ISSN 0016-7029, Geochemistry International, 2006, Vol. 44, No. 8, pp. 791–807. © Pleiades Publishing, Inc., 2006.
Original Russian Text © V.E. Strikha, 2006, published in Geokhimiya, 2006, No. 8, pp. 855–872.

Late Mesozoic Collisional Granitoids of the Upper Amur Area: New Geochemical Data

V. E. Strikha

Amur Institute of Integrated Research, Far East Division, Russian Academy of Sciences, Relochnyi per. 1, Blagoveshchensk, 675000 Russia

e-mail: strikhav@mail.ru

Received August 16, 2004

Abstract—Geochemical and isotopic data were used for a comparative analysis of Late Mesozoic (150–120 Ma) granitoids in various geological structures of the upper Amur area. The granitoids are metaluminous high-potassic I-type rocks of the magnetite series. They have variable alkalinity and consist of the monzonite–granite and granosyenite–granite associations. The monzonite–granite association consists of calc–alkaline granitoids of normal alkalinity belonging to the Umlekan–Ogodzhinskaya volcanic–plutonic zone and the Tynda–Bakaran Complex of the Stanovoy terrane. The rocks are characterized by negative anomalies of U, Ta, Nd, Hf, and Ti (in patterns normalized to the primitive mantle), with Eu anomalies pronounced weakly in the granodiorites and quartz and monzodiorites and more clearly in the granites: Eu/Eu* = 0.37–0.95, and $(La/Yb)_n$ = 7–24, Tb_n/Yb_n = 1.4–3.2. The granosyenite–granite association comprises of moderately alkaline rocks, which are subdivided into three groups according to their geochemistry. The first group consists of phase-I granosyenites of the Uskalinskii Massif of the Umlekan–Ogodzhinskaya zone with the highest concentrations of Sc, V, Cr, Co, Ni, Cu, Cs, Rb, Sr, Y, Zr, Yb, and Th; negative anomalies at Ba, Ta, Sr, and Hf; Eu/Eu* = 0.50–0.58, $(La/Yb)_n$ = 15–16, and Tb_n/Yb_n = 1.8. The second group comprises of moderately alkaline granitoids of the Umlekan–Ogodzhinskaya zone and the Khaiktinskii Complex of the Baikal–Vitim superterrane. Geochemically, the granitoids of this group are generally similar to the monzodiorite–granite association and differ from it in having lower concentrations of REE and Y, Eu/Eu*= 6.2–1.0, $(La/Yb)_n$ = 28–63, and Tb_n/Yb_n = 2.1–4.5. The third group consists of granitoids of the Chubachinskii Complex of the Stanovoi terrane, which typically show negative Cs, Rb, Th, U, Ta, Hf, and Ti anomalies; the lowest concentrations of V, Cr, Co, and Ni; and the highest contents of Sr. The granosyenites of the first phase display clearly pronounced negative Eu anomalies (Eu/Eu* = 0.53–0.68), $(La/Yb)_n$ = 7–24, and Tb_n/Yb_n = 0.8–2.0. The granitoids of the second phase have $(La/Yb)_n$ = 51–84, no Eu anomalies, or very weak Eu anomalies (Eu/Eu* = 0.97–1.23). The silica-oversaturated leucogranites of the third phase are characterized by elevated concentrations of REE, clearly pronounced Eu anomalies (Eu/Eu* = 0.48), and flat REE patterns (Tb_n/Yb_n = 1.3). The diversity of the granitoids is demonstrated to have been caused largely by the composition of the Precambrian source, which was isotopically heterogeneous. The rocks of the monzodiorite–granite association and first-group granosyenites of the granosyenite–granite association of the Tynda–Bakaran Complex were supposedly derived from garnet-bearing biotite amphibolites. In contrast to these rocks, the source of the second-group granites of the granosyenite–granite association was of mixed amphibolite–metagraywacke composition. The third-group of granitoids were melted out of Early Proterozoic crustal feldspar-rich granulites of variable basicity, with minor amounts of Archean crustal material. The granitoids were emplaced in a collisional environment, perhaps, during the collision of the Amur superterrane and Siberian craton. This makes it possible to consider these rocks as components of a single continental volcanic–plutonic belt.

DOI: 10.1134/S0016702906080040

INTRODUCTION

The upper Amur area is characterized by widespread granitoid massifs of a Late Mesozoic age, which are often accompanied by numerous gold placers and deposits and occurrences of gold mineralization of hydrothermal, skarn, and greisen types [1, 2]. The areas of granitoids are traditionally considered in relation to major regional structures. The territory of the upper Amur area now consists of a complicated mosaic of heterogeneous blocks (Fig. 1). The analysis of literature data indicates that this territory includes the Aldan–Stanovoi, Baikal–Vitim, and Amur superterranes and the Mongolia–Okhotsk orogenic belt [3, 4]. The Aldan–Stanovoi composite terrane consists of two large blocks of the Early Precambrian continental crust: Aldan and Stanovoi [3]. The upper Amur area is composed of Archean rocks belonging to the Stanovoi block. The Late Mesozoic granitoids of the Stanovoi block comprise the Tynda–Bakaran (Uda–Zeya) and Chubachinskii complexes, which make up the long (>700 km) Uda belt of batholiths in the southern part of the superterrane, along its boundary with the Mongolia–Okhotsk foldbelt. In the southwest, the Aldan–Stanovoi superterrane is separated by the Dzheltulak fault from the Baikal–Vitim superterrane, which includes massifs of the Early Cretaceous Khaiktinskii Complex [5]. The Early Mesozoic granitoids in the northeastern part of the Amur superterrane and the southern part of the Mongolia–Okhotsk belt are ascribed to the submeridiodally trending Umlekan–Ogodzhinskaya volcanic–plutonic zone, which is interpreted as the northeastern termination of the Great Khingan volcanic–plutonic belt [6]. The geochemistry of granitoids in these areas is still studied much more poorly than in the adjacent teritories: eastern Transbaikalia and the lower Amur area. The recognition of numerous intrusive complexes in the upper Amur area, all of which have generally similar ages (150–120 Ma [5, 7–10]), calls for the geochemical comparison and correlation of these rocks. This comparative analysis is of crucial significance for determining the conditions under which these granitoids were produced, for assessing their possible sources and geodynamic environments, and for predicting the occurrence of related gold ore mineralization in the area.

The genesis of Late Mesozoic magmatic rocks in the upper Amur area was reportedly related to tectono-magmatic reactivation [11], subduction of the oceanic crust beneath an active continental margin [3, 12, 13], collision [8–10], or rifting [14, 15]. Our newly obtained materials on the concentrations of a broad spectrum of elements, including REE, in the local Late Mesozoic granitoids provide the basis for quantitatively reevaluating their correlations and geodynamic environments in which these rocks were produced.

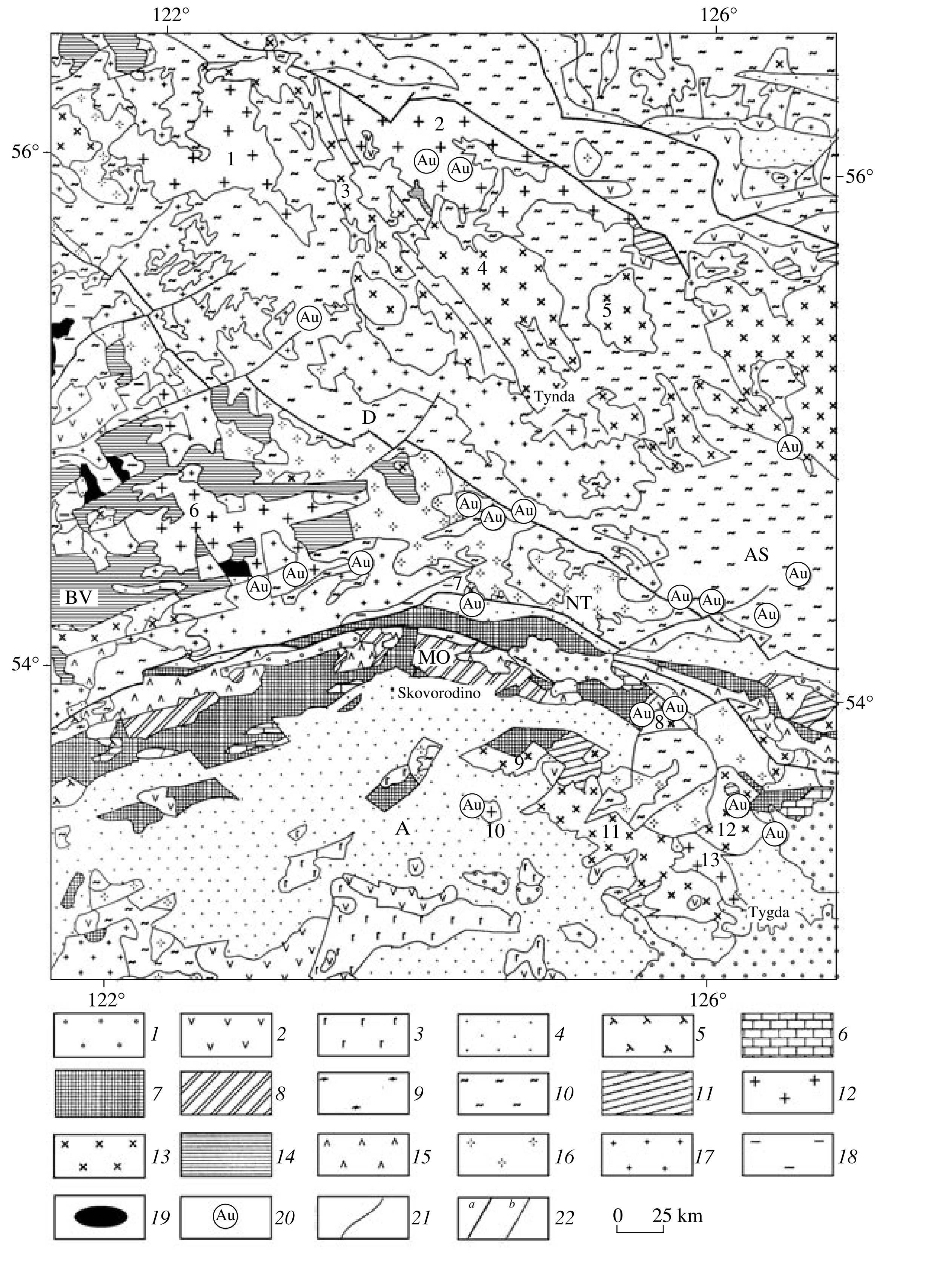
GEOLOGICAL AND PETROGRAPHIC OVERVIEW

The results of latest research demonstrate that, according to their composition, petrochemistry, and isotopic–geochemical characteristics, granitoids in the western part of the Umlekan–Ogozhinskaya volcanic–plutonic zone can be subdivided into two major groups: monzodiorite–granite and granosyenite–granite associations.

