

Metamorphism, *P-T-t* Conditions of Formation, and Prospects for the Practical Use of Al₂SiO₅ Polymorphs, Chloritoid, and Staurolite (Yenisei Ridge)

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Abstract. The Yenisei Ridge is an accretion–collisional orogen located in the southwestern frame of the Siberian Craton in the interfluvium between Podkamennaya Tunguska, Angara, Kan, and Yenisei rivers. The Precambrian mono- and polymetamorphic complexes composed predominantly of the Mesoarchean–Neoproterozoic metapelitic rocks have been studied.

Based on the typification of metamorphic complexes by pressure, temperature, metamorphic gradient, as well as age of metamorphism, the location scheme of the fields of the Precambrian sedimentary–metamorphic rocks which are prospective for searching deposits of high-alumina metamorphic minerals (andalusite, kyanite, and sillimanite, chloritoid, and staurolite) in the Trans-Angara segment of the Yenisei Region, was compiled. The Teya sillimanite and Panimbinsk andalusite deposits, which are confined to the fields of regional metamorphic complexes of iron-alumina metapelites of the And–Sill facies series, are recommended as a priority for the organization of prospecting works and the subsequent involvement to the metallurgical industry. These metapelites are classified as monomineral. Owing to widespread occurrence and abundance of andalusite and sillimanite, the above deposits have significant inferred resources. Stratiform deposits of garnet–staurolite and chloritoid high-alumina rocks are still insufficiently studied and should be investigated further.

The prospects for the possible use of high-alumina andalusite and sillimanite together with Middle Tatarka and Kiya nepheline syenite massifs and the bauxites of the Chadobets uplift, already being explored in the region, for production of aluminum oxide, silumin, and aluminum, as well as, the prospects for the expansion of the raw material base of the Boguchansk Electrometallurgical Complex, brought into operation in 2016 in the Lower Angara region, are considered.

1. Introduction

The Yenisei Ridge is an accretion–collisional orogen located in the southwestern frame of the Siberian Craton in the interfluvium between Podkamennaya Tunguska, Angara, Kan, and Yenisei rivers (Krasnoyarsk Krai). The Yenisei Ridge is composed of Precambrian mono- and polymetamorphic complexes, consisting predominantly of metapelitic rocks. The latter provides valuable information about the history of geological development of the studied region in the interval from Neoproterozoic to Late Vendian. The mapping and typification of metamorphic complexes is of practical importance for effective target search for high-alumina schists (HAS) among ferruginous–aluminous metapelites.



These schists contain large amounts of such minerals as Al_2SiO_5 polymorphs (andalusite, kyanite, and sillimanite), chloritoid, and staurolite, which are widely used in aluminum industry worldwide.

Over the last 20-25 years, new data on the metamorphism of the Yenisei Ridge based on detailed geological mapping, petrological–geochemical and geochronological studies have been obtained ([5, 23] and references therein; etc.). The regional metamorphic complexes of the region are identified in the structure of the paleocontinental sector (1) (PCS, the age of polymetamorphism in a range of 1950–600 Ma) belonging to the western marginal part of the Siberian Craton, the paleoceanic sector (2) (POS, NP_3) of the northern flank of the Sayan–Yenisei accretion belt at the boundary with the Phanerozoic cover of the West Siberian Plate, and the Cis–Yenisei Regional Shear Zone (3) (CYRSZ, 620–600 Ma) between the above sectors [6]. Mono- and polymetamorphic complexes of the paleocontinental sector of the marginal part of the Siberian Craton, characterized below, are considered to be prospective for paleoreconstruction of the prolonged evolution (~1.5 Ga) of metamorphism (PP– NP_3) and for the practical application for petrological studies of metamorphic complexes. Metamorphic complexes are typified by pressure, metamorphic gradient, and age of metamorphism.

2. Brief description of metamorphism and high-alumina schists of the PCS

The following regional polymetamorphic complexes are mapped here (from ancient to young): *Kan*, *Garevka*, *Teya*, and *Cis-Angara*, *Angara–Pit*, and *Angara–Tissa* complexes of green schist metamorphism.

