ISSN 1070-3632, Russian Journal of General Chemistry, 2011, Vol. 81, No. 6, pp. 1277–1287. © Pleiades Publishing, Ltd., 2011.
Original Russian Text © V.V. Belyaev, 2010, published in Rossiiskii Khimicheskii Zhurnal, 2010, Vol. 54, No. 2, pp. 29–37.

Mineralogy, Spread, and Use of Bauxites

V. V. Belyaev†

Institute of Geology, Komi Scientific Center, Ural Branch, Russian Academy of Sciences,
ul. Pervomaiskaya 54, Syktyvkar, Komi Republic, 167982 Russia
e-mail: institute@geo.komi.sc.ru

Received January 1, 2010

Abstract—Rock-forming high-aluminous, associated, and accessory (the most common) bauxite minerals were described in detail, along with their corresponding diagnostic variables, chemical composition, and spread. A geological-economic overview of the world bauxite ore deposits and reserves was presented, and the specific features of Russian bauxite deposits and practical value of bauxites were discussed.

DOI: 10.1134/S107036321106034X

INTRODUCTION

Bauxite is a product of intense chemical weathering of aluminosilicate rocks. It consists predominantly of aluminum hydroxides and is the basic or even the unique (in foreign countries) ore from which metallic aluminum can be produced. Bauxites virtually invariably contain certain amounts of iron oxides and hydroxides, clay minerals, and other impurities; there are also titanium and a number of valuable less-common elements in bauxites. First discovered in 1820 by Pierre Berthier in the Fouta-Jallon region in Africa, this rock had the following composition, wt %: 40 Al_2O_3, 33.6 Fe_2O_3, 2.0 SiO_2, and 24.4 H_2O. Berthier believed that it does not occur elsewhere in the world, but only after one year a rock even richer in alumina was found in southern France, in the vicinity of the village of Le Baux; it contained, %: 52 Al_2O_3, 27.6 Fe_2O_3, and 20.4 H_2O. Berthier took this rock to be a mineral, with iron oxides being mechanical impurities, and derived a chemical formula $Al_2O_3{\cdot}2H_2O$ for the compound that was though to be a mineral, but did not provide it with a name. Only after half a century A. Dufferenoy gave to this hypothetic mineral the name of bauxite after the place of its occurrence near Le Baux. Subsequently, this name gained wide acceptance and is still used nowadays, though in respect to high-alumina rocks rather than to a mineral.

However, bauxite has long been treated by many foreign researchers as an individual mineral with the composition $Al_2O_3{\cdot}2H_2O$, although even in the beginning of the XX century it was found that it is comprised by several minerals and cannot be formulated as an individual compound. Nevertheless, even such a fundamental work as “The Encyclopedia of Mineralogy” edited by K. Frye and published in the US in 1981 [1] still attributes to bauxite the above-mentioned composition.

At the same time, the very concept of bauxite is still ambiguously interpreted on an international scale. The aluminous rocks classed with bauxites strongly differ in the composition of substances and are difficult to compare. In terms of the content of useful, ballast, and harmful components not all of these rocks satisfy the requirements posed by aluminum industry, as well as by some bauxite-consuming industries releasing nonmetallurgical products. This necessitated classification of bauxites by types, brands, and grades. However, neither of the bauxite classifications available today (over ten in number) was universally recognized, because they all are underlain by differently interpreted criteria and characteristics.

The first classification proposed by J. Lapparent as early as 1930 was based on the Al_2O_3 and SiO_2 content and their weight ratio Al_2O_3:SiO_2, the so-called silica (alumina) modulus, which were suggested as the main criteria to be used for attribution of aluminous rocks to bauxite. In this classification, bauxites were treated as rocks containing >40% Al_2O_3 and < 30% Fe_2O_3, the modulus being over unity. Proceeding from this modulus value, Lapparent distinguished among high-

---

† Deceased.

aluminous (>20), aluminous (10–20), siliceous (4–10), and high-siliceous (1–4) bauxites, and based on the iron content, high-iron (>25% Fe_2O_3), medium-iron (10–25% Fe_2O_3), and low-iron (<10% Fe_2O_3) bauxites. Based on the dominating mineral form of occurrence of aluminum, Lapparent recognized the gibbsite, boehmite, diaspore, and kaolinite types of bauxites.

The Lapparent's chemical classification, though in a slightly modified form, is still used in some countries for typization of bauxites: Aluminous rocks characterized by low silica moduli (<2) are referred to as allite, bauxite clay, or aluminous-clay rock, rather than as bauxite. At the same time, different experts drew different lines between bauxites and similar rocks. For example, V.T. Allen [2] attributed to bauxite clays even rocks containing 60–73% Al_2O_3, which clearly fell under the category of bauxites. As to the former USSR and Russia, GOST (State Standard) 972-74 treats as bauxites those aluminous rocks that contain over 37% Al_2O_3 and have a silicon modulus of no less than two.

The mineralogical classification suggested by Lapparent disregards many of mixed-composition bauxites. A much fuller classification of bauxites was proposed in the former USSR by E.A. Rozhkova and M.V. Solov'eva from the All-Union Institute of Mineral Raw Materials. Depending on the forms of occurrence of aluminum hydroxides, bauxites in this classification were subdivided into three large groups: monohydrate, trihydrate, and mono/trihydrate bauxites. This classification covers virtually all the mineral types of bauxites known in nature, as identified from their main aluminous and aluminiferous minerals.

Main Bauxite-Forming Minerals

All the mineral constituents of bauxites, with rare exception, form very small crystals, whose analysis is complicated by their being intimately intergrown with one another. Their diagnostics requires the use of special analytical techniques: X-ray phase analysis, DTA, IR spectroscopy, electron microscopy, etc.