The monzodiorite–granite association includes calc–alkaline rocks of normal alkalinity that intrude structures of the Amur superterrane and the Mongolia–Okhotsk orogenic area. These rocks were previously considered to be the early phases of the upper Amur (Olginskii, Igakskii, Talalinskii, and other massifs) and Burinda (Dzhiktadinskii, Burinda, and other massifs) complexes [16]. Our data indicate the identity of the compositions of the analogous rock-forming minerals and similarities in the petrography and geochemistry of the rocks composing the Burinda Complex and the early phases of the Upper Amur Complex, which led us to combine them into a single calc–alkaline monzodiorite–granite association. The intrusive bodies of this association consist of rocks of three phases: phase I is biotite–hornblende (often with pyroxene) quartz monzodiorites, phase II consists of biotite–hornblende granodiorites, and phase III is made up of biotite–hornblende granites. Phase I of the Elninskii Massif, which is located east of our study area, is made up of subalkaline gabbroids [16]. The quantitative proportions of the rocks composing various phases in individual massifs significantly vary, but generally the rocks of phases I and II are volumetrically predominant. The sizes of the intrusive bodies range from a few dozen to a few hundred square kilometers, and most of them have tabular (as the Dzhiktandinskii, Olginskii, Igakskii, and other massifs) or, more rarely, stock-shaped (as the Dzhalinda Massif) morphologies. The massifs of the monzodiorite–granite association are accompanied by gold placer deposits, the Kirovskoe gold–rare-metal deposit, occurrences of gold–rare metal, gold–quartz, and skarn ore mineralization, such as in the Solov'evskii, Igakskii, and Tynda–Ulunginskii groups of primary and placer deposits.

The granosyenite–granite association of the Umlekan–Ogodzhinskaya zone consists of mildly alkaline granitoids. The rocks of this association were previously considered to belong to the Magdachinskii (Magdachinskii, Gorchakovskii, and Isagachinskii massifs), Upper Amur (Sergeevskii Massif and the granites of the Uskalinskii Massif), and Burinda (the granites of the Uskalinskii Massif) complexes. The association consists of rocks of two phases: phase I comprises granosyenites, and phase II comprises granosyenites, biotite–hornblende or, more rarely, biotite subalkaline granites. The intrusive bodies are quantitatively dominated by the rocks of phase II. The granite massifs of this association are exposed over areas as large as a few hundred square kilometers. The plutons are commonly tabular and, rarely, stock-shaped (Burgaliiskii Massif). The

Fig. 1. Schematic geological map of intrusive massifs in the upper Amur area (modified after [6]). (*1*) Neogene–Quaternary deposits; (*2*) Cretaceous volcanic rocks; (*3*) Late Jurassic–Early Cretaceous volcanic rocks of predominantly basic composition; (*4*) Jurassic sedimentary deposits; (*5*) Late Triassic sedimentary deposits; (*6*) Early Carboniferous deposits; (*7*) Devonian deposits; (*8*) Silurian deposits; (*9*) Proterozoic metamorphic rocks; (*10*) Archean metamorphic and ultrametamorphic rocks; (*11*) Cretaceous subvolcanic rocks of predominantly intermediate and acid composition; (*12*) Early Cretaceous granosyenite–granite association; (*13*) Late Jurassic–Early Cretaceous monzodiorite–granite association; (*14*) Late Permian–Early Triassic mildly alkaline granitoids; (*15*) Early Paleozoic intrusive rocks of a gabbro–granite composition; (*16*) Proterozoic granitoids; (*17*) Archean granites; (*18*) Early Archean metamorphic and intrusive granites; (*19*) Early Archean gabbroids; (*20*) deposits and occurrences of gold mineralization (*Au*); (*21*) geological boundaries; (*22*) faults: (*a*) major, (*b*) minor. AS—Aldan–Stanovoi superterrane, BV—Baikal–Vitim superterrane, A—Amur superterrane, MO—Mongolia–Okhotsk orogenic belt; D—Dzheltulakskii Fault, NT—Northern Tukuringra Fault. Numbered massifs: 1—Chil'chinskii, 2—Chubachinskii, 3—Larbinskii, 4—Bakaranskii, 5—Dyupkoiskii, 6—Khaiktinskii, 7—Dzhalindinskii, 8—Igakskii, 9—Dzhiktandinskii, 10—Uskalinskii, 11—Talalinskii, 12—Olginskii, 13—Sergeevskii.


122°
126°
56°
54°
1
2
3
4
5
6
7
8
9
10
11
12
13
Au
Tynda
D
BV
NT
AS
MO
Skovorodino
A
Tygda
0 25 km

granitoid massifs of this association have exposed areas of up to a few hundred square kilometers, and the intrusive bodies are dominated by the rocks of phase II. The plutons are commonly tabular and, occasionally, stock-shaped. Massifs of the granosyenite–granite association are accompanied by placer gold deposits and occurrences of gold–rare-metal, gold–quartz, skarn, and hydrothermal mineralization in the Osezhinskii, Magdagachinskii, and Tygda–Ulunginskii groups of primary and placer deposits.

The Tynda–Bakaran Complex comprises of large (up to 4000 km^2) polyphase granitoid intrusions [10, 17]. Their phase I consists of biotite gabbro and occurs as small bodies near or within the inner-contact zones of large granitoid intrusions. Phase II is made up of biotite–pyroxene quartz monzodiorites, which are spread more widely than the rocks of phase I (it is largely restricted to the inner-contact zone of granite–granosyenite intrusions and occurs in small bodies, together with gabbroids). Phase III consists of biotite–hornblende quartz monzodiorites and granodiorites, with the latter rocks quantitatively dominating in the massifs. Phase IV comprises of biotite–hornblende granites that compose small bodies of variable morphology in the phase-III granodiorites.

The Chubachinskii Complex of the Stanovoi terrane forms the Chubachinskii Massif in the watershed area between the Nyukzha and Timpton rivers [8, 9]. In map view, the massif is a nearly geometrical oval (which is slightly elongated sublatitudinally), exposed over an area of approximately 2500 km^2. The massif is composed of three phases with intrusive relations between them: phase I consists of biotite, occasionally biotite–hornblende porphyritic (with potassic feldspar phenocrysts 1–3 cm and more across) granosyenites; phase II is made up of variably grained porphyritic biotite–muscovite granites and leucogranites of normal and mildly elevated alkalinity and subordinate amounts of their biotite and biotite–hornblende varieties; and phase III is silica-oversaturated leucogranites of normal and moderate alkalinity. The most ubiquitous rocks are the moderately alkaline granites of phase II. The least eroded domes of phase II in the southern part of the Chubachinskii Massif are accompanied by occurrences of greisen mineralization with gold and gold placers of the Apsakan group of primary and placer deposits.

The Khaiktinskii Complex of the Baikal–Vitim superterrane composes the Khaiktinskii Massif. The latter has an irregular shape, is elongated to the northwest (70 × 25 km), and has an area of >1000 km^2 [5]. The massif is accompanied by gold placers, the Berezitovoe gold–rare-metal greisen deposit [17, 18], and numerous occurrences of gold–rare metal and gold–quartz ore mineralization in the Berezitovoe group of primary and placer deposits. The massif consists of rocks of two phases with intrusive relations between them: phase I consists of quartz monzodiorites and granosyenites, and phase II is composed of porphyritic (with potassic feldspar phenocrysts up to 1–3 cm across) granodiorites, granosyenites, granites, and subalkaline granites that grade into one another. The massif is volumetrically dominated by subalkaline granites.

FACTUAL MATERIALS

The concentrations of major elements in rocks were determined the laboratory of the Amur Institute of Integrated Research, Far East Division, Russian Academy of Sciences, by conventional silicate analysis (analysts were S.M. Radomskii, L.P. Noskova, and O.A. Zubova). The contents of most trace elements, including REE, were analyzed by ICP-MS on an Elan DRC II PerkinElmer (United States) mass spectrometer at the Khabarovsk Analytical Center of the Institute of Tectonics and Geophysics, Far East Division, Russian Academy of Sciences (analysis were D.V. Avdeev, L.S. Bokovenko, and V.E. Zazulina), with relative errors of no larger than 5%. Ba and Zr were determined in some samples the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, St. Petersburg by XRF, accuracy was not worse than 10%. The accuracy and precision of the analytical methods were assayed by conducting replicate analyses of internal and internationally certified standards.

The results obtained on the concentrations of trace elements in representative samples from individual massifs in the upper Amur territory are summarized in the table.

The granitoids are mostly metaluminous, high-K rocks of I type of the magnetite series, with a high degree of Fe oxidation. They differ by the $SiO_2/(Na_2O + K_2O)$ proportions and the distributions of trace elements. The multielemental diagrams in Fig. 2 present the ratios of the average concentrations of trace elements in the Late Mesozoic granitoids of the upper Amur area normalized to the primitive mantle. The concentrations of most LILE and HFSE in the granitoids are generally close to those in the upper crust. The contents of Ba and Sr are also close to the upper crustal values or are somewhat higher; and the concentrations of Ta, Hf, Tb, Y, and Yb in most of the rocks are close to the lower crustal values or are lower than these values.

The patterns of the primitive mantle-normalized concentrations of trace elements for the rocks of the monzodiorite–granite association of the Umlekan–Ogodzhinskaya zone display U, Ta, Nd, Hf, and Ti minima. These rocks have concentrations of the most trace elements close or identical to those in rocks of the Tynda–Bakaranskii Complex (Fig. 2c). The gabbroids of the Tynda–Bakaranskii Complex show, along with anomalies characteristic of granitoids, negative Rb anomalies and clearly pronounced positive anomalies at Sr.

