8.9) and subduction-related basic rocks (6.3). In combination with isotopic data, this similarity may testify to genetic links between the above-mentioned rocks. Like at the Khalzanburgetdei deposit, compositional fields of rare-metal granites extend along the axis Zr/Nb, Th/Ta, La/Yb, and Ce/Pb (Figs. 11b–11e, respectively) and cross the MORB–IAB and MORB–OIB mixing lines at a relatively constant $\epsilon_{\text{Nd}}(t)$. Such wide variations for the element ratios most likely are caused by saturation of magmas with the respective elements (Fig. 8) and fractionation of the respective minerals rather than by variation in source composition (see above). According to the geological, geochemical (Nb/U), and isotopic data, the MIP alkali granites are parental rocks. The average Zr/Nb, Th/Ta, La/Yb, and Ce/Pb ratios for the parental granite are shown in Figs. 11b–11e. All these ratios, like the Nb/U ratio, are close to the model IAB component with a small admixture of MORB. Thus, as in the case of isotopic data alone, we arrive at a conclusion about genetic links of rare-metal granites of the Khan Bogd occurrence with the MIP alkali granite and a source of IAB type with an insignificant admixture of MORB.

Relationships between ratios of incompatible elements presented in the form of diagrams that involve numerous analyzed samples make it possible to judge more definitely the nature of sources of rocks and ores. The relationships between ratios of canonical pairs of incompatible elements are shown in Fig. 12 for rocks and ores from the Khalzanburgetdei deposit. As can be seen from the Nb/U vs. La/Yb diagram (Fig. 12a), the

