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HIGH-ALUMINA NONBAUXITE ROCKS OF THE TRANS-ANGARA SEGMENT OF THE YENISEI RIDGE: COMPOSITION, TRENDS AND APPLICATION POTENTIAL

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Высокоглиноземистые небокситные породы Заангарья Енисейского кряжа: состав, направления и перспективы использования

Цель статьи – показать направления и перспективы возможного использования метаморфогенных высокоглиноземистых пород региона (андалузитовых, силлиманитовых, кианитовых, хлоритоидных, ставролитовых высокоглиноземистых сланцев) в комплексе с нефелиновыми сиенитами и бокситами, актуальные для расширения сырьевой базы Богучанского электрометаллургического комплекса (БЭМК) в Нижнем Приангарье (Красноярский край).
Методы исследования. Картирование метаморфических комплексов и выделение перспективных площадей метаморфогенных высокоглиноземистых пород осуществлялось в процессе геологического доизучения площадей М 1:50 000 и глубинного геологического картирования М 1:200 000 с применением прецизионных петрологических и геохимических методов.
Результаты исследования. Проведена предварительная оценка перспектив вовлечения докембрийских высокоглиноземистых метаморфогенных и магматиче-ских пород региона. По показателю полной мощности 588 000 т алюминия в год Богучанский алюминиевый завод (введен в эксплуатацию в 2016 г.) будет занимать третье место в России. В перспективе основным отечественным сырьем для производства алюминия должны стать железистые бокситы месторождений Ча-добецкого поднятия вблизи БЭМКа. Проведенные ранее технологические эксперименты (Г. Г. Лепезин, В. Д. Сёмин, А. С. Альшаков и др.) показали, что при производстве глинозема и далее алюминия могут быть дополнительно и эффективно использованы андалузитовые и силлиманитовые концентраты в комплексе с нефелиновыми сиенитами по технологиям спекания и электротермии. Впервые приводится схема докембрийских осадочно-метаморфических пород Заангарья с площадями размещения высокоглиноземистых метаморфогенных минералов (андалузита, дистена, силлиманита, хлоритоида и ставролита) и массивов нефелино-вых сиенитов. Первоочередными объектами для вовлечения в металлургическое производство признаны Панимбинское андалузитовое и Тейское силлиманитовое месторождения Центрального поднятия в поле развития железисто-глиноземистых метапелитов (глинозема до 30 %) андалузит-силлиманитовой фациальной серии. Месторождения разведаны с применением горных работ. Они относятся к мономинеральному типу, содержат значительное количество андалузита (до 30 %) и силлиманита (до 40 %), характеризуются большими площадями распространения и значимыми прогнозными ресурсами на глубину 50 м (70 и 100 млн т соответственно).
Выводы. Высокоглиноземистые небокситные породы Заангарья Енисейского кряжа в перспективе могут быть востребованы и вовлечены в металлургическое производство в связи с развитием в регионе инфраструктуры, производственных мощностей и расширением ассортимента продукции БЭМКа.
Разведанные в регионе запасы нефелиновых сиенитов Средне-Татарского месторождения (глинозема в рудах 22–24 %) весьма значимы: по категории С1 + С2 составляют 3,9 млрд т; прогнозные ресурсы по категории Р1 – около 1,5 млрд т. Стратифицированные залежи гранат-ставролитовых и хлоритоидных высокоглино-земистых метаморфогенных пород сравнительно слабо изучены и требуют дополнительных исследований.

Ключевые слова: Енисейский кряж; Богучанский алюминиевый завод; докембрий; высокоглиноземистые метаморфические минералы; глинозем; электротермия.

The aim of this work is to show trends and the prospects for the possible use of metamorphogenic high-alumina rocks of the studied region (andalusite, sillimanite, kyanite, chloritoid, staurolite high-alumina schists) together with nepheline syenites and bauxites for expansion of the raw material base of the Boguchansk Electrometallurgical Complex Lower Angara Region, Krasnoyarsk Krai, Russia).
Research methods. The mapping of metamorphic complexes and identification of promicing areas for metamorphogenic high-alumina rocks in the course of the 1:50 000 additional site exploration and 1:200 000 depth mapping using high-precision petrological and geochemical methods.
Research results. The prospects of using Precambrian metamorphogenic and igneous high-alumina rocks of the studied region for expansion of the raw material base of the Boguchansk Electrometallurgical Complex (BEC) were preliminary evaluated According to the planning production capacity (up to 588 000 tons of aluminum per year), the Boguchansk Electrometallurgical Smelter is estimated to be the third aluminum manufacturer in Russia. In the future, the deposits of ferruginous bauxites from the Chadobets uplift located near BEC are intended to be used as the main domestic raw materials for the production of aluminum.
According to technological tests (G. G. Lepezin, V. D. Semin, A. S. Al'shakov et al.), andalusite and sillimanite concentrates together with nepheline syenites can be used effectively for the production of aluminum oxide and then aluminum using sintering technology and electrothermy. The location scheme of distribution of Precambrian sedimentary-metamorphic rocks of the Trans-Angara segment of the Yenisei Ridge with zones of metamorphogenic high-alumina minerals (andalusite, kyanite, sillimanite, chloritoid, and staurolite) and massifs of nepheline syenites is first presented. The Panimbinsk andalusite and Teya sillimanite deposits of the Central uplift confined to iron-alumina metapelites (aluminum oxide up to 30%) of the andalusite-sillimanite facies series are regarded as the top-priority objects for the metallurgical industry. Deposits were prospected with mining works and attributed to the monomineral type. They are characterized by large amounts of andalusite (up to 30%) and sillimanite (up to 40%), large distribution areas, and significant inferred resources traced to a depth of 50 m (70 and 100 million tons, respectively).
Conclusions. High-alumina nonbauxite rocks of the Trans-Angara segment of the Yenisei Ridge are expected to be in demand and used in the metallurgical industry due to the development of infrastructure of the region studied, the increase in production capacities, and the expansion of the BEC range of products. Explored deposits of nepheline syenites of the Middle Tatarka deposit (22–24% alumina in ores) amount to 3.9 billion tons in category $C_1 + C_2$, and forecast resources are about 1.5 billion tons in P_1 category. Stratified sequences of the garnet-staurolite and chloritoid high-alumina metamorphogenic rocks are relatively unexplored and need further research.