The rocks of the granosyenite–granite association of the Umlekan–Ogodzhinskaya zone are heterogeneous. The phase-I granosyenites (samples 432 and 433) differ from the phase-II granitoids in having higher concen-

Concentrations of major (wt %) and trace (ppm) elements in representative samples of Late Jurassic granitoids from the upper Amur area

Component	Dzhalindinskii massif			Dzhiktandinskii massif			Igakskii massif		Olginskii massif	
	S-135	S-1060	S-92	417-1	438	416	503	K-5-673	1-P	23105
	1	2	3	4	5	6	7	8	9	10
SiO_2	58.30	65.80	68.00	61.60	63.70	64.30	65.00	69.60	60.6	64.5
TiO_2	0.71	0.53	0.49	0.65	0.53	0.48	0.62	0.46	0.61	0.62
Al_2O_3	16.98	16.80	15.43	15.87	16.20	15.36	15.20	15.16	15.23	6.01
Fe_2O_3	2.23	0.65	1.71	1.71	1.74	1.86	1.70	2.37	1.28	2.27
FeO	3.24	2.87	2.35	2.99	1.72	1.87	2.70	1.00	3.61	2.60
MnO	0.07	0.07	0.11	0.08	0.09	0.09	0.10	0.14	0.11	0.12
MgO	4.76	1.56	1.56	4.48	2.66	3.25	4.01	0.84	5.5	2.78
CaO	6.42	4.12	3.40	4.36	4.22	4.89	2.31	2.37	4.42	4.62
Na_2O	4.08	3.91	4.11	3.58	4.34	3.41	3.87	3.09	3.59	2.68
K_2O	2.45	3.01	3.08	2.96	3.56	3.52	2.97	3.15	2.2	2.83
P_2O_5	0.22	0.16	0.17	0.15	0.11	0.14	0.22	0.15	0.18	0.19
LOI	0.31	0.31	0.00	0.94	0.69	0.61	0.41	0.80	1.23	0.98
Total	100.77	99.75	100.40	99.37	99.56	99.78	99.11	99.09	98.56	100.20
Sc	11.5	6.1	5.5	9.0	24.6	7.3	10.8	9.9	15.87	12.07
V	125	85	56	98	190	72	90	90	110	107
Cr	163	92	39	209	63	131	32	31	204	115
Co	19	12	8	17	15	12	9	8	15	13
Ni	48	30	14	66	19	41	7	10	23	11
Cu	26	10	10	37	42	18	7	12	8	8
Zn	80	67	47	84	128	77	47	48	43	48
Rb	76	86	94	111	172	137	97	95	59	81
Sr	760	683	651	576	711	534	520	548	521	526
Y	14	12	9	13	23	11	20	20	16	21
Zr	74*	125*	50	157*	268*	154*	39	39	27	25
Nb	5.7	5.9	8.2	6.9	8.4	6.6	13.5	8.8	7.57	9.45
Cs	4.1	4.9	3	5.9	2.3	5.7	4.6	6.4	2.87	3.44
Ba	926*	888*	1100	813*	701*	825*	851.8	–	791	877
La	28.03	30.88	22.77	29.88	27.42	32.03	38.86	28.48	15.18	28.26
Ce	57.43	61.51	45.37	61.91	55.56	63.25	70.90	54.02	33.81	57.53
Pr	6.90	7.23	4.88	7.20	7.05	7.06	7.66	6.79	4.31	6.70
Nd	25.55	25.57	20.13	25.36	27.72	23.68	26.44	25.63	16.65	25.07
Sm	4.75	4.41	3.93	4.57	5.67	3.85	4.09	4.87	3.00	4.88
Eu	1.29	1.14	0.57	1.04	1.71	0.86	1.12	0.56	0.94	0.77
Gd	4.53	3.88	3.35	4.14	5.58	3.55	5.61	4.42	3.85	4.56
Tb	0.56	0.49	0.41	0.56	0.77	0.43	0.67	0.6	0.51	0.62
Dy	2.80	2.34	1.70	2.53	4.22	2.13	3.32	3.2	2.65	3.31
Ho	0.55	0.46	0.32	0.47	0.85	0.42	0.67	0.65	0.56	0.67
Er	1.43	1.25	0.77	1.26	2.28	1.12	1.93	1.72	1.56	1.87
Tm	0.20	0.18	0.12	0.18	0.33	0.17	0.29	0.27	0.24	0.29
Yb	1.32	1.10	0.64	1.08	2.07	1.02	1.78	1.71	1.50	1.83
Lu	0.20	0.16	0.11	0.16	0.31	0.15	0.27	0.26	0.23	0.28
Hf	0.85	0.69	1.66	1.37	2.56	1.65	1.36	1.31	1.14	1.17
Ta	0.67	0.70	0.71	0.87	0.62	0.98	1.8	0.93	0.68	0.76
Pb	19.8	25.4	25.6	24.0	13.8	33.5	72.7	26.0	48.1	25.1
Th	7.8	11.2	9.4	13.1	4.4	18.6	10.4	10.7	5.68	10.28
U	1.9	3.1	2.7	3.1	0.9	3.2	2.2	2.3	1.74	2.12
Eu/Eu*	0.84	0.82	0.47	0.72	0.92	0.70	0.71	0.37	0.84	0.49
$(La/Yb)_n$	14	19	24	19	9	21	15	11	4	6

Table. (Contd.)

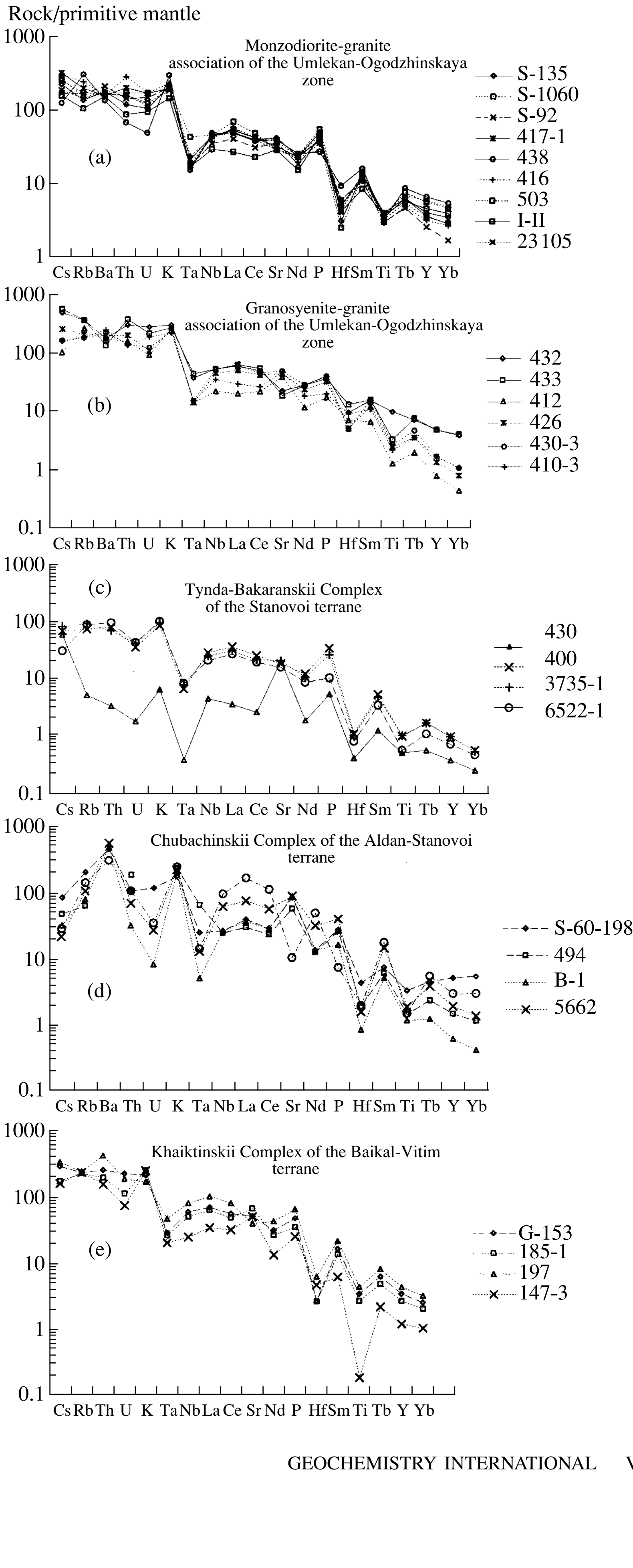
Component	Uskalinskii massif			Sergeevskii massif		Magdagachinskii massif	Bakaranskii massif			
	432	433	412	426	430-3	410-3	430	400	3735-1	6522-1
	11	12	13	14	15	16	18	19	20	21
SiO_2	63.40	66.80	70.30	69.00	67.80	72.40	47.10	57.68	58.08	65.20
TiO_2	1.60	0.54	0.21	0.41	0.45	0.36	0.56	0.93	0.94	0.61
Al_2O_3	16.30	15.10	15.08	15.95	16.93	15.25	18.00	16.20	16.37	14.80
Fe_2O_3	1.49	1.50	1.28	1.73	1.37	0.63	3.63	3.22	2.51	2.47
FeO	2.38	2.07	0.21	0.66	1.02	0.30	5.17	3.07	3.40	1.95
MnO	0.08	0.06	0.10	0.11	0.04	0.01	0.11	0.07	0.07	0.06
MgO	2.32	1.82	0.55	0.85	1.05	0.36	9.49	3.77	3.84	1.92
CaO	3.23	2.53	2.06	2.31	2.47	1.25	10.61	6.17	5.26	4.11
Na_2O	3.39	3.75	5.59	5.27	5.63	5.40	2.21	3.68	3.78	3.64
K_2O	4.58	4.11	4.06	3.89	3.54	3.37	0.47	3.17	3.46	3.60
P_2O_5	0.16	0.15	0.07	0.13	0.16	0.08	0.08	0.32	0.26	0.13
LOI	0.78	0.86	0.39	0.75	0.53	0.43	1.50	0.84	1.69	1.60
Total	99.71	99.28	99.90	99.96	100.99	99.84	98.93	99.12	99.66	100.09
Sc	4.5	4.5		0.4	1.3	1.3	25.9	13.8	13.7	12.1
V	74	65	10	31	34	35	171	123	121	89
Cr	62	53	9	18	20	37	450	92	90	40
Co	10	9	2	4	5	3	42	19	18	11
Ni	23	20	4	6	7	7	104	33	32	13
Cu	15	26	1	4	5	9	6	11	19	12
Zn	60	57	67	61	77	87	59	69	93	57
Rb	207	206	148	117	103	107	11	79	93	90
Sr	407	338	705	808	887	851	968	896	976	807
Y	17	17	3	5	6	6	10	20	19	16
Zr	260*	237*	103*	145*	164*	118	–	–	–	–
Nb	9.7	11.1	4.0	5.1	5.7	5.3	1.6	14.9	13.8	11.3
Cs	9.2	10.6	1.9	4.8	3.0	2.9	2.2	2.4	2.8	1.3
Ba	926	706	920	1040	1157	1287	343	1557	1215*	1548*
La	33.95	35.88	11.34	28.32	34.21	16.52	8.27	46.39	41.06	37.18
Ce	72.35	80.52	32.15	61.15	66.95	38.70	17.19	92.68	81.23	75.40
Pr	8.72	8.75	3.39	7.23	8.56	5.17	2.07	9.72	9.60	8.77
Nd	30.48	30.27	12.61	25.85	30.92	19.88	9.96	39.57	35.91	31.04
Sm	5.47	5.59	2.35	4.38	5.47	3.84	2.38	7.01	6.47	5.11
Eu	0.99	0.88	0.59	0.99	1.28	0.97	0.96	1.12	1.65	1.18
Gd	4.89	5.06	1.74	3.23	4.21	2.90	2.40	6.31	6.52	4.85
Tb	0.64	0.67	0.18	0.32	0.42	0.32	0.33	0.76	0.76	0.54
Dy	3.22	3.27	0.66	1.15	1.45	1.29	1.75	3.67	3.34	2.47
Ho	0.63	0.62	0.10	0.18	0.22	0.21	0.35	0.69	0.63	0.49
Er	1.70	1.68	0.25	0.46	0.54	0.55	0.88	1.71	1.66	1.38
Tm	0.25	0.24	0.03	0.05	0.07	0.07	0.12	0.23	0.24	0.20
Yb	1.49	1.55	0.17	0.30	0.41	0.42	0.77	1.42	1.36	1.23
Lu	0.21	0.23	0.02	0.04	0.05	0.05	0.11	0.21	0.21	0.18
Hf	2.61	3.59	1.94	1.41	1.37	2.47	0.81	1.69	1.60	1.34
Ta	1.52	1.78	0.58	0.58	0.63	0.62	0.11	0.96	1.08	1.12
Pb	24.5	32.6	48.1	30.3	32.6	42.0	8.2	20.8	49.7	27.0
Th	19.7	24.8	10.3	13.1	9.3	8.8	0.92	9.74	8.7	11.1
U	5.1	3.9	1.7	2.0	2.3	3.4	0.16	1.50	1.7	1.7
Eu/Eu*	0.58	0.50	0.85	0.77	0.79	0.85	1.21	0.50	0.77	0.72
$(La/Yb)_n$	15	16	46	63	57	27	7	22	20	20

