

## Lu–Hf Isotope Composition of Zircon and Magma Sources of the Vendian–Early Paleozoic Granitoids in Tuva (by the Example of the Kaa-Khem and East Tannu-Ola Batholiths)

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**Abstract**—We present results of geochemical and Sr–Nd isotope studies of rocks and of local dating and determination of the Lu–Hf isotope composition of zircons from late Vendian–early Cambrian and Cambrian–Ordovician intrusive associations (granitoids and gabbroids) of the Kaa-Khem and East Tannu-Ola batholiths in Eastern Tuva. The wide ranges of the  $e_{\text{Nd}}$  values (6.9 to 0.5) of rocks and the  $e_{\text{Hf}}$  values of magmatic and inherited zircons reflect the diversity of the magma sources of late Vendian–early Paleozoic intrusive associations formed at the island arc and accretion–collision stages. Late Vendian (572–562 Ma, Kopto and Buren massifs) and early Cambrian (522–518 Ma, East Tannu-Ola batholith) island arc tholeiitic and calc-alkalic plagiogranitoids resulted from the melting of the Vendian–early Cambrian island arc crust without the contribution of a more ancient crustal material. The subalkalic gabbro–monzodiorite–granosyenite association of the Zubovka massif (510 Ma) formed from a mantle source depleted isotopically but enriched in incompatible elements, with the participation of an island arc crust material; this process took place in the early phase of plume activity at the accretion–collision stage. Island arc complexes were the main source of Cambrian–Ordovician accretion–collision calc-alkalic plagiogranitoids (500–450 Ma, Terektyg–Cheder, Karaos, Tapsa, Baisyut, and other massifs). Variations in their composition were due to the melting of thick crust, whose isotopic heterogeneity was caused by the different contributions of a more ancient crustal source. The crust of the Tuva–Mongolian terrane made the main contribution to the formation of the potassic granitoids of the Bren' massif (450 Ma), marking the completion of accretion–collision processes in this region. The isotope parameters of the Vendian–early Paleozoic granitoids are indicators of the crust formation and evolution in the course of subduction and accretion–collision processes.

**Keywords:** Early Caledonides; granitoid and basic magmatism; geochemistry; isotopy; Altai–Sayan folded area; Eastern Tuva

### INTRODUCTION

Batholiths are a typical component of the early Caledonian structures of the Central Asian Orogenic Belt (CAOB). They form large areas at the present-day erosional truncation (Fig. 1, inset A) among Vendian–early Cambrian volcanic and volcanosedimentary deposits. These areas have an intricate structure and are characterized by long-term magmatism, different geodynamic settings of formation, diverse rocks (granitoids and gabbroids), and their varying chemical compositions.

The East Tuva batholiths (Kaa-Khem, East Tannu-Ola, Khamsara, Bii-Khem, Fig. 1, inset B) are the largest in the Altai–Sayan folded area. They form large magmatic areas in the early Caledonian structures of the Tannu-Ola island arc. The batholiths are made up of granitoid and gabbroid associations formed at the island arc (572–518 Ma) and accretion–collision (512–450 Ma) stages of the regional evolution (Kovalev et al., 1997; Kozakov et al., 1998, 1999; Rudnev et al., 2004a,b, 2006, 2013, 2015; Mongush et al., 2011b; Sugorakova, 2011; Mongush and Sugorakova, 2013). The late Vendian–early Paleozoic granitoid associations of the batholiths are of different geochemical types (*M*-, *I*-, and *A*-types), with a predominance of low-K *I*-granites. According to the geochemical composition of granit-

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oids, the parental melts for predominant plagiogranites resulted from the partial melting of metabasites at 3–8 and >10–12 kbar in equilibrium with amphibole- and garnet-containing restites, respectively (Rudnev et al., 2015). The Sr–Nd isotope parameters of the granitoid and gabbroid associations formed at the island arc and accretion–collision stages (Kaa-Khem and East Tannu-Ola batholiths) point to the essentially juvenile composition of the initial substrates and different contributions of a more ancient crustal material (Kozakov et al., 1998, 1999; Rudnev et al., 2006, 2015; Mongush et al., 2011b).

Since the Nd isotope composition of granitoids provides average characteristics of magma-forming substrates, it does not permit a correct assessment of the contribution of sources of different compositions and ages to the rock formation. Today, data on the Hf isotope composition of zircons from granitoids are used to elucidate the nature of magma sources and the role of mixing processes in the rock formation. Study of zircons shows wide variations in Lu–Hf isotope parameters in some grains and zones, which are explained by granite formation as a result of the mixing of melts from different sources or the interaction of mantle-related melts and continental-crust material (Griffin et al., 2002; Belousova et al., 2006; Yang et al., 2007; Turkina and Kapitonov, 2017). The variation in the isotope composition of zircons from granitoids of the same belt indicates the heterogeneous composition of the melting crust (Kemp et al., 2007; Kurhila et al., 2010; Shaw et al., 2011; Villaseca et al., 2012; Turkina and Kapitonov, 2019). The developed local-analysis methods make it possible to get important information about the type of crustal sources from the age and isotope composition of inherited zircon cores in granites.

In this work we perform a local study of the Lu–Hf isotope composition of zircon generations of different ages from the late Vendian and early Paleozoic granitoid and gabbroid associations of the Kaa-Khem and East Tannu-Ola batholiths in Eastern Tuva. The objects for study were chosen based on the fact that the batholith granitoids formed in different geodynamic settings (island arc and accretion–collision ones) for more than 100 Myr and have different petrogeochemical compositions and wide variations in isotope parameters, which indicates compositionally different magma sources. The main goal of this research was to elucidate the most likely sources of melts for granitoid and gabbroid associations of these batholiths, invoking new data on the Lu–Hf isotope parameters of magmatic and xenogenic zircons.

## THE TECTONIC POSITION AND STRUCTURE OF THE EAST TUVA BATHOLITHS

The late Vendian–early Paleozoic batholiths in Eastern Tuva (Kaa-Khem, East Tannu-Ola, Khamsara, and Bii-Khem) are the largest in the CAOB. They are localized mainly in the early Caledonian structures of the Tannu-Ola

island arc in the southwestern folded framing of the Siberian Platform (Fig. 1, inset A). The batholiths are hosted by the late Vendian volcanic rocks of the Kadvoi and Ondum formations (basalts, basaltic andesites, andesites, plagioryholites, and their tuffs) and early Cambrian volcanic rocks of the Irbitei, Serlig, and Tapsa formations (basalts, basaltic andesites, andesites, plagioryholites, porphyrites, dacites, rhyolites, and their tuffs) with subduction-related geochemical characteristics (Mongush et al., 2011b) and by the metamorphic and sedimentary rocks (presumably of Proterozoic age) of the Tuva–Mongolian composite terrane. The batholith granitoid and gabbroid associations differ in geodynamic setting, chemical composition, and age (Kozakov et al., 1998, 1999; Sotnikov et al., 2003; Borodina et al., 2004; Rudnev et al., 2006, 2015; Sugorakova, 2011; Mongush et al., 2011b; Mongush and Sugorakova, 2013). The sequence of formation of the granitoids and gabbroids of the Kaa-Khem and East Tannu-Ola batholiths and their ages and geodynamic settings are presented in Table 1. Diorite–tonalite–plagiogranite and granodiorite–granite rocks are predominant intrusions; they form plutons and massifs. Rocks of mafic and intermediate compositions are subordinate; these are the peridotite–pyroxenite–gabbronorite association of the Mazhalyk complex (Mazhalyk, Brungan, Kalbagdag, Shuya, and other massifs) and the gabbro–monzodiorite–granosyenite association of the Zubovka complex (Zubovka and other massifs). The available geological and geochronological (U–Pb and Ar–Ar) data (Kozakov et al., 1998, 1999; Sal’nikova et al., 2003; Borodina et al., 2004; Rudnev et al., 2004a,b, 2006, 2015; Mongush et al., 2011b; Mongush and Sugorakova, 2013; Rudnev, 2013) indicate that granitoid and basic magmatism occurred in the Kaa-Khem and other batholiths in several epochs (571–562, 522–518, 514–490, 485–470, and 460–450 Ma, Table 1).

**The island arc stage** (572–518 Ma). Two periods of island arc magmatism were established in the Kaa-Khem and East Tannu-Ola batholiths: late Vendian (572–562 Ma) and early Cambrian (522–518 Ma) (Rudnev et al., 2015). In the late Vendian, plagiogranitoid magmatism was locally manifested. It is recorded as a chain of small massifs (Kopto, Buren, etc.) within the Kaa-Khem batholith (Fig. 1), which probably mark fragments of a late Vendian island arc preserved in younger (Cambrian–Ordovician) granitoids. There are no geochronological data on the Vendian gabbroids of the Kaa-Khem area. According to the geological data, large xenoblocks and xenoliths of altered peridotites, pyroxenites, and gabbronorites are present among the younger plagiogranitoids of the Kopto and Buren massifs. In addition, gabbroids of Vendian age (560–570 Ma) were found in the ophiolite belts of the Kaa-Khem zone in the northern framing of the Kaa-Khem batholith, in the Agardag zone of the West Sangilen upland, and in the Kurtushiba zone of Western Tuva. They are fragments of late Vendian island arcs (Kurenkov et al., 2002; Pfänder et al., 2002; Mongush et al., 2011a). In the early Cambrian (522–518 Ma), granitoid

**Table 1.** Sm–Nd isotope data for Vendian–early Paleozoic intrusive associations of the Kaa-Khem and East Tannu-Ola batholiths in Eastern Tuva