Keywords: Yenisei Ridge; Boguchansk Aluminum Smelter; Precambrian; high-alumina metamorphic minerals; alumina; electrothermy.

Introduction

A preliminary evaluation of the prospects of using nonbauxite raw materials for the production of aluminum products is of interest in terms of expansion of the raw material base of the Boguchansk Electrometallurgical Complex

(BEC), brought into operation in 2016 in the Lower Angara Region (the joint project of the United Company RUSAL (the world's second largest aluminum company) and the Russian state-controlled hydroelectric power producer RusHydro) are considered. The Boguchansk Electrometallurgical Complex includes Boguchansk Aluminum Smelter (BAS) with a design capacity of about 600 thousand tons of aluminum per year and Boguchansk Hydroelectric Power Plant (BHPP) with a capacity of 3000 MW.

According to the planning production capacity (up to 588 000 tons of aluminum per year), the Boguchansk Electrometallurgical Smelter is estimated to be the third aluminum manufacturer in Russia. The major sales market for the aluminum products from the BAS is Asia, where about 50% of global consumption aluminum is concentrated. At the initial stage, raw materials for the aluminum production will be supplied to BAS from different parts of the world. The primary aluminum is planned to be supplied by RUSAL's Aughinish refinery located in Ireland. Anode blocks will be supplied to BAS from China. All other raw materials (fluorspar, aluminum fluoride, etc.) are supplied by domestic manufacturers [1].

Over the long term, the main domestic raw materials for the production of aluminum are expected to be local ferruginous bauxites–the complex waste-free and environmentally friendly iron-aluminum raw materials of the Chadobets uplift, applicable for production low-silica ferrosilicon (grades F20 and F25), aluminum oxide, and high-quality cement raw materials [2]. According to technological tests, no all bauxites can be applicable for complex processing in direct way. For this purpose, a furnace charge corresponding to the parameters of the iron-aluminum raw material is prepared. Apart from the basic components (ferruginous bauxites and aluminous iron ores), other alumina rocks can be used as additives: allites, kaolines, chloritoids, and high-alumina schists [2], that is, nonbauxite aluminum raw materials [3]. Such minerals as Al_2SiO_5 polymorphs (andalusite, kyanite, and sillimanite), which are constituents of high-alumina schists (HAS) contain more than 60% of aluminum oxide.

The products made of them are used in metallurgical, glass, electrochemical, and chemical industries due to high refractoriness and mechanical strength at high temperatures, chemical inertness with respect to acids and alkalis. An issue of using the concentrates of minerals of the sillimanite group (MSG) for the production of aluminum and modern alloys (silumin etc.) is urgent [4–7 etc.].

The aim of this work is to show trends and the prospects for the possible use of metamorphogenic high-alumina rocks of the studied region (andalusite, sillimanite, kyanite, chloritoid, staurolite high-alumina schists) together with nepheline syenites and bauxites for expansion of the raw material base of the Boguchansk Electrometallurgical Complex.

Results of the searching works for HAS schists containing sillimanite-group minerals, chloritoid and staurolite

Within the Trans-Angara segment of the Yenisei Ridge, targeted prospecting works for high-alumina andalusite, kyanite, and sillimanite schists were started in the 1956–1960s by the Goltsovskaya and Panimbinskaya geological crews of the Angarsk Geological Survey Expedition of the Krasnoyarsk Geological Survey Expedition. As a result, the Golets, Panimbinsk, and Chirimbinsk occurrences of andalusite schists were discovered (1956), and, later, Teya and Noiba occurrences of sillimanite schists (1958–1960).