The ancient *Kan prograde charnokite–granulite polymetamorphic complex* is distinguished in the southern segment of the Yenisei Ridge within the Angara–Kan uplift [11]. *P–T* conditions of the metamorphic evolution of this complex are as follows: *P* up to 9–10 kbar, *T* = 850–950°C, age is 2.0–1.75 Ga ([25] and references therein); there are local occurrences of the UHT metamorphism (*P* = 6.8–7.8 kbar, *T* > 930°C, age is 1.85–1.75 Ga, *dT/dH* = 100–200°C/km) [24]. High-alumina rocks (Al_2O_3 , up to 28 wt %) are widespread in the Kan complex [25]. However, there are no commercial sillimanite accumulations among iron-alumina metapelites. The geodynamic setting of the lower crust extension is constrained by the occurrence of orthopyroxene–sillimanite paragenesis (Al_2O_3 up to 9 wt %). However, the orthopyroxene–sillimanite gneisses formed under UHT metamorphism (*P* = 6.8–7.8 kbar, *T* = 930°C, 1850–1750 Ma) and the andalusite-bearing rocks developed on granulites in the exocontact aureole of the Tarak massif of granitoids (1950–1750 Ma), do not form industrial accumulations of sillimanite and andalusite. The *Yenisei migmatite–amphibolite–gneiss complex* is formed under the upper epidote–amphibolite and amphibolite facies of metamorphism (*P* = 7.3–9.2 kbar, *T* = 633–770°C; age is 750 Ma [16], framing from west and north the Kan complex. There are no industrial accumulations of sillimanite here.

In the Trans-Angara Region are regional metamorphic complexes, which evidence the manifestation of the Grenville Orogeny under the extension–compression conditions (~1.1–0.85 Ga) in the Cis–Yenisei and Central uplifts (Fig.1). The *Garevka deeper metamorphic complex*, which was formed under moderate to higher pressure conditions (moderate–upper amphibolite facies) (*P* = 7.2–8.64 kbar, *T* = 582–630°C, age is 1050–850 Ma, *dT/dH* = 20–25°C/km) and locally under the epidote–amphibolite facies of the exhumation dynamometamorphism (*P* = 3.9–4.9 kbar, *T* = 461–547°C, age is 880 Ma, *dT/dH* = 10°C/km) [9]. Within the CYRSZ, kyanite–staurolite–garnet gneisses (up to 5 m thick) are locally developed. The latter are genetically connected with accretion of the POS to the Siberian Craton (600 Ma) and suprasubduction metamorphism.

The Garevka complex is accreted by the *Teya* (*P* = 3.5–5 kbar, *T* = 400–650°C, age is 973–953 Ma, *dT/dH* = 20–30°C/km) and the *Cis-Angara* (*P* = 4.1–6.6 kbar, *T* = 500–650°C, age is 1100–850 Ma, *dT/dH* = 20–30°C/km) [22] zonal metamorphic complexes of And–Sill type formed under *P–T* conditions varying from the green schist to amphibolite facies of metamorphism. Within the zonal Teya metamorphic complex of andalusite–sillimanite (And–Sill) type (*P* = 3.5–5 kbar, *T* = 400–650°C; age is 973–953 Ma) and the Central Uplift there are promising areas of HAS rich in andalusite and sillimanite. Owing to mining works the Teya sillimanite and Panimbinsk andalusite deposits

formed under the P - T conditions of the amphibolite and epidote-amphibolite facies were explored. The following areas of garnet–staurolite HAS with a staurolite content of up to 30% and more (Al_2O_3 , up to 30 wt%) were distinguished in the field of metapelites of the epidote-amphibolite facies: Cis-Angara complex (Kulakovskoe uplift), northward of the Kan complex, the area of the mining works Slyudorudnik explored, in the lower reaches of the Taseeva River (a left tributary of the Angara River).

Blastomylonites of kyanite–sillimanite (Ky–Sill) type ($P = 3.9$ – 8 kbar, $T = 450$ – $650^\circ C$, the metamorphic gradient – 2.5 to $12^\circ C/km$, age is 864 – 851 to 600 Ma) are locally developed after andalusite–sillimanite schists of the Teya complex in fault (thrust) zones of the Ishimbino–Tatarka regional strike-slip zone (3 – 5 to 7 km thick). As a result, the HAS occurrences containing andalusite (relicts) + kyanite (Chirimbinskoe, Mayakon) or andalusite (relicts) + kyanite + sillimanite (fibrolite) (Kolorominskoe, Nerazgadannoe, etc.) associations were formed.

The P - T conditions and P - T - t evolution trends of metamorphic complexes of the Trans-Angara are plotted in Fig. 1; the position of the Teya complex relative to the Garevka one is shown.

