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Petrology of Plagiogranites of the Yenisei Batholith, Western Sayan

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Abstract—The tonalite–plagiogranite (tonalite–trondhjemite) association only occasionally occurs in the form of large granitoid bodies, such as the Yenisei Batholith (>500 km^2 in area). The granitoids of the Yenisei Batholith belong to Na-rich tholeiitic rock series and differ from granitoids of the calc–alkaline series in having lower contents of alkalis and alumina (12–14 wt % Al_2O_3) and low contents of granitophile elements (Rb, Li, Cs, Be, Nb, Ta, and W), Cr, and Ni. The Cr/V (<0.10) and Rb/Sr (0.01–0.1) ratios of these rocks are at a minimum, and their K/Rb (600–1000) and Na/K (5–10) ratios are at a maximum compared to those of the rocks of the most widely spread granitoid batholiths. The plagiogranites typically have REE concentrations higher than those in oceanic plagiogranites and display weakly fractionated REE patterns (La/Yb = 1.4–3.4) with weak (or without) Eu anomalies. The lower initial Sr ratios of these rocks (0.704) and their relatively high concentrations of Pb, Zr, and B testify to the predominantly mantle provenance of their protolithic material. Geological and geochemical characteristics of the Yenisei pluton suggest that its genesis can be considered within the scope of the model of retrograde-type magmatic replacement and that the batholith was produces by the earliest granitization processes in the oceanic crust. The granitic melt was derived at low pressures (<5 kbar) and intermediate temperatures (~700°C), at the inflow of an aqueous transmagmatic fluid into the magma-generating area and the subsequent fluid–magmatic differentiation. Considering the volumes and compositions of rocks composing the Yenisei Batholith, the latter can be attributed, similarly to other typical granitoid batholiths, to crustal plutons, which differ from both oceanic plagiogranites in ophiolitic belts and continental trondhjemites. The rocks can be regarded as an individual geochemical type of crustal plagiogranites.

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INTRODUCTION

The comparative geochemical analysis of granitoid batholiths in various tectonic settings is highly promising in the context of the development of models for the origin of great masses of granitic rocks, the assessment of their potentially possible protoliths, and the understanding of the genesis of the continental crust as a whole. While the relations between the granitoids of autochthonous plutons (granite–gneiss domes) and granitized rocks are now clear enough (Korzhinskii, 1952; Letnikov, 1975, 2000; and others), the identification of the composition of the protolith of allochthonous batholiths requires a specialized investigation (Koval, 1998; Koval et al., 1999; Grebenshchikova et al., 1999). This analysis of granitoid associations that include both autochthonous and displaced batholithic bodies demonstrates that the use of the latter rocks is highly promising as a tool for the geochemical "sampling" of crust-producing regions. In this context, the most interesting and disputable intrusions are plagiogranite bodies that are normally associated with gabbroids and commonly thought to be derivatives of basic (tholeiitic) magmatism. The genesis of these associations has long been discussed by geologists in both this country (Kuznetsov, 1964; Popolitov et al., 1973; Tauson, 1977; Polyakov et al., 1978; Saiz, 1984; Kuz'min, 1985; Alabin, 1987; Purtov, 1998, 2002; Distanova, 2000; Samarkin et al., 2001; Yarmolyuk et al., 2002; Grebenshchikova and Koval, 2004a; Rudnev et al., 2005) and abroad (Coleman and Peterman, 1975; Arth, 1978; Barker and Arth, 1976; Coleman and Donato, 1979; Barker, 1983; Drummond et al., 1996; Selbekk et al., 2002; and others).

Plagiogranites proper are acid intrusive rocks containing 68–75 wt % SiO_2 (*Petrography and Petrology…*, 2001), which are believed to be analogues of trondhjemites and leucocratic tonalites (*Classification of Magmatic…*, 1997). These rocks consist mostly of quartz and sodic plagioclase and contain practically no potassic feldspar and only minor amounts of mafic minerals. Plagiogranites occur commonly in the form of small intrusions and only very rarely compose large batholithic massifs.

Gabbro–plagiogranite associations usually occur in areas with widespread tholeiitic basalts and ophiolitic complexes, which are typical of the initial stages of continental crustal growth. In particular, in the geodynamic classification (Barbarin, 1999), plagiogranites are regarded as the granites of tholeiitic series, which can be produced in mid-oceanic ridges during the divergence of two oceanic slabs (ophiolitic complexes) and in volcanic island arcs during the melting of the oceanic crust.

The comparative analysis of plagiogranites in various territories indicates that they consist of two geochemically distinct groups: (i) typical oceanic plagiogranites that compose small bodies and dikes in ophiolitic belts and (ii) plagiogranites that make up larger intrusions, such as the Yenisei Batholith. According to their geochemical characteristics, the latter rocks are intermediate between oceanic plagiogranites and continental trondhjemites (Coleman and Donato, 1979).

This publication presents a petrological and geochemical model for the genesis of plagiogranites in the Yenisei Batholith in the Western Sayan Mountains. The unusually large sizes of this batholith are in conflict with the traditional opinion that plagiogranites occur as relatively small bodies. As a model object, this massif was previously used in the classification (Tauson, 1977), in which these plagiogranites were classed with a geochemical type derived by tholeiitic magmas. Tischendorf and Palchen (1985) also considered the plagiogranites of the Yenisei pluton in the Western Sayan to be derivatives of conditionally mantle magmas.

GEOLOGY, GEOCHRONOLOGY, AND PETROGRAPHY OF THE ROCKS

The Yenisei Batholith (Fig. 1) is located in the northern part of the Western Sayan, at the boundary of the Minusinsk depression. The batholith was described in detail by Smyshlyaev (1958, 1963), Polyakov et al. (1978), and Rudnev et al. (2003, 2005).

In map view, the batholith is exposed as a strongly elongated distorted ellipse, approximately 100 km long and 10–11 to 2–3 km wide (Fig. 1), at a total area of more than 500 km^2. The southern contact surface of the batholith dips to the south and southwest at angles of 60°–70°, and its southeastern boundary is truncated by the Northern Sayan Fault. The northern part of the batholith is cut by the Sayan–Minusinsk Deep Fault and is overlain by Devonian terrigenous–carbonate and sedimentary–volcanic deposits of the Minusinsk depression. The Yenisei Batholith and gabbroid bodies within it are usually ascribed to the Cambrian Mainskii gabbro–plagiogranite complex.

The batholith is hosted by an ophiolite association of supposedly Vendian age and by Cambrian predominantly tholeiitic volcanic–sedimentary rocks. The intrusive massifs of the Early Cambrian Lysogorskii peridotite–pyroxenite–gabbronorite and Subbotinskii gabbro–diorite–diabase complexes are also older than the batholith (Rudnev et al., 2005). The aforementioned rocks compose a trough-shaped structure, which trends W–E and is controlled by the Sayan–Minusinsk and Northern Sayan deep faults.

Late Cambrian–Early Ordovician (Sadrinskii Complex) and Silurian–Devonian (Syutkhol'skii, Dzhoiskii, Bol'sheporozhskii, and Kukshinskii complexes, undifferentiated) granitoid massifs are known south of the Northern Sayan Fault (Rudnev et al., 2005). These complexes are not considered in this publication.

According to geological evidence, the age of the batholith was determined to be Cambrian (Smyshlyaev, 1958, 1963), which was confirmed by later dating. The U–Pb age of the magmatic zircon from the plagiogranites was determined as 525 ± 10 Ma (Rublev, 2001) and 523.8 ± 2.1 Ma (Rudnev et al., 2003, 2005). The latter value was obtained for the insoluble residue after zircon treatment with a mixture of HF and HNO_3. The ages obtained for zircon crystals that had not been treated by acids are younger: correspond to 442.9–455.7 Ma.