Table. (Contd.)

Component	Chubachinskii massif					Khaiktinskii massif			
	S-60-198	494	B-1	5662	4544/1	G-153	185-1	197	147-3
	22	23	24	25	26	27	28	29	30
SiO_2	63.70	67.20	69.80	68.15	74.20	66.20	66.46	68.30	70.60
TiO_2	0.55	0.24	0.24	0.40	0.23	0.55	0.43	0.70	0.03
Al_2O_3	19.60	18.03	16.77	16.17	12.66	15.69	16.46	13.65	14.71
Fe_2O_3	1.08	1.03	1.08	1.00	1.97	1.30	1.35	2.44	0.03
FeO	1.51	1.09	0.77	1.03	0.92	2.04	1.24	2.17	1.09
MnO	0.14	0.02	0.03	0.03	0.03	0.03	0.02	0.11	0.02
MgO	0.98	0.69	0.40	0.88	0.20	1.82	0.77	2.08	0.67
CaO	2.82	2.17	1.53	2.37	1.08	3.16	2.34	3.40	1.21
Na_2O	5.58	4.95	5.28	4.71	3.35	3.90	4.18	3.67	3.99
K_2O	3.48	4.65	3.93	4.42	4.86	4.34	5.14	3.45	5.10
P_2O_5	0.11	0.10	0.07	0.16	0.03	0.19	0.14	0.26	0.10
LOI	0.71	0.15	0.60	0.26	0.42	0.35	0.42	0.10	0.74
Total	100.26	100.33	100.49	99.58	99.95	99.57	98.79	100.33	99.48
Sc	3.1	2.6	1.9	4.7	3.5	3.0		2.5	–
V	7	13	12	27	7	52	32	59	21
Cr	9	15	161	7	5	65	25	46	17
Co	1	2	2	4	1	8	5	8	3
Ni	3	4	5	4	3	16	9	13	6
Cu	4	6	3	2	1	11	8	9	10
Zn	30	35	61	54	37	55	43	83	43
Rb	111	34	43	57	77	133	129	138	133
Sr	1500	1021	1568	1576	187	922	1210	718	910
Y	18	5	2	7	11	11.6	9.1	14.8	4.1
Zr	167*	–	75*	141*	246*	–	–	–	–
Nb	7.4	5.1	2.3	5.3	5.8	8.6	7.5	13.7	5.8
Cs	1.5	0.8	0.6	0.4	0.5	5.4	3.2	6.3	3.0
Ba	2314*	1242	2475*	2841*	1548*	1207*	1806 *	1163*	1337*
La	21.56	16.37	20.15	41.11	91.62	39.04	35.31	57.09	19.15
Ce	41.47	33.47	40.37	81.18	160.17	81.92	71.17	118.39	46.60
Pr	4.49	3.91	4.25	9.54	16.91	9.73	8.12	13.53	4.29
Nd	14.68	13.68	14.54	34.11	52.87	33.98	28.60	46.11	14.14
Sm	2.65	2.18	1.84	5.19	6.26	5.68	4.70	7.55	2.14
Eu	0.46	0.46	0.67	1.46	0.92	1.38	1.43	1.43	0.75
Gd	2.58	1.85	1.39	3.75	5.13	4.90	3.85	6.22	1.86
Tb	0.41	0.22	0.11	0.35	0.50	0.55	0.42	0.71	0.19
Dy	2.56	1.03	0.41	1.42	2.01	2.41	1.81	3.14	0.84
Ho	0.60	0.20	0.08	0.25	0.39	0.45	0.32	0.55	0.15
Er	1.78	0.55	0.22	0.68	1.16	1.17	0.87	1.48	0.42
Tm	0.32	0.08	0.03	0.09	0.18	0.16	0.12	0.20	0.06
Yb	2.12	0.45	0.16	0.54	1.17	0.95	0.76	1.20	0.39
Lu	0.32	0.06	0.02	0.07	0.18	0.13	0.10	0.17	0.06
Hf	1.20	0.54	0.24	0.44	0.55	0.72	0.72	1.72	1.27
Ta	0.99	2.57	0.20	0.52	0.57	1.17	1.07	1.91	0.82
Pb	26.6	276.4	32.3	32.5	25.6	34.5	45.1	34.8	37.3
Th	6.7	11.7	2.0	4.3	6.6	16.9	12.8	28.1	10.2
U	2.1	30.2	0.1	0.5	0.6	4.2	2.1	3.5	1.4
Eu/Eu*	0.53	0.68	1.23	0.97	0.48	0.78	1.00	0.62	1.12
$(La/Yb)_n$	7	24	84	51	53	28	32	32	34

Note: Quartz monzodiorites of phase I (1, 4, 5, 9), phase II (19), and phase III (20); granodiorites of phase II (2, 6, 7, 10) and phase III (21); granites of phase II (29) and phase III (3, 8); granosyenites of phase I (11, 12, 22, 23, 27) and phase II (15, 28); subalkaline granites of phase II (13, 14, 16, 17, 24, 25, 30); biotite gabbro of phase I (18); subalkaline leucogranites of phase III (26).

*XRF data; dashes mean no data.


Rock/primitive mantle
Monzodiorite-granite association of the Umlekan-Ogodzhinskaya zone
(a)
S-135
S-1060
S-92
417-1
438
416
503
I-II
23 105
Cs Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Sm Ti Tb Y Yb
Granosyenite-granite association of the Umlekan-Ogodzhinskaya zone
(b)
432
433
412
426
430-3
410-3
Cs Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Sm Ti Tb Y Yb
(c)
Tynda-Bakaranskii Complex of the Stanovoi terrane
430
400
3735-1
6522-1
Cs Rb Th U K Ta Nb La Ce Sr Nd P Hf Sm Ti Tb Y Yb
Chubachinskii Complex of the Aldan-Stanovoi terrane
(d)
S-60-198
494
B-1
5662
Cs Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Sm Ti Tb Y Yb
Khaiktinskii Complex of the Baikal-Vitim terrane
(e)
G-153
185-1
197
147-3
Cs Rb Th U K Ta Nb La Ce Sr Nd P Hf Sm Ti Tb Y Yb
1000
100
10
1
0.1

trations of Cs, Rb, Th, Zr, Yb, Co, Ni, and Cu and lower concentrations of Sr (Fig. 2b). These rocks have Ta, Sr, and Y concentrations close to those in the upper crust and show negative Ba, Ta, Sr, and Hf anomalies in the primitive mantle-normalized patterns. In contrast to them, the phase-II granitoids display negative U, Ta, Nd, Hf, and Ti anomalies, which make these rocks similar to those of the monzodiorite–granite association and the rocks of the Khaiktinskii Complex (Figs. 2a, 2e).

The Chubachinskii granitoids differ from all other granitoids of the upper Amur area by having the lowest concentrations of Cs, Rb, Th, and U at higher contents of Ba and Sr (except those in the silica-oversaturated granites). These rocks have negative anomalies at Cs, Rb, Th, U, Ta, Hf, and Ti in the primitive-mantle normalized patterns (Fig. 2d).

The REE concentrations in the granitoids of the upper Amur area broadly vary: from 65.6 to 339.45 ppm. All of the granitoids are characterized by a predominance of LREE over HREE, and thus, the chondrite-normalized REE patterns of the rocks display negative slopes (from LREE to HREE, Fig. 3). The $(La/Yb)_n$ ratios of these rocks (these ratios are a measure of their differentiation) range from 7 to 84.

The rocks of the monzodiorite–granite association differ from the granitoids of the Tynda–Bakaranskii Complex in having lower concentrations of REE (124–141.5 and 170.9–190.6 ppm, respectively) and subparallel REE patterns (Fig. 3a). The right-hand parts of these REE patterns differ from those of the other rocks by steeper slopes (Tb_n/Yb_n = 2.8–3.2). The rocks of this association are characterized by clearly pronounced (for the granites) or weaker (for the granodiorites and quartz monzodiorites) negative Eu anomalies (Eu/Eu* = 0.37–0.95).

The rocks of the granosyenite–granite association display REE patterns different from those of the rocks of the monzodiorite–granite association (Fig. 3b) and are characterized by a wider scatter of REE contents. The granosyenites of the first group differ from the rocks of the second group in bearing higher concentrations of LREE and, even more so, HREE (SumY = 13.0–13.3 ppm and 3.1–7.4 ppm, respectively), gently inclined normalized REE patterns (Tb_n/Yb_n = 1.8 and 3.2–4.5), and the absence of pronounced Eu anomalies (Eu/Eu* = 0.50–0.58; the analogous values for the second-group granites are 0.79–0.85). The $(La/Yb)_n$ ratio is equal to 15–16 for the granosyenites of the first group and 27–63 for the granitoids of the second group.