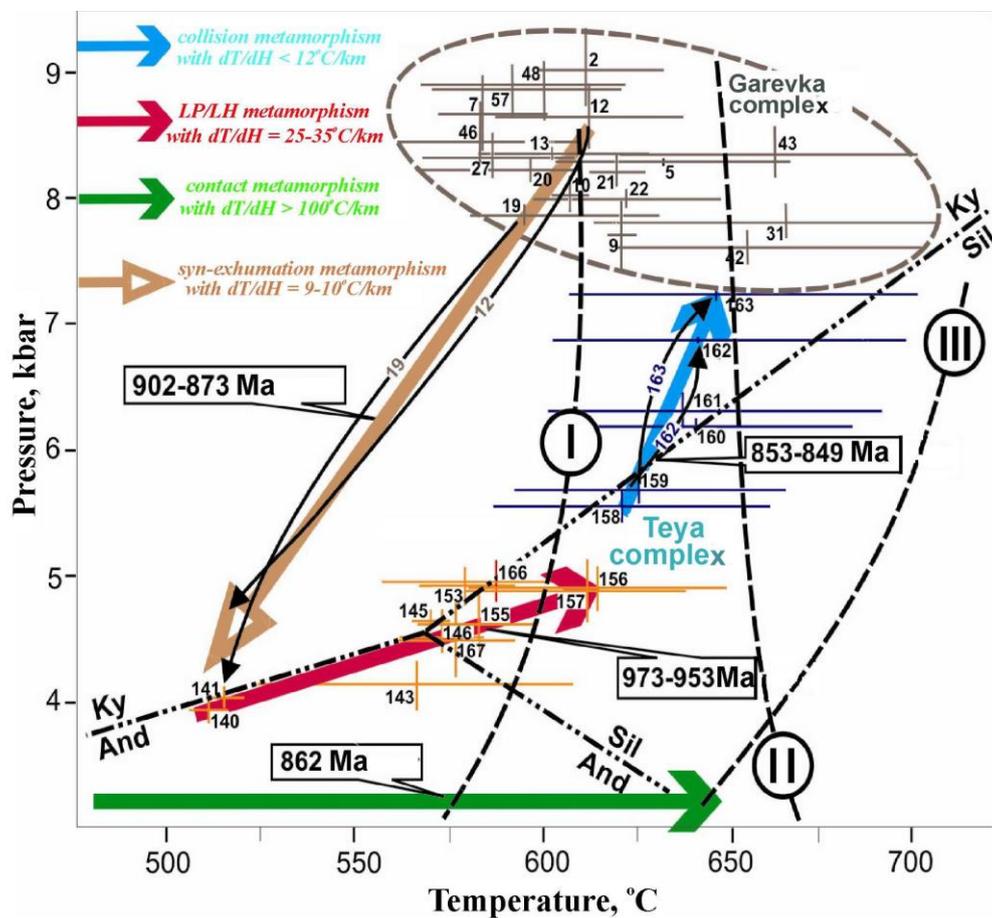


Figure 1. The P - T conditions and P - T - t metamorphism evolution trends of rocks of the Teya and Garevka metamorphic complexes (Yenisei Ridge) of the Trans-Angara segment of the Yenisei Ridge ([23] and references therein):

Average P - T values and their spread, obtained using different geothermobarometers are shown for every sample by crosses (color corresponds the type of metamorphism). Numbers by crosses are numbers of samples. The evolutionary P - T trends of metamorphism, calculated based on zonal metamorphic minerals in metapelites are shown by black curves with arrows. Dashed lines with Roman numerals show known mineral equilibria for the metapelite system: I, $Chl + Ms + St + Qz =$

Als + Bt + H₂O (Pattison, 2001); II, solidus line of metapelites in water-saturated system (Le Breton and Thompson, 1988); III, (Chatterjee and Johannes, 1974). Coordinates of the triple point and lines of monovariant equilibria of Al₂SiO₅ polymorphs are shown by dash-and-point lines after (Pattison, 1992).

The polymetamorphic complexes are surrounded by Late–Neoproterozoic *Angara–Pit* and *Angara–Tissa* complexes of regional greenschist metamorphism (NP₃). Chloritoid-bearing schists of the stratiform type with the content of chloritoid of up to 30–40% are mapped in these complexes, but they are insufficiently studied. In the zones of low-*P* (contact) plutonometamorphism (*P* = 2.5–3.5 kbar, *T* = 450–650°C, age is 864–861 Ma), superimposed on low-temperature metapelites of the Angara–Pit complex (the middle reaches of the Pit River [34], a weak high-alumina mineralization was established near granitoids. The following mineral zoning is distinguished: chloritoid (outer zone), andalusite (middle zone), and sillimanite (inner zone) (Fig.1).