Sample	Massif (association, geochemical type)	U–Pb age, Ma	$\varepsilon_{\text{Nd}}(T)$	$T_{\text{Nd}}(\text{DM})$ , Ma	Reference
<b>Island arc complexes</b>					
D675/1	Buren (diorite–tonalite–plagiogranite, <i>M</i> -type, <Al)	572 ± 3 536 ± 4*	6.4 —	—	(This paper) (Rudnev et al., 2013, 2015)
D828	Kopto (diorite–tonalite–plagiogranite, <i>M</i> -type, <Al)	562 ± 4	6.5	—	(Rudnev et al., 2006, 2013, 2015)
TI-126	Irbitei (peridotite–gabbronorite)	539 ± 6*	7.8	—	(Mongush et al., 2011)
RT-10	Framing of the Irbitei gabbroid massif	522 ± 4	6.9	686	(Rudnev et al., 2015)
RT-8/5	(diorite–tonalite–plagiogranite, <i>I</i> -type, <Al)	520 ± 2	—	—	(This paper)
T-1		518 ± 2	6.9	—	(Mongush et al., 2011)
<b>Accretion–collision complexes</b>					
D35	Zubovka (gabbro–monzodiorite, <i>A</i> -type)	510 ± 3 4.7 514 ± 2*	5.3 4.7 2.6	811 864 1036	(This paper) (This paper) (Rudnev et al., 2006; Rudnev, 2013)
D108	Terektyg–Cheder (tonalite–plagiogranite, <i>I</i> -type, >Al)	499 ± 5	6.2	727	(Rudnev et al., 2015)
D22666	Karaos (diorite–tonalite–plagiogranite, <i>I</i> -type, >Al)	490 ± 3	5.7	767	(Rudnev et al., 2015)
	Mazhalyk (peridotite–gabbronorite)	484–480	5.2	—	(Borodina et al., 2004) (Sal'nikova et al., 2004)
D895	Tapsa (diorite–tonalite–plagiogranite, <i>I</i> -type, <Al)	486 ± 4	5.3	790	(Rudnev et al., 2015)
D634	Framing of the Baisiyut massif (diorite–tonalite–plagiogranite, <i>I</i> -type, <Al)	480 ± 2	4.1	884	(Rudnev et al., 2006, 2015)
D624	Baisiyut (diorite–tonalite–plagiogranite, <i>I</i> -type, >Al)	474 ± 5	3.9	898	(Rudnev et al., 2006)
1526	Shuya (peridotite–gabbronorite)	449 ± 4	2.7	—	(Mongush et al., 2013)
D1000	Granitoid outcrops in the Unzhei Village region	450 ± 5	—	—	(This paper)
5563	(diorite–tonalite–plagiogranite, <i>I</i> -type, <Al)	451 ± 6	3.4	921	(Kozakov et al., 2003)
D1019e	Bren'	450 ± 5	1.7	1064	(Rudnev et al., 2006)
5561	Baibalyk (granodiorite–granite, <i>I</i> -type)	450 ± 4	0.5	1165	(Kozakov et al., 2003)
5742	Samagaltai–Shuurmak pass (diorite–tonalite–plagiogranite, <i>I</i> -type)	457 ± 3	4.5	—	(Kozakov et al., 2003)

Note. For the massif location, see Fig. 1. <Al, low-alumina plagiogranitoids, >Al, high-alumina plagiogranitoids, after Arth's (1979) classification.

\* Ar–Ar amphibole ages (Rudnev et al., 2006).

magmatism was of large-scale occurrence. At the recent erosional truncation, its products form large areas within the East Tannu-Ola batholith (Fig. 1). The Irbitei pyroxenite–gabbro massif (539 ± 6 Ma (Mongush et al., 2011b)) located in the western margin of the East Tannu-Ola batholith is the best studied among the early Cambrian batholith gabbroids. The massif rocks are intruded by plagiogranitoids with an age of 522–518 Ma (Rudnev, 2013; Rudnev et al., 2015), which are the youngest products of the early Cambrian island arc magmatism in this region.

The accretion–collision stage (512–450 Ma) of formation of the East Tuva Caledonides was characterized by large-scale granitoid magmatism, which resulted in both diorite–tonalite–plagiogranite and granodiorite–granite associations (Table 1). Gabbroids that formed at this geody-

namic stage (Zubovka gabbro–monzodiorite massif, 514–510 Ma; Mazhalyk and Shuya pyroxenite–gabbro massifs, 484 ± 2 and 449 ± 4 Ma, respectively) (Borodina et al., 2004; Rudnev et al., 2004a; Rudnev, 2013; Mongush and Sugorakova, 2013) mark different stages of plume magmatism in this and adjacent areas and the formation of Large Igneous Provinces (LIPs) in Central Asia in the late Cambrian–Ordovician (Izokh et al., 1998; Vladimirov et al., 1999; Yarmolyuk et al., 2000; Izokh and Polyakov, 2009). These basic intrusions of different ages and compositions might have been the main source of heat (and, probably, of substance) that repeatedly warmed the collisional structure at different depths and favored the generation of progressively larger volumes of felsic melts (Rudnev et al., 2015).

## PETROGEOCHEMICAL AND Sr–Nd ISOTOPE CHARACTERISTICS OF VENDIAN–EARLY PALEOZOIC INTRUSIVE ASSOCIATIONS OF EASTERN TUVA, THEIR FORMATION CONDITIONS, AND THE MELT SOURCES

The Kaa-Khem and East Tannu-Ola batholiths include the following rock associations: diorite–tonalite–plagiogranite, granodiorite–granite, pyroxene–gabbro, and gabbro–monzodiorite. By petrochemical composition, the granitoids are assigned to tholeiitic (*M*-type), calc-alkalic (*I*-type), and subalkalic (*A*-type) series (Rudnev et al., 2006, 2015; Mongush et al., 2011b; Rudnev, 2013). The *I*-type plagiogranites are subdivided into low- and high-alumina varieties, which differ in the *P*–*T* conditions and tectonic setting of formation (Arth, 1979; Drummond and Defant, 1990; Beard and Lofgren, 1991; Rapp and Watson, 1995; Drummond et al., 1996; Turkina, 2000; Martin et al., 2005; Castillo, 2006).

The late Vendian (572–562 Ma) island arc diorite–tonalite–plagiogranite associations of the Buren and Kopto massifs (Kaa-Khem batholith) are tholeiitic rocks (*M*-type). They are characterized by low total contents of alkalies (Fig. 2a) and low contents of K<sub>2</sub>O (Fig. 2b), trace elements, and REE, low (La/Yb)<sub>N</sub> values (1.0–0.4), and negative Nb, Ta, and Ti anomalies in multielement patterns (Figs. 2 and 3). In the Ab–An–Or diagram (Fig. 2c), the massif rocks fall in the fields of tonalites and trondhjemites. These rocks are of low-alumina type; they resulted from the partial melting of metabasites at 3–7 kbar (Fig. 2e) in equilibrium with the Pl + Cpx + Opx restite in the basement or in the lower parts of the island arc system (Rudnev et al., 2015).

The early Cambrian (522–518 Ma) island arc diorite–tonalite–plagiogranite associations of the East Tannu-Ola batholith (framing of the Irbitei gabbroid massif) are assigned to calc-alkalic series (*I*-type). They are characterized by higher contents of alkalies, K<sub>2</sub>O (Fig. 2), and (La/Yb)<sub>N</sub> values (1.6–5.1, Fig. 3) as compared with the tholeiitic plagiogranitoids. In composition they correspond to low-alumina plagiogranites (Fig. 2e) whose parental melts resulted from the partial melting of metabasites at ~8 kbar in equilibrium with the Hbl + Pl ± CPx ± Opx restite.

The late Vendian and early Cambrian island arc plagiogranitoids (Mongush et al., 2011b; Rudnev et al., 2015) show high ε<sub>Nd</sub> values (6.9–6.4) (Table 1, Fig. 4), which indicates that their metabasic sources were generated from the depleted mantle.

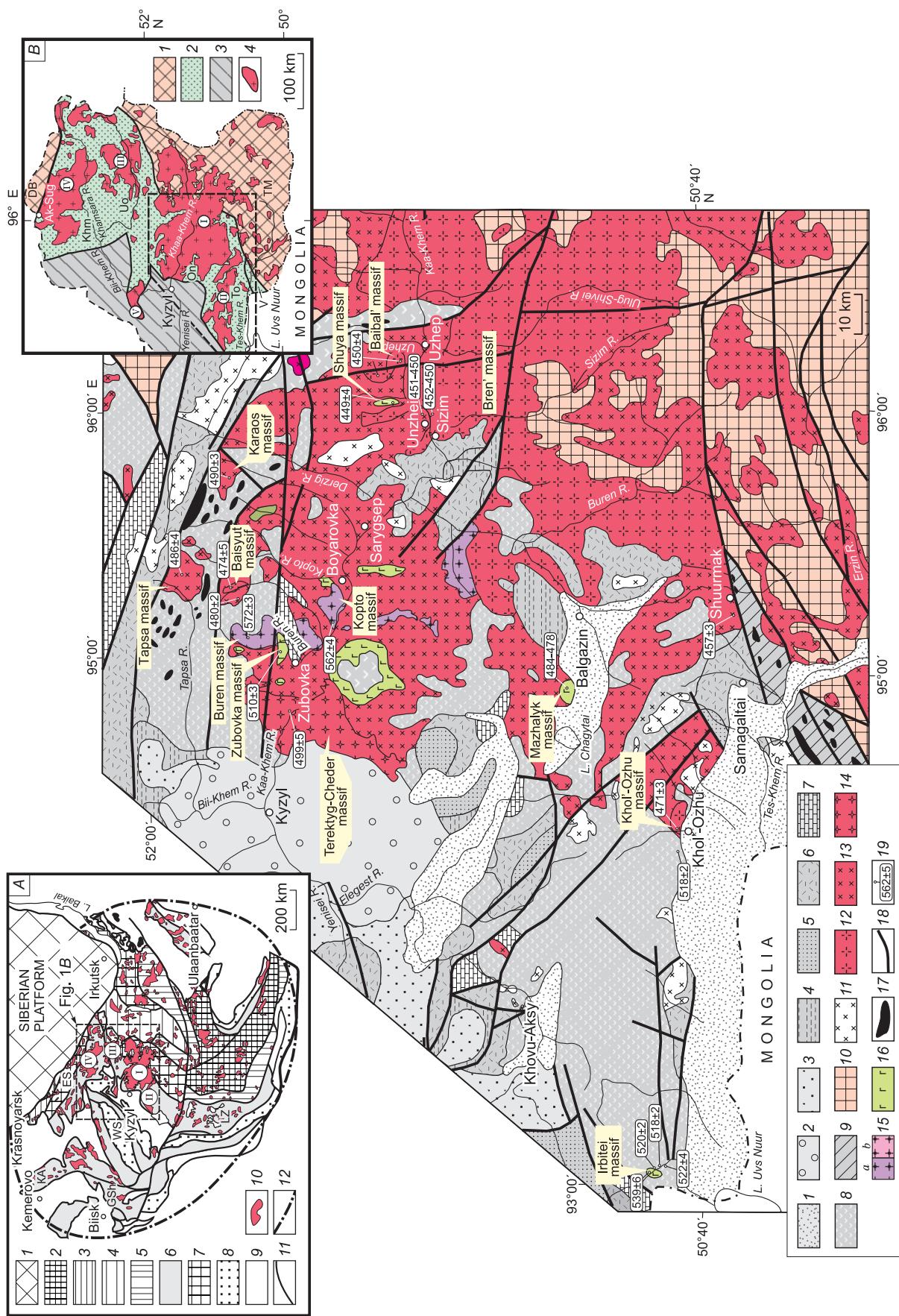
Diorite–tonalite–plagiogranite and granodiorite–granite associations of calc-alkalic series are the main rocks that formed at the accretion–collision stage (514–450 Ma). Gabbroid associations (Zubovka, Mazhalyk, and Shuya massifs) are subordinate; their chemical composition is considered elsewhere (Kovalev, 1990; Kovalev et al., 1997; Borodina et al., 2004; Rudnev et al., 2006; Mongush and Sugorakova, 2013).