The main bauxite-forming minerals are aluminum hydroxides gibbsite, boehmite, and diaspore associated in bauxites with hematite, goethite, and less frequently with hydrogoethite, as well as with clay minerals, predominantly kaolinite, occasionally chamosite, and rarely halloysite. Virtually always bauxites contain titanium minerals rutile, anatase, ilmenite and, in some cases (most often in sedimentary bauxites), newly formed iron sulfides pyrite, marcasite, in places siderite, calcite, occasionally corundum, magnetite, and some other more rare minerals.

Aluminium Hydroxide Minerals

Aluminum hydroxides, similarly to iron hydroxides, were formerly thought of as crystal hydrates until it was found more recently that hydrogen and oxygen occur in them as hydroxy ions (OH) and represent a structural constituent. Below, this type of minerals will be represented by two formulas, a crystal-chemical and a crystal-hydrate one.

Aluminum Trihydroxides

The major aluminum trihydroxide mineral in bauxites is gibbsite, and the minor ones, bayerite, nordstrandite and tučanite which are found occasionally at the level of impurities.

Gibbsite $Al(OH)_3$, or $Al_2O_3 \cdot 3H_2O$, aluminum hydroxide mineral that is most widespread in the Mesozoic and Cenozoic bauxites, has the following chemical composition, %: 65.4 Al_2O_3 and 34.6 H_2O. Gibbsite was first discovered as an irregularly shaped cryptocrystalline mass. Its crystalline varieties were detected by I.R. Lisenko near the town of Zlatoust in South Urals and in 1839 were submitted for examination by Gustav Rose who attributed them to hydrargillite. Similar crystals were studied and identified as gibbsite by P.I. Evreinov in 1843. In the years that followed these two terms were used interchangeably until the Third Session of the International Mineralogical Association (1962) put an end to this confusing duality and suggested that the mineral of interest be further termed gibbsite.

In bauxites, crystalline gibbsite occurs as hexagonal tables, scaly masses, and less commonly as columnar aggregates. As regards bauxites from South-Timan deposit, it was found [3] that they are fairly frequently represented by simple and polysynthetic twins and occasionally by drusy aggregates (Fig. 1). Coarse-grained gibbsite often occurs as a newly formed, secondary mineral which lines the walls of cavities, often fills entirely small pores and fractures, substitutes quartz and other minerals, and can be easily identified when examined under a microscope in thin sections. Fine-grained, cryptocrystalline gibbsite in bauxites is closely associated with other minerals and typically can be reliably diagnosed with the use of thermoanalytical and X-ray methods only. The DTA curve of gibbsite contains an endothermic peak at 325–350°C, which is associated with its dehydration, as clearly

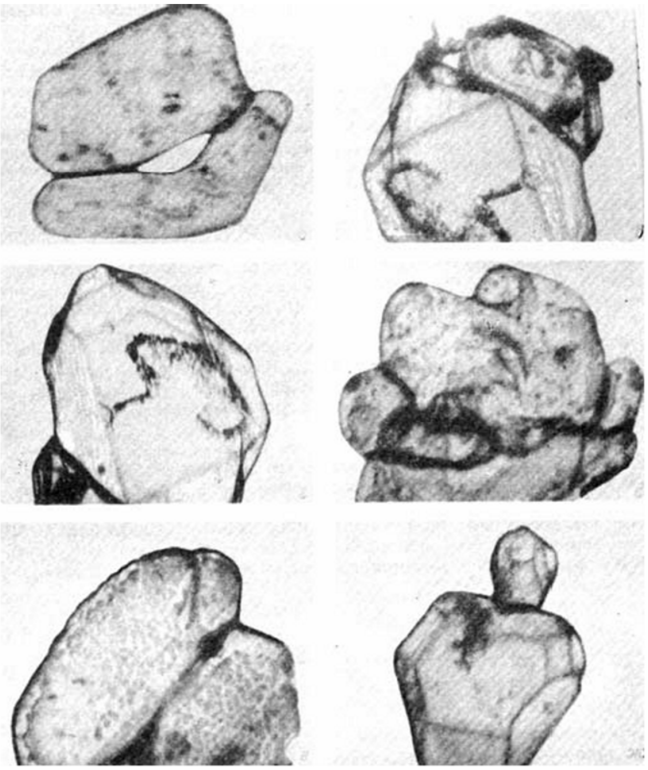

Fig. 1. Gibbsite crystals, intergrowths, and druses as viewed under an electron microscope. Pseudoreplicas; ×25000 magnification.

Fig. 2. Finely dispersed boehmite crystals (black) as viewed under an electron microscope. Hollow forms correspond to kaolinite; selective dissolution method; ×20000 magnification.

seen from the corresponding weight loss step in the thermogravimetric curves as well. Gibbsite, in particular when mixed with other minerals, can be reliably identified by X-ray methods, based on the characteristic reflections: 4.85, 4.37, and 4.31 Å.

Among bauxites composed by gibbsite, the most abundant species are those of eluvial and sedimentary types, associated with the Mesozoic-Cenozoic crusts of weathering and lateritic covers of the tropical belt. Gibbsite bauxites are widely spread in Australia, Brazil, Ghana, Guinea, India, and Venezuela, as well as in the US (Arkansas), Indonesia, Oceania, and Kazakhstan. They were also found in Norway, Malaysia, Colombia, and China (Chao'an and Hainan counties). In Russia, bauxites of gibbsite type occur in Central and West Siberia, Middle Urals, East Transurals, and South Timan (Upper-Ukhta deposit). Gibbsite also has a widespread occurrence in gibbsite-boehmite bimineral bauxites typical for a number of Early Carboniferous-age sedimentary rocks, including those from the deposits in Tikhvin, North-Onega, and partly South-Timan (Kedva deposit) bauxite-bearing regions of Russia.