The moderate-*P* blastomylonites of kyanite–sillimanite (Ky–Sill) type of the collision metamorphism (*P* = 3.9–8 kbar, *T* = 450–650°C; the metamorphic gradient is –2.5 to 12°C/km; age is 864–851 to 600 Ma) are locally developed after andalusite–sillimanite schists in Cis-Yenisei and Tatarka–Ishimbino-Kan regional fault (thrust) zones [20, 35).

3. The evaluation the prospects for practical use of HAS of the Yenisei Ridge

The formation of the most promising deposits and occurrences of the Precambrian HAS in the Trans-Angara segment of the Yenisei Ridge is genetically related to the manifestations of the metamorphism of the And–Sill and Ky–Sill types. The prospects for the possible use of HAS together with nepheline syenites and bauxites, already being explored in the region, to produce aluminum oxide, silumin, and aluminum, as well as, prospects of the expansion of the raw material base of the Boguchansk Electrometallurgical Complex, 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 [2]. 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 [3, 33]. According to technological tests, not 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 [3], that is, nonbauxite aluminum raw materials [10].

In recent years, such minerals as Al₂SiO₅ polymorphs (andalusite, kyanite, and sillimanite), which are constituents of high-alumina schists (HAS) containing more than 60% of alumina, have become increasingly important in practical terms. 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 [13, 16].

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 of the XX century 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 Chiriminsk occurrences of andalusite schists were discovered (1956), and, later, Teya and Noiba occurrences of sillimanite schists (1958–1960). According to the results of prospecting works,

andalusite and sillimanite schists of the Panimbinsk and Teya occurrences, correspondingly are promising for the expansion of aluminum raw material. Of these, two technological samples with a weight of 500 kg each were collected. Samples were examined at the Leningrad Institute of Refractory Materials and these occurrences were recommended for geological appraisal works.

The searching works for HAS were resumed in 1978 in connection with the expansion of the raw material base of Achinsk Alumina Combine. 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 [14]. 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 ([12], etc.).

In the 1979–1980s of the XX century, 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 Motygin 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 ([5] and references therein). As a result, 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 was compiled (Fig. 2) [7].

From the point of view of the production of alumina, silumin and aluminum, minerals of the sillimanite group or MSG (Al_2SiO_5 : andalusite, sillimanite, kyanite) are of particular interest. The HAS of the region are divided into mono-, bi- and polymineral, depending on the occurrence in its composition one or more Al_2SiO_5 polymorphs. The andalusite- (Panimbinsk deposit) and sillimanite-bearing (Teya deposit) HAS formed under the conditions of regional metamorphism of And–Sill type in the Teya and chloritoid schists formed under the greenschist facies of metamorphism in the Angara–Pit metamorphic complexes are classified as monomineral [7].

3.1. Panimbinsk deposit

In this area, first of all, of practical interest are andalusite occurrences of the Panimbinsk deposit, found in the distribution area of Mesoproterozoic carbonaceous metapelites of the Kordin Formation (over 10 km² [4]), 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 m 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 %.