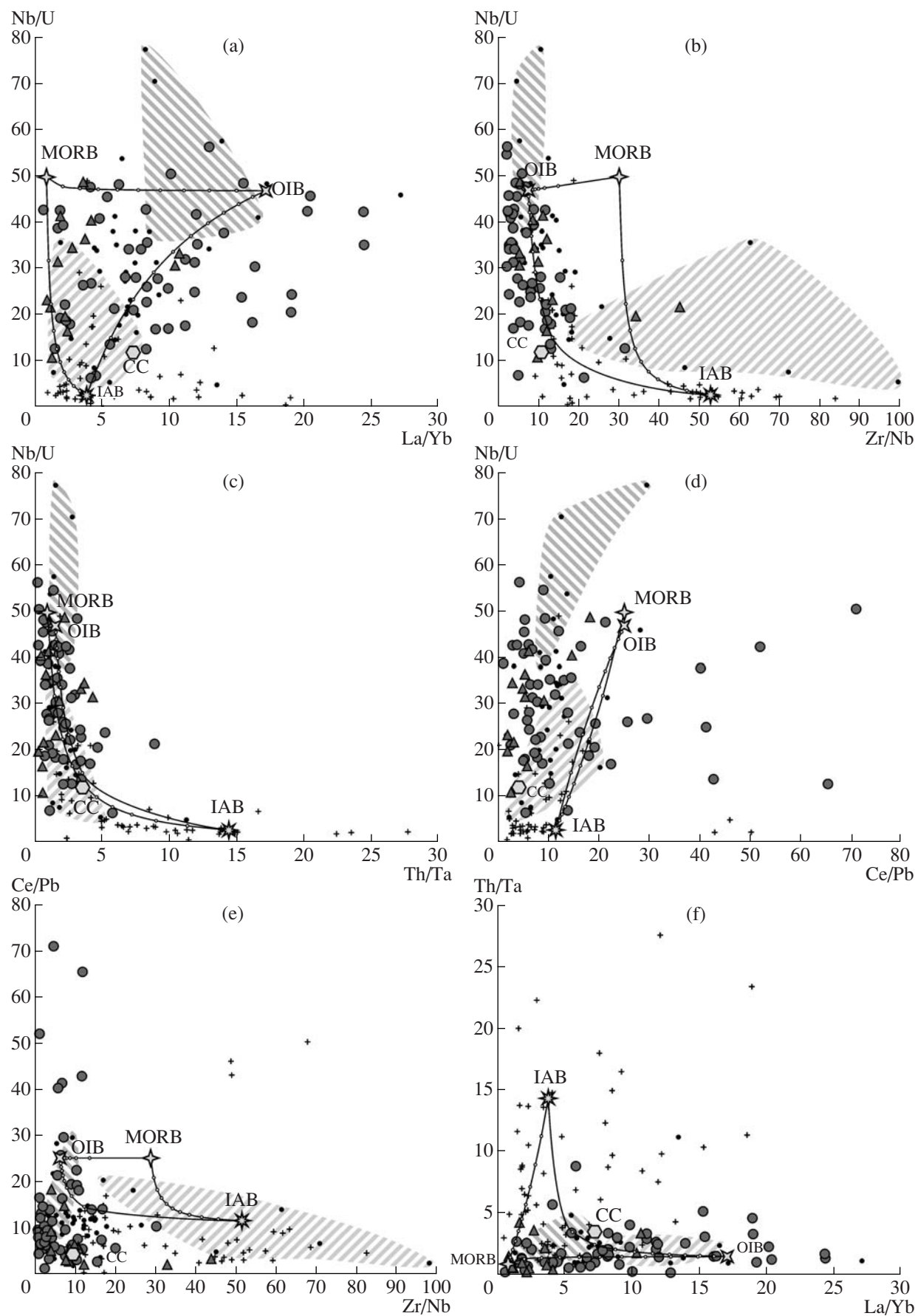


Fig. 12. Correlations between Nb/U, Zr/Nb, Th/Ta, La/Yb, and Ce/Pb ratios for rocks at the Khalzanburgetdei rare-metal deposit. The hyperbolic mixing lines for model MORB, OIB, and IAB melts graduated by 10% are shown. See Figs. 5 and 9 for legend and the text for explanations.

compositions of rare-metal ore at this deposit, as well as of parental rocks, vary between compositions of enriched (OIB), depleted (MORB), and island-arc (metasomatized) IAB mantle sources and the CC. Recall that rare-metal granitic magmas are saturated with LREE minerals and this feature can lead to both a decrease in the La/Yb ratio of the La-saturated melts and to an increase in this ratio caused by enrichment in LREE minerals as cumulates. If this was the case, at least partly, we must have intermediate values of this ratio that fall into the field of mixed sources of OIB with an admixture of MORB, as is typical of the pantellerite-syenite group of parental magma compositions, or of IAB with an admixture of CC, as is characteristic of the ekerite group of parental magmas formed with participation of country ophiolites derived, in turn, from IAB, CC, and probably MORB sources.

The overwhelming majority of rare-metal ore compositions are grouped along the hyperbolic mixing lines that control the compositions of parental pantellerite-syenite and ekerite magmas related to OIB sources with an admixture of MORB and to sources of country ophiolites with a CC admixture (Figs. 12b, 12c). Sporadic shifts of rare-metal ore compositions toward elevated Zr/Nb and Th/Ta ratios most likely are caused by accumulation of Zr and Th minerals. As a rule, such cumulates are of subordinate importance. Approximately the same patterns are typical of other canonical pairs of elements shown in Fig. 12. Thus, the rare-metal ore at the Khalzanburgetdei deposit was derived from OIB sources combined with MORB and IAB and insignificant amounts of CC. The parental pantellerite-syenite group of rocks is close to the OIB source in composition, whereas the composition of the ekerite group is close to that of the IAB source. It may be inferred that the rare-metal ore of the Khalzanburgetdei deposit is a final product of fractionation of two types of parental magmas both of which had mixed sources. The intra-plate OIB-type source is not surprising. At the same time, the participation of ophiolitic rocks in the formation of alkali granites was not expected. It is suggested that spilites or glaucophane schists as components of ophiolites could be sources of alkali granites; however, this suggestion requires experimental justification.

At the Khan Bogd occurrence, the distribution of the same incompatible element ratios in the rare-metal and parental granites (Fig. 13) differs from the distribution at the Khalzanburgetdei deposit. In contrast to the latter, the compositions of rare-metal granites, like other igneous rocks, group close to the composition of suprasubduction IAB. The compositions of rare-metal ekerites and related alkali granitic pegmatites of the second

phase, clustering near the average IAB composition, deviate toward both enriched (OIB) and depleted (MORB) sources. As in Fig. 11, the compositions of rare-metal granites are variable and often depart far from all known model sources, e.g., as concerns the La/Yb, Th/Ta, and Zr/Nb ratios (Fig. 13), owing to the same causes as at the Khalzanburgetdei deposit. In particular, the rare-metal granitic magmas of the Khan Bogd occurrence are saturated with Yb and HREE as a whole but undersaturated with LREE (Fig. 8), so that an increase in the La/Yb ratio of magma is controlled by ongoing enrichment in LREE in the course of fractionation at a constant HREE content. Therefore, in this case, the La/Yb ratio of rare-metal granites cannot be used for estimation of the source composition, which is close to the parental MIP alkali granite. The deviation of the Nb/U ratio of rare-metal granite toward higher values cannot be related to the fractionation of Nb and U minerals because of undersaturation with respect to these elements and most likely is caused by MORB or/and OIB admixtures.