Granitoids of the Chubachinskii Complex show the most diverse REE patterns (Fig. 3d). The phase-I granosyenites have the lowest REE concentrations (74.5–96.0 ppm), low contents of LREE, and clearly pronounced negative Eu anomalies (Eu/Eu* = 0.53–0.68). Their chondrite-normalized patterns are gently sloping, $(La/Yb)_n$ = 7–24, flat over HREE (Tb_n/Yb_n = 0.8–2.0). The phase-II granitoids are characterized by more differentiated REE patterns, $(La/Yb)_n$ = 51–84, with weakly or nonexisting pronounced negative Eu anomalies (Eu/Eu* = 0.97–1.23). The silica-oversaturated leucogranites of phase-III bear much higher concentrations of REE (both LREE and HREE) than the phase-II granitoids and have clearly pronounced Eu anomalies (Eu/Eu* = 0.48) and flat patterns over HREE (Tb_n/Yb_n = 1.3).

The granitoids of the Khaiktinskii Complex (Fig. 3e) have REE patterns similar to those of the granitoids of the granosyenite–granite association of the Umlekan–Ogodzhinskaya zone. In contrast to the analogous rocks of the Uskalinskii Massif, the phase-I granosyenites of the Khaiktinskii Complex have weakly pronounced Eu anomalies (Eu/Eu* = 0.78), higher concentrations of LREE, and low concentrations of HREE. The phase-II granitoids differ from the analogous rocks of the Umlekan–Ogodzhinskaya zone in having higher concentrations of HREE and weaker differentiated REE patterns, $(La/Yb)_n$ = 28–34, with poorly pronounced negative or positive Eu anomalies (Eu/Eu* = 0.62–1.14), a feature suggesting the fractionation of feldspars in the chamber.

DISCUSSION

The monzodiorite–granite association of the Umlekan–Ogodzhinskaya zone have an age, petrography, petrochemistry, and geochemistry comparable with those of the rocks of the Tynda–Bakaranskii Complex of the Stanovoi terrane. Except the phase-I granosyenites, all of the granosyenite–granite association of the Umlekan–Ogodzhinskaya zone have the aforementioned parameters similar to those of the rocks of the Khaiktinskii Complex of the Baikal–Vitim superterrane. The phase-I granosyenites of the Umlekan–Ogodzhinskaya zone and the granitoids of the Chubachinskii Complex of the Stanovoi terrane differ from other rocks of this association in geochemistry.

Based on the data on distribution of REE and some other elements in the rocks, literature data on their Sr and Nd isotopic composition, and experimental data obtained on the melting of various mafic rocks, we will consider below the genesis of granitoids in the upper Amur area and assay the sources from which their parental magmas could be derived.

The rocks of the monzodiorite–granite association are characterized by a general decrease in REE concentrations with increasing silicity and alkalinity. Inasmuch as the decrease in the concentrations of REE occurs at the expense of HREE, the normalized REE

Fig. 2. (a–e) Primitive mantle-normalized [19] spider diagrams for Late Mesozoic granitoids of the upper Amur area. Sample numbers correspond to those in the table.

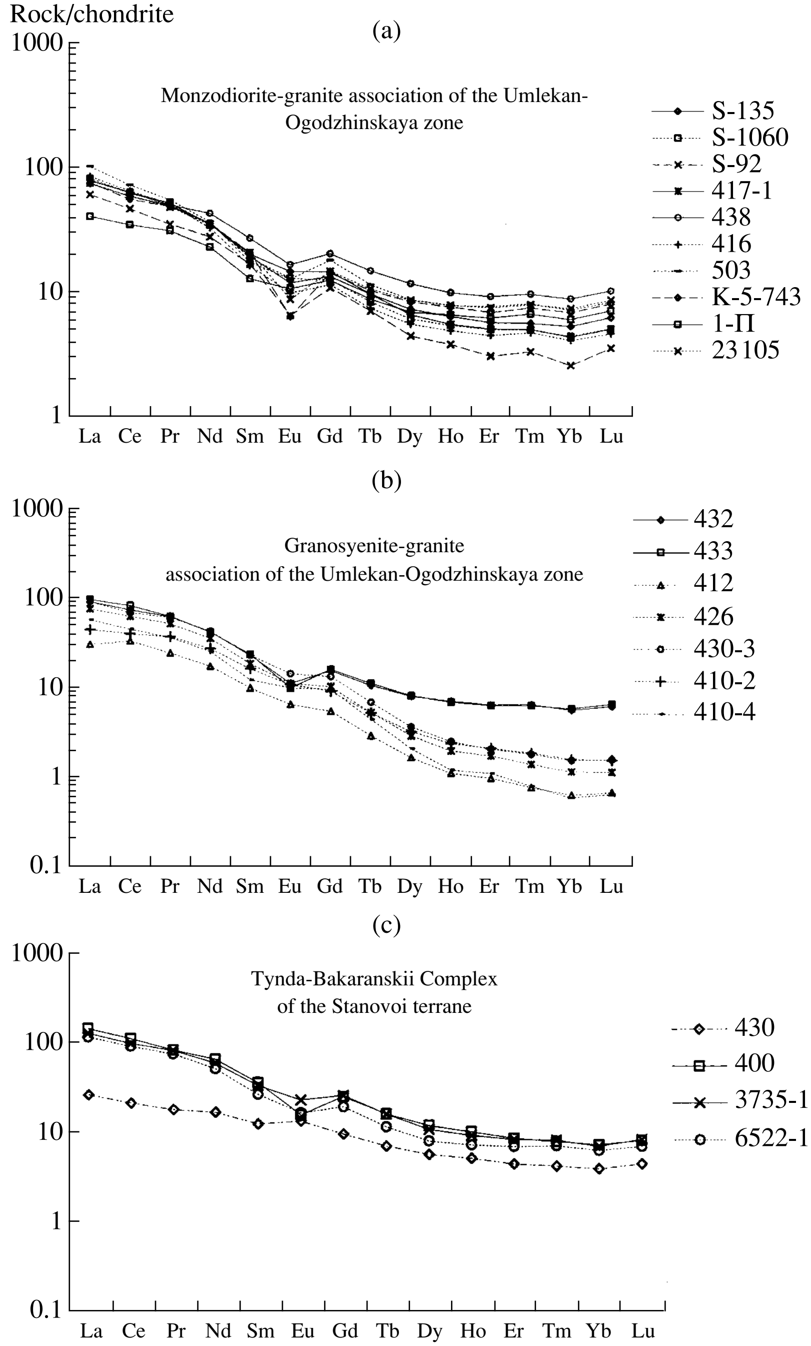


Fig. 3. (a–e) Chondrite-normalized [19] REE patterns for Late Mesozoic granitoids of the upper Amur area. Sample numbers correspond to those in the table.

patterns of the monzodiorite–granite association acquire a fan-shaped configuration (Fig. 2a). This could be caused by the fractionation of pyroxenes, amphiboles, and accessory zircon, (i.e., minerals whose HREE partition coefficients with intermediate and acid melts are higher than one [20, 21]) in the parental melts with the transition from early to later phases. The participation of accessory minerals in the fractionation of the melts also follows from the positive correlation between the concentrations of REE, P_2O_5, and Zr. Judging by the poorly pronounced Eu anomaly, plagioclase played a subordinate part in the melts of the early phases, but the participation of this mineral in the fractionation process became more significant in the parental melts of the granites of the final phases.

The rocks of the Tynda–Bakaranskii Complex show an increase in REE concentrations from the phase-I gabbroids to younger rocks. The gabbroids display positive Eu anomalies, which are correlated with positive

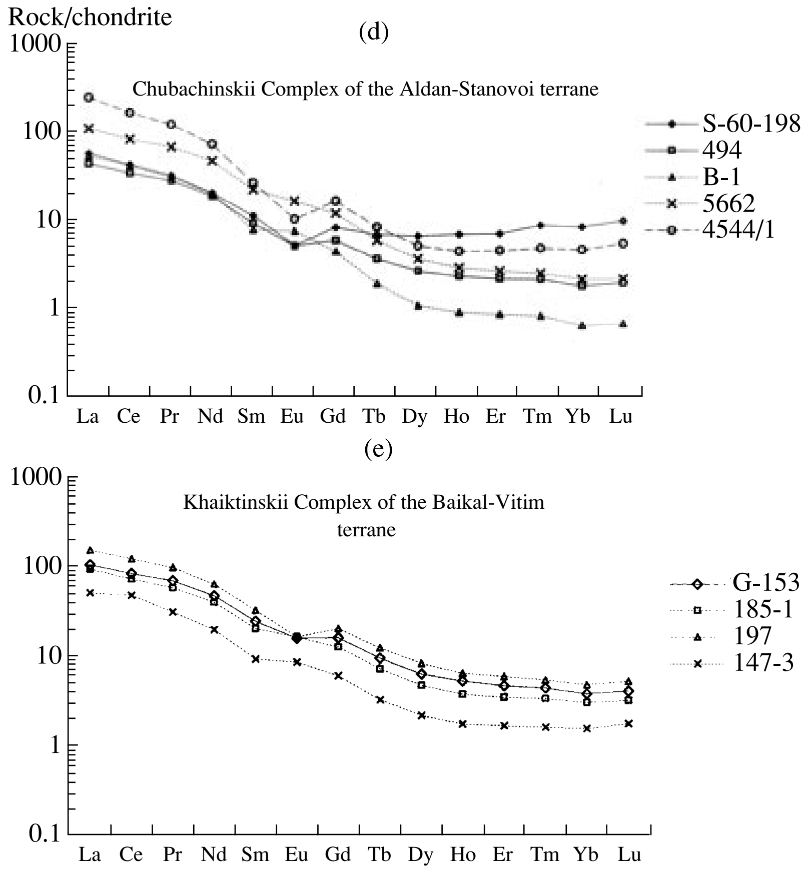


Fig. 3. (Contd.)

Sr anomalies in the primitive mantle-normalized patterns. The quartz monzodiorites have negative Eu anomalies, which suggest the accumulation of plagioclase in the residual phase. The granodiorites of the main phase of the Tynda–Bakaranskii Complex differ from the quartz monzodiorites in having lower concentrations of MREE, a feature that could be caused by the fractionation of hornblende and pyroxene, which are minerals with high mineral–melt partition coefficients for these elements [22].

