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New Data on Granitoids of the Kara Gold Ore Cluster (Eastern Transbaikalia): Age, Genesis, and Sources of Material

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Abstract—Study of granitoids spatially and genetically associated with gold mineralization within the Kara gold ore cluster has provided a new insight into their genesis, association with ore mineralization, and the sources of their ore material. The regional granitoids associated with gold mineralization are part of two individual complexes. One of them, earlier assigned to the Amanan complex, has an isotopic age of 182.9 ± 2.6 Ma and must be related to the subduction zone that existed on the southern margin of the Siberian continent in that period. Its granitoids differ in age and composition from the granitoids of the Amanan complex and must be separated as an independent taxonomic unit after an additional geological study. The second, Amudzhikan–Sretensk, complex has an isotopic age of 151.7 ± 1.9 Ma and might be related to the collision of the Siberian and Mongol–Chinese continents after the closure of the Mongol–Okhotsk ocean. In geochemistry the granitoids of the Amanan(?) complex correspond to adakites and must be considered melting products of the basaltic layer of the oceanic lithosphere. The granitoids of the Amudzhikan-Sretensk complex are similar in geochemistry to sanukitoids, melting products of subcontinental sources contaminated with continental-crust material. The granitoids of both complexes have high contents of gold and must be considered gold-bearing. In the Amanan(?) complex, adakites are the gold-richest rocks (as estimated from the slab melt composition), which indicates the primary nature of this gold. In the Amudzhikan–Sretensk complex, the highest contents of gold are specific to primitive sanukitoids, melting products of a mantle source with gold signatures. This suggests the primary nature of gold, whose content is determined by the portion of slab melt in the source of the rock material. The presence of adakites and primitive sanukitoids in the regional granitoid complexes indicates the existence of a subcontinental mantle source with gold signatures during the magma generation. The source formed in the subduction zone that existed on the southern margin of the Siberian continent in the Early Jurassic and was remobilized under collision of the Siberian and Mongol–Chinese continents in the Late Jurassic. This source might have controlled both granitoid magmatism and ore mineralization.

Keywords: ore-magmatic systems, age of igneous rocks, geochemical typification of granitoids

INTRODUCTION

Elaboration of criteria for the ore potential of granitoid intrusions is an important task of practical geology. The most extensive research in this field was carried out in the 1980–1990s.

In that period, study of rare-metal, ore-magmatic, and granitoid systems yielded good results. This made it possible to elaborate criteria for the ore potential and ore productivity of rare-metal granitoid intrusions and to use them in subsequent metallogeny research and geological prospecting (Tauson, 1977; Kozlov, 1985).

Similar research was also performed for gold, but the results were not sufficient to elaborate unambiguous criteria for the gold ore potential of granitoids despite the genetic control of gold deposits by some granitoid intrusions (Spiridonov et al., 2006).

In our opinion, the absence of results during the elaboration of criteria for the gold potential of granitoid intrusions is due to a patchy understanding of the factors controlling the behavior of gold in a felsic magmatic system and to the lack of unambiguous concepts of its sources.

This paper is an attempt to solve one of the above problems, namely, identification of the sources of gold in the deposits of the Kara ore cluster, using recent analytical data and hypotheses of granitoid formation.

GEOLOGIC STRUCTURE OF THE STUDY AREA

The Kara gold ore cluster is localized within the Shilka mobile zone of the Mongol–Okhotsk structural suture (Fig. 1) resulted from the collision of the Siberian and Mon-

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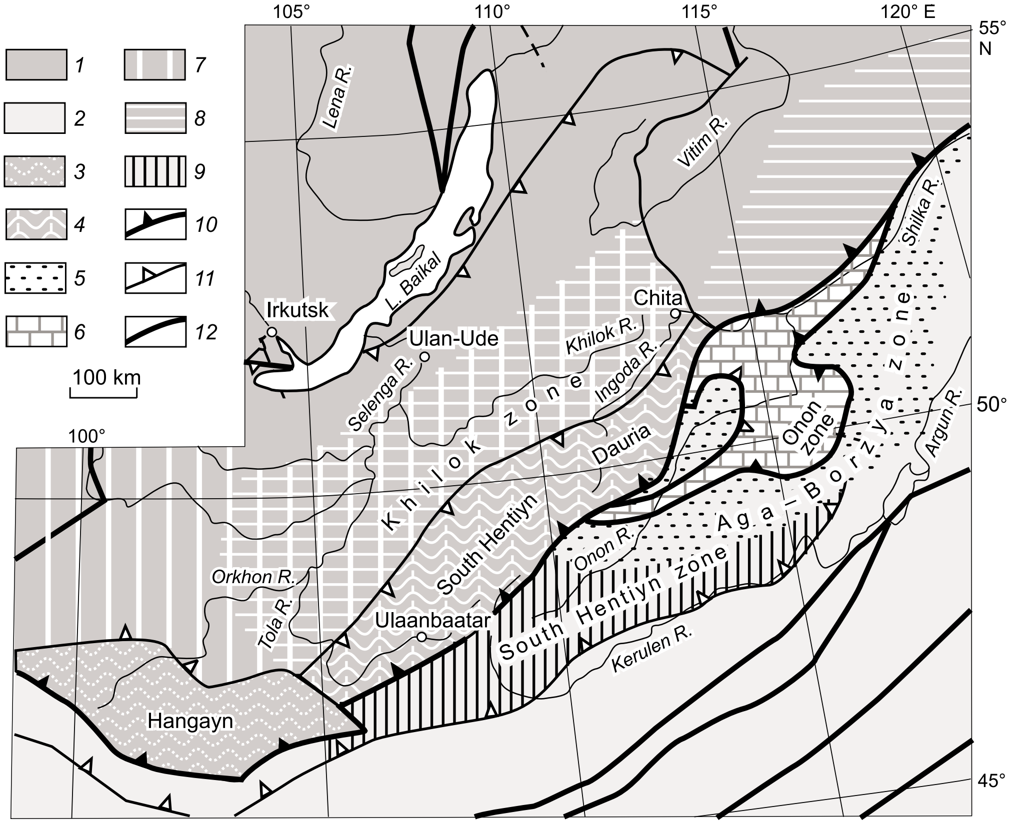

Fig. 1. Schematic geodynamic regionalization of the Transbaikalian part of the Mongol–Okhotsk Orogenic Belt and its framing (Zorin et al., 1998). *1*, Siberian continent in the Late Permian–Early Jurassic; *2*, Mongol–Chinese continent in the Late Permian–Early Jurassic; *3*, Devonian–Carboniferous accretion–subduction wedge near an Andean-type active continental margin; *4*, the same wedge with the superposed Permian–Early Jurassic frontal part of an Andean-type active continental margin; *5*, Late Permian–Early Jurassic passive continental margin (shelf, continental slope, and slope piedmont); *6*, Onon island-arc terrane with Devonian–Carboniferous accretion–subduction wedges and Late Triassic back-arc basin; zones of the influence of the Mongol–Okhotsk Orogenic Belt (Andean-type active margins): *7*, Devonian–Middle Carboniferous, *8*, Late Carboniferous–Early Permian, *9*, Late Carboniferous–Early Jurassic; *10*, Mongol–Okhotsk suture; *11*, thrusts; *12*, normal faults.

gol–Chinese continents after the closure of the Mongol–Okhotsk ocean (Zonenshain et al., 1990; Zorin, 1999).

Early Proterozoic gneissoid diorites, quartz diorites, and biotite granites expose within the study area. The rocks of the area framing are intruded by granitoids of Early Jurassic Amanan(?) and Middle–Late Jurassic Amudzhikan–Sretensk complexes (Fig. 2).

Gold deposits and gold–sulfide–quartz ore occurrences are localized in Early Jurassic and Early Proterozoic granitoids. In the north and northwest they “envelope” the Kara–Chacha pluton composed of granitoids of the Amudzhikan–Sretensk complex. The association of gold mineralization with these granitoids is due to the synchronous intrusion of grorudite dikes and the deposition of ore mineralization at the productive stage (Spiridonov et al., 2006).

The rocks hosting gold mineralization were studied within the Amurskaya Daika (Amur Dike) site, where numerous excavations made it possible to study the ore–rock association and take geochemical samples from unaltered igneous rocks.