Smyshlyaev (1958, 1963) originally recognized five phases of the Yenisei Batholith. Three of them are distinct structural–textural varieties of plagiogranites. Phase I comprises gabbroids that occur within the batholith. In most later publications, these rocks were regarded as xenoliths of an earlier gabbroid rock association (Polyakov et al., 1978; Rudnev et al., 2005). Varieties of the plagiogranites that were distinguished as individual phases based on their textural–structural features are considered here to compose the main phase. The final phase comprises dikes of fine-grained and aplitic leucogranites.

Gabbroids account for approximately 10% of the Yenisei Batholith by area. They were found in various parts of the pluton as xenoliths and nodules of variable size and shape and, more rarely, also as larger dike-shaped, equant, and irregularly shaped bodies (Fig. 1). According to their mineralogy, the rocks are subdivided into gabbro, gabbronorites, and hornblende and quartz gabbro (Smyshlyaev, 1958, 1963; Polyakov et al., 1978). Contacts between gabbroid nodules and the plagiogranites are marked by "hybrid facies", which were not detected at contacts with the host volcanic–sedimentary rocks (Polyakov et al., 1978). This diverse spectrum of rocks includes gabbro-diorites, diorites, quartz diorites, and tonalites with characteristic taxitic structures (schlieren, patches, shreds, etc.).

The contact influence of the plagiogranite magma induced the recrystallization and the development of hornfels, and, in places, granitization and the magmatic replacement of the host rocks (Popolitov et al., 1973; Polyakov et al., 1978).

The plagiogranites are the main phase of the Yenisei pluton and account for approximately 90% of its exposed area. These are pale gray equigranular and porphyritic rocks. Their major minerals are quartz (45–50%), andesine ($An_{33–36}$) and albite-oligoclase ($An_{8–22}$) (up to 47–48%), and minor amounts of hornblende (~4%) and biotite (up to 5%). The phenocrysts are subhedral grains of quartz and plagioclase up to

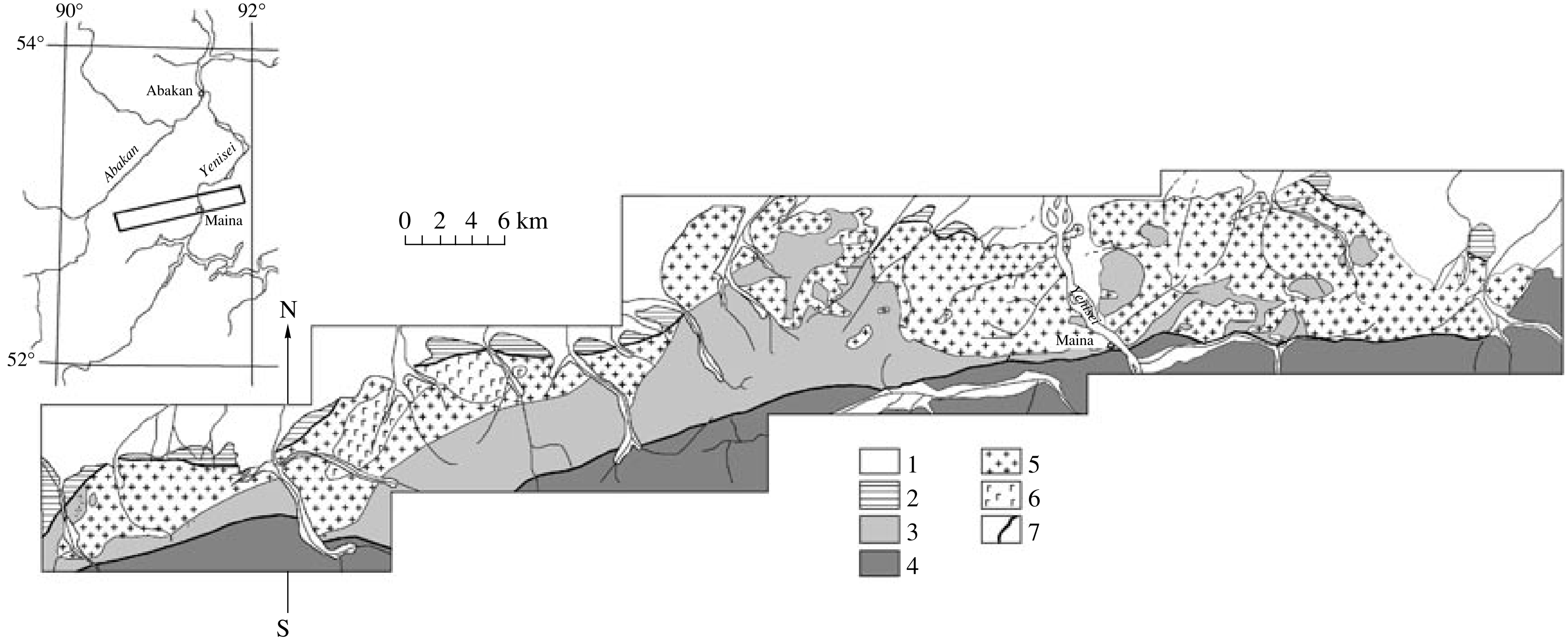

Fig. 1. Schematic map of the Yenisei Batholith, Western Sayan (modified after Smyshlyaev, 1958; Rudnev et al., 2005). The central part of the batholith has the coordinates 53°05′ N, 91°20′ E.

(1) Alluvial deposits; (2) Devonian terrigenous–carbonate and sedimentary–volcanic rocks of the Minusinsk depression; (3) Low Cambrian island-arc volcanic–sedimentary complex; (4) Vendian (?) ophiolite association; (5, 6) intrusive rocks: (5) Cambrian plagiogranites of the Mainski Complex, (6) Early Cambrian gabbroid associations (Lysogorskii and Subbotinskii complexes, undifferentiated); (7) deep faults. The inset is an index map of the study area.

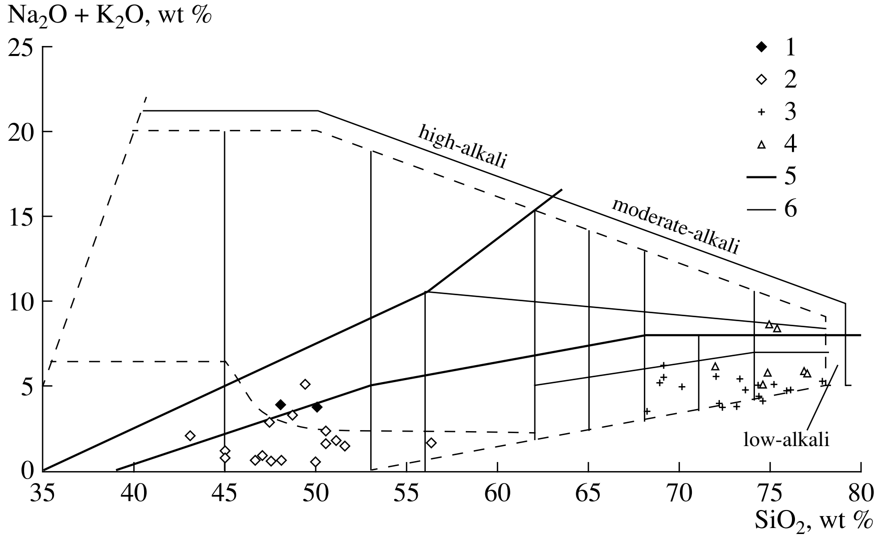

Fig. 2. ($Na_2O + K_2O$)–SiO_2 classification diagram for the rocks of the Yenisei Batholith, Western Sayan, and its host basalts and gabbro.