The rocks of the granosyenite–granite association and those of the Khaiktinskii Complex also display a decrease in the concentrations of REE with increasing silicity and alkalinity in the rocks of various phases. The granosyenites of the first group show clearly pronounced negative Eu anomalies (Eu/Eu* = 0.50–0.58), which suggest that these rocks were produced by more mafic magmas via plagioclase fractionation [20]. These rocks are also strongly enriched in HREE compared to the rocks of the second group. The moderately alkaline granites and granosyenites of the second group are characterized by subparallel elemental patterns, which suggest genetic links between these rocks. The principal differences in the concentrations of some LILE, HFSE, and transition elements (Cs, Rb, Sr, Th, Zr, Yb, Co, Ni, and Cu) between the rocks of the first and second groups of the Umlekan–Ogodzhinskaya zone at similar contents of feldspars and in the presence of poorly pronounced negative Eu anomalies in the second-group granitoids suggest that the parental melts of these rocks were independently derived from geochemically heterogeneous sources.

The granites of the Khaiktinskii Complex have REE concentrations higher than those of all other varieties, including the melanocratic granosyenites of the first phase. Judging from the occurrence of poorly pronounced negative Eu anomalies in these rocks and the absence of these anomalies or the presence of weak positive Eu anomalies in the other varieties of the second phase, the granites of normal alkalinity were produced as a facies variety owing to the fractionation of feldspars during differentiation in the chamber and the accumulation of these minerals in the subalkaline varieties with positive Eu anomalies.

The granitoids of the Chubachinskii Complex are generally characterized by an increase in REE concentrations as their silicity increases from the granosyenites of phase I to the silica-oversaturated granites of phase III (Fig. 2d). This transition is associated with a decrease in the overall alkalinity of rocks (mostly due to a decrease in Na_2O contents). The phase-I granosyenites display clearly pronounced negative Eu anomalies, low concentrations of LREE, high concentrations of HREE, and gently sloping, asymmetric normalized REE patterns. The biotite–hornblende varieties (sample 494) have lower concentrations of HREE than the biotite-bearing varieties (sample S-60-198). This character of REE distribution suggests that the parental melts of the granosyenites were derived from more mafic magmas by means of plagioclase fractionation and the enrichment of the residual melts in such accessory minerals as zircon and apatite, a concept that is also confirmed by high Zr and P_2O_5 contents of the rocks. A lower MREE concentration than those of HREE in the biotite varieties suggest that amphibole and pyroxene played a significant part in the process of fractionation.

The occurrence of positive Eu anomalies in the phase-II granites was most probably caused by crystallization differentiation in the chamber with the redistribution of feldspars between facies varieties of the granitoids. The weak positive anomalies appear during the accumulation of feldspars; the absence of these anomalies suggests that these minerals did not participate in the processes of crystal fractionation. Moreover, the absence of negative anomalies in the phase-II granites possibly indicates that the parental melts of the rocks of phases I and II were derived independently, and the rocks themselves were produced separately, because the transition from phase-I granosyenites to granites is associated with a remarkable decrease in the contents of Na_2O (table) and plagioclase in these rocks [9]. In this situation, when the parental melt of the phase-II granites was derived from a granosyenite magma with the participation of plagioclase in the fractionation process, these rocks should have displayed a negative Eu anomaly, which is, however, not the case.

The phase-III silica-oversaturated leucogranites (sample 4544/1) are much richer in REE and Zr than phase-II granitoids and have pronounced negative Eu anomalies. With regard for the decrease in the Na_2O concentration in the rocks, these data led us to the conclusion that the rocks were produced by the fractionation of moderately silicic granitic melts with an effective removal of plagioclase during fractionation and the enrichment of the residual melt in accessory zircon, the main concentrator of HREE.

The strong predominance of LREE over HREE in the granitoids of the upper Amur area, considered together with the high concentrations of Na_2O and Sr in these rocks and their low Y contents, suggest that the source of their parental melts contained garnet, amphibole, and plagioclase. According to the experimental data on the anhydrous melting of metabasites, the amphibole in assemblage with garnet is stable under pressures of 12–15 kbar, which suggests that the parental magma of the granitoids was generated in the lower crust. With regard to the experimental data [23], the high K_2O concentrations in the granitoids led us to suggest that their protolith was enriched in K_2O owing to the presence of biotite and/or potassic feldspar. This, in turn, implies that the protolithic material was of elevated alkalinity. Petrochemical, geochemical, and isotopic geochemical features of the granitoids indicate that they were derived from sources of different compositions.

The rocks of the monzodiorite–granite association, of the Tynda–Bakaranskii and Khaiktinskii complexes, the granosyenites of the early phases of the granosyenite–granite association and the Chubachinskii Complex are characterized by low $(Na_2O + K_2O)/(FeO_{tot} + MgO + TiO_2)$ and $Al_2O_3/(FeO_{tot} + MgO + TiO_2)$ ratios and high contents of $Al_2O_3 + FeO_{tot} + MgO + TiO_2$ and $CaO + FeO_{tot} + MgO + TiO_2$ (Fig. 4). These rocks plot within the compositional fields of melts obtained experimentally by the partial melting of amphibolites [24].

The initial Sr isotopic ratio $(^{87}Sr/^{86}Sr)_0$ (which characterizes the isotopic composition of the source when the magmas were derived from it) varies for the rocks of the monzodiorite–granite association of the Umlekan–Ogodzhinskaya zone from 0.7058 to 0.7073 [25]. The two-stage Nd model age T_{Nd}(DM-2st) for the rocks of the association is 1.26–1.23 Ga and $\varepsilon_{Nd}(T)$ from –3.9 to –3.6 [25].

The two-stage Nd model age of compositionally similar granitoids of the Tynda–Bakaranskii Complex of the Stanovoi terrane varies within broader limits: T_{Nd}(DM-2st) = 2.2–1.1 Ga at $\varepsilon_{Nd}(T)$ from –15.7 to –2.4 [26]. The $(^{87}Sr/^{86}Sr)_0$ ratio of the rocks composing this complex is equal to 0.7066–0.7088 [7], which is slightly higher than the ratio of the monzodiorite–granite association.

The Khaiktinskii Complex is characterized by similar $(^{87}Sr/^{86}Sr)_0$ values of 0.7075–0.7083 [5] but differs from the granitoids of the Tynda–Bakaranskii Complex in having lower concentrations of transitional elements (V, Co, and Ni), LILE (Cs, Rb, K, and Pb), and HFSE (Th and U), which suggests that the source was more leucocratic and more alkaline. The occurrence of subalkaline granites in the fields of melts during the partial melting of metagraywackes likely resulted from the mixed composition of the source from which the parental melts were derived.

The lowest Sr concentrations, high contents of Rb, Zr, Yb, Th, and U, and weaker REE fractionation at flat REE patterns of the group-I granosyenites of the Umlekan–Ogodzhinskya zone as compared to the analogous characteristics of other granitoids of this association suggest that the source was more melanocratic and most probably consisted of biotite-rich amphibolites with low garnet concentrations.

The data presented above for the Sr and Nd isotopic composition of granitoids, whose melts were supposedly derived from an amphibolite protolith, are similar and, hence, characterize the same lower crustal heterogeneous source. The variations in the $(^{87}Sr/^{86}Sr)_0$ ratio of the rocks are typical of continental basalts of elevated alkalinity, which suggests that the protoliths were of predominantly of a trachybasaltic composition and contained variable amounts of the mafic and feldspathic constituents. The data presented above and the $(^{87}Sr/^{86}Sr)_0$ ratios of the rocks suggest that the sources of the Tynda–Bakaranskii Complex were likely more alkaline than the sources of the monzodiorite–granite association, which also follows from the higher alkalinity of the intermediate rocks of the Tynda–Bakaranskii Complex. The $\varepsilon_{Nd}(T)$ values indicate that the source of these rocks could not be either the depleted mantle or the ancient sialic crust itself and suggest that the sources most probably consisted of a mixture of mantle and crustal material. The model age of the granitoids indicates that their parental melts were generated with the participation of the Early Proterozoic juvenile crustal and mantle material [26].

The phase-II granitoids of the granosyenite–granite association are characterized by high $(Na_2O + K_2O)/(FeO_{tot} + MgO + TiO_2)$ ratios and high concentrations of $Al_2O_3 + FeO_{tot} + MgO + TiO_2$ and plot within the field of melts produced by the partial melting of metagraywackes (granites of the Uskalinskii and Magdagachinskii massifs) and amphibolites (Fig. 4). The likely reason for the ambiguity of the interpretations of the parental melts in these diagrams (Fig. 4) is the mixed composition of the source with the predominance of certain components. The derivation of the rocks from two distinct sources is corroborated by the geochemistry of the granitoids. The granitoids derived from an amphibolite source commonly bear higher concentrations of Sc, V, Cr, Co, Ni, Cu, Y, and Yb at lower concentrations of Sr and Ba than those of the granitoids derived from metagraywackes (which had a feldspar-rich composition). Judging from the Sr and Nd isotopic composition $[(^{87}Sr/^{86}Sr)_0 = 0.7064–0.7077$, $\varepsilon_{Nd}(T) = –4.6]$ and the Nd model age (1.3 Ga) [25], the protoliths of the phase-II granitoids of the granosyenite–granite association were close to the sources of the monzodiorite–granite association, but the high $(La/Yb)_n = 27–63$ and $Tb_n/Yb_n = 3.2–4.5$ values at lower Y concentrations of the granitoids argue that their protoliths were richer in garnet. A metagraywacke composition of the protolith of I-type calc–alkaline granitoids with high K_2O concentrations was proposed for analogous rocks in the north of Schwarzwald [27] and southeastern Vietnam [28]. Taking into account the initial Sr isotopic composition, it is reasonable to suggest that the original rocks of the metagraywackes were volcanics, and this predetermined the affiliation of the granitoid derivatives to I type, although some granitoid samples of this association have high values of $^{87}Sr/^{86}Sr$ = 0.7113–0.7118, which likely point to the presence of sedimentary material in their protolith.