Bayerite α-$Al(OH)_3$, or α-$Al_2O_3 \cdot 3H_2O$, was thought of as an exclusively artificial mineral until 1950. Native bayerite was found more recently in bauxite deposits of Hungary, Montenegro, Greece, and Ukraine. Though similar in the chemical composition with gibbsite, bayerite is distinguished by lower refractive index and birefringence, and also in the X-ray diffraction pattern. Bayerite is represented by small (<1 mm) acicular, columnar, lamellar, trapezoidal, or bladed crystals. Relatively large (up to 0.1 mm) bayerite crystals were detected by D.P. Khorosheva [4] in bauxite deposits of the Middle-Dnieper Region.

When heated, bayerite undergoes dehydration at lower temperatures compared to gibbsite. This is a two-stage process, as clearly seen from the endothermic peaks in the thermograms recorded at temperatures close to 215 and 270°C. Diagnostics of

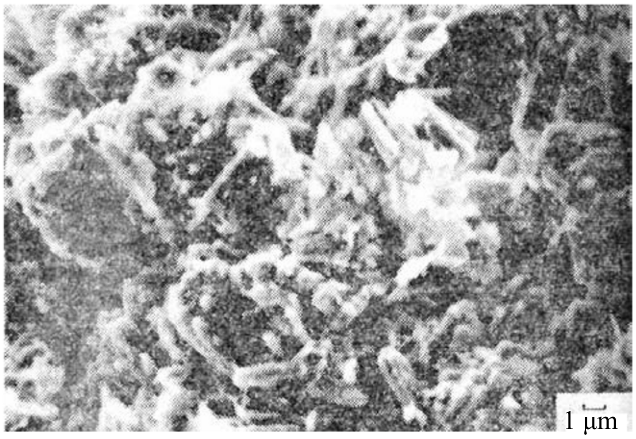

Fig. 3. Acircular diaspore crystals in Middle-Timan bauxites. Scanning electron microscopy.

bayerite in some cases requires an additional IR-spectroscopic examination. Bayerite in bauxites is often intergrown with gibbsite.

Nordstrandite $Al(OH)_3$,or $Al_2O_3 \cdot 3H_2O$, was first detected in the natural form in association with diaspore in West Sarawak red soils [5], and more recently, in clays of Hungary jointly with bayerite and gibbsite. Nordstrandite was revealed in bauxites from Cretaceous-Paleogene deposits of Siberia [6, 7] and in the Ozernoe deposit in Kazakhstan.

Nordstrandite is represented by colorless transparent crystals up to 0.3 mm in size, which form radiated and mosaic aggregates, polysynthetic twins. It can be differentiated from gibbsite based on the position of the endothermic peak in the thermogram (310°C) and the reflections (lines) at 4.780, 4.322, 4.207, and 2.392 Å in the X-ray diffraction pattern.

Tučanite $2Al_2(OH)_6 \cdot H_2O$ has the following chemical composition of its air-dry species, %: 0.46 SiO_2, 52.94 Al_2O_3 , and 46.30 H_2O. This mineral is still insufficiently studied. It should be noted that bayerite, nordstrandite, and tučanite have no commercial value.

Aluminum Monohydroxides

Aluminum monohydroxide minerals in bauxites are represented by boehmite and diaspore.

Boehmite γ-AlO(OH), or γ-$Al_2O_3 \cdot H_2O$, with the chemical composition, %, 85 Al_2O_3 and 15 H_2O, is contained in bauxites virtually always in finely- and cryptocrystalline form. It is closely aggregated with iron oxide and hydroxide minerals, as well as with kaolinite, often with gibbsite and diaspore, occasionally with chamosite. Boehmite typically occurs as very small lenticular or rhomb-shaped (Fig. 2), sometimes acicular, hexagonal crystals which are often discernible under an electron microscope only. By contrast to gibbsite, the secondary, newly formed boehmite in bauxites is not widespread; it was detected in few deposits solely. The Belgorod Ore Region bauxites have the walls of small voids and microfractures encrusted by coarser newly formed boehmite crystals [9].

Boehmite is an ore-forming mineral of bauxites of different ages, from Devonian to Paleogene. Boehmite bauxite deposits, of predominantly Jurassic-Cretaceous age, occur in some European countries: Austria, Hungary, Greece, Italy, and France. Older bauxites of the boehmite type were revealed in Afghanistan (pre-Jurassic) and Turkey (Late Permian), as well as in Belgorod and South-Timan bauxite-bearing regions (Early Carboniferous) and in Middle Timan (Devonian). Boehmite is also widely spread in bimineral bauxites of the gibbsite-boehmite and boehmite-diaspore types. The former constitutes several European deposits, both foreign (Hungary, Montenegro) and Russian (Tikhvin, North Onega, partly South Timan); some of the Australian and Brazilian deposits are represented by gibbsite-boehmite bauxites. As to the latter, they are known to occur in Greece, former Yugoslavia, China, India, Vietnam, Pakistan, and Central Asian region. In Russia, this type of bauxites is most typical for North-Urals bauxite-bearing region deposits [16] and is also found in East Sayan (Bokson deposit). Boehmite occurs as impurity in bauxites of many countries of the world.

Diaspore α-AlO(OH) with the chemical composition, %, 85 Al_2O_3 and 15 H_2O, occasionally contains Fe, Mn, and Cr as isomorphous impurities. Diaspore occurs as tabular, lamellar, acircular [3], or (rarely) prismatic columnar crystals (Fig. 3).