Within the study area, there is an exposed geologic body of massive equigranular fine-grained diorites intruded by a stock of amphibole tonalites, which, in turn, are cut by dikes of biotite–amphibole plagioclase granites. In general, the studied igneous rocks are a three-phase granitoid intrusion, whose Early Proterozoic age is highly questionable.

The mineral composition of the granitoids of three phases is almost identical. The only difference is the proportions of amphibole and plagioclase, with a decrease in the plagioclase number from andesine to oligoclase and the appearance of quartz and primary biotite in more felsic varieties. The rocks are almost free of K-feldspar; its scarce grains are found in the groundmass of granites of the third intrusive phase.

Comparison of these rocks by appearance and mineral composition with other granitoids within the Kara ore cluster showed their best similarity to the granitoids arbitrarily referred by the authors of the ore cluster map to the Amanan complex. Compared with the Amanan granitoids, they are enriched in plagioclase and are depleted in biotite and virtually lack K-feldspar. Granites of the first two phases contain secondary biotite replacing amphibole. In granites of the third phase, biotite is present in small amounts as an individual rock-forming mineral.

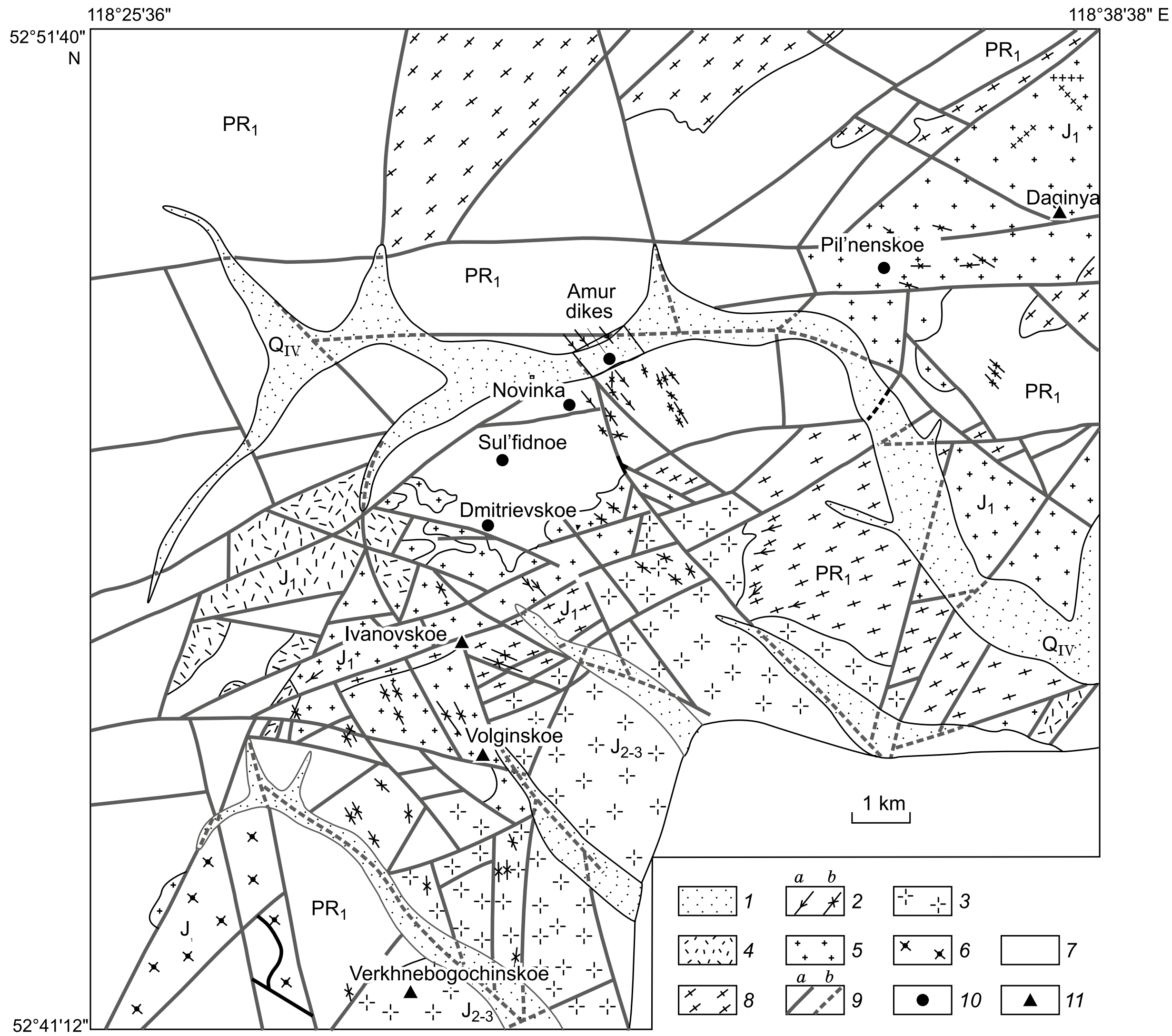

Fig. 2. Schematic geological map of the Kara ore cluster (Spiridonov et al., 2006). *1*, Quaternary deposits; *2*, dikes (J_3) of: *a*, grorudites, *b*, hybrid porphyry; *3*, biotite–amphibole granodiorites and granites of the Amudzhikan–Sretensk complex; *4*, andesite porphyrites (J_1); *5*, *6*, Amanan(?) complex: *5*, granitoids, *6*, gabbro; *7*, gneissoid quartz diorites, granodiorites, and granites (PR_1); *8*, gneissoid biotite diorites and granodiorites (PR_1); *9,* dislocations: *a*, proved, *b*, predicted; *10*, gold deposits; *11*, gold ore occurrences.

The Amanan complex is, most likely, an individual "plagiogranite" complex of uncertain age. A specific feature of its granitoid plutons is their spatial association with most of ore occurrences and deposits of the Kara ore cluster, which is well seen in Fig. 2. The spatial association of granitoids with gold mineralization can be considered an additional controlling factor and permits regarding the granitoids as a primary collector (source of gold) and, possibly, as an independent ore-generating center with its own gold mineralization.

The above hypothesis is supported by the appearance of primary gold deposits and gold placers northeast of the Kara gold ore cluster, in the basin of the Luzhanka River, where granitoids of the Amudzhikan–Sretensk complex are absent (Golbert and Chatskis, 1981). In addition, there is an early gold–sulfide–quartz association in the Kara ore field, whose orebodies are cut by granitoids of the Kara–Chacha pluton that controlled the Late Jurassic mineralization (Spiridonov et al., 2006).

Granitoids of the Amudzhikan–Sretensk complex were studied in the northeastern part of the Kara–Chacha pluton, in the basin of the Ivanovka River, a right tributary of the Kara River. The pluton has a three-phase structure (Antipin, 1969). Granitoids of the first phase form an endocontact rim in the northern part of the pluton and also occur as xenoliths in granitoids of the second phase. They closely resemble the "hybrid" porphyry composing dikes at the exocontact of the pluton.

Petrographic study has shown that these granite varieties are compositionally similar amphibole–plagioclase rocks with a small amount of biotite replacing amphibole and a large number of grains of fused quartz and intergrowths of coarse plagioclase, perthitic K-feldspar, amphibole, and biotite grains with a reaction rim. The above minerals are obviously in disequilibrium, which was reported by many geologists who studied these igneous rocks (Tikhomirov, 1964; Antipin, 1969; Rutshtein and Chaban, 1997).

Granitoids of the second phase are porphyritic biotite–amphibole granodiorites. They contain numerous glomeroporphyritic amphibole intergrowths similar to those in the granitoids of the first phase. In places, there is a reaction between intergrowths of large plagioclase and K-feldspar crystals and finer amphibole and plagioclase grains of the rock groundmass. All this suggests the "hybrid" nature of the rocks.

Granitoids of the third phase are giant porphyritic biotite–amphibole granites. Their groundmass is composed of quartz, plagioclase, and K-feldspar. Dark-colored minerals are represented by amphibole and biotite.

The dike rocks of the Amudzhikan–Sretensk complex are grorudites (aegirine granites) and hybrid porphyry[1]. They are considered to be the latest products of the evolution of the magmatic system and are present solely at the exocontact of the intrusion. We sampled only hybrid porphyry for petrographic and geochemical studies and failed to sample grorudites because of the absence of unaltered varieties in the surface excavations.