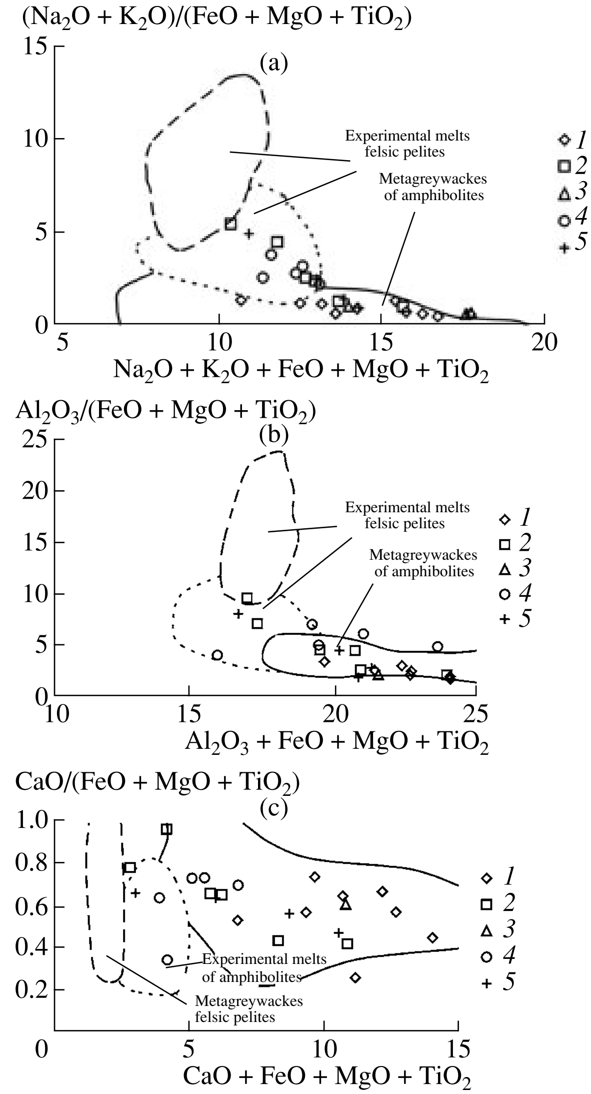


Fig. 4. (a–c) Correlations between the contents of major oxides in granitoids of the upper Amur area. The compositional fields of melts produced by the experimental partial melting of muscovite schists (pelites), metagraywackes, and amphibolites are given after [24]. (*1*) Monzodiorite–granite association of the Umlekan–Ogodzhinskaya zone; (*2*) granosyenite–granite association of the Umlekan–Ogodzhinskaya zone; (*3*) Tynda–Bakaranskii Complex of the Stanovoi block; (*4*) Chubachinskii Complex of the Stanovoi block; (*5*) Khaiktinskii Complex of the Baikal–Vitim superterrane.

The rocks of the Chubachinskii Complex differ from other granitoids of the upper Amur area by lower concentrations of such lithophile elements as Rb, Cs, U, and Th, which led us to suggest that the source of these rocks consisted of garnet-bearing granulites, which had a feldspar-rich composition and are known to be generated in the lower crust and depleted of the aforementioned elements [29]. These elements are thought to be transported by fluids enriched in CO_2 and,

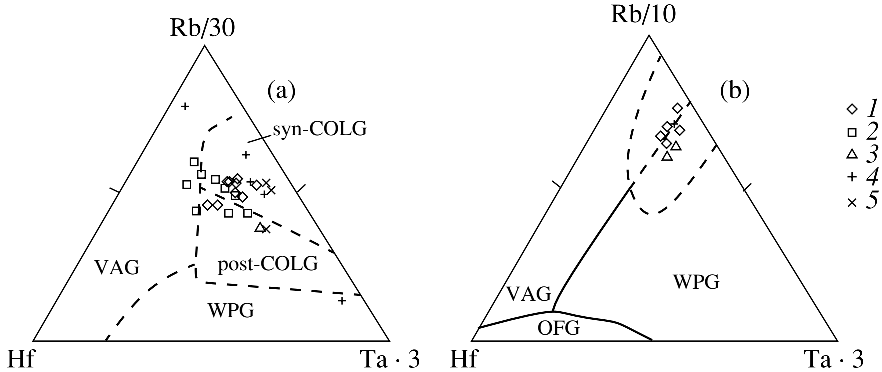


Fig. 5. Ternary Rb–Hf–Ta discriminant diagrams [32] for granitoids of the upper Amur area. (a) Granitoids with >64% SiO_2; (b) intermediate and acid rocks with >55% SiO_2. Fields: VAG—volcanic-arc granites, syn-COLG—syncollisional granites, post-COLG—postcollisional granites, WPG—within-plate (anorogenic) granites, OFG—ocean-floor magmatic rocks (the field of collisional magmatic rocks is outlined with a dashed line in the diagram of Fig. 5b). (*1*) Monzodiorite–granite association of the Umlekan–Ogodzhinskaya zone; (*2*) granosyenite–granite association of the Umlekan–Ogodzhinskaya zone; (*3*) Tynda–Bakaranskii Complex of the Stanovoi block; (*4*) Chubachinskii Complex of the Stanovoi block; (*5*) Khaiktinskii Complex of the Baikal–Vitim superterrane.

perhaps, also halogens. In these fluids, Ba and Sr are less mobile than Rb, K, U, and Th. The high concentrations of Ba, Sr, and K in the rocks of the first and second phases suggest that their protoliths were rich in feldspars.

The phase-I granosyenites bear higher concentrations of $Na_2O + K_2O + FeO_{tot} + MgO + TiO_2$ and $Al_2O_3 + FeO_{tot} + MgO + TiO_2$ than those in the granitoids of the younger phases, and most of them plot within the amphibolite field, in contrast to the granites of phases II and III, which plot mostly within the metagraywacke field (Fig. 4). The granosyenites of the Chubachinskii Complex have the lowest initial Sr isotopic ratios, $(^{87}Sr/^{86}Sr)_0 = 0.7038$ [9], among the granitoids of the upper Amur area, with these ratios reflecting the primary magmatic composition of the source.

The values of T_{Nd}(DM-2st) for the phase-II granitoids of the Chubachinskii Complex vary from 2.5 to 2.1 Ga at $\varepsilon_{Nd}(T)$ from –18.5 to –14.0, which suggests a mixed character of the source of their parental melts (the source was dominated by the material of the ~2.0-Ga Early Proterozoic juvenile crust with a minor admixture of an Archean crustal component [8, 26]).

The analysis of geochemical data suggests that the spatial distribution of granitoids in the upper Amur area was largely controlled by regional variations in the composition of the crustal source, which predetermined the petrochemical zoning of the fields of Late Mesozoic granitoids in the upper Amur area [30, 31].

Experimental data [23] indicate that the high-K varieties of I-type granitoids can be generated only by the partial melting of calc–alkaline hydrous metamorphic rocks of mafic or intermediate composition, enriched in K_2O, within the crust under the effect of deep mafic magmas. Considered together with the polyphase character of the granitoid massifs of the monzodiorite–granite association and the Tynda–Bakaranskii Complex, the normal (from basic to acid) character of their evolution, and the occurrence of melanocratic schlieren and nodules in the rocks of intermediate and moderately acid composition, these data led us to suggest that the most probable mechanisms of interaction between these sources was the assimilation of lower crustal material by basic melts or the syntexis of basic and crustal melts. The absence of gabbroids from the massifs of the granosyenite–granite association and the Khaiktinskii and Chubachinskii complexes and the autonomy of the sources of the rocks of the first and second phases (except the Khaiktinskii Complex) imply that they were most probably generated by the partial melting of a crustal source under the effect of magmatic masses from the mantle.

Petrographic evidence (occurrence of hornblende and magnetite in the rocks) and the petrochemical characteristics of the rocks (their moderate Al contents, high degrees of Fe oxidation, and others) indicate that these rocks belong to high-K type I of granitoids, whose distributions of trace elements, particularly REE, are close to those in the petrochemical rock types of collision environments. As follows from geotectonic reconstructions, by the time when granitoids of the upper Amur area were generated, the Mongolia–Okhotsk ocean had closed as a consequence of the collision of the Siberian continent and the Amur superterrane, a process that gave rise to the Mongolia–Okhotsk superterrane [4]. The occurrence of Late Mesozoic plutons that "staple" the structures of the Amur superterrane and the Mongolia–Okhotsk belt (for example, the Dzhiktandinskii, and Igakskii plutons), the Baikal–Vitim superterrane and Mongolia–Okhotsk belt (Dzhalindinskii Massif) rules our their origin in a continental margin in relation to subduction processes during the closure of the Mongolia–Okhotsk paleocean before the granitoid magmatism. The absence of subduction complexes complementary to the hypothetical Great Khingan active continental margin [3, 15] east of it also argues against regarding the granitoids of the Umlekan–Ogodzhinskaya zone as subduction-related rocks. These facts and the position of the data points of these granitoids in a Rb–Hf–Ta ternary discriminant diagram (Fig. 5) led us to hypothesize that the granitoids in the upper Amur area were formed in a collisional environment, possibly, during the collision of the Amur superterrane and the Siberian craton [4, 33].

CONCLUSIONS

The Late Mesozoic (150–120 Ma) granitoids hosted by various structures in the upper Amur Area can be subdivided into monzodiorite–granite and granosyenite–granite associations.

The monzodiorite–granite association includes calc–alkaline granitoids of normal alkalinity of the Umlekan–Ogodzhinskaya volcanic–plutonic zone and the Tynda–Bakaranskii Complex of the Stanovoi terrane. The rocks have negative U, Ta, Nd, Hf, and Ti anomalies; Eu anomalies are poorly pronounced in the granodiorites and quartz monzodiorites and are clearly expressed in the granites: Eu/Eu* = 0.37–0.95, $(La/Yb)_n$ = 7–24, Tb_n/Yb_n = 1.4–3.2.

The granosyenite–granite association comprises of moderately alkaline rocks, which are classified into three groups according to their geochemical characteristics. The first group is made up of granosyenites of phase I of the Uskalinskii Massif of the Umlekan–Ogodzhinskaya zone. These rocks have the highest concentrations of Sc, V, Cr, Co, Ni, Cu, Cs, Rb, Sr, Y, Zr, Yb, and Th; negative Ba, Ta, Sr, and Hf anomalies; Eu/Eu* = 0.50–0.58, $(La/Yb)_n$ = 15–16, Tb_n/Yb_n = 1.8.

The second group includes mildly alkaline granitoids of the Umlekan–Ogodzhinskaya zone and the Khaiktinskii Complex of the Baikal–Vitim superterrane. The geochemical features of these granitoids are generally similar to those of the monzodiorite–granite association, but the former rocks have lower concentrations of REE and Y, Eu/Eu* = 0.62–1.0, $(La/Yb)_n$ = 28–63, and Tb_n/Yb_n = 2.1–4.5.

The third group consists of the granitoids of the Chubachinskii Complex of the Stanovoi terrane, which are characterized by negative Cs, Rb, Th, U, Ta, Hf, and Ti anomalies; the lowest V, Cr, Co, and Ni concentrations; and the highest concentrations of Sr. The phase-I granosyenites show clearly pronounced negative Eu anomalies (Eu/Eu* = 0.53–0.68), $(La/Yb)_n$ = 7–24, and Tb_n/Yb_n = 0.8–2.0. The phase-II granitoids have $(La/Yb)_n$ = 51–84, are devoid of Eu anomalies, or show only weak positive anomalies (Eu/Eu* = 0.97–1.23). The silica-oversaturated leucogranites of phase III are characterized by elevated concentrations of REE, pronounced Eu anomalies (Eu/Eu* = 0.48), and flat patterns over HREE (Tb_n/Yb_n = 1.3).