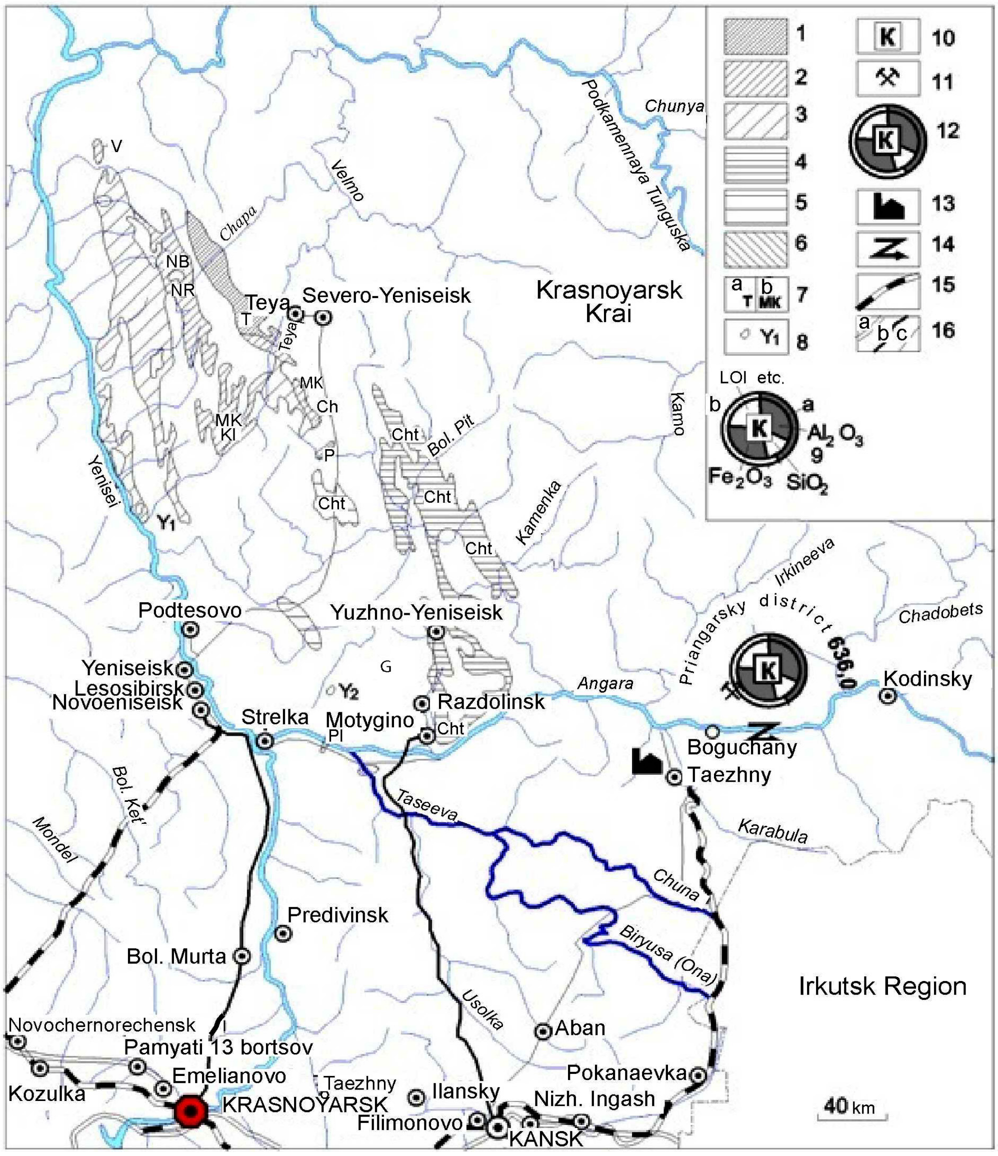
The searching works for HAS were resumed in 1978 in connection with the expansion of the raw material base of Achinsk Alumina Smelter. The works were based on the results of studying the processing of nepheline ores at the Krasnoyarsk Institute of Non-Ferrous Metals. It was found that the addition of high-alumina concentrates (andalusite, kyanite, and sillimanite) significantly reduced the specific consumption of nepheline ores, limestones and fuel [8]. By this time, two massifs of nepheline syenites, Kiya and Tatarka, were discovered and explored in the Trans-Angara Region. Prospects for their joint use are shown with confidence in [8, 9].

In the 1979–1980s the Nemchan geological crew of the Angarsk GSE PGO "Krasnoyarskgeologiya" carried out prospecting and mining works in 21 sites within the central part of the Yenisei Ridge (North Yenisei and Motygino districts, as well as the Evenk Autonomous Okrug of the Krasnoyarsk Krai). As a result, the prospects of the Panimbinsk and Teya deposits were confirmed with the reserves calculated of 3.1 billion tons and 90.3 million tons of aluminum oxide, respectively. However, this evaluation of resources seems somewhat overestimated, since the ore occurrences with drilling works. Moreover, it was not possible to achieve significant results during this period due to lack of special research works on the metamorphism of the region as an effective methodological basis for searching metamorphogenic high-alumina raw materials.