The hybrid porphyry corresponds in appearance and mineral composition to the granitoids of the first phase. This suggests that it is the earliest rock of the granitoid complex. Below, we will consider it together with the granitoids of the first phase of the pluton. The grorudites might also be one of the phases of the granitoid pluton and not be the latest products of the magmatic system. This is indirectly evidenced by the absence of grorudite dikes and hybrid porphyry within the Kara–Chacha pluton.

To obtain correct data on the relationship of gold mineralization with granitoid magmatism within the ore cluster, it is necessary to perform isotope dating of granitoids of both complexes, measure their contents of gold, and determine their geochemical types. This will permit application of modern genetic models to determine the sources of this metal.

THE ISOTOPIC AGE OF GRANITOIDS

The isotopic age of granitoids of the Amanan complex was determined by K/Ar, U/Pb isochron (Aleksandrov and Rublev, 1979, 1983), and Rb/Sr (Sokolov, 1990) dating. The spread in dates was 193–260 Ma. Taking into account the wide interval of date variations, we evaluated the isotopic age of granitoids using the well-agreeing U/Pb and Rb/Sr dates for the Itaka massif: It is 229–240 Ma, i.e., Middle Triassic. We take it as the age of the granitoids of the Amanan complex.

The available data on the isotopic age of the Amudzhikan–Sretensk complex were obtained by the K/Ar and Rb/Sr methods. The K/Ar age varies from 145 to 165 Ma (Rublev et al., 1985) and thus corresponds to the Middle–Late Jurassic. The isotopic age of granitoids of the Kara–Chacha massif obtained by Rb/Sr isochron dating is 132 ± 12 Ma (Dril' et al., 2010) and corresponds to the Early Cretaceous. The true age of the granitoids remains unclear because of the great difference in the obtained dates. We can only limit it to the Late Jurassic–Early Cretaceous interval.

To obtain more reliable results, the granitoids of the Amanan(?) and Amudzhikan–Sretensk complexes were dated by the $^{40}Ar/^{39}Ar$ method, with stepwise heating of the samples and measurement of the isotopic composition of released argon on a Micromass 5400 (Micromass UK Limited) mass spectrometer. The method was described earlier (Travin et al., 2009). Amphiboles from the granitoids were used for dating. The results are given in Fig. 3 and in the text.

The isotopic age of the granitoids of the Amanan(?) complex was determined using amphibole from plagioclase–amphibole gabbro of the first phase (sample AM-8). The sample was subjected to six-stage heating from 500 to 1130 ºC. The age spectrum is presented in Fig. 3. It has two plateaus with ages of 180.1 ± 2.6 and 191.2 ± 3.0 Ma corresponding to 55 and 45% of released ^{39}Ar, respectively. The small scatter of the obtained dates does not interfere with the unambiguous conclusion about the Early Jurassic age of the granitoids. It is worth taking an integrated age of 182.9 ± 2.6 Ma as the isotopic age of these rocks.

The results of dating and the characteristics of rocks suggest that they belong, most likely, to an individual granitoid complex younger than the Amanan one. With regard to its age, this complex might have formed in the subduction zone that existed on the southern border of the Siberian continent in the Early Jurassic.

These granitoids differ from the petrotypical ones in age and geochemical features, which gives grounds to recognize them as an individual complex. However, this requires additional geological work, including determination of the spatial limits of the occurrence of these granitoids, refinement of their phase–facies composition, geochemical features, and metallogenic signatures, and confirmation of their isotopic age. Taking into account the uncertainty on these issues, we will continue calling the above granitoids the Amanan(?) complex.

The dating of granitoids of the Amudzhikan–Sretensk complex included solution of two problems: (1) evaluation of the isotopic age of granitoids of one of the bulk phases and (2) determination of the age difference between the granitoids and associated subvolcanic intrusions. For this purpose, amphibole was separated from amphibole–biotite granite of the third phase (sample AM-18), which composes most of the granitoid pluton.

[1] The terms grorudites and hybrid porphyry are used following the geologists who earlier studied granitoids of the Amudzhikan–Sretensk complex (Tikhomirov, 1964; Antipin, 1969; Rutshtein and Chaban, 1997).

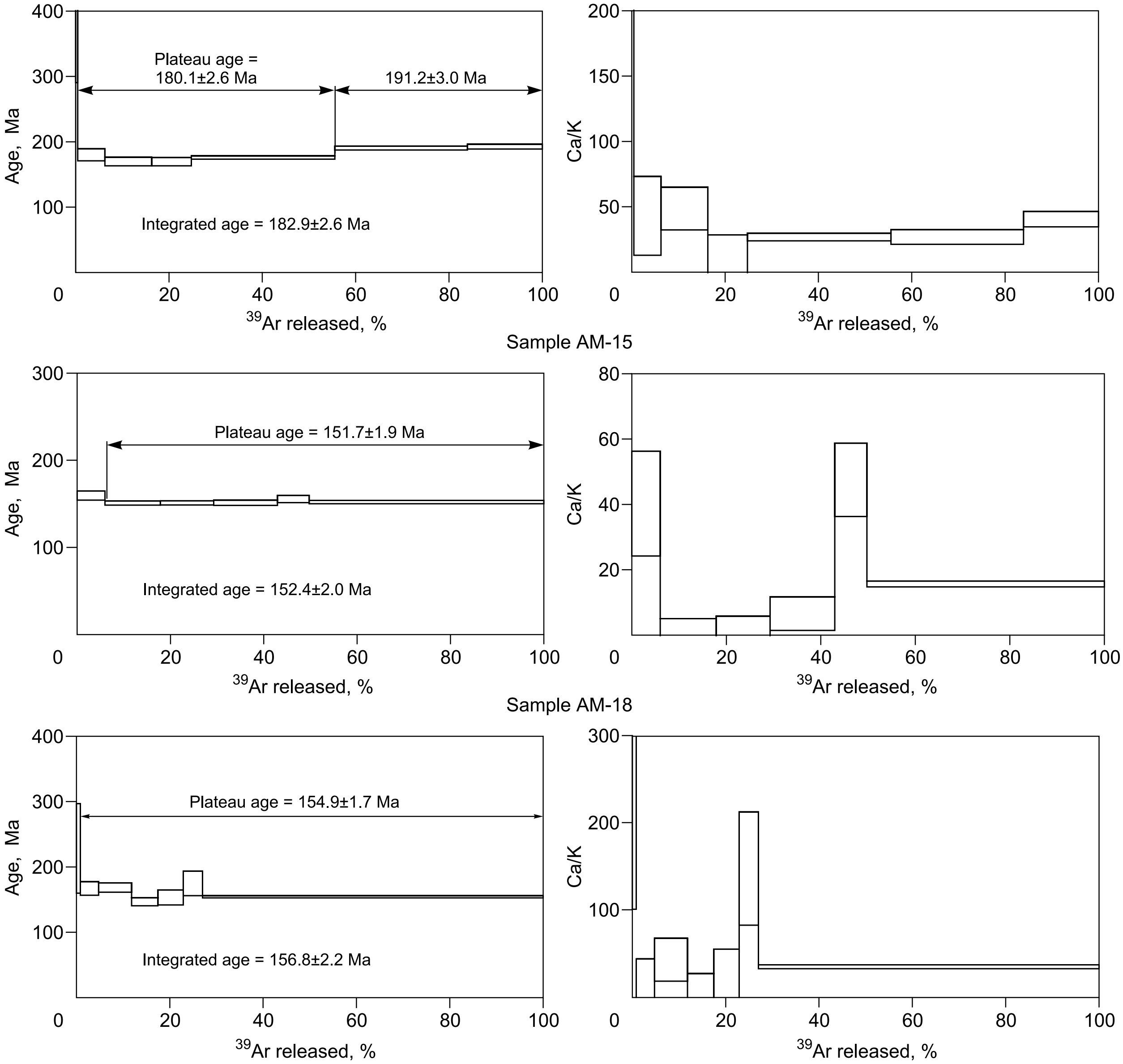

Fig. 3. Results of Ar/Ar dating of Mesozoic granitoids of the Kara gold ore cluster. For explanation, see the text.