(1) Tholeiitic basalts; (2) gabbro; (3) trondhjemites–plagiogranites; (4) dikes of aplites and fine-grained granites; (5) boundaries between rock series of different alkalinity: low-, moderate-, and high-alkali; (6) boundaries between rock types (*Petrography and Petrology…*, 2001).

1.0–1.5 cm across. The usual accessory minerals are zircon and sphene.

The leucogranites of the final phase occur as single dikes. The fine-grained and aplitic leucogranites compose bodies up to 2.5 m thick and 50–100 m long (occasionally up to 250–500 m). They consist of microcline, microcline-perthite, albite, and quartz; the minor minerals are biotite, muscovite, garnet, and tourmaline.

Judging from the thickness of the volcanic–sedimentary cover, the batholith was emplaced at a depth of 1.0–1.5 km (Smyshlyaev, 1958, 1963), which is also confirmed by the predominantly porphyritic textures of the inner-contact facies and the predominant development of hornfels after host rocks in the outer-contact zone.

The Mainskii gabbro–plagiogranite complex in the Western Sayan is accompanied by small gold-bearing base-metal sulfide deposits and occurrences of ore mineralization, most of which are localized in the outer-contact zones of the intrusions (Alabin, 1987).

GEOCHEMISTRY

Table 1 reports the chemical composition of granitoids from the Yenisei Batholith, the host basalts, and gabbroid nodules in the main-phase rocks. Petrographic and geochemical data indicate (Fig. 2) that the rock association of the batholith is not full and complete if considered together with dikes of fine-grained granites and aplites. In compliance with currently adopted concepts, it can be determined as low-alkali tonalite–plagiogranite association (*Petrography and Petrology…*, 2001) or tonalite–trondhjemite (*Classification of Magmatic…*, 1997). The granitoids of these associations are characterized by low concentrations of most lithophile elements (Popolitov et al., 1973; and others).

In variation diagrams (Fig. 3), the rocks of the Yenisei pluton define a bimodal compositional trend with clearly separated gabbro and plagiogranites. The gap in between includes only the data points of reworked nodules, which are not shown in the diagrams. The compositions of the leucogranites and aplites of the final phase define their own potassic trend, which is perpendicular to the main trend.

Gabbroid nodules in the batholith are relatively poor in alkalis and Ti and have concentrations of Mg, Ca, and B slightly elevated compared to the clarkes for gabbro (Table 1, Fig. 3). Vanadium is the only element of the iron group whose concentrations in the rocks are elevated. The contents of Co and Ni are slightly elevated, and those of Cr, Cu, and Sc are relatively low. The REE concentrations in the gabbroids are generally corresponding to those in gabbro of the tholeiitic series (Table 2). The REE patterns are practically horizontal (tholeiitic pattern), with La/Yb ~ 3. The geochemical characteristics of the gabbroids of the batholith place these rocks among low-Cr and low-Ti tholeiitic gabbro. The composition of these rocks is generally close to the average composition of the lower continental crust (Taylor and McLennan, 1975). The rocks exhibit strong positive anomalies at Zr, Pb, and, particularly, B and negative anomalies at Cr and Li (Fig. 4).

The granitoids of the Yenisei pluton are characterized by significant variations in the concentrations of SiO_2 (from 68% in tonalites to 76% in plagioclase

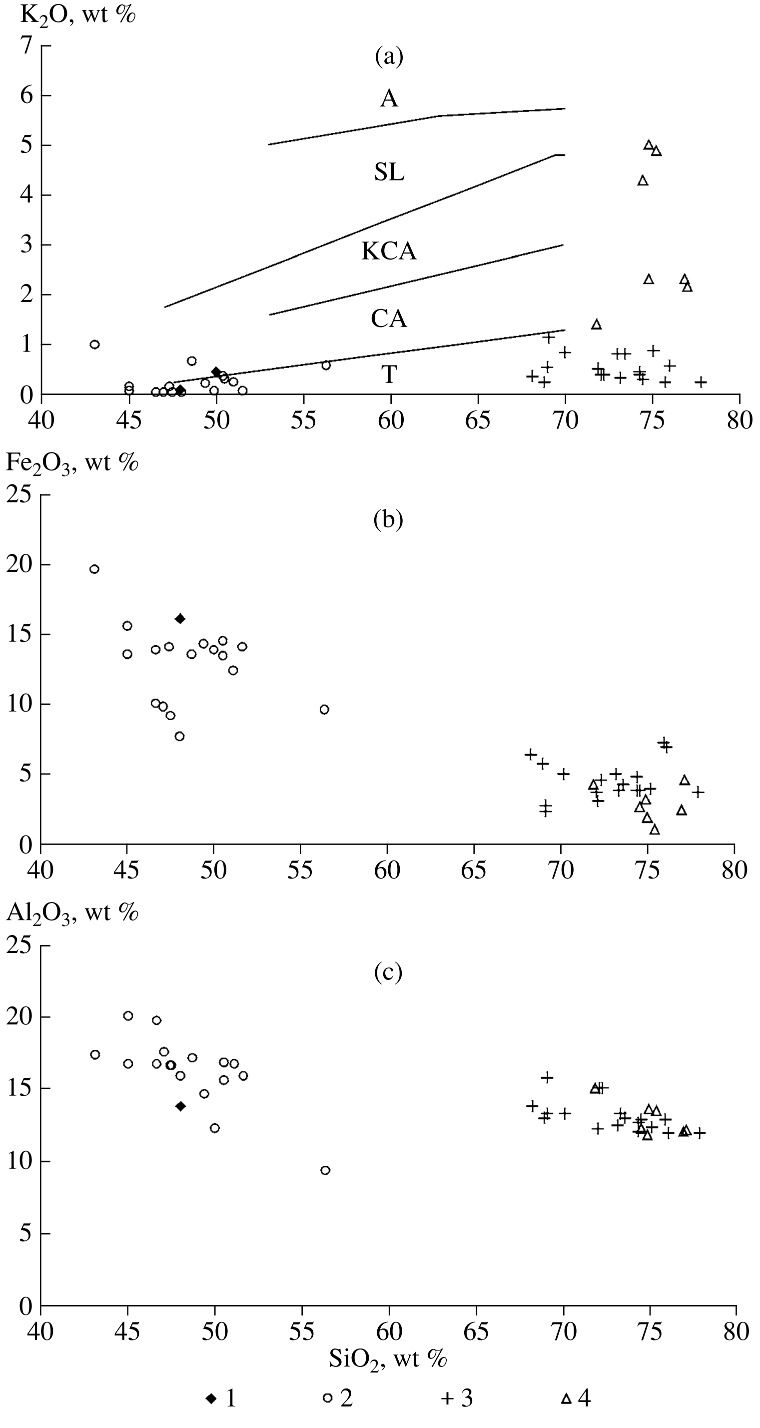

Fig. 3. Harker diagram for the rocks of the Yenisei Batholith, Western Sayan, and its host basalts and gabbro.

Solid lines in Fig. 3a separate rock series (Peccerillo and Taylor, 1976): T—tholeiitic, CA—calc–alkaline, KCA—potassic calc–alkaline, SL—shoshonite–latite, and A—alkaline.

(1) Tholeiitic basalt; (2) gabbro; (3) trondhjemites–plagiogranites; (4) dikes of fine-grained granites and aplites.

leucogranites, Fig. 2). They are metaluminous [according to Arth's (1979) classification: $Al_2O_3 < 14.5$ wt %, Al coefficient = 2–3, Na/K = 5–10] and have low concentrations of rare alkalis (Li, Rb, and Cs), most rare granitophile elements (Be, Nb, Ta, Sn, and others), and, correspondingly, high K/Rb ratios (600–1000) at high concentrations of Pb and B (Table 1) compared to those in the more widely spread granitoids of calc–alkaline series.