In subsequent years, after the end of the searching works, the legend and map of the metamorphism of the Trans-Angara segment of the Yenisei Ridge were developed, typification of metamorphic complexes was carried out, as well as geological and P–T formation conditions and chemistry of high-alumina schists of the most promising Teya polymetamorphic complex were analyzed. As a result, the location scheme of distribution areas of Precambrian sedimentary–metamorphic rocks, containing high-alumina minerals, within the Trans-Angara segment of the Yenisei Ridge was compiled (Fig.), which are considered to be the potential raw material for production of aluminum alloys at the Boguchansk Aluminum Smelter.

The high-alumina schists of the studied region are divided into mono-, bi- and polymineral, depending on the occurrence in its composition one or more Al_2SiO_5 polymorphs [11, 12]. The HAS of the Panimbinsk andalusite and Teya sillimanite deposit formed under the conditions of regional metamorphism of And–Sill type within the Teya metamorphic complex and chloritoid-bearing schists formed under the greenschist facies of metamorphism in the Angara–Pit metamorphic complex are classified as monomineral.

The Panimbinsk andalusite deposit was discovered in the distribution area of Mesoproterozoic carbonaceous metapelites of the Kordin Formation (over 10 km^2 [13]), altered under the *P–T* conditions of the epidote–amphibolite facies of regional metamorphism. Lens-shaped ore bodies extend in submeridional direction in accordance with a general strike of rocks. The northern and southern bodies with parameters (1200 × (50–750) and (650 × 40) m, correspondingly were distinguished. The mineralogical composition of ores: quartz, andalusite (chiastolite) (5–30%), sericite, graphite. Based on results of chemical analysis of four samples, Al_2O_3 content in ore bodies: 19.08%, 19.32%, 21.16, and 19.06 wt % (20.7 wt %, on average), correspondingly. Inferred resources of the deposit on commercial component basis (andalusite, 16.1% on average) to a depth 50 м are estimated to be 70 million tons. The HAS, similar in composition to those of the Golets ore occurrence contain 7.4 % of andalusite, on average, at Al_2O_3 content of 18.1 wt %.



The location scheme of distribution areas of Precambrian sedimentary-metamorphic rocks, potential for searching high-alumina minerals, within the Trans-Angara segment of the Yenisei Ridge. Distribution areas of high-alumina metamorphogenic rocks with occurrences of high-alumina minerals (1–7). 1 – areas, potential for sillimanite, 2 – finds of andalusite, sillimanite, and kyanite, 3 – ore occurrences, 4 – potentially chloritoid-bearing occurrences, 5 – finds of chloritoid, 6 – mica–garnet–staurolite schists, 7 – deposits (a) (T – Teya, P – Panimbinsk); (b) occurrences of high-alumina minerals (V – Vorogovskoe, NR – Nerazgadannoe, MK – Malokiiskoe, Kl – Kiya, Ch – Chirimbinskoe, NB – Noiba, G – Golets, Pl – Polovinkinskoe), 8 – massifs of alkaline syenites (1 – Kiya, 2 – Middle Tatarka); 9–16 – Cis-Angara area with bauxite reserves 636.0 million tons (after [10]). 9 – reserves (a) and inferred resources (b); 10 – Cretaceous age of the ore formation; 11 – possible open-cut mining, 12 – composition of ores, 13 – Boguchansk Smelter, 14 – Boguchansk hydroelectrostation, 15 – railways, 16 – highways of different level.

The Mayakon ore occurrence is located to the north of the Panimbinsk deposit and is similar to the latter in the age and the composition of host rocks. This occurrence consists of the products of polymetamorphism due to local superimposition of dislocation metamorphism of kyanite–sillimanite facies series on andalusite–sillimanite one. As a result, ore bodies contain andalusite and kyanite and are classified as bimineral. Lens-shaped ore bodies extend for a distance of up to 1000 m at a thickness of 80 m. High-alumina schists are composed of quartz, biotite, graphite, andalusite (6.5–15%), staurolite, muscovite, and kyanite (up to 3.5%). Beyond the local "kyanite" zone of kyanite–sillimanite type of metamorphism andalusite (chiastolite) crystals reach 8 cm in length and up to 1.5 cm wide. The Al_2O_3 content in ores reaches 23.9 wt % (20.3%, , on average). Inferred resources on the commercial component basis for two ore bodies (andalusite + kyanite 15%) are traced to a depth of 50 m and estimated to be 2.5 million tons.

The Teya deposit is confined to the Paleoproterozoic HAS (metapelites, the amphibolite facies of the regional metamorphism) of the Karpinsky Ridge Formation. The HAS occupies an area of 14 km^2. Schists of the productive unit consist of quartz (15–50%), biotite (20–60%), sillimanite (fibrolite) (10–40%; 16.5%, on average). An average Al_2O_3 content is 19.16 wt %. The largest ore body is lens-shaped and extends in sublatitudinal direction; a total length is 2.9 km; thickness is 130–190 m; a distribution area is 0.4 km^2. At the concentration of sillimanite of 22% the inferred resources, traced to a conventional depth of 50 m, is estimated to be 100 million tons.