Diaspore in bauxites can be fairly easily identified when viewed under a microscope in thin sections and in immersion preparations from high refractive index and strong birefringence. Using thermal analysis techniques diaspore can be reliably diagnosed only in the absence of boehmite and kaolinite, from the endothermic peak in the DTA curve at 560–600°C and the associated weight loss in the gravimetric curve due to dehydration. In cryptocrystalline bauxites, fine-grained diaspore can be unambiguously identified from the characteristic reflections at 3.98; 2.553; 2.315; and

2.076 Å in the X-ray diffraction patterns [11]. Diaspore is known to be an ore-forming mineral for Paleozoic and (rarely) Mesozoic, bauxites; in the latter case these are typically metamorphosed or hydrothermally altered rocks.

Diaspore in bauxites most often occurs in paragenesis with other aluminous minerals, typically with boehmite and rarely with corundum and gibbsite. Monodiaspore bauxites are common in the US (Massachusetts), Romania, Greece, Turkey, Slovenia, China (Xiuwen deposit), and India (Jammu and Kashmir); they occur in Switzerland, Greenland, and the Central Asian Republics of CIS as well.

In Russia, diaspores form (partly) North-Urals bauxite deposits, as well as the Kukshik deposit in South Urals, Obukhovo deposit on Salair, and Volodinskoe deposit in Middle Timan [12]. Diaspore-type bauxites were also revealed for Kizel area in North Urals and for the Kara ore occurrences in the Polar Urals and Pai-Khoi.

As regards anhydrous aluminum oxides, corundum Al_2O_3 occurs in bauxites from some deposits either in the low- (microcorundum) or the high-temperature (macrocorundum) form. It is believed that the former resulted from dehydration of aluminum hydroxides under surface conditions, and the latter, from hydrothermal alteration and metamorphism of bauxites. Certain amounts of microcorundum were detected in bauxites from Middle and North Urals, Pai-Khoi, Middle Timan, Siberia, and Kazakhstan, as well as from Romania, Greece, Turkey, the US (Arkansas). Large, occasionally up to 45–50%, amounts of macrocorundum associated with magnetite, spinel, diaspore, chlorite, and mica occur in virtually all metamorphosed bauxites.

Iron Oxide and Hydroxide Minerals

The prevalent iron oxide and hydroxide minerals in bauxites are hematite and goethite, whose total content in red bauxite ores may reach 40–45%. Bauxites can also contain magnetite, lepidocrocite, and hydrogoethite, though much less frequently and in small amounts.

Hematite α-Fe_2O_3 occurs in red bauxites in amounts of 20–25%, on the average, as a typically finely-divided impregnation; less frequently it is concentrated in pisolites and oolites, microfractures. When viewed in thin sections under a microscope and in reflected light hematite has a blood-red and blue-shaded white color, respectively. It can be unambiguously identified from X-ray reflections at 3.67, 2.69, and 2.51 Å.

Fig. 4. Electron image of splinter-like goethite crystals. Electron transmission microscopy; suspension; ×18000 magnification.

Goethite α-FeOOH, or α-$Fe_2O_3 \cdot H_2O$, with the chemical composition, %, 89.89 Fe_2O_3 and 10.11 H_2O, occurs as acicular, splinter-like columnar, and tabular crystals. Bauxites contain predominantly finely dispersed goethite. It may form oolites and pisolites and, occasionally, vein-like masses, splinter-like crystals, though less commonly and in smaller amounts (Fig. 4). It is not infrequent that red bauxites contain 30% goethite. In mixtures with other minerals goethite can be identified from the endothermic peak at 350–400°C and from the weight loss due to dehydration in thermograms and from the reflections at 4.18 and 2.69 Å in the X-ray diffraction patterns.

Goethite may contain increased levels of aluminum which isomorphically substitutes iron, in which case it is termed aluminogoethite. The latter, along with aluminohematite, was detected in Hungarian bauxites, but it is not improbable that aluminum in it is a mechanical impurity.

Hydrogoethite $FeOOH \cdot nH_2O$, which is thought of as an independent mineral by some researchers, is most likely essentially a kind of goethite with a high (up to 13%) content of water of hydration.

Lepidocrocite γ-FeOOH is a very rare mineral of bauxites, polymorphous with goethite and isostructural with boehmite, which in some cases occurs as an earthy, more often as finely dispersed, mass. The thermogram of lepidocrocite is distinguished from that of goethite by a typical exothermic effect at 380–500°C. Lepidocrocite can be identified more reliably from X-ray reflections at 6.27, 3.29 and 2.473 Å.

Though as negligible impurity, lepidocrocite occurs in bauxites of France, as well as of Sokolovskoe deposit of the Urals, Timsher deposit in South Timan, and in some other deposits.

Magnetite $FeFe_2O_4$, or Fe_3O_4, is abundant only in metamorphosed and hydrothermally altered bauxites, in which case iron often occurs in this mineral form virtually entirely. The magnetite content in these bauxites is 30–35% against several fractions of per cent in original bauxites. Also, maghemite and titano-magnetite occur in bauxites occasionally.

Regardless of the form of occurrence, iron oxide and hydroxide minerals are treated as ballast for the alumina refining process, which, even when in small quantities, significantly deteriorates the quality of diversified technical materials produced from bauxites.

Clay Minerals

The most abundant clay minerals in bauxites are kaolinite and much less commonly occurring chamosite.

Kaolinite $Al_4Si_4O_{10}(OH)_8$, or $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$, with the chemical composition, %, 39.5 Al_2O_3, 46.5 SiO_2, and 14.0 H_2O, is contained in bauxites in amounts broadly varying from 2 to 50%; it is usually mixed with aluminum and iron hydroxide minerals. Occasionally, kaolinite veins, stripes, and spots of a more recent (epigenetic) origin may be found. Restricted distribution in bauxites have relatively coarse-crystalline occurrences ranging from pseudo-hexagonal plates (Fig. 5) to vermiculite- and sheaf-like aggregates and intergrowths segregating into individual sheets. Finely dispersed kaolinite, when viewed under an electron microscope, is represented by both whole and chipped lamellar and thin platy crystals ranging in size from 0.02 to 1.0 μm.