To estimate the age of subvolcanic rocks, we sampled amphibole from the granitoids of the first phase (sample AM-15) similar in appearance and composition to the hybrid porphyry of dike bodies at the exocontact of the massif and to xenoliths in the granitoids of the second and third phases.

The sample AM-15 was subjected to six-stage heating from 500 to 1130 ºC. Its age spectrum is presented in Fig. 3. It has a distinct plateau with an age of 151.7 ± 1.9 Ma, corresponding to the release of 93% ^{39}Ar.

The sample AM-18 was also subjected to six-stage heating from 500 to 1130 ºC. Its age spectrum is given in Fig. 3. There is a significant scatter of date values, and the plateau is not as distinct as for the above sample. The plateau age is 154.9 ± 1.7 Ma.

The obtained isotope dates unambiguously indicate the Late Jurassic age of the granitoids of the Kara–Chacha pluton. The older age of the granitoids of the third phase might be due to the significant scatter of date values caused by secondary alterations of amphibole. To obtain more precise data, it is necessary to date another sample from the same phase of the granitoid pluton.

The estimated isotopic age indicates that the granitoids of the Kara–Chacha pluton resulted from the collision of the Siberian and Mongol–Chinese continents after the closure of the Mongol–Okhotsk ocean (Zorin, 1999). These conclusions agree with the results of other researchers who studied the above granitoids (Spiridonov et al., 2006; State..., 2010).

GEOCHEMICAL TYPIFICATION OF GRANITOIDS

Granitoids of the Amanan(?) complex. The granitoids of the second phase of the complex are most similar in mineral and chemical compositions to tonalites. They are characterized by low contents of SiO_2 (58.27–59.96 wt.%), high contents of Al_2O_3 (18.09–20.68 wt.%) and Na_2O (4.47–5.90 wt.%) (with a significant domination of the latter over K_2O, Na_2O/K_2O = 3.35–4.23), and high Mg# values (0.48–0.51).

The granitoids have a specific trace-element composition: high contents of Sr (>823 ppm) and low ones of Y (<9.51 ppm), high contents of LREE and low ones of HREE (La/Yb = 27.25–43.00), and elevated contents of Cr (12–24 ppm) and Ni (8–14 ppm).

All these geochemical characteristics are typical of adakites, the melting products of rocks of the basaltic layer of the oceanic lithosphere in subduction zone (Martin et al., 2005). The similarity of the above granitoids to adakites is evidenced from the classification diagrams in Fig. 4.

According to the prevailing viewpoint, adakites form only within island arcs and active continental margins. Our isotope dates do not contradict this viewpoint, because they give grounds to associate the granitoids of the Amanan(?) complex with the subduction zone that existed on the southern border of the Siberian Platform in the Early Jurassic.

The results obtained permit us to assign the second-phase granitoids of the Amanan(?) complex to adakites. This conclusion is important for assessing the ore potential of granitoid intrusions in the study area, because adakites are the only geochemical type of granitoids for which Au, Cu, and Mo signatures have been proved (Gonzalez-Partida et al., 2003; Qiang et al., 2006).

The gabbroids of the first phase also have an unusual geochemical composition: high total alkalinity (Na_2O+K_2O= 4.18–4.91 wt.%), low contents of SiO_2 (49.56–54.35 wt.%), high contents of Ti (1.10–1.45 wt.%) and P (0.20–0.42 wt.%), and elevated Mg# values (0.51–0.59). They are most similar in chemical composition to subalkalic gabbro (Bogatikov, 1981).

In trace-element contents, however, they are closer to normal calc-alkalic basalts, differing from them in slightly higher contents of alkaline and alkaline-earth elements, U, Th, and LREE (Table 1). They show a distinct "subduction mark" expressed as relative enrichment of rocks in elements with a large ionic radius (LILE) and as relative deficit of high field strength elements (HFSE). This is most clearly demonstrated by the spidergram in Fig. 5*a*.

Highly alkaline rocks with geochemical characteristics of calc-alkalic basalts are sometimes present within island arcs and active continental margins. They are always spatially associated with adakites; all researchers consider this association genetic. These rocks are commonly called high-Nb basalts (HNB) (Defant et al., 1992) or Nb-enriched basalts (NEB) (Sajona et al., 1996), although sometimes they are poor in Nb (Wyman et al., 2000).

According to the prevailing viewpoint, the above rocks result from the melting of mantle wedge rocks or lithospheric-mantle rocks metasomatized by adakite melts (Martin, 1999; Martin et al., 2005). It is adakite melt as a metasomatizing agent that is responsible for the high alkalinity and island-arc geochemical characteristics of magmas generated through the melting of such mantle rocks.

The relationship between the first-phase gabbroids (NEB) and second-phase tonalites (adakites) is seen from the spidergram in Fig. 5*a*. Both rocks show conformal geochemical patterns and differ in contents of some groups of elements. The tonalites are enriched in alkaline and alkali-earth elements, U, Th, Pb, and LREE and depleted in HREE relative to the gabbro.

Since the geochemical characteristics of basic magmas in subduction zones are governed by the composition of a metasomatizing agent, the conformity of the geochemical patterns suggests that the tonalites (adakites) are a metasomatizing agent that transformed the mantle source of basic magmas. The pattern slope is indicative of the portion of the

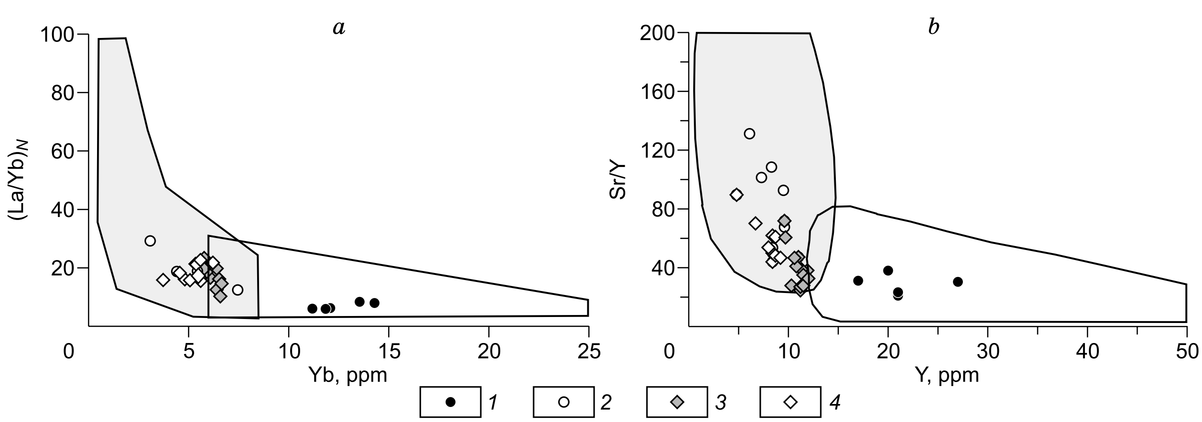

Fig. 4. Classification diagrams for adakites. *a*, After Martin (1999), *b*, after Defant and Drummond (1990). *1*, *2*, Amanan(?) complex: *1*, gabbro, *2*, tonalites; *3*, *4*, Amudzhikan–Sretensk complex: *3*, hybrid porphyry, *4*, granitoids. Gray field, derivates of slab magmas, white field, derivates of calc-alkalic magmas.