The relationship Nb/U–Zr/Nb at Zr/Nb < 30 (Fig. 13b) may be a result of mixing of IAB, OIB, and MORB sources. At higher Zr/Nb values, such mixing can hardly take place because of saturation with Zr. As was mentioned, the variation of the Zr/Nb ratio from 30 to 600 at Nb/U < 10 is caused by accumulation of Zr minerals in moderately evolved magmas. Hence, the source of rare-metal magmas at the Khan Bogd occurrence is close to IAB and contains admixtures of OIB and MORB. The fractionation of these magmas resulted in growth of the Zr/Nb ratio up to 600.

The relationship shown in Fig. 13c is approximately the same as in Figs. 13a and 13b; i.e., the compositions are clustered near the average IAB composition with small admixtures of OIB and MORB and close to the MIP alkali granite. The Th content in magmas likely was close to saturation (Fig. 8), as follows from accumulation of Th minerals with deviation of the Th/Ta ratio up to 120 (Fig. 13c, inset) and depletion of melt in Th with deviation of the Th/Ta ratio down to 2 in the Th-saturated melt.

The other relationships shown in Fig. 13 also can be explained by participation of the suprasubduction source (IAB) modified by small admixtures of enriched (OIB) and depleted (MORB) sources and MIP alkali granite under conditions of accumulation of Ce, Th, and Yb minerals in the magma chamber. However, the behavior of La (Fig. 8) does not provide unambiguous evidence for accumulation of LREE.