Kaolinite can be unambiguously identified in bauxites by thermal and X-ray diffraction analyses. Thermograms of kaolinite contain a characteristic endothermic peak at 580–620°C and a sharp exothermic peak at 960–1000°C. In mixtures with other minerals kaolinite can be reliably identified from reflections at 7.15, 3.57 and 2.379 Å in the X-ray diffraction patterns. Kaolinite-containing bauxites are widespread in most of world's deposits, which are predominantly of sedimentary type.

Chamosite, iron hydroxyaluminosilicate comprised of variable proportions of its chemical constituents, can be approximately formulated as $3SiO_2 \cdot Al_2O_3 \cdot 4FeO \cdot 6(OH) \cdot nH_2O$ [8] which formula does not incorporate, however, Fe_2O_3 and MgO. The chamosite composition, %, is as follows: 18–33 SiO_2, 21–28 Al_2O_3, 3.2–12.3 Fe_2O_3, 19–37 FeO, 1–5 MgO, and 10–11 H_2O. In bauxites, chamosite segregations can be identified from their greenish-gray or greenish-black color. Bauxites contain chamosite in the monoclinic and rhombic modifications whose abundances and chemical compositions govern the number, position, and intensity of the reflections observed in the X-ray diffraction patterns. The first basal interplanar spacing for the both modifications varies within 7.04–7.11 Å, the most typical value being 7.05 Å. Monoclinic chamosite can be identified from the 2.40 Å reflection which is not characteristic for the rhombic modification, as well as from an endothermic peak at ~550°C and a not very prominent exothermic peak at 940–950°C in the thermograms.

Chamosite occurs as impurity in a number of bauxite-ore deposits; it was found in bauxites of France, Romania, and Northern Ireland and is especially abundant in bauxites of the Belgorod region of the Kursk Magnetic Anomaly (KMA), where it occurs as a rock-forming mineral in many ore loci [9]. Chamosite is also abundant in the Middle-Timan bauxite deposits, especially in the Vezhayu-Vorykvin and Volodinskoe deposits, in which chamosite-boehmite and chamosite-diaspore types of bauxites, respectively, were identified [12]. Significant amounts of kaolinite and chamosite strongly deteriorate the quality of bauxite raw materials and limit their commercial application.

Bauxites from some deposits comprise other clay minerals, specifically, dickite [13], nacrite, and halloysite, though as minor impurities.

Titanium Minerals

Titanium minerals in bauxites are represented mostly by rutile and anatase and, to a lesser extent, by