Table 1. Average compositions of igneous rocks of the Ust'-Kara region

Element	1	± S	2	± S	3	± S	4	± S	5	± S	6	± S
SiO_2, wt.%	51.38	1.80	59.63	1.40	58.48	0.73	61.42	0.69	69.00	1.05	71.92	0.82
TiO_2	1.20	0.22	0.64	0.18	0.72	0.05	0.68	0.06	0.40	0.04	0.42	0.20
Al_2O_3	18.22	0.65	19.68	1.43	14.03	0.07	14.48	0.33	14.58	0.46	14.16	0.60
Fe_2O_{3tot}	10.03	1.79	5.19	1.03	6.40	0.87	5.36	0.70	3.47	0.85	2.58	0.75
MnO	0.15	0.02	0.09	0.04	0.11	0.03	0.09	0.00	0.05	0.01	0.04	0.01
MgO	5.26	1.07	2.66	0.71	6.43	0.66	5.10	0.82	2.17	0.39	1.55	0.63
CaO	8.88	0.91	5.72	0.70	4.95	0.58	4.34	0.19	2.72	0.17	2.32	0.21
Na_2O	3.46	0.30	5.12	0.66	3.75	0.47	4.13	0.71	4.01	0.22	4.91	1.04
K_2O	1.04	0.24	1.48	0.33	3.76	0.44	3.53	0.27	3.65	0.47	3.67	0.29
P_2O_5	0.28	0.10	0.20	0.05	0.19	0.01	0.20	0.01	0.12	0.01	0.10	0.03
LOI	0.03	0.65	0.15	0.35	1.17	1.03	0.64	0.08	0.00	0.26	0.57	0.59
Total	99.93		100.56		99.99		99.97		100.18		102.22	
N	4		5		4		3		6		4	
Mg#	0.52	0.05	0.48	0.05	0.67	0.02	0.66	0.01	0.57	0.05	0.57	0.06
Be, ppm	1.20	0.06	0.95	0.07	2.02	0.16	2.40	0.60	3.17	0.22	2.78	0.42
F	506	204	370	101	1123	429	1144	407	820	119	865	481
B	9	7	14	5	18	8	14	11	17	6	14	5
Li	16	4	16	4	34	21	23	11	67	19	30	16
Rb	24	19	28	5	183	45	114	14	128	21	128	11
Cs	5.6	5.1	2.6	1.6	22.6	14.0	5.8	1.1	9.5	2.3	7.1	0.4
Ba	449	290	783	230	542	181	536	151	396	142	209	81
Sr	698	135	929	73	394	96	503	69	471	45	413	38
Ga	19.8	1.6	21.7	0.7	20.3	1.4	20.7	1.2	19.6	1.2	19.4	0.5
Ge	1.06	0.10	0.97	0.03	4.23	1.30	1.51	0.32	1.35	0.11	1.46	0.10
Zr	122	74	200	106	129	13	142	2	117	11	100	29
Nb	4.6	0.8	4.2	1.1	7.1	0.5	7.2	0.1	7.2	1.4	7.7	0.4
Ta	0.25	0.03	0.26	0.08	0.48	0.05	0.61	0.07	0.75	0.18	1.01	0.17
Hf	1.2	0.5	0.4	0.1	3.2	0.3	3.3	2.3	4.4	0.8	4.0	0.3
Ni	35	23	10	3	147	23	112	35	42	13	25	8
Co	37	9	15	6	24	3	25	6	12	2	8	3
Cr	55	46	16	6	409	59	255	96	148	49	100	31
V	242	44	101	51	139	13	114	17	57	8	44	17
Sc	21.0	3.4	6.6	3.0	15.5	1.7	11.3	2.8	5.8	0.9	4.3	0.3
Cu	50.6	11.3	22.8	11.7	8.7	4.8	23.4	2.5	9.1	4.1	12.8	4.5
Zn	99	18	73	14	84	22	68	13	48	5	40	5
Pb	4.9	0.3	9.0	1.5	18.6	7.3	19.2	5.3	35.1	3.1	30.3	2.2
Mo	1.5	1.7	1.2	0.3	1.2	1.3	2.1	1.7	1.1	1.0	6.0	4.9
Sn	2.1	0.4	1.5	0.5	1.8	0.2	2.5	0.1	2.4	0.5	2.6	0.3
W	0.4	0.1	0.2	0.1	9.2	21.7	11.6	14.6	1.4	2.2	85.0	94.2
Sb	0.34	0.05	0.48	0.35	6.25	1.03	0.51	0.06	0.93	0.51	0.84	0.27
La	20.5	5.6	21.8	2.0	25.5	4.7	33.3	4.5	25.9	6.5	19.3	1.2
Ce	45.6	13.2	39.3	6.0	54.8	8.6	68.9	6.5	52.2	12.5	46.1	3.3
Pr	5.2	1.7	3.8	0.9	5.6	0.7	7.5	0.2	6.0	1.2	4.9	0.2
Nd	23.3	7.0	15.6	4.5	23.8	2.3	29.1	0.9	21.7	4.2	18.1	0.7
Sm	4.6	1.2	2.5	0.9	4.3	0.2	5.0	0.1	3.7	0.7	3.2	0.1
Eu	1.50	0.24	1.23	0.13	1.04	0.07	1.26	0.08	0.87	0.11	0.70	0.04
Gd	4.6	0.8	2.2	0.8	3.5	0.2	4.2	0.2	3.2	0.6	2.8	0.2
Tb	0.70	0.10	0.31	0.12	0.42	0.02	0.49	0.10	0.35	0.08	0.29	0.01
Dy	3.9	0.5	1.6	0.5	2.3	0.1	2.5	0.4	1.9	0.5	1.6	0.1
Ho	0.80	0.10	0.31	0.10	0.41	0.03	0.44	0.08	0.35	0.09	0.29	0.01

(*continued on the next page*)

Table 1 (*continued*)

Element	1	± S	2	± S	3	± S	4	± S	5	± S	6	± S
Er	2.2	0.3	0.8	0.3	1.1	0.1	1.2	0.2	0.9	0.2	0.8	0.0
Tm	0.31	0.03	0.11	0.03	0.15	0.01	0.15	0.03	0.13	0.03	0.11	0.01
Yb	2.0	0.1	0.7	0.2	1.0	0.1	1.1	0.2	1.0	0.3	0.8	0.1
Lu	0.29	0.03	0.11	0.02	0.14	0.01	0.15	0.03	0.15	0.04	0.13	0.01
Y	21.2	3.6	8.2	1.5	11.1	0.7	12.9	2.8	9.3	2.9	7.6	1.9
U	1.03	0.06	1.53	0.49	3.15	0.45	3.50	0.81	6.05	2.61	3.30	0.80
Th	2.9	0.6	3.4	0.6	9.0	0.9	11.4	1.8	17.6	3.2	18.3	1.8
Au	0.0087	0.005	0.012	0.008	0.014	0.008	0.0120	0.007	0.0100	0.009	0.010	0.007
N	4		5		19		3		6		4	

Note. Mg# = $Mg^{2+}/(Fe^{2+} + Mg^{2+})$; Fe^{2+}, all iron in the ferrous form; *S*, standard deviation; *N*, number of samples used for the calculation of the average compositions. Analyses were carried out at the Common Use Center for Isotope-Geochemical Research of the Institute of Geochemistry, Irkutsk. Rock-forming elements were determined by X-ray fluorescence analysis; Au, by AAS; and the other elements, by ICP-MS. Amanan(?) complex: 1, gabbro, 2, tonalites; Amudzhikan–Sretinsk complex: 3, hybrid porphyry, 4, monzodiorites of the first phase, 5, granodiorites of the second phase, 6, granites of the third phase.

metasomatizing agent in the products of melting of this source: As the slope becomes smaller, the pattern turns counterclockwise, thus indicating an increase in the portion of the mantle source of material (DM), which is expressed as a decrease in the contents of incompatible elements and an increase in the contents of compatible elements in the produced melt.

This is better demonstrated by the REE patterns of tonalites and gabbroids (Fig. 5*b*). The lower contents of HREE in the tonalites indicate the formation of felsic magmas (metasomatizing agent) at higher pressures. The low contents of HREE in the diorites are due to the interaction of the metasomatizing agent with the overlying mantle wedge/lithospheric-mantle rocks beyond the garnet stability zone.

The appearance of igneous rocks similar to the first-phase gabbroids suggests the wide occurrence of metasomatic transformations in the regional subcontinental mantle (the existence of mantle chambers with geochemical signatures) and permits regarding adakite (slab) melt as a metasomatizing agent.

Comparison of the geochemical features of the first-phase gabbroids and NEB shows their similar compositions. The only difference is the lower contents of Nb in the gabbroids. Since Nb is part of the NEB name, let us consider this discrepancy in more detail.

Enrichment of these magmas with HFSE cations (Nb, Ta, Ti, P, Zr, and Hf) is controlled by the stability of the phases concentrating them in the source of magma generation. In particular, magma enrichment in Nb giving the name to this class of rocks is governed by the stability of amphibole (Sajona et al., 1996; Martin, 1999) and depends on the type of its melting (hydration or dehydration) (Rapp and Watson, 1995). This is important because different associations of peritectic minerals during the melting of amphibole will lead to the redistribution of Nb either into the melt or into the restite and the formation of magmas enriched or depleted in this element and preserved the "dual" geochemical characteristics. In other words, the content of Nb in this group of rocks depends on the melting conditions and can be considered a regional specific feature. All this gives grounds to regard the first-phase gabbroids of the Amanan(?) complex and NEB as rocks of a single genetic group and use the generally accepted genetic models for NEB in genetic reconstructions.