In the 1960s the technological tests on the concentration of two samples of 500 kg each from the Panimbinsk andalusite

Table 1. The average compositions of ores containing sillimanite group minerals of the Yenisei Ridge.

MSG Groups	Monomineral And; Sill			Bimineral And + Ky	Polymineral And + Sill + Ky
Oxides	*1 (n = 98)*	*2 (n = 60)*	*3 (n = 37)*	*4 (n = 11)*	*5 (n = 14)*
SiO_2 S	61.2 2.85	61.99 5.36	57.41 3.48	59.73 2.93	60.95 3.52
TiO_2 S	1.07 0.05	0.86 0.19	1.34 0.88	0.81 0.06	0.96 0.23
Al_2O_3 S	18.71 2.13	19.16 3.57	22.98 2.86	20.55 2.02	19.98 .98
Fe_2O_3 S	4.08 1.25	3.69 1.69	1.82 0.02	3.92 1.00	1.97 1.46
FeO S	3.95 1.42	4.73 1.57	6.41 0.26	4.29 1.13	5.10 1.60
MnO S	0.07 0.05	0.06 0.03	0.06 0.01	0.10 0.02	0.07 0.04
MgO S	1.36 0.47	0.94 0.53	0.80 0.09	1.53 0.54	2.07 0.65
Na_2O S	0.89 0.19	0.70 0.22	0.98 0.21	1.08 0.14	1.42 1.02
K_2O S	3.77 0.67	2.98 0.70	2.46 1.00	4.01 0.48	3.42 0.51
LOI S	4.63 0.49	5.76 1.47	4.91 3.65	3.63 0.66	3.40 1.33

Note: 1–3 – monomineral high-alumina schists. 1 – And (Panimbinsk ore occurrence), 2 – Sill (Teya ore occurrence), 3 – Chlt (the basin of Pit–Gorbilok rivers); 4 – bimineral: And + Ky (Mayakon occurrence); 5 – polymineral: And + Sill + Ky (Nizhneveduginskoe, Korolominskoe, Nerazgadannoe, and Kiya occurrences). 1, 2, 4, 5 – channel samples, 3 – hand specimen samples. In the numerator – average deviations, in the denominator – standard deviations, wt %; *n* is a number of samples being averaged.

Table 2. Results of X-ray spectral analysis of of andalusites from the Panimbinsk deposit, wt %.

SiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	Total	Formula
37.20	62.56	0.02	0.21	0.01	0.04	100.44	$Al_{1.99}Si_{1.00}O_5$
36.29	63.10	–	0.24	–	0.03	99.66	$Al_{2.02}Si_{0.98}O_5$
36.89	62.85	–	0.26	0.02	0.04	100.06	$Al_{2.00}Si_{1.00}O_5$
36.66	62.78	0.05	0.24	–	0.01	99.74	$Al_{2.01}Si_{0.99}O_5$
36.55	62.98	–	0.23	0.01	0.03	99.80	$Al_{2.01}Si_{0.99}O_5$
36.51	62.80	–	0.21	0.01	0.03	99.56	$Al_{2.01}Si_{0.99}O_5$
36.62	62.39	–	0.36	–	0.01	99.38	$Al_{2.00}Si_{1.00}O_5$
36.02	63.25	0.01	0.24	–	0.04	99.56	$Al_{2.02}Si_{0.98}O_5$
36.52	62.98	0.04	0.21	–	0.03	99.78	$Al_{2.01}Si_{0.99}O_5$
36.66	62.84	0.02	0.26	0.02	0.04	99.84	$Al_{2.01}Si_{0.99}O_5$
36.55	63.16	0.03	0.20	0.01	0.04	99.98	$Al_{2.01}Si_{0.99}O_5$

and Teya sillimanite deposits were performed at the Leningrad Institute of Refractory Materials. The mineralogical composition of the first sample: andalusite, quartz, biotite, muscovite, sericite, kaolinite; the chemical composition is as follows (wt %): SiO_2 = 60.3–61.99, TiO_2 = 0.95, Al_2O_3 = 22.27, Fe_2O_3 = 7.59, CaO = 0.41–0.55, MgO = 1.51–2.21, $Na_2O + K_2O$ = 2.93–3.12, LOI = 1.97–2.8; refractoriness value is 1350°C. As a result the flotation concentrate of the following composition was obtained: SiO_2 = 36.48, Al_2O_3 = 57.14, TiO_2 = 1.6, Fe_2O_3 = 2.22. The mineralogical composition of the sillimanite-bearing samples: sillimanite, quartz, biotite, graphite, muscovite; chemical composition: SiO_2 = 60.25, TiO_2 = 1.42, Al_2O_3 = 18.2, Fe_2O_3 = 6.69, MgO = 1.58, CaO = 0.42, $Na_2O + K_2O$ = 2.68, SO_3 = 0.35, LOI = 2.48; refractoriness value is 1430°C. The chemical composition of the flotation concentrate: Al_2O_3 = 54.57%, SiO_2 = 41.00%, TiO_2 = 0.32%, Fe_2O_3 = 1.77%, at output of 13.95% and extraction of sillimanite 79%. The concentration was made following the flotation scheme.