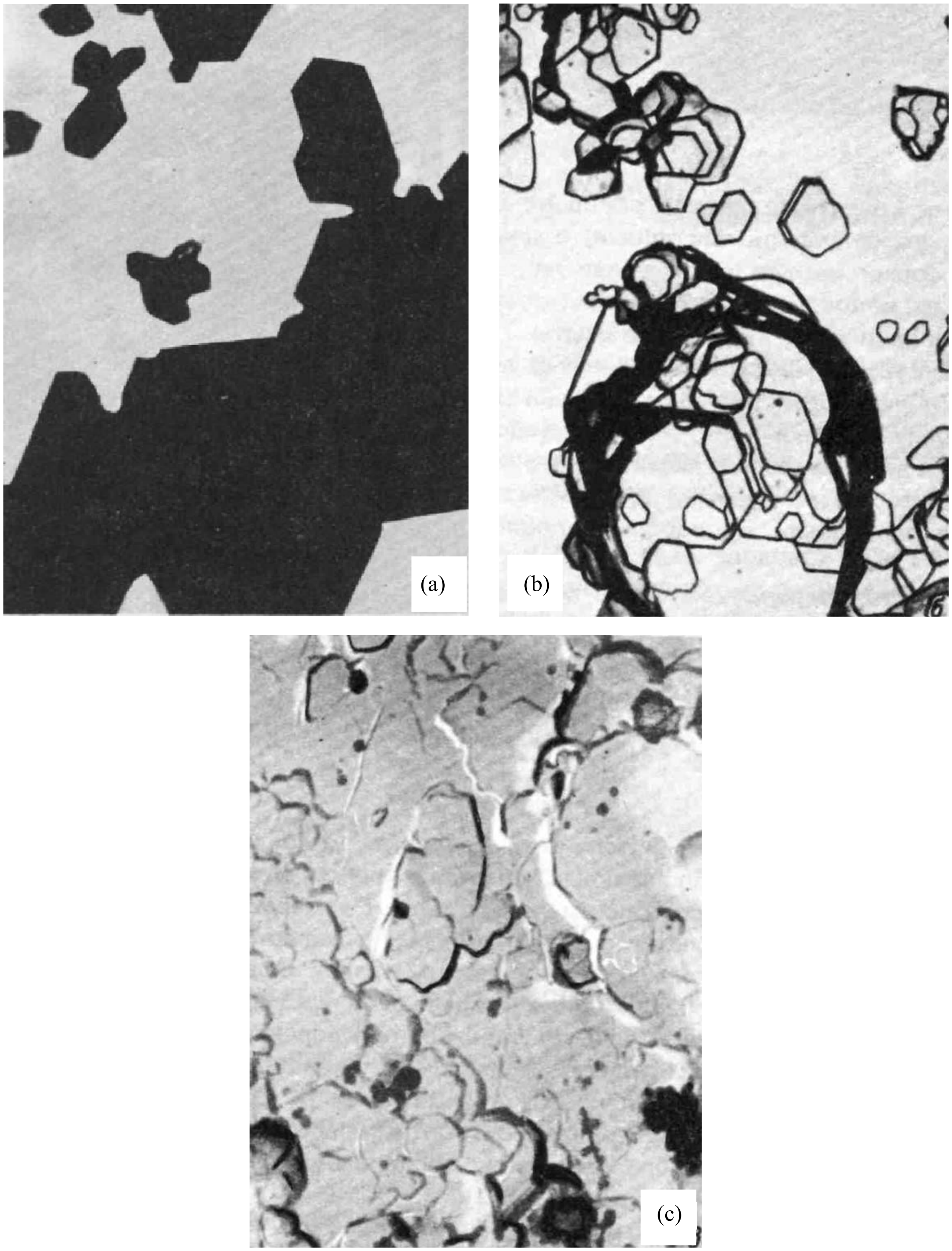

Fig. 5. Electron image of authigenic kaolinite with a chipped kaolinite impurity: (a) suspension in transmitted light, ×18000 magnification, (b) pseudoreplica of a powder, ×20000 magnification; and (c) carbon replica of a cleaved surface, ×20000 magnification.

leucoxenized ilmenite; brookite and sphene are observed occasionally. Leucoxene is abundant in bauxites; it was formerly thought of as an individual mineral until it was established more recently that it is comprised of a mixture of rutile and quartz. The average content of TiO_2 in bauxites is close to 2.5%, but in some deposits of Siberia (Yenisei Ridge) it reaches 9.5%, and Indian bauxites contain 17% TiO_2 [5].

Rutile TiO_2 is the most stable and widespread titanium mineral occurring in bauxites, both in cryptocrystalline and eucrystalline states. Rutile appears as needle-like or prismatic crystals, often in the form of geniculated twins, in a color ranging from yellow and reddish-brown to almost black. Rutile may contain iron, niobium, and tantalum impurities; it occurs in all types of bauxites but mostly as part of leucoxene.

Anatase TiO_2 is a polymorph of rutile, which, being one of leucoxene minerals, is also often present in bauxites. Anatase also occurs separately in the form of small bipyramidal, tabular, or prismatic crystals. Heating to 620°C causes the anatase–rutile conversion.

Ilmenite $FeTiO_3$ typically occurs in bauxites as a relict mineral which rarely preserves its original composition. It is usually leucoxenized, partially or entirely, and undergoes a conversion to rutile and/or anatase. Leucoxenized ilmenite contains iron that is represented mostly or entirely by Fe_2O_3 (hematite).

In the bauxite-bearing weathering crust of Verkhnyaya Shchugor deposit in Middle Timan, I.V. Shvetsova [12] identified ilmenorutile leucoxene with a commercial (up to 4%) content of niobium.

Sulfur-Containing Minerals

Sulfur-containing minerals are fairly common in selected sedimentary bauxite deposits and are mainly represented by iron disulfides: pyrite, marcasite, and melnikovite. They occur primarily in white bauxites as post-mineral new formations.

Pyrite FeS_2 is contained in boehmite bauxites that have a considerable spread in Belgorod, North-Onega, and South-Timan deposits, as well as in North- and South-Urals boehmite-diaspore deposits. The sulfur content in some of the pyrite-bearing bauxite plots and fields in these deposits exceeds that stipulated by appropriate standards.

Marcasite FeS_2 in bauxites occurs most frequently as concretions, spherulites, and irregularly shaped massive pyrite-marcasite segregations. Monomarcasite concretions are mainly composed by druse intergrowths. Highly characteristic for marcasite are spherulites with a fine-grained core and a spherulitic exterior. Also, spherulites may have pyrite in their interior, and marcasite, in the exterior. Occasionally the contractions have a polycentric-polyzonal structure with a pyrite-marcasite composition. Rarely occurring faced marcasite crystals have thick-tabular or prismatic habit [3].

Carbonates

Siderite and calcite represent carbonates that are most abundant in bauxites.

Siderite $FeCO_3$, with a theoretical composition, %, 62.01 FeO and 37.99 CO_2, occurs in bauxites as a varigrained species and varisized crystals associated with pores and fractures. Occasionally it forms spherulites (Fig. 6), sometimes replaces oolites and pisolites, and also may form continuous lenticular-layered masses.

Siderite can be easily identified from thin-section images, as well as from thermal, X-ray diffraction, and chemical analyses data. Thermograms of siderite contain an endothermic peak at 460–500°C and an exothermic peak at 650–750°C, of which the former is due to decomposition into FeO and CO_2, and the latter, to oxidation of ferrous iron. Siderite diagnostics from X-ray diffraction patterns is based on 2.790, 2.132 Å reflections.

Siderite-containing bauxites have restricted distribution and occupy small areas in a few deposits. They occur in Pennsylvania (US), as well as in Krasnooktyabr'skoe and Kushmurunskoe deposits in Kazakhstan and in a number of KMA and Urals deposits. Siderite-bearing bauxites have local distribution in South-Timan deposits.

Calcite $CaCO_3$ occurs in significant amounts as fine impregnation scattered over the main ore mass, but is mostly associated with pores and diversified small fractures. All the above-mentioned methods are suitable for unambiguous identification of calcite in bauxites.

Calcite-containing bauxites have local distribution in West Africa, North Kazakhstan, and Near-Angara deposits, as well as in some fields of South-Timan and North-Onega deposits. Bauxite ores rich in calcite are typically discarded.

Sulfides and carbonates contained in bauxites are new formations. Also, bauxites contain a number of other minerals, but only at the level of accessories that do not significantly affect the crude ore quality.