The geochemical specifics of the granitoids of the Amudzhikan–Sretensk complex were discussed by many researchers (Antipin, 1969; Kuz'min, 1971; Gavrikova, 1985). According to their data, the granitoids of this complex have compositional specifics (Table 1). They are highly magnesian and have high contents of the iron family elements (Cr, Ni, Co, and V), alkaline and alkaline-earth elements, and LREE. By a number of features, these granitoids were assigned to the latite geochemical type (Tauson, 1977) and were earlier regarded as products of mixing of the main primary mantle and felsic crustal magmas followed by the differentiation of hybrid melts (Antipin, 1969; Kuz'min, 1971; Spiridonov et al., 2006).

Hybrid porphyry and xenoliths in the second phase of the complex are most similar in geochemical features to derivates of primary mantle magmas. The rocks have a persistent content of SiO_2 (57–59 wt.%) and are characterized by Mg# = 65–69, $K_2O + Na_2O$ = 7.4–7.6 wt.%, with domination of Na over K (Na_2O/K_2O = 1.1–1.2), low contents of TiO_2 and Al_2O_3, and slightly elevated contents of P_2O_5.

Among the trace elements, we have revealed anomalous contents (ppm) of Cr (470–660) and Ni (140–160), high contents of Rb (118–165), Cs (4.5–14.0), B (11–27), U (3.5–5.0), Th (6.5–11.0), and Pb (11–55), and medium contents of Ba (393–550) and Sr (341–345) as well as high contents of LREE and low contents of HREE and Y.

In chemical composition these rocks totally correspond to primitive sanukitoids, i.e., "mantle" granitoids of Arche-

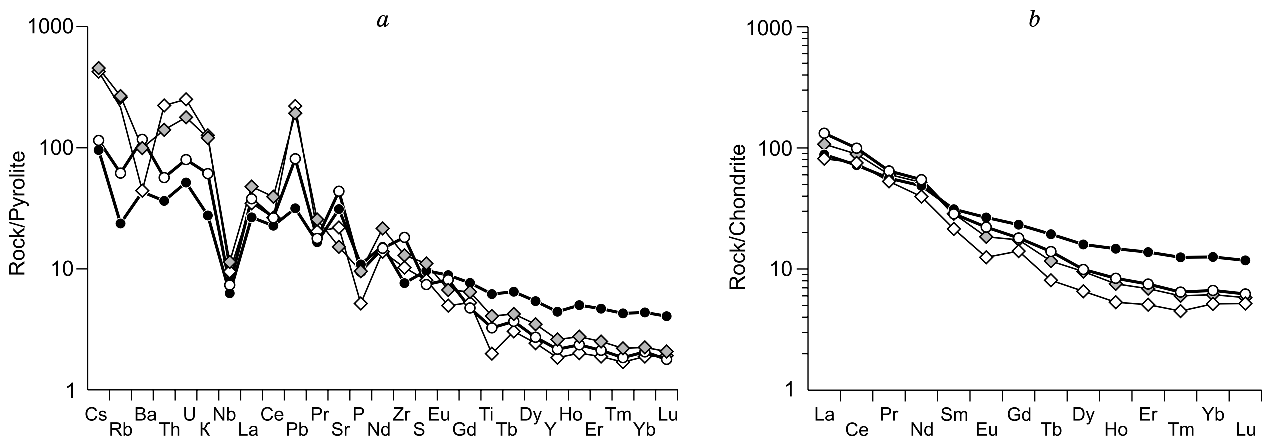

Fig. 5. Pyrolite- and chondrite-normalized (McDonough and Sun, 1995) element spidergrams of of the Ust'-Kara granitoids. *a*, *b*, For explanation, see the text. Designations follow Fig. 4.

an cratons, analogs of low-Si adakites (LSA) contaminated with continental crustal material (Martin et al., 2005). This is clearly seen from the diagrams in Fig. 4, where the composition points of the rocks fall in the fields of adakites with geochemical marks typical of slab magma derivates (high contents of LILE, high degree of REE fractionation, and low contents of Yb and Y (Martin et al., 2005)) (Fig. 5).

The upper mantle peridotites metasomatized by adakite melts in subduction zone are considered to be the source of sanukitoids. Thus, we again come to a conclusion about the source of material with geochemical signatures that formed in subduction zone and existed in the regional subcontinental mantle during the magma formation.

The granitoids of the first, second, and third phases of the complex inherit the geochemical features of more mafic rocks considered in the previous section. They are also highly magnesian (Mg# = 0.65–0.55) and are characterized by abnormal contents of Cr and Ni, domination of Na over K (but the total alkalinity is higher), high contents of alkaline and alkali-earth elements and LREE, and low contents of HREE and Y.

Compared with the above mafic rocks, these granitoids are richer in SiO_2 and salic components. The contents of SiO_2 in the granitoids of the first, second, and third phases are 62.72–64.08, 67.81–70.49, and 71.36–73.14 wt.%, respectively.

The compositional variations of the rocks of the granitoid complex can be explained only by the mixing of mafic and intermediate mantle magmas (primitive sanukitoids) and felsic crustal magmas. This process can be demonstrated by analysis of the distribution of Cr in the rocks of the three intrusive phases. The average contents of Cr decrease from 255 ppm in the granitoids of the first phase to 148 and 100 ppm in those of the second and third phases, respectively (Table 1), but the Mg# values of these rocks change insignificantly (Fig. 6). Taking into account the significant correlation between Mg and Cr (Fig. 6), we can conclude that Cr is concentrated by ferromagnesian silicate minerals; their amount determines the content of Cr in the rocks, and their composition governs the Mg# value.

The minor variations in Mg# in the rocks with different contents of SiO_2 apparently indicate no equilibrium between the dark-colored minerals and the leucocratic matrix. The change in the rock composition might be due to different proportions of melanocratic and leucocratic minerals (mafic and felsic magmas).

The above mixing of materials of two reservoirs of contrasting compositions is defined as "mingling", which implies redistribution of thermodynamically stable minerals from a more mafic source in the felsic melt. The presence of glomeroporphyritic amphibole intergrowths in the granitoids of the first and second phases indicates that the granitoids of the Kara–Chacha pluton resulted from this process.

Thus, we can explain the compositional variations of the studied granitoids by the mixing of derivates of mantle and crustal magmas, which is consistent with the results obtained by other researchers, but our data do not indicate the wide occurrence of crystallization differentiation processes within the Amudzhikan–Sretensk complex.

Our geochemical typification does not totally agree with the interpretations of factual data of other authors. In our opinion, the main specific feature of all Amudzhikan–Sretensk granitoids is their anomalous Mg# values and contents of Cr and Ni, typical of mantle magma derivates, and high contents of alkaline and alkaline-earth elements, U, Th, and LREE, typical of melting products of crustal protoliths. This geochemical "duality" is specific to the most mafic rocks of the complex, which suggests its relationship with the composition of the source of material, localized, most likely, in the Earth's mantle.