The range of the REE contents in the plagiogranites is very broad (Table 2, Fig. 5) and practically com-

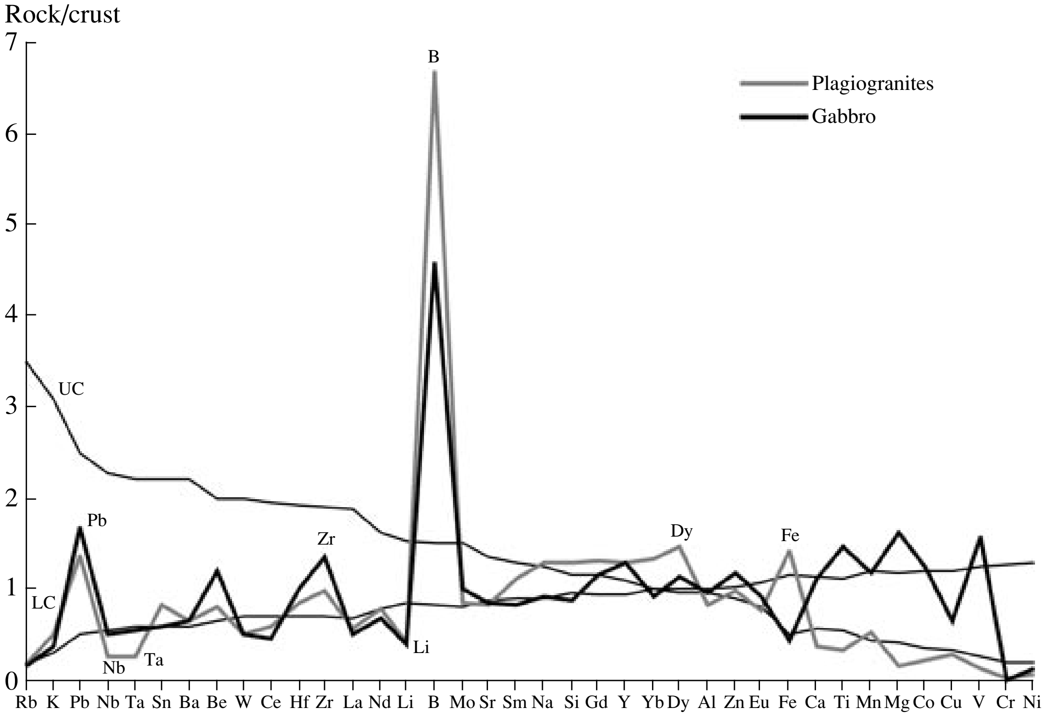

Fig. 4. Elemental patterns normalized to the bulk continental crust (Taylor and McLennan, 1985) for the rocks of the Yenisei Batholith, Western Sayan.

UC and *LC* are the complexes of the upper and lower continental crust (Taylor and McLennan, 1985).

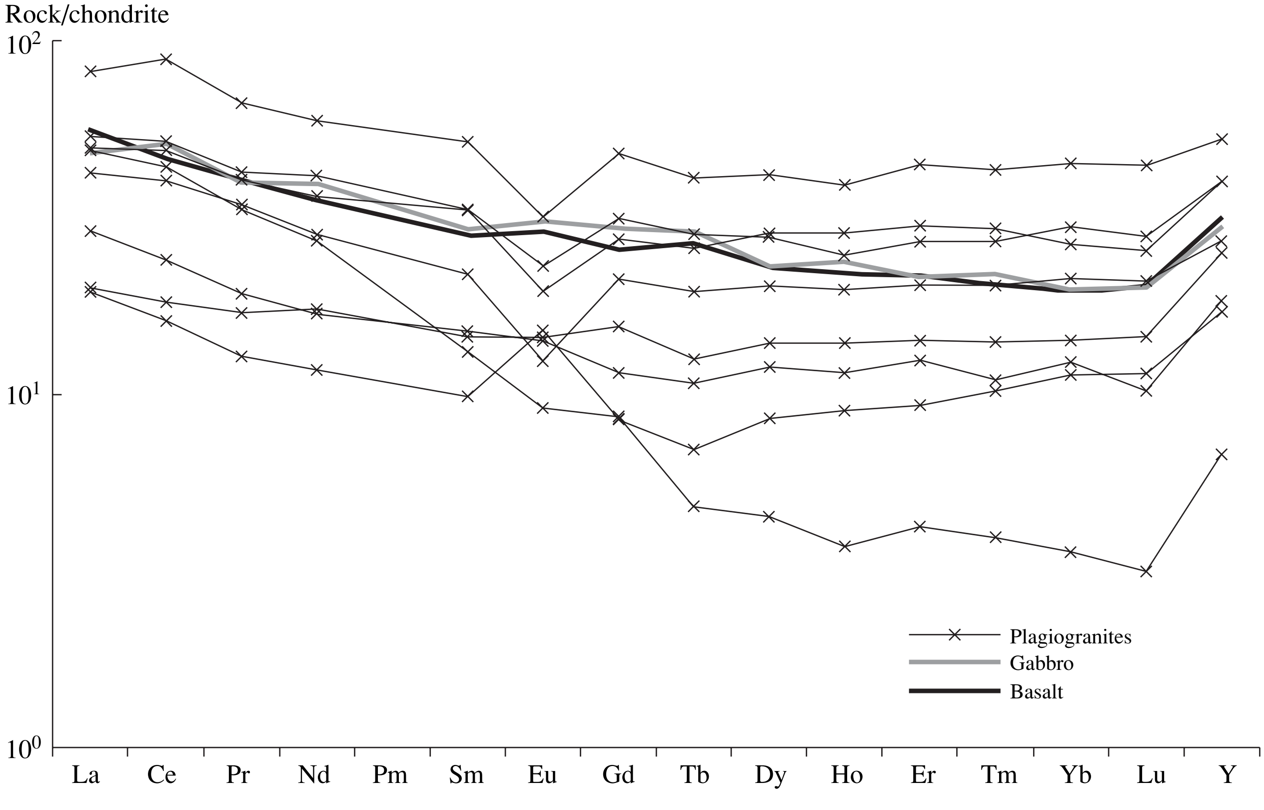

Fig. 5. Chondrite-normalized (Sun and McDonough, 1989) REE patterns for the trondhjemites–plagiogranites of the Yenisei Batholith, Western Sayan, and its host basalts and gabbro.

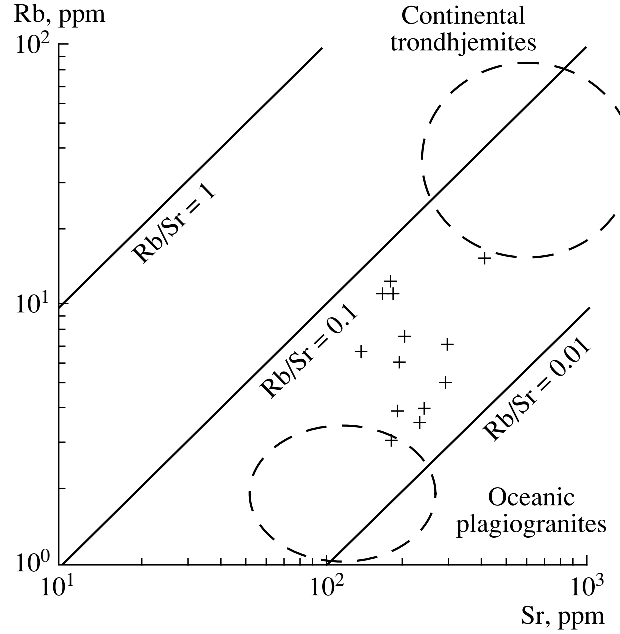

Fig. 6. Rb–Sr variation diagram for the trondhjemites–plagiogranites of the Yenisei Batholith, Western Sayan.