The diversity of collisional granitoids in the upper Amur area was largely predetermined by compositional variations in the lower crustal source, which consisted of Precambrian crustal amphibolites and metagraywackes and was isotopically heterogeneous. The parental melts for the rocks of the monzodiorite–granite association and the first-group granosyenites of the granosyenite–granite association were likely derived by the partial melting of garnet-bearing amphibolites with variable contents of garnet, mafic minerals, and feldspars. The granitoids of the second group of the granosyenite–granite association were derived from a source of mixed composition: amphibolites and metagraywackes, with a predominance of any of these components in the sources of individual massifs. The source of the third-group granitoids consisted of feldspar-rich granulites of variable basicity from the Early Proterozoic crust with minor admixtures of Archean crustal material. Granulites of basic–intermediate composition (perhaps, metamorphosed trachybasalts–trachyandesites) gave rise to the parental melts of phase-I granosyenites of the Chubachinskii Massif, and the mixed source dominated by granulites of intermediate–acid composition (metagraywackes) produced the phase-II granitoids.

An analysis of the REE patterns in granitoids present in the upper Amur area indicates that the leading process that generated these rocks was crystallization differentiation, which occurred during the development of magmatic chambers and intermediate chambers. The granitoids of the monzodiorite–granite association were generated during the fractionation of plagioclase, pyroxenes, amphiboles, biotite, and accessory apatite and zircon. The rocks of the first and second phases of the granosyenite–granite association of the Umlekan–Ogodzhinskaya zone and the Chubachinskii Complex of the Stanovoi terrane were generated independently, by the derivation of their parental melts from autonomous sources. The diversity of granitoids of the second phases of these complexes and the Khaktinskii Complex was predetermined by the differentiation processes in the chambers with the fractionation of feldspars. The phase-III silica-oversaturated granites of the Chubachinsii Massif were produced by the differentiation of granitic melts, with the fractionation of plagioclase, biotite, and apatite.

Our data indicate that the Late Jurassic–Early Cretaceous intrusive rocks in territories of the upper Amur area bearing gold mineralization were formed within a single continental volcanic–plutonic belt, which developed in a collisional environment, during the collision of the Amur superterrane and Siberian craton.

REFERENCES

1. L. P. Gurov, "On Relation of Gold Mineralization with Late Mesozoic Magmatism in the Upper Amur Area," in *Gold Mineralization of the Upper and Middle Amur Area* (Vladivostok, 1978), pp. 3–10 [in Russian].
2. V. G. Moiseenko and L. V. Airish, *Gold Deposits of the Russian Far East* (Dal'nauka, Vladivostok, 1996) [in Russian].
3. G. S. Gusev and V. E. Khain, "On the Relations between the Baikal–Vitim, Aldan–Stanovik, and Mongol–Okhotsk Terranes, Southern Central Siberia," Geotektonika, No. 5, 68–82 (1995).
4. L. M. Parfenov, L. I. Popeko, and O. Tomurtogoo, "Problems of Tectonics of the Mongol–Okhotsk Orogenic Belt," Tikhookean. Geol. **18** (5), 24–43 (1999).
5. V. E. Strikha, N. N. Petruk, K. D. Vakhtomin, et al., "Geology of the Khaikta Intrusive Complex, Upper Amur Area," Tikhookean. Geol. **19** (5), 25–37 (2000).
6. *1 : 2 500 000-Scale Geological Map of the Amur Area and Adjacent Territories. Explanatory Notes* (St.-Petersburg–Blagoveshchensk–Harbin, 1999) [in Russian].
7. A. Yu. Antonov, S. I. Dril', and E. V. Bankovskaya, "Rb–Sr Isotope Characteristics of Allochthonous and Autochthonous Late Mesozoic Granitoids of the Stanovoi Range, Southern Framing of the Aldan Shield," Tikhookean. Geol. **20** (4), 61–75 (2001).
8. A. M. Larin, A. B. Kotov, E. B. Sal'nikova, et al., "Mesozoic Granites of the Chubachin Massif, Tukuringra Complex, Dzhugdzhur–Stanovoi Foldbelt: New Geochemical, Geochronological, and Isotopic-Geochemical Evidence," Petrologiya **9** (4), 416–432 (2001) [Petrology **9** (4), 362 (2001)].
9. V. A. Stepanov, V. E. Strikha, A. A. Cheremisin, et al., *Bamskoe Gold Deposit: Geology, Mineralogy, and Geochemistry* (Dal'nauka, Vladivostok, 1998) [in Russian].
10. V. E. Strikha, V. G. Moiseenko, and A. G. Rublev, "New Evidence for the Age of the Monzonite-Granite Association in the Umlekan–Ogodzha Volcanoplutonic Zone, Upper Amur Region," Dokl. Akad. Nauk **394** (4), 537–539 (2004) [Dokl. Akad. Nauk Earth Sci. **394** (1), 134 (2004)].
11. *Volcanic Belts of Eastern Asia*, Ed. by A. D. Shcheglov (Nauka, Moscow, 1984) [in Russian].
12. L. P. Zonenshain, M. I. Kuz'min, and L. M. Natapov, *Tectonics of Lithospheric Plates the Territory of the USSR* (Nedra, Moscow, 1990), Vol. 2 [in Russian].
13. I. V. Gordienko, V. S. Klimuk, and C. Khen, "Upper Amur Volcanoplutonic Belt of East Asia," Geol. Geofiz. **41** (12), 1655–1669 (2000).
14. A. Yu. Antonov, "Rare-Earth Elements in Late Mesozoic Granitoids of the Southern Surrounding of the Aldan Shield," Tikhookean. Geol. **17** (3), 68–80 (1998).
15. A. A. Stepashko, "Lateral Mantle Heterogeneity beneath the Russian Far East," Tikhookean. Geol. **20** (5), 93–117 (2001).
16. M. V. Martynyuk, S. A. Ryamov, and V. A. Kondrat'ev, *Explanatory Notes to a Classification and Correlation Chart of Magmatic Complexes in the Khabarovsk and Amur Territories (Report on Theme 330, 1987–1990)* (Khabarovsk, 1990) [in Russian].
17. V. D. Beda and N. Ya. Kalinkin, "Mineral Associations and Genetic Types of Gold–Base Metal Mineralization in Greisens, Amur Area," in *New Data on the Geology and Ore Potential of the Mongol–Okhotsk Belt* (DVNTS Akad. Nauk SSSR, Vladivostok, 1983), pp. 64–74 [in Russian].
18. A. S. Vakh, "Gold and Base-Metal Mineralization of One of the Russian Far East Deposit: Relations and Main Mineralogical–Geochemical Features," in *Relations between Different Types of Mineralization in the Volcanoplutonic Belts of the Asian–Pacific Junction Zone* (DVO SSSR, Vladivostok, 1991), pp. 121–153 [in Russian].
19. S. R. Taylor and S. M. McLennan, *The Continental Crust: Its Composition and Evolution. Blackwell* (Oxford, 1985), p. 312.
20. Yu. A. Balashov, *Geochemistry of the Rare-Earth Elements* (Nauka, Moscow, 1976) [in Russian].
21. H. R. Rollinson, *Using Geochemical Data: Evaluation, Presentation, Interpretation* (London Group, Essex, 1994).
22. J. G. Arth, "Behavior of Trace Elements during Magmatic Processes—A Summary of Theoretical Models and Their Applications," J. Res. U.S. Geol. Surv. **4**, 41–47 (1976).
23. M. P. Roberts and J. D. Clemens, "Origin of High-Potassium, Calc-Alkaline, I-Type Granitoids," Geology, No. 9, 825–828 (1993).
24. A. E. Patino Douce, "What Do Experiments Tell Us about the Relative Contributions of Crust and Mantle to the Origin of Granitic Magmas?" in *Understanding Granites: Integrating New and Classical Techniques*, Ed. by A. Castro, C. Fernandez, and J. L. Vigneressese, Geol. Soc. London Spec. Publ., No. 168, 55–75 (1999).
25. V. E. Strikha, "Late Mesozoic Granitoids of the Gold Ore–Magmatic Systems of the Upper Amur Area," in *Proceedings of International Scientific Conference on the Genesis of Gold Deposits and the Mining Methods of Noble Metals, Blagoveshchensk, Russia, 2001* (Blagoveshchensk, 2001), pp. 183–191 [in Russian].
26. A. M. Larin, A. B. Kotov, V. P. Kovach, et al., "Formation Stages of the Continental Crust of the Central Part of the Dzhugdzhur–Stanovoi Fold Area: Sm–Nd Isotope Data on Granites," Geol. Geofiz. **43** (4), 395–399 (2002).
27. R. Altherr, A. Holl, E. Hegner, et al., "High-Potassium, Calc-Alkaline I-Type Plutonism in the European Variscides: Northern Vosges (France) and Northern Schwarzwald (Germany)," Lithos **50**, 51–73 (2000).
28. N. T. B. Thuy, M. Satir, W. Siebel, et al., "Geochemical and Isotopic Constraints on the Petrogenesis of Granitoids from the Dalat Zone, Southern Vietnam," J. Asian Earth Sci. **23**, 467–481 (2004).

29. I. B. Lambert and K. S. Heider, "Chemical Investigations of Deep-Seated Rocks in the Australian Shield," Lithos **1**, 30–53 (1968).

30. A. Yu. Antonov, "On the Regional Petrochemical Zoning of Upper Mesozoic Granitoid Magmatism in the Stanovoi Range," in *Geochemistry of the Endogenous Processes—1977* (Irkutsk, 1979), pp. 48–54 [in Russian].

31. V. E. Strikha, "On the Lateral Zoning of Granitoid Magmatism in the Great Khingan Belt, Upper Amur Area," in *Proceedings of International Scientific Conference on the Genesis of the Gold Deposits and Methods of Mining of the Noble Metals, Blagoveshchensk, Russia, 2001* (Blagoveshchensk, 2001), pp. 192–196 [in Russian].

32. N. B. W. Harris, J. A. Pearce, and A. G. Tindle, "Geochemical Characteristics of Collision-Zone Magmatism," in *Collision Tectonics*, Ed. by M. P. Coward and A. S. Ries, Geol. Soc. London Spec. Publ. **19**, 67–81 (1986).

33. *Geological Basis for Metallogenic Analysis of the Baikal–Amur Railway* (VSEGEI, Leningrad, 1991) [in Russian].