A more thorough analysis of the composition of the above granitoids showed their slight enrichment in Ba, Sr (2–3 times), Nb, Zr, tantalum, Hf (2–3 times), and LREE (2–3 times), lower contents of HREE and yttrium, and ab-

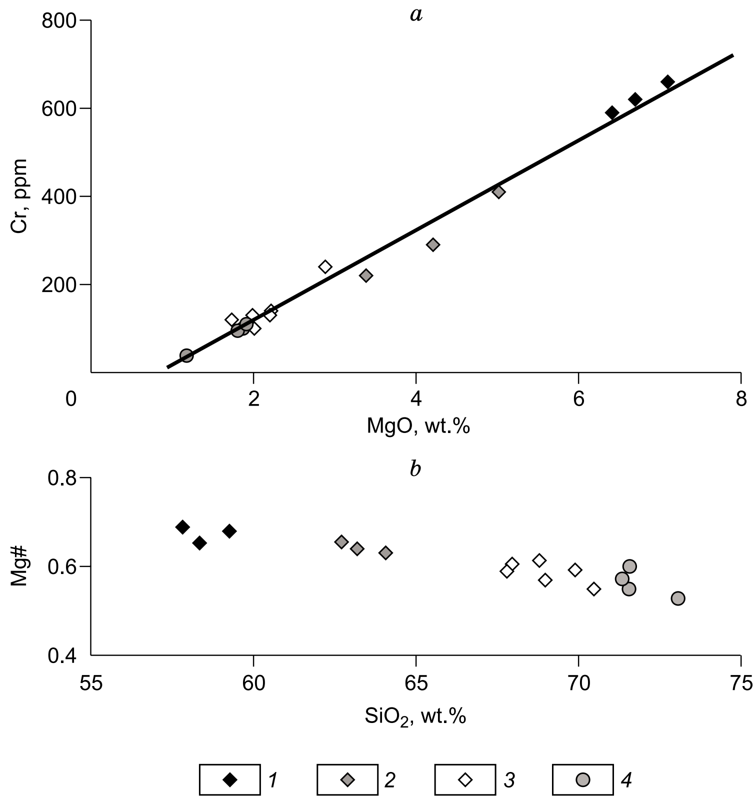

Fig. 6. Cr–MgO (*a*) and Mg#–SiO_2 (*b*) diagrams for granitoids of the Amudzhikan–Sretensk complex. Mg# = $Mg^{2+}/(Mg^{2+} + Fe^{2+} + Fe^{3+})$. Composition of rocks: *1*, hybrid porphyry; *2–4*, granitoids of: *2*, first, *3*, second, *4*, third phases.

normal enrichment in Cr and Ni relative to derivates of latitic magmas. That is, they lack the main geochemical feature specific to derivates of latitic magmas, namely, anomalous enrichment in trace (granitophilic) elements.

The gold content of the granitoids. We analyzed the granitoids of both studied complexes for gold to determine their geochemical signatures. The analytical data are given in Table 1.

The Amanan(?) complex. The data in Table 1 show that the granitoids of this complex have high contents of gold. The first-phase gabbroids contain >8 ppb, which is twice higher than the average gold content in mafic rocks (Voitkevich et al., 1990). The second-phase granitoids contain up to 12 ppb Au, which is three times the clarke content of Au in felsic rocks.

The above data show geochemical signatures for gold in the granitoids. Theoretically, these signatures can be the result of the successive evolution of a magma chamber with the formation of hydrothermal mineralization (early gold–sulfide mineralization) and of gold leaching and redeposition under the impact of later endogenous processes (primary reservoir, fluid system of the Kara–Chacha granitoid pluton).

The high contents of gold in the first-phase gabbroids suggest its high contents in the source of their material. Using modern genetic models and the results of geochemical typification reported in the previous sections, we assume that the granitoids inherited gold from a gold-enriched domain in the regional subcontinental mantle. The domain formed in subduction zone under the impact of a metasomatizing agent (adakite melt) on the mantle wedge/lithospheric-mantle rocks.

According to this concept, adakite melt (basaltic layer of the oceanic lithosphere) must be the real source of gold. This hypothesis does not contradict the obtained results, because the second-phase granitoids (according to the estimated composition of adakite melt) have higher contents of Au than gabbroids.

The Amudzhikan–Sretensk complex. The granitoids of this complex also show geochemical signatures for gold. The highest contents of Au are found in the first-phase granitoids and in hybrid porphyry (primitive sanukitoids) and their xenoliths in the second-phase granitoids. The average content of Au in these rocks reaches 14 ppb, which is three times the gold clarke in mafic rocks. The second- and third-phase granitoids are somewhat poorer in Au (12 and 10 ppb, respectively). That is, the average content of gold successively decreases from first to third phase of the complex.

As in the previous case, we think that the gold enrichment of the most mafic rocks of the complex is associated with the gold enrichment of the source of their material. Using modern genetic models and the results of geochemical typification of the complex granitoids, we again come to the concept of the gold-enriched source of material formed in subduction zone and located in the regional subcontinental mantle.

DISCUSSION

Based on the above-reported data, we propose a genetic model regarding an Au-enriched domain in the regional subcontinental mantle as a source of gold for the studied granitoids. The domain formed in subduction zone under the impact of a metasomatizing agent (slab melt) on the mantle wedge/lithospheric-mantle rocks and was remobilized during collision. The granitoids containing the material of this mantle source inherited its geochemical signatures for gold.

To test the model, it is necessary to show the presence of a mantle domain with geochemical signatures for gold. The existence of this domain is directly evidenced by products of its melting. The geochemical properties of igneous rocks and the used genetic models are discussed in detail in the previous section, so we will not turn back to them.

Indirect evidence for the above domain is the geodynamic setting of magmatism, the temporal inheritance of certain geochemical characteristics of mantle magma derivates, and the metallogenic epochs of gold.

According to modern concepts, the formation of a mantle domain with geochemical signatures must be related to subduction, because adakitic magmas (a metasomatizing agent) are the melting products of slab. Analysis of numerous publications on the regional paleogeodynamic reconstructions shows the existence of subduction zone on the southern margin of the Siberian continent in the Early Jurassic (Zonenshain et al., 1990; Zorin et al., 1998; Zorin, 1999). This conclusion is consistent with our data on the distinct “subduction mark” and Early Jurassic isotopic age of the granitoids of the Amanan(?) complex.

The presence of igneous rocks with the geochemical features of adakites in the continental crust suggests that slab magmas passed through a mantle wedge and the subcontinental lithospheric mantle and is direct evidence for the formation of a mantle domain with geochemical signatures. Slab melt, moving through a mantle wedge, interacts with upper-mantle peridotites, forming zones of metasomatized rocks (mantle domain with geochemical signatures). The felsic melt must be of large volume (melt:rock > 2:1 (Rapp et al., 1999)) to reach the day surface; at least a half of the melt will be spent during its interaction with mantle rocks.

According to this criterion, the volume of metasomatized rocks in the upper mantle is directly proportional to the total volume of the second-phase granitoids, which is equal to few cubic kilometers at the recent denudation level even in the Ust’-Kara region.

Another important issue that needs to be discussed is the temporal inheritance of the geochemical features of mantle magma derivates, which can be judged by determining the source of the material of primitive sanukitoids. In theory, it must be the same mantle domain with geochemical signatures remobilized as a result of collision in the Late Jurassic.

This is indirectly evidenced by the fact that both the adakites and the sanukitoids have geochemical features typical of slab magma derivates and metallogenic signatures for gold that first appeared in the Early Jurassic (State..., 2010)[2], when active subduction took place and a mantle domain with geochemical signatures formed.

To elucidate the above issue, it is necessary to compare the geochemical characteristics of slab magma derivates with similar SiO_2 contents. It would be ideal to compare the melting products of the regional metasomatized mantle, i.e., the first-phase gabbroids of the Early Jurassic granitoid complex and the primitive sanukitoids of the Late Jurassic complex. But this comparison is impossible because of the different contents of SiO_2 in the above rocks (indicating different degrees of their melting from the source).

In our case, it is most convenient to compare the compositions of the metasomatizing agent that formed the mantle domain. They can be estimated from the compositions of the second-phase granitoids of the Early Jurassic Amanan(?) complex and the primitive sanukitoids of the Late Jurassic complex. The coincidence of the estimates will indicate that the primitive sanukitoids might have formed through the melting of a mantle domain with geochemical signatures. Adakitic magmas served as a metasomatizing agent forming the domain; their composition can be estimated from the composition of the tonalites of the Amanan(?) complex.

The possibility of using sanukitoids for estimation of the composition of a metasomatic agent is based on the model of partial melting of a metasomatized source. The first portions of its melt (LSA) are similar in composition to the metasomatic agent, differing from it in higher contents of Cr, Ni, and LREE and Mg# values and in lower contents of Al_2O_3 and Ca, whereas the contents of other elements are usually the same (Rapp et al., 1999; Martin et al., 2005).

All these specific features are revealed on comparison of the average compositions of adakites and primitive sanukitoids (Table 1, Fig. 5). One can see that these rocks have similar contents of most of chemical elements and conformal element patterns (Fig. 5*a*) but different contents of LILE (Cs, Rb, K, Th, U, and Pb); the latter are usually high in rocks of the upper continental crust. All this is well consistent with the concepts of sanukitoids as derivates of adakitic magmas (LSA) contaminated by continental crustal material (Martin et al., 2005).