In the subsequent years, on the basis of the metamorphism map of the Trans-Angara Region, metamorphic rocks were typified and the promising areas of the MSG distribution in the Teya polymetamorphic complex were identified [11, 12]. In practical terms, first of all, sillimanite-bearing high-alumina metamorphic rocks of the amphibolite facies of prograde regional metamorphism are of most interesting for the mining. A noticeable increase in reserves can be expected in a zone about 6 km wide and 75–80 km long to the northeast and south-west from the Teya deposit (the watersheds of the Chapa–Teya–Enashimo Rivers). A site near the Kalamino granitoid massif (the watershed between the Elizavetinsky and Borzetsovsky streams) in the distribution area of the Paleoproterozoic rocks of the Karpinsky Ridge Formation is recommended as a priority for the organization of prospecting works. Here, the "sillimanite" distribution area of about 40 km^2 in square is outlined; the content of alumina in schists (hand specimen samples) reaches 30 wt %. Quartz-sillimanite quartzites, similar in composition to ores of Kyakhta and Bazybai deposits, are also found among HAS. The average compositions of ores, containing sillimanite-group minerals, from different occurrences of the Trans-Angara region are reported in Table 1.

Table 2 presents results of X-ray spectral analysis of andalusite. In terms of composition the studied andalusite is close to the model one. As for the impurities, andalusite contains extremely small amounts of iron and manganese. TiO_2 was not detected.

Below, we briefly describe occurrences of other HAS that are common in the Meso- and Neoproterozoic rocks of the Cis-Angara and Trans-Angara regions. These HAS are poorly studied and are recommended for further study.

Chloritoid-bearing schists are widespread among the regional metamorphosed sedimentary rocks of the Neoproterozoic Tungusik Group within the Angara–Pit greenschist complex in the interfluve of the Gorbilka, Pit, and Angara rivers. The chloritoid-bearing HAS (content Al_2O_3 is 23 wt % and more) are closely associated with metasandstones, carbonaceous phyllites, dolomites, and stromatolitic limestones, forming stratified deposits with subhorizontal bedding. The stratiform bedding, a low degree of greenschist facies metamorphism, and the occurrence of marker horizons in the sections make it possible to trace and map them over many-kilometer distance along the strike. The mineralogical composition of chloritoid schists: quartz, sericite, chlorite, chloritoid. The proportion of the latter reaches 30–40%; chloritoid porphyroblasts are 2 mm or less in diameter [12]. The model content of Al_2O_3 in chloritoid is as high as 40 wt %.

Chloritoid–kyanite schists occur in the Neoproterozoic rocks of the Sukhoi Ridge Formation in the Lower Angara Region (the lower reaches of the Angara River basin). In the Cis-Angara metamorphic complex they are associated with the manifestation of the local late Ky–Sill metamorphism in the Tatarka lineament zone [14]. A total width of “chloritoid” and “kyanite” zones is about 2 km. The distribution of these zones is traced in Early Mesoproterozoic garnet–staurolite metapelites Sukhoi Pit Group in the Kulakovo uplift (south of the Angara River) by drilling works at the deep geological mapping in the southwestern direction for a distance of over 20 km under the cover of the Phanerozoic deposits up to 50 m thick.

Garnet-staurolite crystalline schists were first distinguished in the Taseeva River mouth (a left tributary of the Angara River) in the Cis-Angara polymetamorphic complex [14]. The distribution areas of two-mica garnet–staurolite HAS (SiO_2 – 57.91–50.98, Al_2O_3 – 22.39–27. 95 wt %), which contain abundant idiomorphic large (3–5 cm) staurolite porphyroblasts (up to 40–50% in the rock matrix), are confined to the crystalline schists of the lower part of the Sukhoi Pit Group of the epidote-amphibolite facies of the regional metamorphism (And–Sill facies series). They form a sublatitudinal “staurolite” zone in metapelites in the area of the settlement Slyudorudnik.

Possible variants for processing high-alumina raw materials from the Trans-Angara Region.

Apart from the above-described metapelitic schists containing high-alumina metamorphic minerals (andalusite, kyanite, and sillimanite, chloritoid, and staurolite), other promising high-alumina raw materials: bauxites and nepheline syenites have been found in the Trans-Angara Region.

Bauxites. The aluminum industry of the Russian Federation is kept with own-produced alumina by approximately 30%, the rest is imported from the CIS countries and far abroad. This problem is especially acute for metallurgical smelters of Siberia [15]. In the future, local ferruginous bauxites are proposed to use as the main domestic ferruginous bauxites for the production of aluminum in the region near BAS (Fig. 1). This is the complex waste-free iron-aluminum raw material of the Chadobets structure (uplift), applicable for obtaining low-silica ferrosilicon (grade F20 and F25), aluminum oxide, and high-quality cement raw materials [2, 16, 17].