The rocks of the gabbro–monzodiorite–granofelsite association of the Zubovka massif (514–510 Ma) were the first

to form at the accretion–collision stage. They break through the host Vendian–early Cambrian volcanic deposits and island arc plagiogranitoids of late Vendian (Buren massif, ~572 Ma) and early Cambrian ages and are intruded by younger (499–474 Ma) plagiogranitoids (Fig. 1). According to petrogeochemical composition (Figs. 2 and 3), these are subalkalic rocks (*A*-type) with high contents of Na<sub>2</sub>O + K<sub>2</sub>O, K<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, Nb, Ta, Rb, Sr, Ba, Zr, and Hf and domination of LREE over HREE ((La/Yb)<sub>N</sub> = 15.9–20.9). In the Y/Nb–Yb/Ta diagram (Fig. 2d), their composition points are confined to the field of OIB. The rocks of the Zubovka massif show wide variations in ε<sub>Nd</sub> values (gabbro – 5.3, monzodiorites – 4.7–2.6). The high contents of HFSE (Nb, Ta) in the massif rocks point to the major contribution of enriched-mantle melts, whereas the high ε<sub>Nd</sub> values indicate an isotope-depleted source. The massif rocks might have formed during the fractional crystallization of mafic melts or the melting of metabasites produced from a mantle source enriched in incompatible elements.

The plagiogranitoid associations of the accretion–collision stage in the Kaa-Khem and East Tannu-Ola batholiths are of high- and low-alumina types (Rudnev et al., 2015). The high-alumina plagiogranitoids (Terektyg–Cheder, Karaos, Baisyut, and Khol’-Ozhu massifs, 500–471 Ma, Table 1, Fig. 1) are the oldest. As seen from the SiO<sub>2</sub>–(Na<sub>2</sub>O + K<sub>2</sub>O) and SiO<sub>2</sub>–K<sub>2</sub>O diagrams (Fig. 2), these are normal rocks with medium K<sub>2</sub>O contents. They are also characterized by high total REE contents, domination of LREE over HREE ((La/Yb)<sub>N</sub> = 7–32), high Sr/Y ratios (29–199), and negative Nb, Ta, and Ti and positive Sr anomalies in multielement patterns (Fig. 3). According to these parameters, the parental melts resulted from the partial melting of metabasites at >10–12 kbar in equilibrium with the Hbl + Cpx + Pl ± Grt restite in the basement of the crust thickened under collision. The low-alumina plagiogranitoid associations occur as small intrusions (Tapsa massif, Baisyut massif framing, Unzhei Village and Samagaltau Village regions, 486–451 Ma). They are characterized by higher contents of trace and rare-earth elements and lower (La/Yb)<sub>N</sub> (5–10) and Sr/Y (18–59) values as compared with the high-alumina plagiogranitoids. In the Eu–Yb diagram (Fig. 2e), these rocks fall in the composition field of plagiogranitoids whose parental melts resulted from the partial melting of metabasites at ~8 kbar in equilibrium with the Hbl + Pl ± CP ± OPx restite. In passing from older to younger high- and low-alumina plagiogranitoid associations (from 499 to 451 Ma), their ε<sub>Nd</sub> values regularly decrease from 6.2 to 3.4, and the model Nd ages increase from 0.73 to 0.92 Ga. The isotope data along with the geochemical features of the granitoids indicate that the parental melts resulted from the melting of metabasites formed from a depleted mantle source.

The rocks of the granodiorite–granite association (Sarkhoi complex (Rudnev et al., 2004b, 2006; Rudnev, 2013)) of the Bren’, Baibalyk, Karga, and other massifs complete the early Paleozoic stage of evolution of intrusive magmatism in Eastern Tuva (452–450 Ma). In petrochemical com-



**Fig. 1.** Schematic geological map of the Kaa-Khem and East Tannu-Ola granitoid batholiths in Eastern Tuva (Podkamenniy and Sherman, 1983), with results of geochronological dating of granitoids and gabbroids, after Kozakov et al. (1998, 2001, 2003), Rudnev et al. (2006, 2013, 2015), Mongush et al. (2011b), Sugorakova (2011), Mongush and Sugorakova (2013), and Rudnev (2013). *Stratified deposits:* 1, Quaternary; 2, Jurassic sedimentary and terrigenous; 3, early and late Carboniferous sedimentary and carbonate; 4, Late Devonian red-colored sedimentary; 5, Early and Middle Devonian sedimentary and volcanosedimentary; 6, Early Devonian volcanic; 7, Silurian terrigenous and carbonate; 8, undivided Vendian–early Cambrian volcanic and volcanosedimentary; 9, Vendian–early Cambrian volcanic and volcanosedimentary, of the Agardag zone; 10, Precambrian metamorphic, of the Tuva–Mongolian terrane; *intrusive deposits:* 11–14, granitoid associations of the accretion–collision stage,  $\text{C}_3\text{-O}_3$ ; 11, Bren' granodiorite–granite–leucogranite complex,  $\text{D}_1$ ; 12, diorite–granodiorite–granite association of the Starkhoi type,  $\text{O}_3$ ; 13, undivided low-alumina diorite–tonalite–plagiogranite associations of calc-alkalic series (*J*-type),  $\text{C}_3\text{-O}_3$ ; 14, high-alumina diorite–tonalite–plagiogranite associations of calc-alkalic series (*J*-type),  $\text{C}_3\text{-O}_3$ ; 15, granitoid associations of the island arc stage: *a*, late Vendian low-alumina diorite–tonalite–plagiogranite associations of tholeiitic series (*M*-type),  $\text{b}$ , early Cambrian low-alumina diorite–tonalite–plagiogranite associations of calc-alkalic series (*J*-type); 16, undivided peridotite–pyroxenite–gabbro–monzonodiorite and gabbro–monzonodiorite associations,  $\text{V-O}_3$ ; 17, mafic and ultramafic deposits of ophiolite type,  $\text{V}$ ; 18, disjunctions; 19, sampling localities and results of U–Pb (zircon) dating of granitoids and gabbroids (Ma), after Kozakov et al. (1998, 2003), Rudnev et al. (2006, 2015), Mongush et al. (2011b), Sugorakova (2011), Mongush and Sugorakova (2013), and Rudnev (2013).

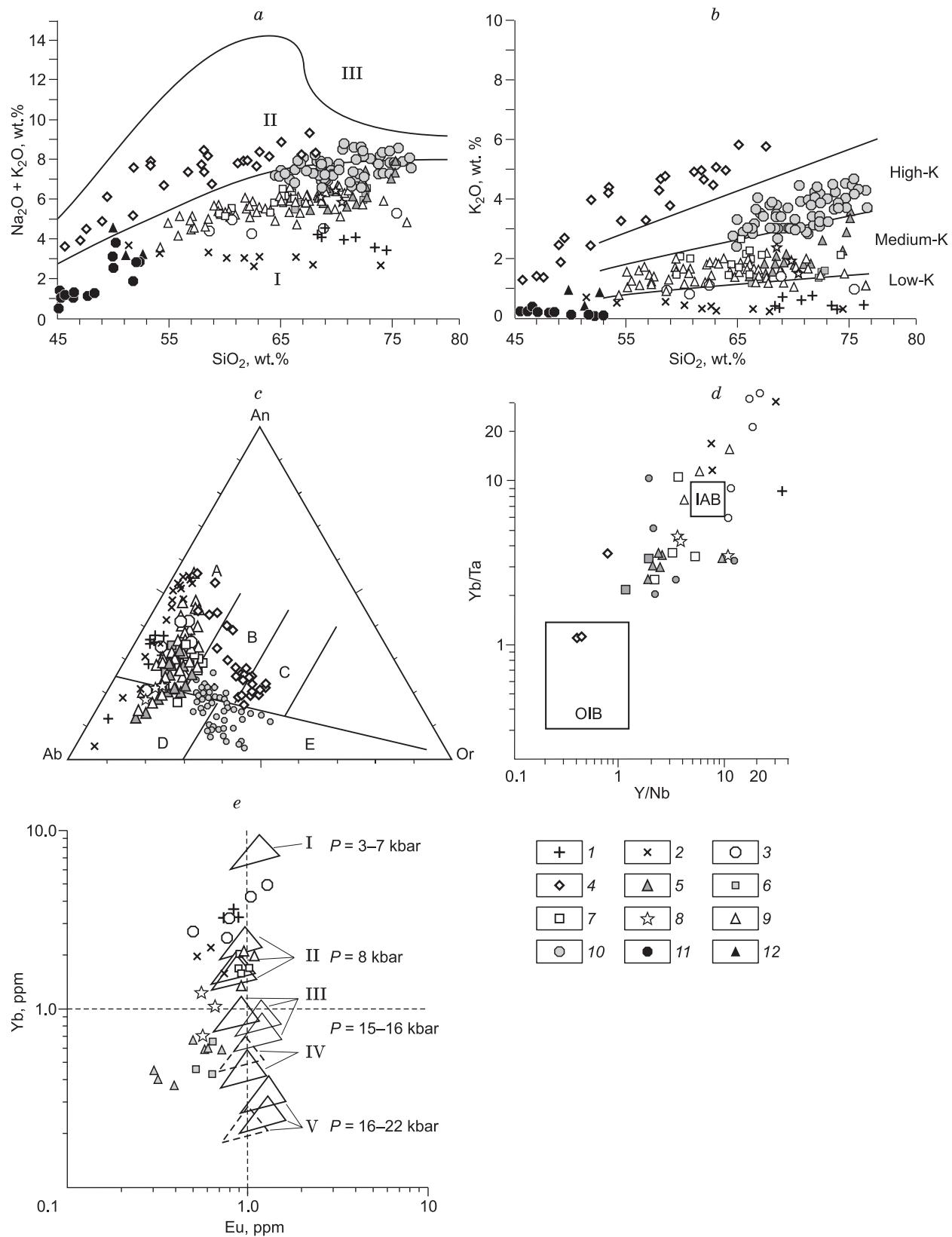
Inset A shows the location of early Paleozoic granitoid batholiths of the CAOB: 1, Siberian Platform; 2, microcontinents with a Riphean terrigenous–carbonate cover; 3, rift complexes ( $\text{R}_3$ ); 4–6, island arc complexes; 4, late Riphean, 5, Vendian, 6, Cambrian; 7, terranes with early Caledonian crust remobilization; 8, orogenic molasses ( $\text{C}_3\text{-O}$ ) and sedimentary basins ( $\text{O-S}$ ); 9, middle Paleozoic and early Mesozoic geologic complexes; 10, granitoid batholiths; 11, major faults; 12, boundaries of a Large Igneous Province (LIP) (Rudnev, 2013; Rudnev et al., 2015). Rectangle marks granitoid batholiths: I, Kaa-Khem, II, East Tannu-Ola, III, Bii-Khem, IV, Khamsara, ES, East Sayan; GSh, Gornaya Shoria; WS, West Sayan; KA, Kuznetsk Alatau; LZ, Lake Zone. Inset B shows a scheme of tectonic zonation of Eastern Tuva: 1, Precambrian deposits of the Tuva–Mongolian massif (TM) and Derbina block (DB); 2, early Caledonides (subzones: On, Ondum, To, Tannu-Ola, Khm, Khamsara, Uo, Ulugoi, and Ag, Agardag); 3, late Caledonides and Hercynides; 4, early Paleozioc batholiths (I, Kaa-Khem, II, East Tannu-Ola, III, Bii-Khem, IV, Khamsara, V, Ozhu). Framed zone marks the area of geological and geochronological studies of granitoids and gabbroids of the Kaa-Khem and East Tannu-Ola batholiths.