Spread, Production, and Applications of Bauxites

Published data concerning the spread and resources of bauxites around the world are highly controversial. Figure 7 shows how bauxite resources (in relative terms) are broken down by continents. Different experts' estimates of the global bauxite resources exhibit two-threefold differences. Foreign authors typically

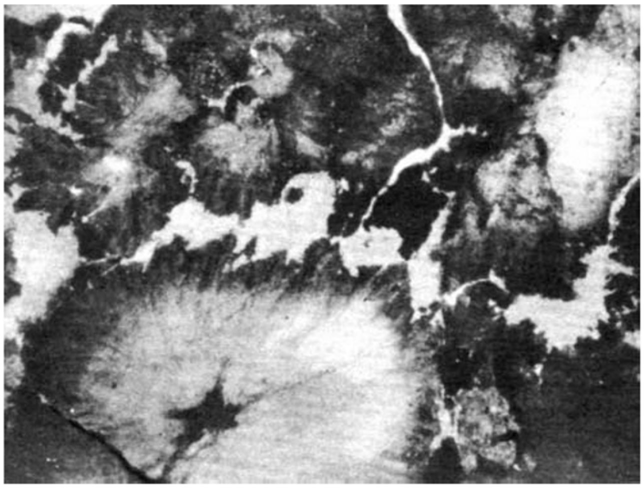

Fig. 6. Siderite spherulites. Thin section; ×20 magnification; parallel nicols.

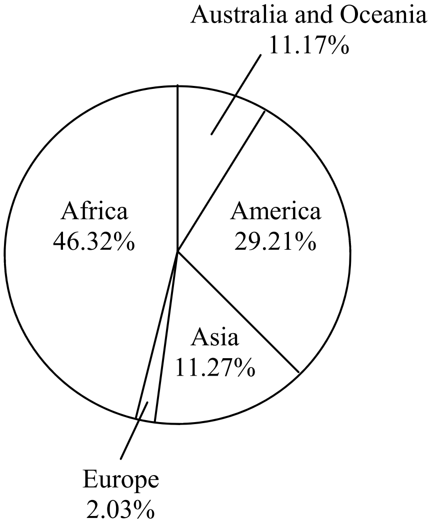

Fig. 7. Breakdown of bauxite resources by continents according to [15].

take into account only already explored reserves of high-grade bauxites, which leads to strongly underestimated bauxite resources availability.

Over 89% of total and ca. 86% of proven bauxite reserves are concentrated in 11 countries only: Australia, Brazil, Guinea, Jamaica, Venezuela, India, Cameroon, Indonesia, Suriname, Mali, and Cote d'Ivoire. The biggest deposits of bauxite ores exist in Australia, Brazil, Guinea, and Jamaica.

The amount of bauxites extracted worldwide is steadily growing, and ever widening range of countries get involved in bauxite extraction. Before the First World War, bauxites were extracted in five countries solely: France, the US, Italy, India, and British Guiana, which extracted a total of ~500 thousand tons of bauxites. On the eve of the Second World War there were already 12 countries involved in bauxite deposit development with the total bauxite production of 2.67 million tons, which level sharply increased to 12.5 million tons during the war period. In the years 1955, 1960, 1970, 1980, 1990, and 2000 the amount of bauxites extracted worldwide exceeded the prewar levels by the factor of 8, 14, 34, 37, and 45, respectively.

Currently, the major producers of bauxite ore raw materials are Australia, Guinea, Brazil, and Jamaica, which account for ca. 70% of the world's total bauxite extraction. The bauxite extraction industry in these countries underwent very rapid development. For example, in Australia the amount of extracted bauxites increased 100 times over the period 1960–1980 and continues to grow. Similar trends are also observed in Guinea. By now, ca. 2 billion 750 million tons of bauxites has been already extracted out of the ground, with the world's bauxite consumption rising by an annual increase of 1.2–1.3 million tons.

As to Russia, it does not possess such large and unique bauxite ore deposits as do Australia, Guinea, and Brazil. Out of fifty bauxite deposits that were put on Russia's state balance sheet only one-fifth was or is being developed. Virtually all commercially profitable deposits are located in the European part of Russia and in the Urals, in which area there exist seven bauxite-ore regions [15]; among them, only three (North Urals, Middle Timan, and North Onega) are involved in commercial mining of bauxites. In the Asian part of Russia, which is not involved in bauxite mining activities as yet, bauxites are dispersed over small deposits most of which are well off highways in hard to develop areas.

Mining industry in Russia is currently unable to satisfy the needs of Russian industry in domestic bauxite ores of acceptable quality. The situation with supply of bauxites to bauxite-consuming production entities continues to deteriorate. This is due to a dramatic decline in bauxite extraction at the North-Urals deposit, which is of primary importance for Russia, and to shutdown of bauxite production at the South-Urals and Tikhvin deposits. The total amount of bauxites extracted in Russia has declined by more than

35%, and the production of alumina intended for aluminum industry applications, by 30%. To satisfy its needs Russia has to import ca. 5 million tons of bauxites and up to 50% alumina from different countries annually.

However, significant improvement of the situation may be expected in the coming years through large-scale development of Middle-Timan bauxite deposits and construction, on their base, of an alumina refinery in the Komi Republic. Upon completion of the second stage of the entire complex the alumina production will be brought to 1.4 million tons (with 7.535 million tons of bauxites planned to be extracted in 2009 at the currently operating mine, including 6.45 million tons of marketable ore) [16, 17]. This will sharply reduce Russia's dependence on imports of these raw materials.