Dashed lines contour the compositional fields of continental trondhjemites and oceanic plagiogranites (Coleman and Donato, 1979).

pletely overlaps the compositional range of the local tholeiitic volcanics and gabbroids. The rocks have weakly fractionated REE patterns (La/Yb ~ 1.4–3.3), mostly with low Eu anomalies or without them. The most siliceous plagiogranites have fractionated REE patterns and, sometimes, positive Eu anomalies (Tables 1, 2: sample E-5).

The concentrations of most trace elements in the plagiogranites of the Yenisei Batholith are close to those in the host tholeiitic basalts and nodules of tholeiitic gabbroids in the main-phase rocks (Tables 1, 2). A notable difference of the plagiogranites from the local tholeiitic volcanics and gabbro is that the former show a tendency toward a general increase in the sum of REE and their stronger fractionation, and relatively low contents of the Fe-group elements (Ni, Co, and V). Correspondingly, the patterns of the plagiogranites normalized to the average crust are generally conformable with the compositions of the lower crust and the gabbro of the nodules in the left-hand part of the plot and deviate toward the composition of the upper continental crust in the right-hand part (starting with Na; Fig. 4). The only exception is the elevated Fe concentration. A remarkable feature of the rocks is also their conformable anomalies of Pb, Zn, and B, which were likely of regional character.

In terms of the Al_2O_3/Yb ratio, the plagiogranites of the Yenisei Batholith are close to the low-Al (metaluminous) oceanic plagiogranites of the Semail, Troodos, and Oregon ophiolite complexes (Arth, 1979; Coleman and Donato, 1979). The concentrations of K_2O (0.3–0.7 wt %) and SiO_2 (68–76 wt %) in these rocks are close to those in oceanic plagiogranites, but our rocks differ from the latter in bearing higher contents of Sr (180–600 ppm) and Rb (3–15 ppm, 5–6 ppm on average). Correspondingly, the field of these plagiogranites in a Rb–Sr diagram is located between the fields of oceanic plagiogranites and classic continental trondhjemites (Fig. 6).

The normative compositions of the main-phase granitoids correspond to those of the least potassic tonalites and trondhjemites (Fig. 7), which plot within

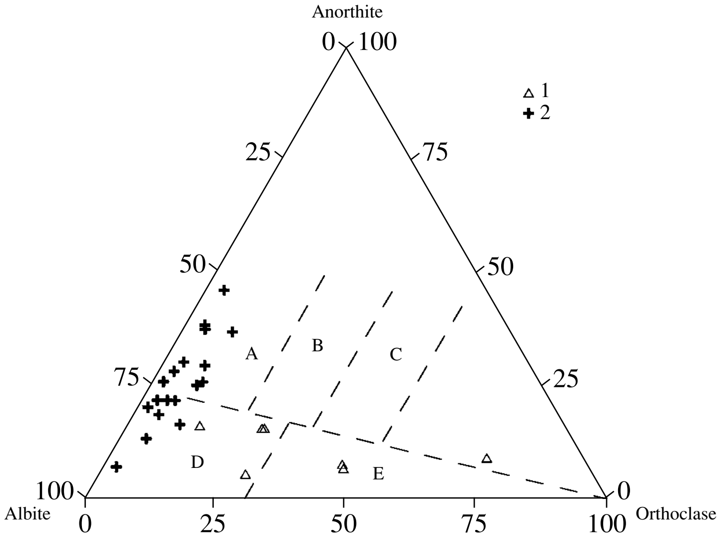

Fig. 7. Ternary albite–anorthite–orthoclase (normative compositions) diagram for (1) the leucogranite dikes of the final phase and (2) trondhjemite-plagiogranites of the main phase of the Yenisei Batholith, Western Sayan.

Normative composition fields (O'Connor, 1965): A—tonalite, B—granodiorite, C—adamellite, D—trondhjemite, E—granite.

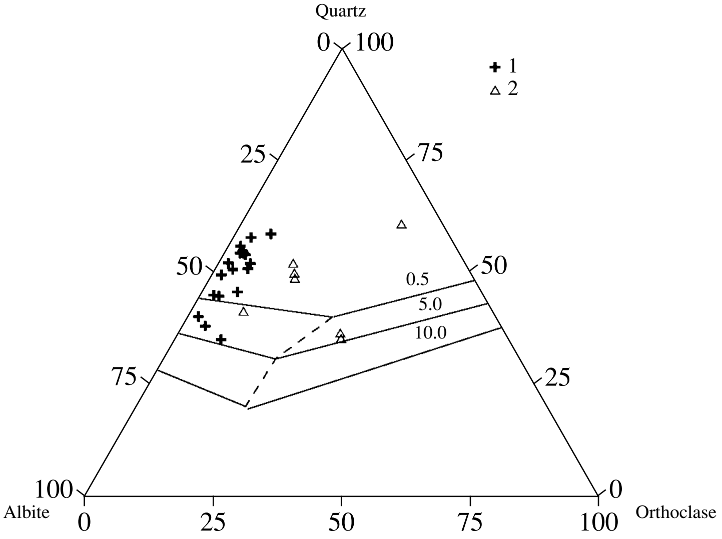

Fig. 8. Ternary albite–quartz–orthoclase (normative compositions) diagram with isopleths of H_2O pressure (Tuttle and Bowen, 1958; Luth et al., 1964; James and Hamilton, 1969) for (1) trondhjemite-plagiogranites of the main phase and (2) the leucogranite dikes of the final phase of the Yenisei Batholith, Western Sayan.

the field of low-pressure single-feldspar granitoids (Fig. 8). The compositions of the vein leucogranites of the final phase define an orthoclase trend.

DISCUSSION

Most popular genetic models. As was mentioned above, the genesis of plagiogranites remains not fully clear and is actively disputed. In his geochemical classification, Tauson (1977) emphasized the low overall alkalinity of these granitoids, their low concentrations of K_2O (no higher than 0.5 wt %) and most lithophile elements (Rb, Li, Cs, Be, Nb, and Ta) and considered the plagiogranites of the Yenisei Batholith to exemplify the tholeiitic geochemical type, a derivative of tholeiitic basalt magmas. A similar viewpoint was also held by Popolitov et al. (1973).

Coleman and Donato (1979) subdivided low-alkali granites into two types: low-alumina oceanic plagiogranites and high-alumina continental trondhjemites. These researchers also believed that oceanic plagiogranites are produced by the differentiation of basaltic magma, but this is a complicated process, for which it is still difficult to provide a clear petrological interpretation. Based on isotopic data, these researchers also admit the possibility that small volumes of plagiogranites can be derived when basalt interacts with seawater or, perhaps, also with meteoric waters.

Based on the comparative analysis of natural high- and low-alumina granites from the Siberian Platform and elsewhere and on published calculated and experimental data on the melting of metabasites, Turkina (2002) proposed scenarios for the genesis of plagiogranites. For example, she suggested that low-alumina oceanic plagiogranites can be produced by the fractional crystallization of a basaltic melt or by the melting of metabasites under low pressures early during the evolution of island arcs or backarc spreading.

From the physicochemical standpoint, plagiogranites can be derived by the melting of basalts like N-MORB under a low total pressure (<5 kbar), with the origin of an orthopyroxene–clinopyroxene–plagioclase residue devoid of garnet (Arth, 1978; Kuz'min, 1985; Turkina, 2002).