position they are intermediate between calc-alkalic and subalkalic high-K granitoids, being closer to the former. In the granodiorite–granite–leucogranite series, the  $\text{K}_2\text{O} + \text{Na}_2\text{O}$  content regularly increases, mainly at the expense of  $\text{K}_2\text{O}$ . In the Ab–An–Or diagram, the rocks of these massifs form a field oriented toward the orthoclase trend of the crystallizing melt. They are characterized by domination of LREE over HREE ( $(\text{La/Yb})_N = 7.7\text{--}12.6$ ) and by negative Eu, Nb, Ta, and Ti anomalies in the multielement patterns. The granitoids have low  $\varepsilon_{\text{Nd}}$  values (1.7–0.5) and a Meso-proterozoic model age (1.2–1.1 Ga). In the  $\varepsilon_{\text{Nd}}(T)$ –age diagram (Fig. 4), their Nd isotope composition points lie between the fields of the island arc volcanic complexes of Eastern Tuva and the Precambrian rocks of the Tuva–Mongolian terrane. This means that the parental melts for the granodiorite–granite association of the Bren' and other massifs might have formed with a significant input of ancient crustal (probably sedimentary) material to the magma generation zone.

## METHODS

U–Pb zircon dating was carried out by LA-ICP-MS at the Analytical Center for Multi-Elemental and Isotope Research, SB RAS, Novosibirsk, and with a SHRIMP II ion microprobe at the Center of Isotopic Research of the Russian Geological Research Institute (VSEGEI), St. Petersburg (analyst D.I. Matukov). The LA-ICP-MS study was performed on an Element XR (Thermo Finnigan) high-resolution ICP mass spectrometer connected with a UP-213 (New Wave Research) laser ablation system (Nd:YAG UV laser with a wavelength of 213 nm). The NIST SRM612 standard was used to optimize the mass spectrometer measurement parameters and to obtain the maximum intensity of the  $^{208}\text{Pb}$  peak at the minimum  $^{248}\text{ThO}^{+}/^{232}\text{Th}^{+}$  value (<2%). All mass measurements were made for  $^{202}\text{Hg}$ ,  $^{204}\text{Pb} + \text{Hg}$ ,  $^{206}\text{Pb}$ ,  $^{207}\text{Pb}$ ,  $^{208}\text{Pb}$ ,  $^{232}\text{Th}$ ,  $^{235}\text{U}$ , and  $^{238}\text{U}$  in the E-scan mode. Signals were detected in the counting mode for all isotopes, except for  $^{238}\text{U}$  (analog mode). The laser beam was 25  $\mu\text{m}$  in diameter, the pulse frequency was 6 Hz, and the laser fluence was  $\sim 3.5 \text{ J/cm}^2$ . Mass spectrometry measurements were processed using the Glitter software (GEMOC, Macquarie University, Australia). The U/Pb isotope ratios were normalized to the TEMORA-2 (Black et al., 2004) and Plesovice (Slama et al., 2008) standard zircons. The errors of single analyses of isotope ratios and isotopic ages were at the  $1\sigma$  level, and the errors of the calculated concordant ages and concordia intercepts were at the  $2\sigma$  level. Concordia diagrams were constructed using the Isoplot program (Ludwig, 2003). Cathodoluminescence (CL) images were obtained on LEO-1430 and JSM-6510 scanning electron microscopes.

Accessory zircons for U–Pb (SHRIMP II) isotope studies were separated by the standard heavy-liquid technique at the Institute of Geology and Mineralogy, Novosibirsk. The ob-



**Fig. 2.** Petrogeochemical diagrams for late Vendian–early Paleozoic plagiogranitoid associations of the Kaa-Khem and East Tannu-Ola batholiths (Borodina et al., 2004; Rudnev et al., 2006, 2015; Mongush et al., 2011b; Mongush and Sugorakova, 2013; Rudnev, 2013). *a*, TAS diagram: composition fields of rocks of: I, normal alkalinity, II, moderate alkalinity, III, high alkalinity (Le Maitre, 1989); *b*, SiO<sub>2</sub>-K<sub>2</sub>O diagram (Le Maitre, 1989); *c*, Ab-An-Or diagram (O'Connor, 1965) with the standard composition fields of felsic rocks of different types (A, tonalites, B, granodio-

tained concentrates were cleaned under a binocular. Optical (in transmitted and reflected light) and CL images reflecting the internal structure and zoning of zircons were used to choose the grain surface sites for dating. The CL images were obtained on an ABT 55 scanning electron microscope. The working distance was 25–28 mm, the accelerating voltage was 20 kV, and the beam current on the Faraday cup was 4–6 nA. The SHRIMP II measurement of the U/Pb ratios was made by Williams' (1998) technique. The intensity of the primary beam of molecular negative oxygen ions was 4 nA, and the spot (crater) was 18  $\mu\text{m}$  in diameter. The obtained data were processed using the SQUID program (Ludwig, 2000). The U/Pb ratios were normalized to the value of 0.0668 of the TEMORA zircon standard (Black et al., 2003). The errors of single analyses (isotope ratios and isotopic ages) were within  $\pm 1\text{s}$ , and the errors of calculated concordant ages and concordia intercepts were within  $\pm 2\text{s}$ . Concordia plots were constructed using the ISOPLOT/EX program (Ludwig, 1999).

The isotope composition of Hf in zircons was determined with a Photon Machines Eximer 193 nm laser sampler on a Nu Plasma multicollector mass spectrometer at the GEMOC Analytical Center of Macquarie University (Sydney, Australia). The measurements were carried out in a helium atmosphere, with a laser beam 40–65  $\mu\text{m}$  in diameter, a frequency of 5 Hz, and the laser fluence of 8.44 mJ/pulse. The correction procedure and used values are described elsewhere (Griffin et al., 2004; Pearson et al., 2008; Belousova et al., 2009). To control the reproducibility of the results and the stability of the device, we used the TEMORA-II and Mud Tank standard zircon samples. The  $\varepsilon_{\text{Hf}}$  values were calculated based on the  $^{176}\text{Lu}$  decay constant equal to  $1.865 \times 10^{-11} \text{ yr}^{-1}$  (Scherer et al., 2001). The model age  $T(\text{DM})$  (relative to the evolution trend of the depleted mantle) was estimated from the following isotope ratios:  $(^{176}\text{Hf}/^{177}\text{Hf})_i = 0.279718$  (for 4.56 Ga) and  $^{176}\text{Lu}/^{177}\text{Hf} = 0.0384$ . The current  $^{176}\text{Hf}/^{177}\text{Hf}$  ratio was 0.28325, which is close to the average value in MORB (Griffin et al., 2000, 2004). The model ages  $T(\text{DM})$  are the minimum ages of the source of magma from which the zircon crystallized. Therefore, the

model age  $T(\text{DM})^{\text{crustal}}$  was also calculated for each zircon under assumption that magma melted from the average continental crust with  $^{176}\text{Lu}/^{177}\text{Hf} = 0.015$ , which, in turn, melted from the depleted mantle (Griffin et al., 2000).