The above genetic concepts can be demonstrated by means of the Th/La–Sm/La diagram (Fig. 7). The Sm/La ratio on its abscissa axis shows the degree of LREE enrichment of the magmatic melt/source of material (the degree of

[2] The authors of this publication recognize two metallogenic epochs of gold, the Early and Late Jurassic. One of them coincides with the time of subduction, and the other, with the time of collision on the southern margin of the Siberian continent. The appearance of gold mineralization in these epochs might be related to the formation and remobilization of a mantle domain with geochemical signatures.

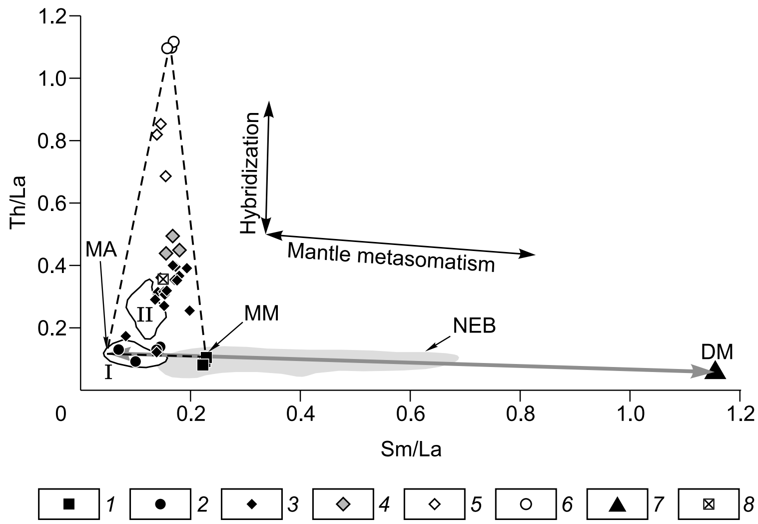

Fig. 7. Sm/La–Th/La diagram for the Ust'-Kara granitoids. Composition of rocks: *1*, *2*, Amanan(?) complex: *1*, gabbro, *2*, tonalites; *3*–*6*, Amudzhikan–Sretensk complex: *3*, hybrid porphyry, *4*, first phase, *5*, second phase, *6*, third phase; *7*, depleted mantle, after McDonough and Sun (1995); *8*, upper continental crust, after (GERM..., 2015). MA, metasomatizing agent. MM, metasomatized mantle. NEB, composition field of high-Nb basalts, I, composition field of adakites, II, composition field of sanukitoids.

metasomatism of the mantle wedge/lithospheric-mantle rocks). The Th/La ratio on the ordinate axis shows the portion of sedimentary material (upper continental crust (Plank, 2005)).

To demonstrate the formation of a subcontinental lithospheric source with geochemical signatures, we plotted the composition fields of NEB, LSA, and sanukitoids (Sajona et al., 1996; Castillo, 1999; Wyman et al., 2000; Hollings, 2002; Martin et al., 2005; Efremov, 2010). It is seen that all these fields are arranged along the depleted mantle–metasomatizing agent (adakite melt) mixing line. The composition points of the granitoids of the Amanan(?) complex are confined to this line, being localized in the fields of adakites and high-Nb basalts and marking the metasomatic transformation of the rocks of the regional upper mantle.

Some of the composition points of primitive sanukitoids are also arranged near this line within the LSA field, which suggests their formation from a similar source. However, most of the composition points of these rocks mark higher Th/La ratios and are shifted upward from the mixing line.

In the framework of the above model, the increase in the Th/La ratio in the primitive sanukitoids must be regarded as an addition of the material of the upper continental crust to primary adakite melt. For visualization, we plotted the point of the average crustal composition on the diagram (GERM..., 2015). It lies in the center of the field of the primitive sanukitoids, and its position cannot explain the compositional variations of all rocks of this group.

In such cases it is believed that mantle magmas are contaminated by felsic crustal melt with a higher Th/La ratio (Plank, 2005). For visualization, we plotted the composition points of the first-, second-, and third-phase granitoids of the Amudzhikan–Sretensk complex on the diagram. Their position shows that the primitive sanukitoids might have formed under interaction between the melting products of a mantle source with geochemical signatures (LSA) and a felsic crustal melt.

The diagram also shows that the granitoids of different phases might have formed as a result of mixing of a certain portion of more mafic magma with a felsic melt, which agrees with the data in the previous section and with the viewpoints of other researchers (Antipin, 1969; Kuz'min, 1971). This approach can be used to estimate the portion of slab melt in the granitoids of different phases of the Amudzhikan–Sretensk complex.

The similar compositions of the metasomatizing agents for igneous rocks of different ages suggest the formation of primitive sanukitoids through the melting of a mantle domain with geochemical signatures, which was formed by adakite melts in the Early Jurassic. The composition of these melts can be estimated from the composition of the tonalites of the Amanan(?) complex.

The above results confirm the hypothesis of the existence of a mantle domain with geochemical signatures during magma generation in the study area and permit considering it the main source of gold. The existence of the mantle domain and the control of gold mineralization by its derivates provide a new concept of metallogenic zoning of areas. Areas within the surficial projection of the mantle domain must be considered gold-promising. This source of gold is indicated by the presence of igneous rocks of the Amanan(?) and Amudzhikan–Sretensk complexes. The granitoids of these complexes bear gold mineralization and can be easily identified by geochemical features.

Based on the relationship between the source of material and an igneous rock, we propose an indirect criterion for the gold ore potential of granitoids. Granitoids either derived from slab magmas or containing a slab melt can bear gold ores. They can be easily identified by geochemical features and from classification diagrams for adakites and sanukitoids. This criterion does not cover all possible variants but suggests the spatial association of gold ore objects with granitoids.

CONCLUSIONS

The study of granitoids spatially and genetically associated with gold mineralization within the Kara gold ore cluster has yielded a new insight into their genesis and association with gold mineralization and into the sources of ore material:

The regional granitoids associated with gold mineralization can be divided into two complexes. One has an isotopic age of 182.9 ± 2.6 Ma. It might have formed in the subduction zone existing on the southern margin of the Siberian continent in this time interval. These granitoids differ in age and composition from the corresponding granitoids of the Amanan complex and can be considered an individual taxonomic unit after additional geological study. The second, Amudzhikan–Sretensk, complex has an isotopic age of 151.7 ± 1.9 Ma. It formed at the time of the collision of the Siberian and Mongol–Chinese continents after the closure of the Mongol–Okhotsk ocean.

The granitoids of the Amanan(?) complex correspond in geochemical characteristics to adakites and must be considered the melting products of the basaltic layer of the oceanic lithosphere. The granitoids of the Amudzhikan–Sretensk complex are most similar in geochemical features to sanukitoids, the products of melting of subcontinental sources with geochemical signatures.

The granitoids of both complexes have high contents of Au and must be considered gold-bearing. Among the granitoids of the Amanan(?) complex, adakites are the richest in gold (according to the estimated composition of the slab melt), which indicates that they have preserved its primary contents. In the Amudzhikan–Sretensk complex, the highest contents of gold are found in primitive sanukitoids, the products of melting of a mantle source with geochemical signatures that formed under interaction of adakitic magma with upper-mantle peridotites. This suggests that the rocks were initially enriched in gold and its content is reflective of the portion of slab melt in the source of material.

The presence of adakites and primitive sanukitoids in the regional granitoid complexes indicates the existence of a subcontinental mantle source with geochemical signatures during the magma generation. This source formed in the subduction zone existing on the southern margin of the Siberian continent in the Early Jurassic and was remobilized under collision of the Siberian and Mongol–Chinese continents in the Late Jurassic. It controlled both granitoid magmatism with geochemical signatures and ore mineralization.

Based on the results obtained, we have proposed an indirect criterion for the gold ore potential of granitoids. Granitoids derived from slab magmas or containing a portion of slab melt can bear gold ores. They can be simply identified by geochemical characteristics and from classification diagrams for adakites and sanukitoids. This criterion does not cover all possible variants but suggests the spatial association of gold ore objects with granitoids.

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