Another mechanism, which was proposed to explain the genesis of plagiogranites of the Zhanchivlan Massif in the Mongolia–Okhotsk zone (Yarmolyuk et al., 2002), is the melting of the oceanic crust during subduction. The isotopic–geochemical simulations of the compositions of the protoliths from which the Yenisei Batholith could be derived (Rudnev et al., 2005) demonstrate that the melanocratic plagiogranitic melt can be obtained via the partial melting of a primitive tholeiitic source under low pressures, with the origin of great volumes (82–84% of the total volume of the protolith) of amphibolite (amphibole ± plagioclase) or gabbroid (plagioclase + clinopyroxene + orthopyroxene + amphibole) residues. Note that the REE patterns of such a source are not conformable with the patterns of the local tholeiitic basalts that are regarded as a potentially possible source (Rudnev et al., 2005, Fig. 9).

As follows from the review of the literature data, the most probable mechanisms of the origin of plagiogranites are commonly thought to be as follows: the melting of ancient plagiogranites (this scenario is at variance with the geologic setting of our batholithic rocks), the crystallization differentiation of tholeiitic magmas, and the partial melting of tholeiitic basic rocks. The latter two mechanisms can usually produce only small or medium-sized intrusions.

Table 1. Composition of rocks composing the Yenisei Batholith, Western Sayan, and of its host tholeiitic basalts and gabbro

Component	Basalt	Gabbro*	Plagiogranites of the batholith (representative samples)											Plagiogranite (average for batholith)	Plagiogranite of the tholeiitic series (Tauson, 1977)	Leucogranite dikes***
			E-1	E-2	E-4	E-5	E-6	E-9	E-16	K43/3**	RS-46**	RS-44**	RS-43**			
SiO_2	47.99	48.47	70.02	73.46	74.24	74.29	73.18	68.12	69.03	67.86	68.01	73.47	75.94	71.60		74.98
TiO_2	2.14	1.35	0.47	0.28	0.25	0.30	0.29	0.47	0.24	0.55	0.47	0.26	0.22	0.36		0.14
Al_2O_3	13.92	16.30	13.36	13.08	12.18	12.75	13.35	13.95	15.87	14.21	13.77	12.37	12.56	13.23		13.01
$Fe_2O_{3\,tot}$	16.13	12.97	5.10	4.31	4.85	3.95	3.92	6.45	2.90	5.52	6.00	3.75	3.05	4.58		3.00
MnO	0.20	0.29	0.11	0.08	0.15	0.06	0.05	0.12	0.08	0.09	0.11	0.12	0.06	0.09		0.04
MgO	4.48	8.69	1.00	0.48	0.29	0.41	0.59	1.65	1.05	1.41	1.27	0.66	0.85	0.99		0.36
CaO	10.09	10.89	3.90	2.49	1.8	3.03	2.43	5.55	3.30	3.17	3.07	2.72	1.80	2.70		1.05
Na_2O	3.72	1.34	4.09	3.94	4.50	3.96	5.04	3.08	5.03	4.76	3.92	4.51	3.31	4.14	3.70	3.26
K_2O	0.10	0.23	0.83	0.81	0.46	0.38	0.34	0.37	1.14	0.42	0.77	0.71	0.41	0.57	0.36	3.19
P_2O_5	0.23	0.05	0.06	0.05	0.04	0.05	0.06	0.03	0.03	0.16	0.11	0.06	0.05	0.05		0.02
H_2O^+	2.60	1.78	0.95	1.09	1.35	1.32	0.93	0.95	1.04					1.09		
F	0.06	0.03	0.06	0.08	0.02	0.01	0.04	0.09	0.04					0.05	0.015	
Cl	0.04	0.05	0.06	0.04	0.02	0.05	0.04	0.04	0.02					0.04		
LOI	0.96	1.00	1.13	0.96	1.19	0.74	0.70	0.95	0.87	1.44	1.71	1.09	0.84	1.23		0.80
Li	3	5	7	5	4	3	5	4	16					5	4.7	
Rb	1	2	11	11	5	4	3	5	10	3.5	12.3	7.5	6.6	6.5	2.6	
Cs	<2	<2	<2	<2	<2	<2	<2	<2	<2			0.2		<2		
Ta	0.5	0.6	0.3	0.3	0.3	0.2	0.3	0.2	0.2	0.56	b.d.l.	0.09	b.d.l.	0.3	0.4	
Nb	5	5.6	3.8	2.4	3.9	2.2	3.2	1.8	2.1	6.63	2.52	1.1	3.28	3.3	2.4	
Zr	162	136	75	48	150	80	105	82	68	202	53	90	97	108	89	
Hf	4.3	3.1	2.2	1.4	4.0	2.2	2.6	1.9	1.6	5.91	1.32	2.8	2.79	3.0	3.0	
Ba	80	165	183	238	95	87	109	103	445	236	259	260	312	246	57	
Sr	321	219	180	288	290	225	240	191	404	228	176	200	137	198	139	

Table 1. (Contd.)

Component	Basalt	Gabbro*	Plagiogranites of the batholith (representative samples)											Plagiogranite (average for batholith)	Plagiogranite of the tholeiitic series (Tauson, 1977)	Leucogranite dikes***
			E-1	E-2	E-4	E-5	E-6	E-9	E-16	K43/3**	RS-46**	RS-44**	RS-43**			
Sn	4.2	1.5	3.1	1.7	1.8	1.8	1.0		0.9					2.1	2.7	
Pb	11	13	16	12	4.6	9	9.4	2.2	4.5					11	2.8	
Zn	160	94	84	88	160	45	36	30	76					79	75	
Co	43	36	9	8.5	4.6	7.2	8.7	13	6.6					7	7.6	
Ni	28	15	6.6	6.9	7.5	7.6	11	12	4					7	7.2	
Cr	<4	<4	<4	<4	<4	<4	4	15	<4					<4		
V	410	360	71	29	8	40	18	131	31					29	61	
Mo	1.2	1	2.4	0.5	0.15	0.6	1.0		0.6					0.9		
Cu	14	49	13	35	11	22	32	23	12					21	1.5	
B	12	46	38	31	19	74	100		140					67		
Sc	35	60	27	38	30	20	30		7					25	16	
Ag	0.15	0.15	0.22	0.13	0.09	0.06	0.06		0.06					0.10		
Ge	2.1	1.7	0.4	2.0	0.4	1.4	0.9	1.8	1.7					1.1		
K/Rb	660	950	627	610	760	800	930	620	950	996	520	786	516	728	1154	
Ba/Sr	0.23	0.75	1.02	0.83	0.33	0.39	0.45	0.54	1.10	1.03	1.47	1.30	2.27	1.24	0.41	
Number of samples	2	11	1	1	1	1	1	1	1	1	1	1	1	24		7

Note: * Analyses of gabbroids include the data of the authors and G.V. Polyakov et al. (1987); ** data from Rudnev et al. (2005); *** data from Smyshlyaev (1963). Blank cells in the table correspond to the absence of data, **b.d.l.**—concentrations below the detection limits. The samples were analyzed at the Vinogradov Institute of Geochemistry, Siberian Division, Russian Academy of Sciences. Rocks were analyzed for major elements by XRF (analysts A.Ya. Finkel'shtein and T.N. Gunicheva); Li, Rb, and Cs were determined by flame photometry (analysts S.I. Shigarova and L.V. Altukhova); Ba, Sr, Sn, Pb, Zn, Co, Ni, Cr, V, Cu, Mo, Be, B, and F were analyzed by quantitative atomic emission spectral analysis (analysts S.K. Yaroshenko, A.I. Kuznetsova, S.S. Vorob'eva, and O.A. Chernysheva); Ta, Nb, Zr, and Hf were determined by the quantitative atomic emission method with preliminary chemical enrichment (analysts L.P. Koval and S.N. Arbatskaya). Major oxides are given in wt %, trace elements are in ppm.