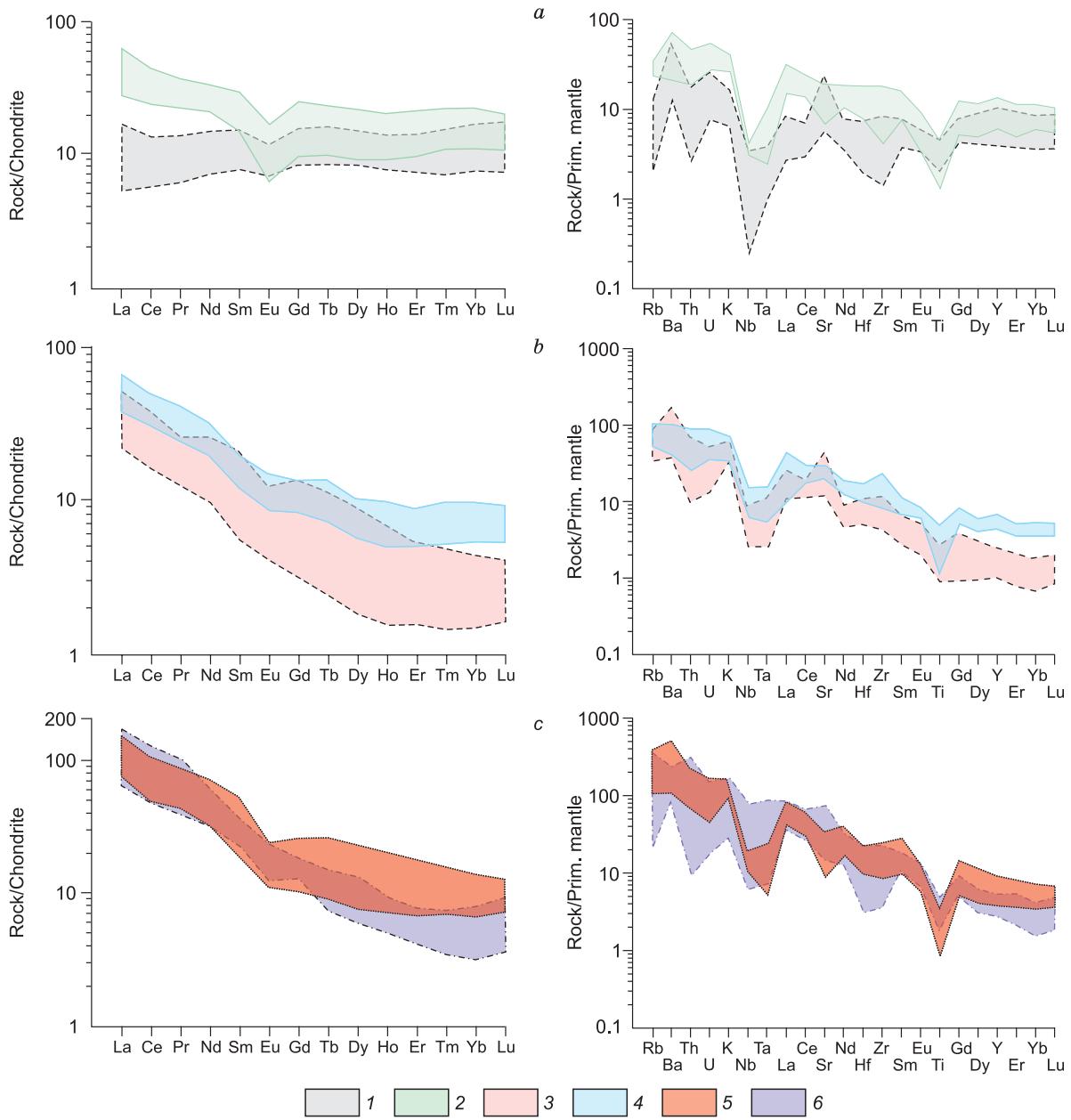
## THE Hf ISOTOPE SYSTEM OF ZIRCONS

Analysis of a Lu–Hf isotope composition was carried out for magmatic and xenogenic zircons from the granitoid and gabbroid samples whose U–Pb age was determined with SHRIMP II (VSEGEI, St. Petersburg), by TIMS (Institute of Geochemistry and Analytical Chemistry, Moscow), and by LA-ICP-MS (Analytical Center for Multi-Elemental and Isotope Research, SB RAS, Novosibirsk). Figure 5 shows the CL images of the studied zircon crystals from the above-described intrusive associations. Figures 6 and 7 and Tables 2–4 present results of U–Pb dating and Lu–Hf isotope studies of magmatic and xenogenic zircons.

## THE AGE AND Lu–Hf ISOTOPE COMPOSITION OF MAGMATIC ZIRCON

The morphology and U–Pb age of magmatic zircons from late Vendian and early Paleozoic intrusive associations of the Kaa-Khem and East Tannu-Ola batholiths are considered in detail elsewhere (Rudnev et al., 2004a,b, 2006; Rudnev, 2013). The only exception is the rocks of the diorite–tonalite–plagiogranite association of the Buren massif and gabbro–monzodiorite–granosyenite association of the Zubovka massif, whose ages were determined earlier by Ar–Ar amphibole dating, 536 and 514 Ma, respectively. Additional U–Pb dating with SHRIMP II (VSEGEI, St. Petersburg) and by LA-ICP-MS (Analytical Center for Multi-Elemental and Isotope Research SB RAS, Novosibirsk) was performed for zircons from the rocks of the Kopto and Zubovka massifs, the Unzhei Village region, and the Bren' massif of the Kaa-Khem batholith and from the plagiogranitoids of the Irbitei massif framing of the East Tannu-Ola batholith; the obtained ages are  $572 \pm 3$ ,  $510 \pm 2$ ,

rites, C, adamelites, D, trondhjemites (plagiogranites), and E, granites); d, Y/Nb–Yb/Ta diagram (Eby, 1990): OIB, oceanic-island basalts, IAB, island arc basalts; e, Eu–Yb diagram depicting the barometric generation conditions of parental melts of plagiogranitoid associations of the Kaa-Khem and East Tannu-Ola batholiths (Rudnev et al., 2006, 2015). Triangles mark the contents of elements in the melts resulted from dehydration (solid lines) and hydrous (dashed lines) melting of TH1, TH2, and MORB (Beard and Lofgren, 1991; Rapp et al., 1991; Rapp and Watson, 1995) in equilibrium with five types of restites (Turkina, 2000): I, Pl + Cpx + Opx, II, Hbl + Pl  $\pm$  Cpx  $\pm$  Opx, III, IV, Hbl + Cpx + Pl  $\pm$  Grt, V, Cpx + Grt  $\pm$  Hbl; Pl, plagioclase, Cpx, clinopyroxene, Opx, orthopyroxene, Hbl, amphibole, Grt, garnet. 1–3, plagiogranitoid associations of the island arc stage: 1, 2, Kaa-Khem batholith (1, low-alumina tonalite–plagiogranite association of the Buren massif, 571 Ma, 2, low-alumina diorite–tonalite–plagiogranite association of tholeiitic type of the Kopto massif, 562 Ma), 3, East Tannu-Ola batholith (low-alumina diorite–tonalite–plagiogranite association in the framing of the Irbitei gabbroid massif, 522–518 Ma); 4–9, plagiogranitoid associations of the accretion–collision stage (Kaa-Khem batholith): 4, monzogabbro–monzodiorite–granosyenite association of the Zubovka massif, 512 Ma, 5, high-alumina tonalite–plagiogranite association of the Terektyg–Cheder massif, 499 Ma, 6, high-alumina diorite–tonalite–plagiogranite association of the Karaos massif, 490 Ma, 7, undivided low-alumina diorite–tonalite–plagiogranite associations of the Tapsa massif, 486 Ma, and of the Baisyt massif framing, 480 Ma, 8, high-alumina tonalite–plagiogranite association of the Baisyt massif, 474 Ma, 9, low-alumina diorite–tonalite–plagiogranite association in the Unzhei Village region, 451 Ma; 10, undivided diorite–granodiorite–granite associations of the Bren' and Baibalyk massifs, 450 Ma, 11, 12, peridotite–gabbronorite associations of the Mazhalyl complex (11, Mazhalyl massif, 12, Shuya massif).



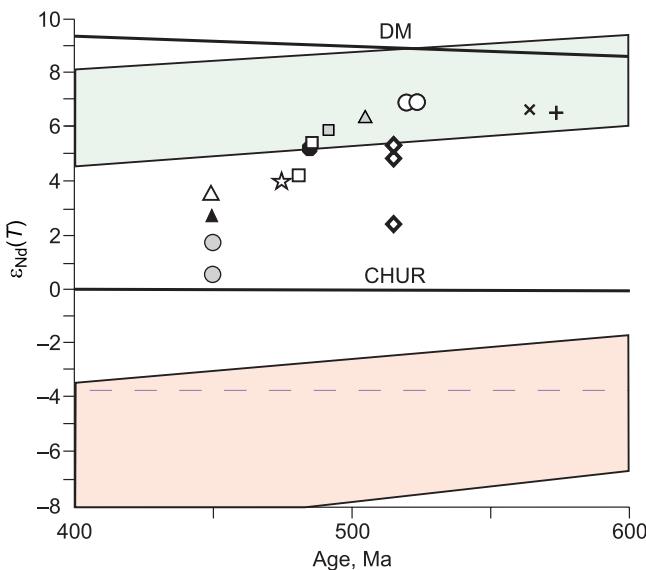
**Fig. 3.** Chondrite- and primitive-mantle-normalized (Sun and McDonough, 1989) multielement patterns of late Vendian–early Cambrian (*a*) and Cambrian–Ordovician (*b*, *c*) intrusive associations of the Kaa-Khem and East Tannu-Ola batholiths (Rudnev et al., 2006, 2015). *Island arc associations*: 1, late Vendian tholeiitic plagiogranitoid (Buren and Kopto massifs), 2, early Cambrian calc-alkalic low-alumina plagiogranitoid (East Tannu-Ola batholith); *late Cambrian–Ordovician accretion–collision associations*: 3, calc-alkalic high-alumina plagiogranitoid (Terektyg–Cheder and Karaos massifs and Baisyt massif framing), 4, calc-alkalic low-alumina plagiogranitoid (Tapsa and Baisyt massifs, Unzhei Village region), 5, calc-alkalic granodiorite–granite (Bren' and Baibalyk massifs), 6, gabbro–monzodiorite–granosyenite (Zubovka massif).

$450 \pm 5$ ,  $452 \pm 2$ , and  $522 \pm 4$  Ma, respectively (Figs. 1, 5, and 6; Tables 2 and 3).