According to various estimates, most (80–85%) of bauxites mined worldwide is used to produce >95% of the world's primary aluminum, and from 10 to 20% goes for nonmetallurgical use, in particular manufacture of refractories, abrasives, alumina cement, coagulants, and high-strength ceramics. In the US, up to 2 million tons of bauxites is spent annually for these purposes. In Russia, only ca. 600 thousand tons of bauxite ores goes for such technical production, but the amount of these products may increase substantially in a short term. In the recent 15–20 years bauxites have found new applications, specifically, in manufacture of many types of advanced materials: structural, engineering, electrically conductive, and armor ceramics; composites having a wide range of performance characteristics; and high-acid-resistant coatings and items. The world production of special ceramics solely is amounting to over 9 billion US dollars. Importantly, the necessary production facilities can be established on the basis of small deposits having from several hundreds of thousands to the first few millions of tons of bauxite reserves. However, this concerns a high-quality ore to be comprised of white bauxites containing no greater than 2.5–3.0% (in terms of Fe_2O_3) iron. Such low-iron bauxites occur in numerous deposits over the world, but their intricate location in ore fields often prevents their selective mining.

The only Russia's real source of low-iron high-grade bauxites may be found in Middle-Timan deposits whose reserves of this bauxite type exceed 5 million tons. Studies undertaken by the Research Institute of Chemistry, Komi Scientific Center, Ural Division, Russian Academy of Sciences, showed that these bauxites are suitable for manufacture of all types of the above-mentioned high-technology products, in particular of ceramic and composite materials intended for special applications [18, 19]. The exploration, research, and technology work dedicated to other promising applications of low-iron bauxites is currently under way both abroad and in Russia.

REFERENCES

1. *The Encyclopedia of Mineralogy*, Frye, K., Ed., Stroudsburg (Pa.): Hutchinson Ross, 1981.
2. Allen, V.T., in *Proiskhozhdenie boksitov* (The Origin of Bauxites), Moscow: Izdatinlit, 1959, pp. 44–121.
3. Belyaev, V.V., *Mineralogiya i genesis boksitov Yuzhnogo Timana* (Mineralogy and Genesis of South-Timan Bauxites), Leningard: Nauka, 1974.
4. Khorosheva, D.P., *Litol. Polez. Iskop.*, 1969, no. 2, pp. 41–50.
5. Beneslavskii, S.I., *Mineralogiya boksitov* (Mineralogy of Bauxites), Moscow: Nedra, 1974.
6. Kulikova, G.V., Tsekhovol'skaya, D.I., and Shutov, V.A., *Dokl. Akad. Nauk SSSR*, 1974, vol. 217, no. 1, pp. 190–193.
7. Sokolova, M.F., *Problemy genezisa boksitov* (Problems of Genesis of Bauxites), Moscow: Nauka, 1975, p. 100.
8. Bushinskii, G.I., *Geologiya boksitov* (Geology of Bauxites), Moscow: Nedra, 1975.
9. Nikitina, A.P. and Sirotin, V.I., *Kora vyvetrivaniya* (Weathering Crust), Moscow: Akad. Nauk SSSR, 1967, issue 8, pp. 29–39.
10. Gutkin, E.S., *Geologiya i geokhimiya boksitov Severnogo Urala* (Geology and Geochemistry of the North-Urals Bauxites), Moscow: Nedra, 1978.
11. Brindley, G.W. et al., *The X-ray Identification and Crystal Structures of Clay Minerals*, Brown, G., Ed., 2nd ed., London: Mineralog. Soc. (Clay Minerals Group), 1961.
12. Belyaev, V.V., Yatskevich, B.A., and Shvetsova, I.V., *Devonskie boksity Timana* (Devonian Bauxites of Timan), Syktyvkar: Komi Nauchn. Tsentr, Ural Otd. Ross. Akad. Nauk, 1997.
13. Belyaev, V.V., *Vestn. Inst. Geol. Komi Nauchn. Tsentr, Ural. Otd., Ross. Akad. Nauk*, Syktyvkar: Geoprint, 2006, no. 3, pp. 2–7.
14. Gutkin, E.S, *Zap. Vses. Mineral. O–va*, 1958, Ser. 2, issue 5, part 87, pp. 614–617.
15. Skotarenko, V.V., in *Mineral'nye resursy razvitykh kapitalisticheskikh i razvivayushchikhsya stran* (Mineral Resources of the Developed Capitalist and Developing Countries), Moscow: Ministry of Geology of the USSR, All-Russia Inst. of Geol. of Foreign Countries/Institute Zarubezhgeologiya, 1990, pp. 137–152.

16. Belyaev, V.V., *Mineral'no-syr'evaya baza alyuminievoi promyshlennosti Rossii: Sostoyanie i perspektivy* (Mineral Resources Base of the Russian Aluminum Industry: Current Status and Prospects), Syktyvkar: Komi Nauchn. Tsentr. Ural Otd. Ross. Akad. Nauk, 1999.

17. Bronevoi, V.A., Mal'tsev, K.R., Karapetyan, A.V., and Ievlev, A.A., *Gorn. Zh.,* 2007, no. 3, pp. 28–31.

18. Goldin, B.A., Sekushin, N.A., and Ryabkov, Yu.I., *Elektroprovodyashchaya keramika na osnove malozhelezistykh boksitov Srednego Timana* (Electrically Conducting Ceramics Based on Low-Iron Middle-Timan Bauxites), Syktyvkar: 1992.

19. Goldin, B.A., Dudkin, B.N., Istomin, P.V., and Ryabkov, Yu.I., *Problemy sozdaniya spetsial'nykh vidov keramiki na osnove prirodnogo mineral'nogo syr'ya: operativno-informatsionnye materialy Prezidiuma Komi Nauchnogo Tsentra Ural'skogo Otdeleniya Rossiiskoi Akademii Nauk* (Problems of Development of Special Types of Ceramics Based on Natural Mineral Raw Materials: Oper. Inf. Mater., Presidium, Komi Scient. Center, Ural Branch, Russ. Acad. Sci.), Syktyvkar, 1994, p. 52.