Table 2. Concentrations (ppm) of REE and Y in the plagiogranites of the Yenisei Batholith, Western Sayan, its host basalts and gabbro xenoliths

Element	E-17	E-3	E-12	E-13	E-5	E-9	E-6	E-2	E-4	E-1	K43/3	RS-46	RS-44	RS-43
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Basalts	Gabbro	Plagiogranites											
La	13.30	11.49	5.14	4.63	6.90	4.74	10.05	11.81	12.76	19.50	17.11	8.90	6.10	4.40
Ce	28.44	31.34	15.36	9.88	14.66	11.13	24.64	29.98	31.88	54.42	41.94	19.67	11.80	10.35
Pr	3.86	3.78	2.09	1.22	1.83	1.62	3.28	3.87	4.05	6.37	6.05	3.03	–	1.68
Nd	16.53	18.45	9.15	5.48	7.91	8.13	13.28	17.04	19.46	27.85	25.65	10.98	6.50	6.37
Sm	4.31	4.48	2.91	1.51	2.31	2.23	3.35	5.08	5.11	7.96	7.42	3.17	1.66	2.22
Eu	1.68	1.79	0.61	0.88	0.82	0.84	0.72	1.14	1.34	1.84	1.63	0.94	0.62	0.65
Gd	5.29	6.08	3.92	1.74	2.36	3.19	4.36	5.66	6.46	9.86	8.45	3.36	1.62	2.28
Tb	1.00	1.08	0.80	0.26	0.40	0.47	0.73	0.97	1.06	1.54	1.36	0.62	0.32	0.42
Dy	5.84	5.86	4.69	2.17	3.03	3.54	5.13	7.26	7.08	10.64	9.44	4.35	–	3.25
Ho	1.24	1.34	1.13	0.51	0.65	0.79	1.12	1.62	1.40	2.22	1.93	0.9	–	0.7
Er	3.60	3.56	3.38	1.54	2.07	2.35	3.38	4.98	4.49	7.42	6.35	2.96	–	2.36
Tm	0.52	0.56	0.55	0.26	0.28	0.36	0.52	0.75	0.69	1.10	0.83	0.44	–	0.38
Yb	3.35	3.36	3.58	1.93	2.10	2.41	3.63	4.53	5.08	7.66	5.90	2.81	1.77	2.42
Lu	0.51	0.51	0.56	0.29	0.26	0.37	0.53	0.65	0.71	1.13	0.94	0.45	0.28	0.43
Y	31.44	29.63	28.54	17.07	18.42	25.13	27.03	40.15	40.15	52.90	51.90	27.50	12.30	19.90
La/Yb	3.97	3.41	1.44	2.40	3.29	1.97	2.77	2.61	2.51	2.55	2.90	3.17	3.45	1.82

Note: Samples 1–10—authors' data obtained by ICP-MS at the Vinogradov Institute of Geochemistry, Siberian Division, Russian Academy of Sciences (analysts E.V. Smirnova, T.N. Galkina, and V.I. Lozhkin) on a PlasmaQuad PQ-2 (VG, Great Britain) mass spectrometer. Samples 11–14—analyses compiled from (Rudnev et al. 2005).

Recent experimental results point to the physicochemical possibility of the origin of a tonalite magma by means of the magmatic replacement (granitization) of amphibolite crustal material (Khodorevskaya and Zharikov, 1998; Khodorevskaya et al., 2002). It was also demonstrated that these processes can occur in nature (Grebenshchikova and Koval, 2004).

It should be mentioned that one can simulate practically any composition of the partial granitoid melt by selecting and fitting compositions for the protolith, the types and degrees of partial melting, and the external conditions (T, P, and P_{H_2O}). The task is thus formulated as the choice of a model most consistent with the empirically established geological and geochemical boundary conditions.

Model. The low aluminous composition of the plagiogranites from the Yenisei Batholith and their weakly fractionated REE patterns make these rocks similar to oceanic plagiogranites (plagiogranites of ophiolitic series). However, we believe that the empirical characteristics of the batholith are inconsistent with the aforementioned petrogenetic schemes that are based on the crystallization differentiation of a tholeiitic magma or on partial melting. Because of this, it seems to be expedient to explain the genesis of the Yenisei Batholith proceeding from its certain geological and geochemical characteristics that can be used as the boundary conditions for the selection of the petrogenetic model.

First of all, this is the huge volume of the granitoid magma, which could hardly be produced during the origin of ophiolitic associations and the partial melting of tholeiitic rocks. Note that the batholith contains no significant volumes of basic and metabasic rocks of composition corresponding to the surmised parental magma or source (Rudnev et al., 2005). Mafic rocks occur in the Mainskii Complex, mostly in the form of nodules, xenoliths, and blocks of the roof rocks. Moreover, there is no evidence of the existence of required volumes (82–84% of the total volume of the source, according to Rudnev et al., 2005) of residues of the calculated composition. Plagiogranitization, a process identified in the near-contact zone of the massif, testifies to a significant fluid potential of the main phase and the possible additional inflow of fluids during the magmatic stage.

Considering the geochemical aspect of this problem, it should be mentioned that the composition of the granitoids of the Yenisei Batholith does not correspond to the composition of oceanic plagiogranites, with the former compositions shifted toward the fields of continental trondhjemites in the Rb–Sr classification diagram (Fig. 6). Our granitoids are characterized by REE concentrations higher than those in oceanic plagiogranites (Coleman and Donato, 1979; Tsukanov et al., 2004), the notable predominance of differentiated REE patterns with a slight enrichment in LREE, and the occurrence of Eu minima (or their absence; Fig. 5). It is reasonable to expect that the partial melting of basic rocks (in our situation, these could be tholeiitic basalts and low-alkali gabbro) should have produced concave REE patterns over MREE and HREE and positive Eu anomalies (Helz, 1976; Nance and Taylor, 1976; Hanson, 1980), which were identified only in one sample (Fig. 5). At the same time, the plagiogranites exhibit obvious evidence of their geochemical relations to the potential tholeiitic source (Figs. 4, 5), as is typical of the granitoids of crustal batholiths (Koval, 1998; Grebenshchikova and Koval, 2004), at relatively weak enrichment in granitophile elements, which usually enrich the partial melts. The polychronous character of the zircons (Rudnev et al., 2005) can also be regarded as additional evidence that the original matrix inherited its composition during granite formation. Note that the composition of the earliest phases of the batholith generally does not correspond to the melting minima of the respective granitic systems (Fig. 8), as could be expected in the situation of partial melting, but is shifted toward the supraeutectic region, similarly to the composition of the early phases and facies of typical crustal batholiths (Koval, 1998).

In light of the data presented above, the model for the origin of granitoids in the Yenisei Batholith via the crystallization differentiation of tholeiitic basalts seems to be hardly realistic.

Significant difficulties are also encountered by the interpretation based on the model of the partial melting of tholeiitic basic rocks. This model is in conflict with both geological and geochemical characteristics of the Yenisei Batholith. Moreover, it fails to explain the segregation of the partial melts (15–18 wt %) and their accumulation in the form of significant magmatic masses.