Magmatic zircons from the late Vendian (572–562 Ma) island arc tholeiitic-plagiogranitoid associations of the Kopto and Buren massifs of the Kaa-Khem batholith (Table 4, Nos. 1–14; Fig. 7) are characterized by stable high  $\varepsilon_{\text{Hf}}$  values (13.2–10.2) and Neoproterozoic model ages  $T(\text{DM})^{\text{Crustal}}$  (0.86–0.66 Ga). Magmatic zircons from the early Cambrian (522–520 Ma) island arc association of the East Tannu-Ola

batholith are similar in isotope parameters ( $\varepsilon_{\text{Hf}} = 14.8–12.4$ ;  $T(\text{DM})^{\text{Crustal}} = 0.77–0.52$  Ga) to those from the late Vendian rock associations, which indicates similar magma sources.

The intrusive associations that formed at the accretion–collision stage of evolution of Eastern Tuva (512–450 Ma, Table 1) are characterized by a more diverse petrogeochemical composition. They include high- and low-alumina diorite–tonalite–plagiogranite associations (Terektyg–Cheder, Karaos, Tapsa, Baisyt, and other massifs), diorite–grano-



**Fig. 4.**  $\varepsilon_{\text{Nd}}(T)$ –age diagram for the late Vendian and early Paleozoic intrusive associations of the Kaa-Khem and East Tannu-Ola batholiths (see Table 1). Designations follow Fig. 2. Green field marks the evolution of the Nd isotope composition of rocks in the Tannu-Ola zone of Eastern Tuva (Mongush et al., 2011b), and pink field, of the supracrustal complexes in the Tuva–Mongolian terrane (Kozakov et al., 2003).

diorite–granite association of the Sarkhoi complex (Bren' and Baibalyk massifs), and the rocks of the Zubovka subalkalic gabbro–monzodiorite–granosyenite massif. Magmatic zircons from the rocks of these massifs are characterized by  $\varepsilon_{\text{Hf}} = 12.6$ –2.4 and  $T(\text{DM})^{\text{Crustal}} = 1.26$ –0.63 Ga (Table 4, Nos. 29–73). The wide range of  $\varepsilon_{\text{Hf}}$  values partly overlaps with that of zircons from island arc plagiogranitoids and is shifted to lower values. The magmatic zircons from the above intrusive associations are divided into two groups according to Hf isotope parameters.

The first group is zircons from the rocks of the diorite–tonalite–plagiogranite associations (Terektyg–Cheder, Karaos, Tapsa, and Baisyt massifs, Baisyt massif framing, and Unzhei Village region) and gabbro–monzodiorite–syenite association of the Zubovka massif, which show a wide range of  $\varepsilon_{\text{Hf}}$  values (12.6–7.0, Table 4; Fig. 7) and Hf model ages ( $T(\text{DM})^{\text{Crustal}} = 1.0$ –0.63 Ga). Zircons from spatially conjugate high- and low-alumina plagiogranitoids of close ages are isotopically inhomogeneous. The high-alumina plagiogranitoids of the Terektyg–Cheder and Karaos massifs contain zircons with high  $\varepsilon_{\text{Hf}}$  values (12.6–11.1) generally similar to those of the zircons from the late Vendian and early Cambrian island arc plagiogranitoids, whereas the zircons from the high-alumina plagiogranitoids of the Baisyt massif have lower  $\varepsilon_{\text{Hf}}$  values (7.5–7.0). A similar phenomenon is observed for the Hf isotope composition of magmatic zircons from the low-alumina plagiogranitoids. Zircons from the plagiogranites of the Tapsa massif have higher  $\varepsilon_{\text{Hf}}$  values (12.1–8.8) than those from the plagiogranitoids of the Bai-

syut massif framing and the Unzhei Village region ( $\varepsilon_{\text{Hf}} = 7.9$ –7.0). The variations in isotope parameters in the magmatic zircons from the high- and low-alumina plagiogranitoids, whose parental melts formed at different depths ( $P > 10$ –12 and  $\leq 8$  kbar), apparently indicate inhomogeneity of the collisional structure resulted from the tectonic conjunction of compositionally different blocks/plates.

The second group is magmatic zircons from the granodiorite–granite association of the Bren' massif (~450 Ma, Table 1), which are characterized by the lowest  $\varepsilon_{\text{Hf}}$  values (3.5–2.4) and a Mesoproterozoic model age ( $T(\text{DM})^{\text{Crustal}} = 1.26$ –1.19 Ga). Note that the nearly coeval (~451 Ma) and spatially conjugate rocks of the diorite–tonalite–plagiogranite association of the Unzhei Village region show higher  $\varepsilon_{\text{Hf}}$  values (7.7–7.6, Table 4; Fig. 7). A similar phenomenon is observed for the Nd isotope compositions of these granitoid associations ( $\varepsilon_{\text{Nd}} = 1.7$ –0.5 for the Bren' granites and  $\varepsilon_{\text{Nd}} = 3.4$  for the Unzhei plagiogranitoids, Table 1). The strong difference in isotope parameters between the Bren' granites and the preceding plagiogranitoids is apparently due to different magma sources.

## THE AGE AND Lu–Hf ISOTOPE COMPOSITION OF XENOCENIC ZIRCON

We found only 22 inclusions of xenogenic zircon in the inner zone of magmatic zircons from the studied intrusive associations (Figs. 5 and 6).

Five grains of xenogenic zircon were revealed in the late Vendian diorite–tonalite–plagiogranite association of the Kopto massif (sample D828, ~562 Ma). One grain has a near-concordant age of 587 Ma, and the other have  $^{206}\text{Pb}/^{238}\text{U}$  ages of 603–611 and 663 Ma (discordance is >20%). The probable sources of these zircons are either the host Vendian volcanic complexes (rhyolites) widespread in the northwest of the Kaa-Khem batholith (Tapsa and other formations) or the ophiolite complexes in the Agardag, Kaa-Khem, Kurtushiba, and Shishkhid belts slightly remote from the Kopto massif (Pfänder et al., 2002; Kuz'michev, 2004; Mongush et al., 2011a). The xenogenic zircon with an age of 587 Ma ( $\varepsilon_{\text{Hf}}(T) = 13.2$  and  $T(\text{DM})^{\text{Crustal}} = 0.69$ , Table 4, No. 14; Fig. 7) does not differ from the magmatic zircons ( $\varepsilon_{\text{Hf}}(T) = 13.2$ –10.5) from the same massif, which suggests its inheritance from the melt source.

The xenogenic zircons from the early Cambrian island arc diorite–tonalite–plagiogranite association of the East Tannu-Ola batholith (522–518 Ma) are divided into two groups with concordant ages of 571–562 and 543–536 Ma (samples RT-10 and RT-8/5, Fig. 6, Table 3). As follows from the geologic structure of the region, these zircons formed in the host island arc volcanic complexes of Vendian (Kadvoi Formation and its analogues) and early Cambrian (Irbitei Formation and its analogues) ages. Most of the xenogenic zircons with ages of 571 and 543–536 Ma (Table 4, Nos. 20, 26, and 27) are characterized by high  $\varepsilon_{\text{Hf}}(T)$



**Fig. 5.** Cathodoluminescence images of zircon grains from granitoids of the Kaa-Khem and East Tannu-Ola batholiths. Samples: D675/1, plagiogranite from the Buren massif; D828, tonalite from the Kopto massif; RT-10, quartz diorite and RT-8/5, plagiogranite from the Irbitei massif framing; D35, monzodiorite from the Zubovka massif; D108, plagiogranite from the Terektyg-Cheder massif; D2266b, plagiogranite from the Karaos massif; D895, tonalite from the Tapsa massif; D634, tonalite from the Baisyut massif framing; D624, plagiogranite from the Baisyut massif; D1000, tonalite from the Unzhei Village region; D1019e, granodiorite from the Bren' massif. Red circles mark the points of U-Pb (SHRIMP II, TIMS) (Rudnev et al., 2006; Rudnev, 2013) and LA-ICP-MS isotope studies of magmatic and xenogenic zircons, and yellow circles, the points of Lu-Hf isotope studies (Table 3). The numerator shows the zircon age (Ma), and the denominator presents the  $\epsilon_{\text{Hf}}(T)$  and  $T_{\text{Hf}}(\text{DM})^{\text{Crustal}}$  (Ga) values.

values (14.1–11.2) and Neoproterozoic model ages (0.77–0.61 Ga). In these parameters they do not differ from the magmatic zircons of the same rocks and from the xenogenic zircon (587 Ma) of the late Vendian island arc plagiogranites of the Kopto massif (Table 4, No. 14), which also suggests their inheritance from the melt source. One grain of xenogenic zircon (562 Ma; Table 4, No. 28) has a lower  $\epsilon_{\text{Hf}}(T)$  value (7.8) and an older model age (1.01 Ga) than the other.

The rocks of the subalkalic gabbro-monzodiorite-granofels-syenite association of the Zubovka massif (514–510 Ma) contain two inclusions of xenogenic zircon (540 and 532 Ma) coeval with the rocks of early Cambrian island arc complexes in Eastern Tuva. They show medium  $\epsilon_{\text{Hf}}(T)$  values (9.6–8.2) and Neoproterozoic model ages ( $T(\text{DM})^{\text{Crustal}} = 0.69$ , Table 4, Nos. 34 and 35; Fig. 7). In these parameters they do not differ from the magmatic zircons of monzodiorite ( $\epsilon_{\text{Hf}}(T) = 9.2$ –8.1, Table 4, Nos. 21–25).

Five grains of xenogenic zircon with concordant ages of 474–460 Ma were found in the rocks of the diorite-tonalite-plagiogranite association of the Unzhei Village region (451 Ma) (Table 4, Nos. 61–65; Fig. 7). These zircons are characterized by  $\epsilon_{\text{Hf}}(T) = 7.9$ –7.0 and  $T(\text{DM})^{\text{Crustal}} = 0.99$ –0.93 Ga and do not differ from the magmatic zircons of the same rocks ( $\epsilon_{\text{Hf}}(T) = 7.7$ –7.6, Table 4, No. 60). In addition, they are similar in isotope parameters and age to the magmatic zircons of the plagiogranitoids of the Baisyut massif and its framing ( $\epsilon_{\text{Hf}}(T) = 7.9$ –7.0), which formed at the earlier stage of accretion–collision processes (480–474 Ma, Table 1). These xenogenic zircons were, most likely, borrowed by melt during its intrusion into plagiogranitoids similar to those of the Baisyut massif and its framing.