The reserves of Chadobets bauxites are 106.4 million tons with average contents of components (%): Al_2O_3 = 29.14, SiO_2 = 11.70, Fe_2O_3 = 32.68, TiO_2 = 8.66, LOI = 15.45. Deposits of bauxite of this type are widely distributed in the Lower Angara Region and the Yenisei Ridge (Turukhansk, Tatarka, Kamenka, Cis-Angara groups, etc.). Chadobets bauxites are characterized by a high content of iron oxide (up to 33 wt %). Due to this, the Bayer-sintering method and the sintering method are not applicable to the processing of these bauxites. The study of the possibilities of the integrated processing of the Chadobets bauxite of the Central deposit using the electrothermal method was carried out in 1989–1990s of the XX century at Siberian Research Institute of Geology, Geophysics and Mineral Resources and State Geological Enterprise “Krasnoyarskgeologiya”.

According to technological tests no all bauxites can be applicable for complex processing in direct way. For this purpose, a furnace charge corresponding to the parameters of the iron-aluminum raw material is prepared. According to [2], other alumina rocks (for example, chloritoid-bearing and high-alumina schists) can be used as additives for ferruginous bauxite and aluminous iron ores. In addition, when leaching bauxites at T = 105–125 °C, the concentration of rare elements in the red mud is 1.5–2 times more, since all of them, except for gallium, do not dissolve in alkaline solutions. Being accumulated in circulating alkaline solutions to a certain concentration, gallium can be extracted with known methods [2]. The most difficult operation in the processing of bauxites is the extraction of iron. In view of the fact that the iron oxide in the red mud occurs is finely dispersed and forms close intergrowths with other components of the mud, the effective separation of iron is possible only with reducing red smelting [18]. In this case, the second commodity product is produced, viz. cast iron, and the content of rare elements in slags after their additional processing can be increased by 3–4 times in comparison with their contents in the raw material.

Preliminary calculations have shown that at the integrated processing of Chadobets bauxite to produce alumina, cast iron, titanium dioxide, and oxides of rare and rare-earth metals, the total value of commodity output is sharply increasing compared to traditionally produced products. Accordingly, an enterprise that performs complex bauxite processing will be highly profitable.

Nepheline syenites. The searching works for HAS were resumed in 1978 in connection with the expansion of the raw material base of Achinsk Alumina Smelter. The works were based on the results of studying the processing of nepheline ores at the Krasnoyarsk Institute of Non-Ferrous Metals. By this time, two massifs of nepheline syenites, Kiya and Tatarka, were discovered and explored in the Trans-Angara Region (Fig.).

The Middle Tatarka deposit of nepheline syenite of the Vendian age is located on the watershed between the Tatarka and Pogromnaya rivers in 30 km to the NNE from the settlement of Novoangarsk (Fig.) and is represented by the Northern and Southern bodies among the Neoproterozoic carbonate rocks of the Gorevka Formation [19]. Within the Northern body, geological prospecting works (trenching, pit sampling at 100x100 m grid, and three core drilling profile with a drilling depth of 100–300 m) were carried out. According to the catalog of deposits and occurrences of the Krasnoyarsk Krai, it is designated as the object "Massif A no. 100". Within the field there are 3 sites: Central one composed of urtites and ijolites; Western and Eastern composed of nepheline syenites. The Western body is characterized by ores of the highest quality with a uniform distribution of useful components; it is referred to the deposits of the first group. Mineralogical composition of ores within the deposit varies (numbers in brackets are given for the Western body): nepheline from 10 to 85% (30.5%), aegirine 4–30% (4.5%), feldspar (microperthite, albite, microcline 65%). Al_2O_3 content in ores is 20–24% (average 22.73%), Na_2O = 3.1–11.1%, K_2O = 4–6%. The reserves of the nepheline syenite of the Northern body to the horizon + 132.5 m (the water level of the Tatarka River) in category $C_1 + C_2$ are 3.9 billion tons. The Southern body similar in composition and structure has estimated ore resources at the P1 category of about 1.5 billion tons [19]. In the immediate vicinity of the deposit there is an 110kV transmission line. South of the object, on the left bank of the Angara River are the settlement of Novoangarsk and the pier, intended for shipment of lead–zinc concentrates from the Gorevka mining and processing combine.

The *Kiya massif* of nepheline syenites (Ordovician–Silurian) is located in the Cis-Yenisei part of the Yenisei Ridge, 12 km above the mouth of the Kiya River, a right tributary of the Yenisei River, 135 km to NNW from the district center and the pier on the Yenisei River. Compared to the Middle Tatar deposit, this object is less studied and is at maximum distance from the BAS.