In this situation, there seems to be good reasons to turn to Korzhinskii's (1952, 1955) hypothesis of magmatic replacement, which is likely able to provide the most realistic explanation for the genesis of crustal granitic batholiths in compliance with our recently obtained data (Koval, 1998; Grebenshchikova and Koval, 2004b) and the experimental results in (Zharikov, 1996; Khodorevskaya and Zharikov, 1998; Khodorevskaya et al., 2002). Proposing a model of magmatic replacement for discussion, it should be emphasized that, following D.S. Korzhinskii, V.A. Zharikov, and F.A. Letnikov (Korzhinskii, 1952; Zharikov, 1987; Letnikov, 1975), we do not question the magmatic genesis of granites but discuss, first of all, the mechanisms producing "batholithic" volumes of granitoid magmas and the consistency between known physicochemical models and empirical boundary conditions for the origin of magmatic associations (Koval, 1998). Korzhinskii (1952, 1955) understood the process of magmatic replacement as the origin of a granitoid magmatic melt under the effect of deep-seated (transmagmatic) solutions, which are enriched in water, alkalis, and some other components. In application to anchiautochthonous plutons (the model of prograde granitization; Koval, 1998), this mechanism is convincingly corroborated by geological observations. The genesis of allochthonous plutons can be explained within the scope of the model of retrograde magmatic replacement, which requires the inflow of granitizing fluids and a temperature of the protolith much higher than that of the melting minimum in the system. The triggering energy pulse and the driving force of granite formation could be provided by the inflow of deep fluids or the emplacement of pre-batholitic low-alkali gabbroids accompanied by fluid inflow. It cannot be ruled out that the reworked nodules of basic rocks contained in the Yenisei Massif are remnants of this initiating basite intrusion.

The granite-producing process that began with the derivation of an anchieutectic initial partial melt should have immediately shifted toward the generation of superheated supraeutectic melts, which is consistent with available data (Fig. 8). The origin and evolution of the granitoid melt proceeded at its continuous interaction with the incoming fluid, and this process of fluid–magmatic differentiation maintained the overall debasification of the system and the "granitoid" character of the REE distribution. The crystallization of the melt ended with the origin of usual residual derivatives: vein granites with a potassic compositional trend.

The high concentrations of B and Pb and the elevated concentration of Zr, which is typical of both the early gabbroids and plagiogranites, were most probably caused by certain regional characteristics of the pre-batholithic magmatic associations (tholeiitic basalts, ophiolites, gabbroids, and volcanic–sedimentary rocks).

Our model proposed to explain the genesis of the Yenisei Batholith eliminates some difficulties encountered by traditional models of partial melting. First of all, this is the supraeutectic composition of the plagiogranites; the absence of geological data on the existence of required volumes of the residues that should have been produced during the partial melting of basalts or gabbroids; the necessity of segregating the partial melts in the form of a batholithic masses; and, finally, the problem of the space occupied by the batholith.

Available materials indicate that the Yenisei Batholith was produced either in an ensimatic island arc (Kuz'min, 1985; Barbarin, 1999; Alabin and Kalinin, 1999; Rudnev et al., 2005) or in a suprasubductional environment (Turkina, 2002). The initial Sr isotopic ratio (0.70401) and the model Sm–Nd age (0.72 Ga) of the possible protolith (Rudnev et al., 2003) suggest that the most probable source from which the plagiogranites of the Yenisei Batholith were derived was the "young" crust that consisted of tholeiitic rocks of composition close to that of the local Vendian–Early

Table 3. Geological and geochemical parameters of the origin of plagiogranite batholiths: an example of the Yenisei Batholith, Western Sayan

Geologic setting	Deep fault zones, linear troughs. The host rocks were tholeiitic volcanics and gabbroids. The age of the host basalts is 720 Ma, the age of the plagiogranites is 523 Ma (Rudnev et al., 2003; 2005)
Supposed crust type	Crust chemically close to the oceanic crust. Thickness ~10–15 km
Magmatic association	Completed, tonalite–plagiogranite (tonalite–trondhjemite) with leucogranites in the final phase. Predominance of supraeutectic compositions. Xenoliths and nodules of variable size and shape of gabbro and volcanic–sedimentary rocks
Mineralogy (modal composition)	Major rock-forming minerals: oligoclase, albite (40–65%), quartz (45–55%), biotite (up to 5%), hornblende (up to 4%). Minor minerals: microcline-perthite (in single grains). Accessory minerals (minor amounts): zircon, sphene
Geochemistry	Low general alkalinity; high Na/K ratios (5–10); generally elevated silica concentrations (68–76 wt % SiO_2) and low alumina contents (12–14 wt % Al_2O_3); low (even compared to those in the lower continental crust) concentrations of K, Li, Rb, Cs, Sn, W, Mo, Cu, Be, Ta, Nb, Zr, Hf, and Cr; elevated concentrations of Pb (4–35 ppm), Zn (35–700 ppm), B (30–200 ppm); high K/Rb ratios (600–1000), low Ba/Sr ratios (~1); elevated (relative to those in oceanic plagiogranites) concentrations of REE and their weak fractionation; relatively low La/Yb ratios (1.4–3.4); low Cr/V ratios (<0.1). Plagiogranite trend of the main phase
P–*T* conditions of crystallization and H_2O concentration	$T \geq 700°C$, $P < 5$ kbar, >6 wt % H_2O
Petrogenetic mechanism	Magmatic replacement of prograde type. Protolith—oceanic crust
Analogues	Kundustuyul'skii and Lavrenovskii massifs in the Kuznetsk Alatau; Salbinskii Massif in the Western Sayan; and others
Supposed tectonic environment	Early ensimatic ancient island arcs (Kuz'min, 1985; Alabin and Kalinin, 1999; Barbarin, 1999; Rudnev et al., 2005); suprasubduction environments (Turkina, 2002)

Cambrian granitoids and gabbroids. Table 3 summarizes the general characteristics of the model proposed for the Yenisei Batholith.

Obviously, the origin of batholiths similar to the Yenisei Batholith should be regarded as resulting from the earliest crustal granite formation and continental crustal growth at the expense of the primary oceanic crust.

Regardless of the model assumed for the derivation of the plagiogranites from their crustal basic protolith, it is quite evident that the geochemistry of these rocks is principally different from the geochemistry of the oceanic plagiogranites of ophiolitic complexes. Because of this, our granitoids should be distinguished as an individual geochemical type of early crustal plagiogranites.

CONCLUSIONS

The Yenisei Batholith is made up of a gabbro–trondhjemite–plagiogranite rock association, which is rare in batholiths and whose main phase composes a large (>500 km^2) plagiogranite pluton. This association belongs to the tholeiitic rock series.

The granitoids of the Yenisei Batholith differ from analogous rocks elsewhere, including tonalite batholiths (Grebenshchikova and Koval, 2004b), in being low-alkali and low-alumina (<15 wt % Al_2O_3, Al coefficient = 2–3) rocks with low concentrations of most granitophile components, low Cr/V (<0.1) and R/Sr (0.01–0.1) ratios, and the maximum values of the K/Rb (600–1000) and Na/K (5–10) ratios. The normative composition of these rocks corresponds to the composition of supraeutectic quartz–plagioclase magmas derived under low pressures.

The Yenisei pluton differs from typical oceanic plagiogranites not only by rock volumes but also in having higher concentrations of K, Rb, and Sr (which are intermediate between the concentrations in oceanic plagiogranites and continental trondhjemites) and the character of REE patterns (Figs. 5, 6). The geological and geochemical features of the plagiogranites of the Yenisei Batholith (Table 3) indicate that they can be recognized as a separate geochemical type of crustal plagiogranites.

The comparative analysis of the diversity of the petrogenetic models indicates that the most consistent explanation of the geological and geochemical characteristics of the Yenisei Batholith can be given within the scope of the model of retrograde magmatic replacement. According to it, the overheated supraeutectic magma was produced under relatively low pressures (<5 kbar), at temperatures of >700°C, and at the inflow of an aqueous granitizing fluid into the magma-generating area and the subsequent fluid–magmatic differentiation.

The geology of the Yenisei Batholith and the compositional features of its rocks suggest that it can be classed, along with most other granitoid batholiths, with crustal plutons, which were produced by the earliest processes of crustal granitization. The protolith of the batholithic rocks consisted of "young" oceanic crustal material, and the conditions suitable for the origin of the batholith could exist during the development of the Northern Sayan island arc.

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