The granodiorites of the Bren' massif (~450 Ma) contain xenogenic zircons with a wide range of ages and Hf isotope parameters. Five grains of xenogenic zircon are divided into three age groups: 485–479, 570, and ~1141 Ma (Table 2). The zircons of the first and second groups have concordant ages. The zircon with an age of ~570 Ma (Table 4, No. 73; Figs. 5 and 6) is characterized by  $\epsilon_{\text{Hf}}(T) = 7.0$  and  $T(\text{DM})^{\text{Crustal}} = 1.07$  Ga. In these parameters it does not differ from the xenogenic zircon from the island arc plagiogranitoids of the East Tannu-Ola batholith ( $\epsilon_{\text{Hf}}(T) = 7.8$ , Table 4, No. 28). Two grains, despite their close ages (485 and 479 Ma), differ strongly in isotope parameters ( $\epsilon_{\text{Hf}}(485) = -0.1$ ,  $T(\text{DM})^{\text{Crustal}} = 1.45$  Ga and  $\epsilon_{\text{Hf}}(479) = 5.3$ ,  $T(\text{DM})^{\text{Crustal}} = 1.1$  Ga, Table 4, Nos. 71 and 72, respectively), which indicates their different sources. The latter grain is somewhat similar in isotope parameters and age to the xenogenic zircons from the Unzhei plagiogranitoids, whereas the former

(with  $\epsilon_{\text{Hf}}(T) = -0.1$ ) has no analogues among the studied zircons. The xenogenic zircon with an age of ~1141 Ma is highly discordant because of the disturbed U-Pb isotope system; therefore, we did not perform its Hf isotope study. Nevertheless, such an ancient zircon unambiguously indicates that the formation of parental melts for the Bren' massif granitoids was contributed by terrigenous sedimentary rocks resulted from the erosion of Precambrian blocks (e.g., the Tuva–Mongolian terrane).

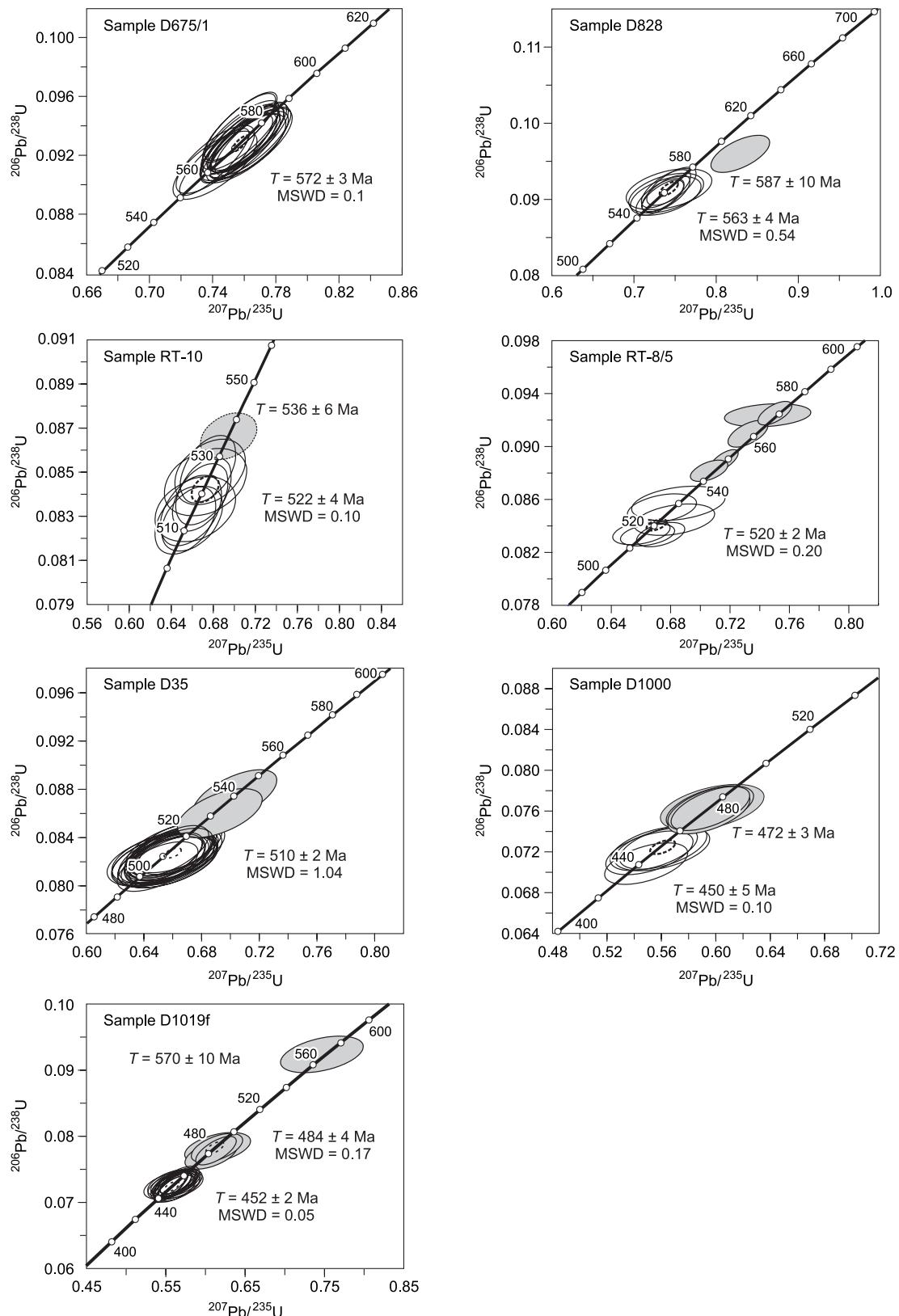
## DISCUSSION

The performed Hf isotope studies of magmatic and xenogenic zircons from the late Vendian and early Paleozoic intrusive associations of the Kaa-Khem and East Tannu-Ola batholiths showed a wide range of  $\epsilon_{\text{Hf}}(T)$  values, from +14.8 to –0.1 (Table 4). In the  $\epsilon_{\text{Hf}}(T)$ –age diagram (Fig. 7), the fields of Vendian–early Cambrian (island arc) and Late Ordovician (accretion–collision) granitoids significantly overlap by  $\epsilon_{\text{Hf}}$  values, which indicates the involvement of the same crust in the magma formation. The only exception is the Bren' massif granitoids with  $\epsilon_{\text{Hf}}(T)$  strongly shifted to low values (<7). The studied granitoids are subdivided into four groups according to their Nd isotope composition and the Hf isotope composition of their zircons. These groups mark different melt sources.

Group I is the island arc associations including the late Vendian (572–562 Ma) tholeiitic plagiogranitoids of the Buren and Kopto massifs of the Kaa-Khem batholith and the early Cambrian (522–518 Ma) calc-alkalic plagiogranitoids of the East Tannu-Ola batholith. These plagiogranitoids are identical in Nd isotope composition ( $\epsilon_{\text{Hf}}(T) = 6.9$ –6.4, Table 1) (Mongush et al., 2011b; Rudnev et al., 2015) to the host Vendian and early Cambrian island arc volcanics ( $\epsilon_{\text{Hf}}(T) = 8.4$ –6.3) (Mongush et al., 2011b); therefore, the latter can be considered the main source of melts. The same source is also evidenced by the presence of xenogenic zircons of Vendian–Cambrian ages (579–571 and 543–536 Ma) in the plagiogranitoids. These zircons show high positive  $\epsilon_{\text{Hf}}(T)$  values (14.1–11.2 and 13.6–11.2, respectively, Table 4) and overlap by them with the magmatic zircons of the plagiogranitoids ( $\epsilon_{\text{Hf}}(T) = 14.8$ –10.2) (Fig. 7), which proves that the rocks resulted from the melting of the Tannu-Ola island arc crust. The above  $\epsilon_{\text{Hf}}$  values are the first estimate of the Hf isotope composition of this crust. The lower  $\epsilon_{\text{Hf}}(T)$  value (7.8) for one xenogenic zircon (~562 Ma) from the early Cambrian plagiogranitoids of the East Tannu-Ola batholith was prob-







**Fig. 6.** Concordia diagrams for magmatic and xenogenic zircons from the studied massifs. Samples: D675/1, plagiogranite from the Buren massif (Table 1); D828, tonalite from the Kopto massif (Rudnev et al., 2006) (Table 2); RT-10, quartz diorite (Rudnev, 2013) and RT-8/5, plagiogranite (Table 3) from the Irbitei massif framing; D35, monzodiorite from the Zubovka massif (Table 2); D1000, tonalite from the Unzhei Village region (Table 2); D1019e, granodiorite from the Bren' massif (Table 2). Light ellipses show the ages of magmatic zircons, and gray ellipses, the ages of xenogenic zircons.