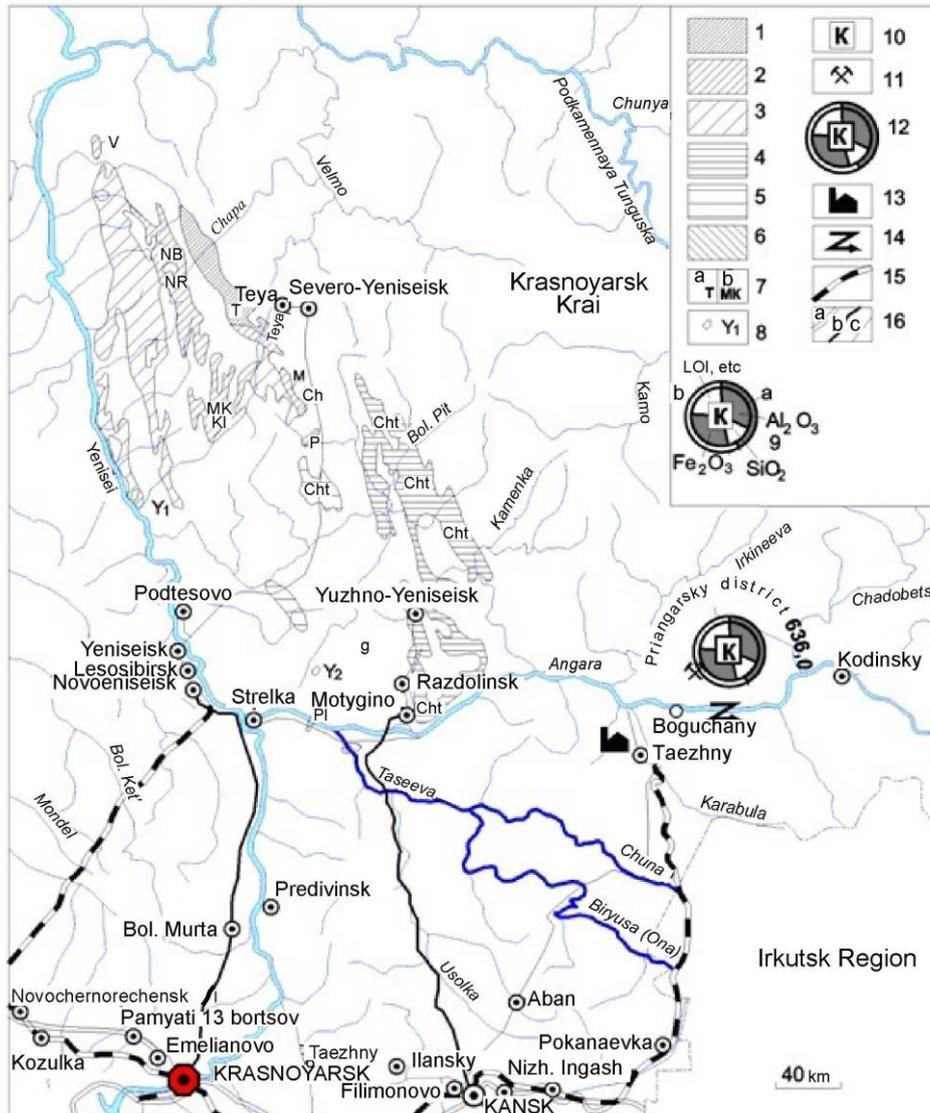


Figure 2. The location scheme of distribution areas of Precambrian sedimentary–metamorphic rocks, potential for searching high-alumina minerals, within the Trans-Angara segment of the Yenisei Ridge: (1) areas, potential for sillimanite, (2) finds of andalusite, sillimanite, and kyanite, (3) ore occurrences, (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, NZ – Nerazgadannoe, MK – Malokiiskoe, KU – Kiya, C – Chirimbinskoe, N – Noiba, G – Golets, Pl – Polovinkinskoe), (8) massifs of alkaline syenites (1, Kiya, 2, Middle Tatarka); (9–17) Cis-Angara area with reserves 636.0 mln t [33]: (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.

3.2. The Mayakon ore occurrence

This 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 biminerals. 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 % ($\bar{X} = 20.3\%$). 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.

3.3. Teya deposit

Of the sillimanite occurrences, the Teya deposit, which is confined to the Paleoproterozoic HAS (metapelites, the amphibolite facies of the regional metamorphism) of the Karpinsky Ridge Formation is the most promising. The HAS occupies an area of 14 km². 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 km². 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 of the XX century, the technological tests on the concentration of two samples of 500 kg each from the Panimbinsk andalusite 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 %): $\text{SiO}_2 = 60.3\text{--}61.99$, $\text{TiO}_2 = 0.95$, $\text{Al}_2\text{O}_3 = 22.27$, $\text{Fe}_2\text{O}_3 = 7.59$, $\text{CaO} = 0.41\text{--}0.55$, $\text{MgO} = 1.51\text{--}2.21$, $\text{Na}_2\text{O} + \text{K}_2\text{O} = 2.93\text{--}3.12$, $\text{LOI} = 1.97\text{--}2.8$; refractoriness value is 1350°C. As a result the flotation concentrate of the following composition was obtained: $\text{SiO}_2 = 36.48$, $\text{Al}_2\text{O}_3 = 57.14$, $\text{TiO}_2 = 1.6$, $\text{Fe}_2\text{O}_3 = 2.22$.