Prospects for the aluminum oxide production by sintering technology based on the combined processing of nepheline ores and MSG concentrates

Nepheline syenites of the Angara region are characterized by a low alumina content (20–23 wt %). Due to this they are of little use for the production of aluminum oxide following the traditional sintering technology, as is done at the Achinsk Alumina Smelter. The variant of the combined processing of nepheline syenites and MSG was proposed for the Achinsk Alumina Smelter by G. G. Lepezin and V. D. Semin [8]. Addition of 30% MSG (Al_2O_3 = 57 wt %) to the undressed nepheline rock (Al_2O_3 = 22 wt %) will increase the proportion of aluminum oxide in the mixture to 32%. The Kola nepheline ores of the highest quality contain 28–29% Al_2O_3; Kiya–Shaltyr ores – 27%. The best preparation methods yield an output of 27-30%, the theoretical content of Al_2O_3 in nepheline is 35.89%. If the mixture is composed of 60% MSG concentrate and 40% nepheline ore, then the proportion of Al_2O_3 reaches 43% reaching its concentration in bauxite. The practical implementation of this proposal would allow using nepheline ores with relatively low alumina content without enrichment.

Possibilities of application of electrothermy of MSG for the silumin production

In addition to the production of refractories, ceramics, proppants, and other high-tech products, minerals of the sillimanite group can be used to produce silumin. In addition, it is promising to introduce arc-plasma technology for the processing of mechanically activated minerals of the sillimanite group in the production of silumin [7].

Silumin is an aluminum–silicon alloy. Silumin is currently obtained by fusion of crystalline silicon and aluminum in electric or combustion furnaces. Electrothermy is an alternative technology. A detailed review of the development of electrothermy in Russia and abroad as a whole is given in [20]. According to numerous expert estimates, this method of silumin production, and, then, aluminum, has a number of advantages, leading to reduction in specific and capital costs and a significant economic effect. The advantages of the electrothermal method for the production of silicoaluminum are compared with the currently used technology of obtaining silumin by fusing electrolytic aluminum and silicon. Comparative calculations of the economic efficiency of the production of aluminum–silicon alloys using the traditional method for fusing the alumina and crystalline silicon and the electrothermal method of aluminum production from kaolin and sillimanite were carried out. If a new technology (plasma arc melting furnace is used [7], the approximate electric energy consumption will decrease by approximately 25–30% and amount to 10–12 thousand kW/h per one ton of aluminum–silicon alloy.

Conclusions

Thus, metamorphogenic deposits and numerous ore occurrences of the minerals of sillimanite group and high-alumina chloritoid and garnet–staurolite schists have been found in the Trans-Angara segment of the Yenisei Ridge. They belong to the aluminous formation of the fold belts of the Siberian Craton frame and to the class of orthometamorphic high-alumina rocks, which was formed from the protolith of iron-alumina metapelites under the regional metamorphism [3]. In the future, after the additional appraisal survey, including drilling works (the top-priority Teya and Panimbinsk deposits), they can be used as high-alumina raw materials in combination with bauxites of the Chadobets uplift and nepheline ores of the Middle Tatarka and Kiya massifs.

Over the long term, the urgency of such an assessment for the Krasnoyarsk Krai is important for expanding the raw material base of the Boguchansk Electrometallurgical Complex, brought into operation in 2016 in the Lower Angara region. The Boguchansk Aluminum Smelter (BAS) is located on the left bank of the Angara River, 40 km to the south-west of Boguchansk deposit (Fig.) and MGS and chloritoid manifestations and other occurrences of aluminum raw materials (Chadobets bauxites, Middle Tatarka, and Kiya massifs of nepheline syenites) are located in the Trans-Angara Region.

The Teya sillimanite and Panimbinsk andalusite deposits are located north-west of the BAS about 400 and 300 km, respectively, from the highway of Yeniseisk (the left bank of the Yenisei River) – settl. Bryanka – Severo-Yeniseisk – settl. Teya. The Panimbinsk andalusite deposit is considered to be most promising for exploration. It is located near the highway at a distance of about 200 km to the right bank of the Yenisei River. The waterway upstream the Yenisei River and then along the Angara River to Boguchany is about 400 km. The Teya deposit, located 50 km west of the settlement of Teya is less economical in terms of its development, since it is necessary to construct a road and a bridge across the Teya River for the transportation of ores. As a result, there appear some difficulties in the development of promising ore occurrences distant from the BAS.

In terms of involvement of HAS in the production of the Boguchansk Electrometallurgical Complex, the investment project "Integrated Development of the Lower Angara Area" (2005), developed by the Institute for Regional Strategy is actual [14]. According to this project, the infrastructure development of the region (construction of a bridge over the Angara River, construction of roads in the Trans-Angara region, etc.) is under consideration. According to the adopted program of the development of the Lower Angara region, the "Pikhtovaya" railway station is under construction on the Karabula–Reshety railway branch for the transport support of the Boguchansk Aluminum Smelter. It is planned that this railway branch connects the general railways with railway lines belonging to the BAS.

Thus, high-alumina nonbauxite rocks of the Trans-Angara segment of the Yenisei Ridge are expected [10, 15, 16 etc.] to be in demand and used in the metallurgical industry due to the development of infrastructure of the region studied, the increase in production capacities, and the expansion of the BEC range of products.

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