**Table 3.** Results of U–Pb (SHRIMP II) isotope studies of single zircon grains from plagiogranites of the East Tannu-Ola batholiths

Point	$^{206}\text{Pb}_c$ , %	U	Th	$^{232}\text{Th}/^{238}\text{U}$	$^{206}\text{Pb}^*$ , ppm	Age, Ma	Isotope ratios						D, %			
							$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$ , %	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 1\sigma$ , %	$^{207}\text{Pb}^*/^{206}\text{Pb}^*$	$\pm 1\sigma$ , %	$^{207}\text{Pb}^*/^{235}\text{U}$	$\pm 1\sigma$ , %	$^{206}\text{Pb}^*/^{238}\text{U}$	$\pm 1\sigma$ , %
							ppm	%	%	%	%	%	%		%	
<b>Framing of the Irbitei massif, plagiogranite, sample RT-8/5</b>																
4.1	0.05	344	85	0.25	25.4	531.3	$\pm 5.1$	533	$\pm 63$	0.0581	2.9	0.688	3	0.08591	0.99	0
5.1	0.02	439	187	0.44	31.9	522.9	$\pm 4.7$	551	$\pm 53$	0.0586	2.4	0.682	2.6	0.0845	0.94	5
6.1	0.02	1228	384	0.32	88	516.2	$\pm 3.6$	550	$\pm 31$	0.05855	1.4	0.673	1.6	0.08337	0.73	7
7.1	0.06	591	221	0.39	43.4	528	$\pm 4.3$	502	$\pm 47$	0.0573	2.1	0.674	2.3	0.08535	0.85	-5
8.1	0.69	2579	1209	0.48	186	516.1	$\pm 3.3$	522	$\pm 37$	0.0578	1.7	0.664	1.8	0.08335	0.67	1
9.1	0.20	1228	588	0.49	88.3	517.2	$\pm 3.6$	504	$\pm 39$	0.0573	1.8	0.66	1.9	0.08353	0.73	-3
3.1*	0.06	965	515	0.55	72.9	543.4	$\pm 3.9$	527	$\pm 29$	0.05792	1.3	0.702	1.5	0.08794	0.76	-3
3.3*	0.18	7407	4593	0.64	567	549.3	$\pm 3.3$	543	$\pm 14$	0.05835	0.7	0.7156	0.91	0.08894	0.63	-1
3.2*	0.01	1744	603	0.36	136	561.3	$\pm 3.9$	543	$\pm 21$	0.05836	1.0	0.732	1.2	0.09097	0.73	-3
2.1*	0.31	5686	2535	0.46	453	570.5	$\pm 3.5$	560	$\pm 17$	0.0588	0.8	0.7502	1	0.09253	0.64	-2
1.1*	1.18	7108	4559	0.66	571	569.5	$\pm 3.4$	549	$\pm 55$	0.0585	2.5	0.745	2.6	0.09236	0.62	-4

Note.  $\text{Pb}_c$  and  $\text{Pb}^*$  are common and radiogenic lead, respectively. Correction for common lead was made using the measured  $^{204}\text{Pb}$  amount.

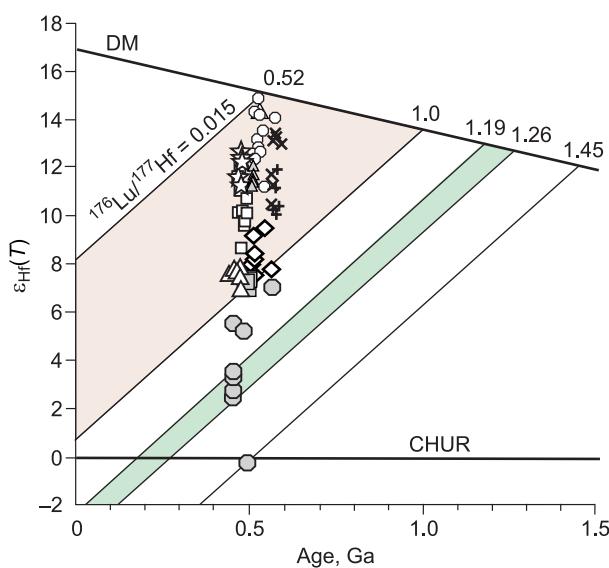
\* Points of isotope measurements for xenogenic zircons; the rest, for magmatic zircons.

ably inherited from the felsic island arc volcanics of the host Kadvoi, Irbitei, and Serlig Formations. Thus, according to the obtained isotope data, the plagiogranitoids of group I resulted from the melting of island arc crust formed from the depleted mantle.

Group II is the rocks of the subalkalic gabbro–monzodiorite–granosyenite association of the Zubovka massif (514–510 Ma), which formed at the early stage of accretion–collision processes. They probably record the beginning of the plume activity in the CAOB (Izokh et al., 1998, 2009; Yarmolyuk et al., 2000). As follows from the high contents of REE and HFSE (Nb, Ta, Zr, and Hf), the intrusive rocks of

this massif resulted from the differentiation of mafic magmas, derivates of the enriched mantle. The isotope parameters of the gabbroids and monzonitoids ( $\epsilon_{\text{Hf}}(T) = 5.3\text{--}2.6$ ) point to a depleted mantle source; this indicates that the latter became enriched in incompatible elements not long before the rock generation, possibly, owing to the plume contribution. The Hf isotope compositions of magmatic ( $\epsilon_{\text{Hf}}(T) = 9.2\text{--}8.1$ ) and xenogenic ( $\epsilon_{\text{Hf}}(T) = 9.6\text{--}8.2$ , 540–532 Ma) zircons are similar and also correspond to an isotope-depleted source. The xenogenic zircons, which might have been trapped from the island arc rocks, have lower  $\epsilon_{\text{Hf}}(T)$  values (14.8–10.2) than the zircons from the island arc plagiogranitoids, which might be due to the isotopic heterogeneity of the crust formed at the subduction stage. Note that the zircons from the accretion–collision plagiogranitoids also have lower and more widely varying  $\epsilon_{\text{Hf}}(T)$  values (12.6–7.0) as compared with the island arc plagiogranites. Thus, the petrochemical and trace element compositions of the rocks of the Zubovka gabbro–monzodiorite–granosyenite massif, the Nd isotope parameters of the rocks, and the Hf isotope parameters of the magmatic and xenogenic zircons indicate the formation of parental magmas from the mantle enriched in incompatible elements but isotopically depleted, with the contribution of the island arc material.

Group III unites the high- and low-alumina plagiogranitoids of the Kaa-Khem batholith, which formed at the accretion–collision stage (Terektyg–Cheder, Karaos, and Tapsa massifs, Baisyt massif and its framing, plagiogranitoids in the Unzhei Village region, 499–451 Ma). These plagiogranitoid associations, in contrast to the early island arc ones, are characterized by a wider range of Nd isotope parameters and a decrease in  $\epsilon_{\text{Hf}}(T)$  values (from 6.2 to 3.4) with the rock rejuvenation (Fig. 4). The Nd isotope parameters along with the major and trace element composition indicate mostly a



**Fig. 7.**  $\epsilon_{\text{Hf}}(T)$ –age diagram for zircons from the late Vendian–early Paleozoic granitoids and gabbroids of the Kaa-Khem and East Tannu-Ola batholiths (Table 2). Designations follow Figs. 2 and 4.





plagiogranitoids that formed at different depths (>10–12 and ≤8 kbar, respectively) are apparently due to the vertical isotopic heterogeneity of the crust.

Group IV is the calc-alkalic potassic rocks of the Bren' granodiorite–granite massif (~450 Ma), which formed at the final stage of accretion–collision processes. The intrusive rocks of the massif, in contrast to the preceding nearly coeval plagiogranitoids, are characterized by lower  $\epsilon_{\text{Hf}}(T)$  values (1.7–0.5) and Mesoproterozoic model ages (1.2–1.1 Ga). Magmatic zircons from these rocks also have the lowest  $\epsilon_{\text{Hf}}(T)$  values (3.5–2.4) and Mesoproterozoic model ages (1.3–1.2 Ga). The change in the isotope parameters of the rocks and zircons indicates a drastic change in the composition of the magma source. This phenomenon might have been caused by the junction of island arc structures with the margin of the Tuva–Mongolian terrane as a result of accretion–collision processes and by the following involvement of rocks with widely varying isotope parameters in the magma generation zone. The same is argued by the geologic position of the Bren' massif intruding the Precambrian complexes of the Tuva–Mongolian terrane and the Vendian–early Cambrian volcanic deposits of the Tannu-Ola island arc and by the presence of xenogenic zircons with ages of 570, 485–479, and ~1140 Ma (single grains) and a wide range of  $\epsilon_{\text{Hf}}(T)$  values (from +7.0 to –0.1) in the massif granitoids (Table 4, Fig. 7). The rocks of the Bren' massif are similar in Nd isotope parameters to the granitoids of the Tuva–Mongolian terrane (western Sangilen, southeastern Tuva), e.g., the Cambrian–Ordovician rocks of the Nizhnii Ulor, Erzin, and Bayan-Kol massifs ( $\epsilon_{\text{Hf}}(T)$  vary from +1.8 to –2.5). The parental melts for these rocks formed mostly from depleted-mantle derivates, with the contribution of older crustal rocks (Kozakov et al., 2003). The composition and age of the crust that might have been involved in the mantle melting can be judged from the detrital zircons in the host metaterrigenous rocks of the Moren and Erzin complexes ( $^{207}\text{Pb}/^{206}\text{Pb}$  age of 2.56 to 0.85–0.66 Ga) (Salnikova et al., 2001; Kozakov et al., 2005). Thus, the geologic relations of the Bren' massif granitoids with the host rocks, the presence of xenogenic zircons with an age of 1140–570 Ma in these granitoids, and the isotope parameters of the magmatic ( $\epsilon_{\text{Hf}}(T) = 3.5\text{--}2.4$ ) and xenogenic ( $\epsilon_{\text{Hf}}(T) = +7.0\text{--}0.1$ ) zircons suggest that the crust of the Tuva–Mongolian terrane with Mesoproterozoic Nd model ages (up to 1.45 Ga) was the main source of magma for the Bren' massif granitoids and the island arc crust with depleted-mantle isotope properties made a subordinate contribution.

## CONCLUSIONS

Based on the obtained data on the geochemical, Sm–Nd isotope, and Lu–Hf isotope compositions of magmatic and xenogenic zircons from the Vendian–early Paleozoic granitoids of the Kaa-Khem and East Tannu-Ola batholiths in Tuva, we have drawn the following conclusions:

(1) The late Vendian (572–562 Ma) and early Cambrian (522–518 Ma) subductional plagiogranitoids resulted from the melting of the Vendian–early Cambrian island arc crust without the contribution of a more ancient crustal material.

(2) The parental magmas for the subalkalic gabbro–monzodiorite–granosyenite association of the Zubovka massif (514–510 Ma) formed from a mantle source depleted isotopically but enriched in incompatible elements, with the participation of an island arc crust material.

(3) Island arc complexes were the main source of the Cambrian–Ordovician accretion–collision plagiogranitoids (500–450 Ma). The variations in the rock composition were due to the melting of thick crust, whose isotopic heterogeneity was caused by the different contributions of a more ancient crustal source. The crust of the Tuva–Mongolian terrane made the main contribution to the formation of the potassic granitoids of the Bren' massif (450 Ma), marking the completion of accretion–collision processes in this region.

(4) The isotope parameters of the Vendian–early Paleozoic granitoids are indicators of the crust formation and evolution in the course of subduction and accretion–collision processes.

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