The mineralogical composition of the sillimanite-bearing samples: sillimanite, quartz, biotite, graphite, muscovite; chemical composition: $\text{SiO}_2 = 60.25$, $\text{TiO}_2 = 1.42$, $\text{Al}_2\text{O}_3 = 18.2$, $\text{Fe}_2\text{O}_3 = 6.69$, $\text{MgO} = 1.58$, $\text{CaO} = 0.42$, $\text{Na}_2\text{O} + \text{K}_2\text{O} = 2.68$, $\text{SO}_3 = 0.35$, $\text{LOI} = 2.48$; refractoriness value is 1430°C. The chemical composition of the flotation concentrate: $\text{Al}_2\text{O}_3 = 54.57\%$, $\text{SiO}_2 = 41.00\%$, $\text{TiO}_2 = 0.32\%$, $\text{Fe}_2\text{O}_3 = 1.77\%$, 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 [5]. In practical terms, first of all, sillimanite-bearing high-alumina metamorphic rocks of the amphibolite facies of prograde regional metamorphism are of most interest 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 km² 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.

3.4. Chloritoid-bearing schists

These schists are widespread among the regional metamorphosed sedimentary rocks of the Neoproterozoic Tungusik Group within the Angara–Pit greenschist complex in the interfluvium of the Gorbilka, Pit, and Angara rivers. The chloritoid of HAS (content Al_2O_3 is 23 wt % and more) is 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. The model content of Al_2O_3 in chloritoid is as high as 40 wt %.

3.5. Chloritoid–kyanite schists

These 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 [9]. 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.

3.6. Garnet–staurolite crystalline schists

These schists were first distinguished in the Taseeva River mouth (a left tributary of the Angara River) in the Cis-Angara polymetamorphic complex [9]. The distribution areas of two-mica garnet–staurolite HAS ($\text{SiO}_2 = 57.91\text{--}50.98$, $\text{Al}_2\text{O}_3 = 22.39\text{--}27.95$ wt %, $n = 2$), which contain abundant idiomorphic large (3–5cm) 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 and in the Kulakovo uplift.

4. 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.

4.1. 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 [1]. In the future, local ferruginous bauxites are proposed to use as the main domestic raw materials for the production of aluminum in the region. Bauxites are 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 [1, 32].

The Chadobets deposit, located on the right bank of the Angara River near the BAS is regarded to be applicable for industrial operation. The reserves of Chadobets bauxites are 106.4 million tons with average contents of components (%): $\text{Al}_2\text{O}_3 = 29.14$, $\text{SiO}_2 = 11.70$, $\text{Fe}_2\text{O}_3 = 32.68$, $\text{TiO}_2 = 8.66$, $\text{LOI} = 15.45$. 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 [3], 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 $T = 105\text{--}125^\circ\text{C}$, 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 [3]. 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 [30]. 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.

4.2. *Nepheline syenites*

The searching works for HAS were resumed in 1978 in connection with the expansion of the raw material base of Achinsk Alumina Combine. 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.

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 and is represented by the Northern and Southern bodies among the Neoproterozoic carbonate rocks of the Gorevka Formation [33].

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%), $\text{Na}_2\text{O} = 3.1\text{--}11.1\%$, $\text{K}_2\text{O} = 4\text{--}6\%$. 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 [33]. 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. 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. Due to this, it is not given in the description.

5. 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 [14]. Addition of 30% MSG ($\text{Al}_2\text{O}_3 = 57 \text{ wt } \%$) to the undressed nepheline rock ($\text{Al}_2\text{O}_3 = 22 \text{ wt } \%$) 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.

6. Possibilities of application of electrothermy of MSG for the silumin production

In recent years, minerals of the sillimanite group have become increasingly important. 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 ([15] and references therein).

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 ([28] and references therein). 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 of the AK12M2MN and AK18 grades using the traditional method for fusing the alumina A0, A7 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, 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.

7. 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 [10]. 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, brought into operation in 2016 in the Lower Angara region (Fig.2). In terms of involvement of the 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 [1]. 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 Electrometallurgical Complex. It is planned that this railway branch connects the general railways with railway lines belonging to the BEC.

According to our ideas, the research results, and the infrastructure development program in the region [1], the high-alumina schists will be in demand in connection with the development of production capacities and the expansion of the BEC product range, which will require the involvement of domestic iron-alumina raw materials and minerals of the sillimanite group together with nepheline syenites and bauxites in the metallurgical production.

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