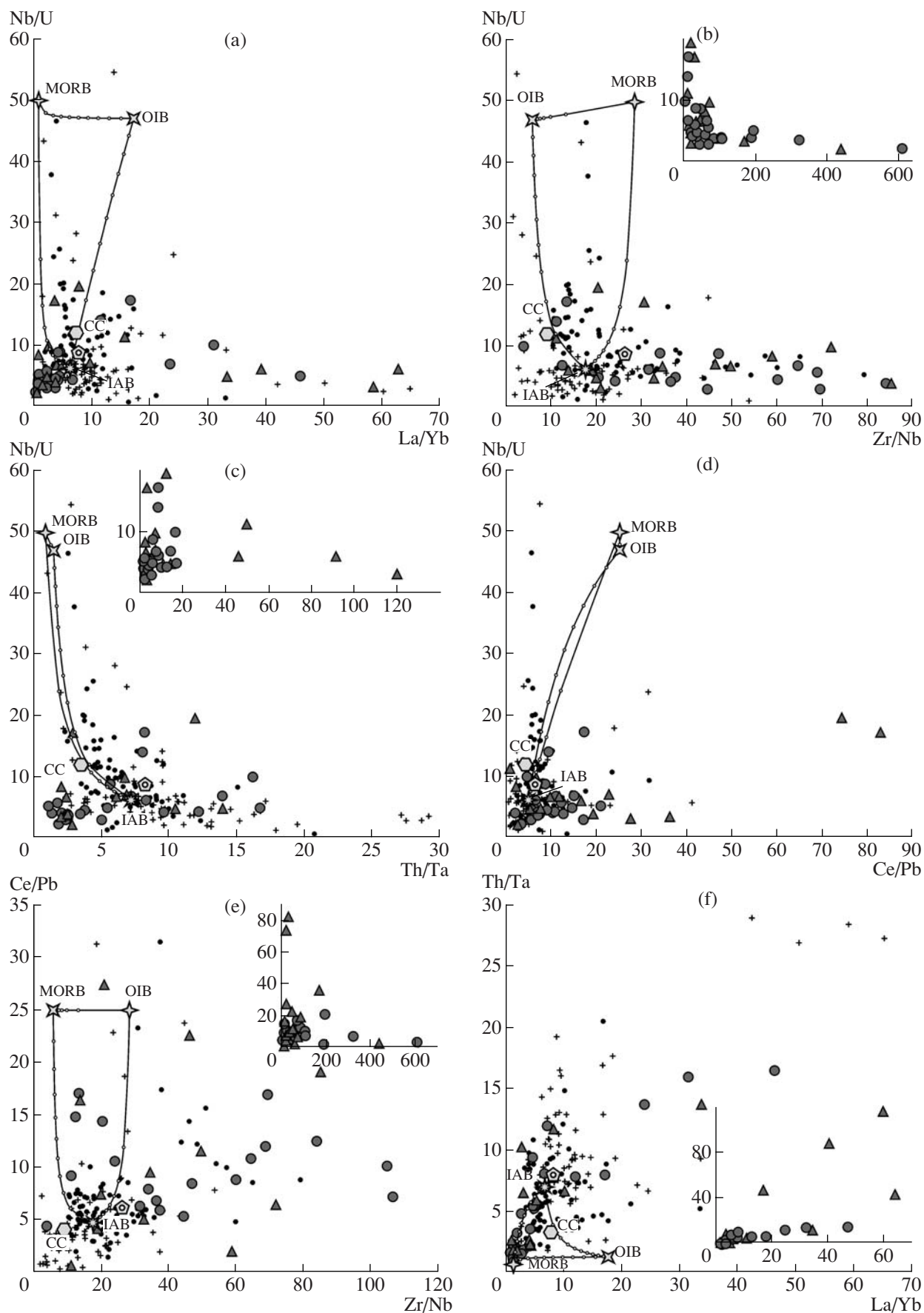


Fig. 13. Correlations between Nb/U, Zr/Nb, Th/Ta, La/Yb, and Ce/Pb ratios for rocks at the Khan Bogd rare-metal occurrence. The hyperbolic mixing lines for model MORB, OIB, and IAB melts graduated by 10% are shown. See Figs. 6 and 9 for legend and the text for explanations. The modern spelling of Mongolian proper names is used.

CONCLUSIONS

The fractionation of primary mafic magma is the most important process responsible for the formation of rare-metal alkali granites (Kovalenko, 1977). This mechanism is exemplified in classic pantellerites from Pantelleria Island as products of fractionation of hawaiite magma (Civetta et al., 1998; Kovalenko et al., 1994); peralkaline silicic lavas from Afar Rift, Ethiopia (Barberi et al., 1975); and many other cases. Some other formation mechanisms, including exotic ones, were proposed as well. For example, the origin of pantellerites was explained by partial melting of hawaiites (Mahood, 1990). Likewise, we will not dwell on the apogranitic hypothesis of the formation of rare-metal granites, which did not find support in subsequent detailed investigations (Kovalenko, 1977; Kovalenko et al., 1995). It is enough to remember only the volcanic analogues of rare-metal granites with minerals that contain melt inclusions similar to rare-metal granites in composition (Kovalenko et al., 1995) without recalling other evidence for the magmatic origin of rare-metal alkali granites.

In this paper, the possible role of crystal fractionation in the formation of the Khalzanburgetdei deposit and the Khan Bogd occurrence is demonstrated by relationships between pairs of canonical incompatible elements. As was established by Ryabchikov (1975), while the bulk partition coefficients of two elements between crystals and melts are close to each other, the contents of these elements in products of fractionation show a linear relationship. If these contents are below the level of saturation, their ratios may be used for estimation of magma source composition. The Nb–U pair is the most reliable in this respect in contrast to other trace elements that reach saturation in rare-metal granitic melts, and their ratios may be used for estimation of magma source composition only with the limitations considered above.

The most important conclusion drawn from this study concerns the polygenetic character of magma sources responsible for the formation of rare-metal alkali granites. The alkali granites and related deposits were derived from different sources and different types of melts pertaining to particular intrusive phases. The Khalzanburgetdei deposit was related to magmas derived from intraplate magma sources close to OIB sources in composition and contained an admixture of crustal material composed of various country rocks belonging to the ophiolitic assemblage. In contrast to this deposit, the Khan Bogd rare-metal occurrence was mainly related to a suprasubduction magma source, probably, with subordinate participation of an intraplate component and the depleted mantle. This source was close in composition to the average composition of the CC. The so-called fault-line metasomatic rocks were previously regarded as a possible crustal source of alkali granites. However, in light of recent data, it has

become evident that formerly existing alkali granites underwent metasomatic alteration within fault zones. The frequently observed spatial relation of alkali granites to ophiolitic belts (Map..., 1989) is noteworthy. Since glaucophane–riebeckite metamorphic rocks occur in ophiolitic complexes, the question arises of whether these rocks could be sources of crustal alkali granites. This question remains unsettled to date because of lacking experimental substantiation.

The case of the Khalzanburgetdei rare-metal deposit indicates that rare-metal alkali granites may be residual products of the long evolution of different magmas pertaining to the pantellerite–syenite and ekerite groups. It cannot be ruled out that the mixing of residual melt of different parental magmas contributed to the formation of rare-metal alkali granites. The specific implications of their contributions are yet to be studied.

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