Mineral and Elemental Composition Features of “Loose” Oolitic Ores in Bakchar Iron Ore Cluster (Tomsk Oblast)

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Abstract. Geo-technological investigation considerations of iron ore deposits within the Bakchar ore cluster are being carried out. The mineral and elemental composition of “loose” ores have been studied, embracing such important aspects as the distribution pattern of valuable and harmful impurities, the determination of element concentrators (such as vanadium, phosphate and sulphur) in basic minerals and the analysis of ore composition variation in volume ore cluster. Based on investigation results the mineral and elemental composition characteristic features of “loose” ores were defined. Although hydrogoethite was the basic identified ore mineral, such minerals as goethite, lepidocrocite, leptochlorite, siderite and hisingerite were also found. The deportment of calcium phosphate (anapaite) and phosphates of rare-earth elements (monazite, killarite), which are associated with the harmful impurity- phosphorous, are described. It has been defined that the ore constituent composition contains such persistent impurities as vanadium and manganese, the content of which is 0.35% and 0.03%, respectively. The “loose” ores are continuous in mineral composition, both in area and cross-section throughout the Bakchar ore cluster. Based on the sample element composition analysis the most perspective areas for further mineral processing could be: western with the fraction of 1...0.2mm. and eastern- fraction of 1...0.1mm.

1. Introduction
Bakchar ore cluster is located in south-eastern West-Siberian iron-ore basin, about 200km. north-westward from Tomsk (Figure 1). The total cluster area is 1200km² and the ultimate inferred resources involve 28bln. tonnes, classifying this formation as unique. These iron-producing deposits are typical coastal-marine facies sediments- gridstone, oolitic ores (minette), sandstone, siltstone (aleurolite) and clays. The ores are generally oolites of goethite-hydrogoethite and chlorite-hydrogoethite composition and are located in three formations (upward): Narimsk, Kolpashevsk and Bakchar [1, 2]. “Loose” ores formed under conditions of oolitic sand facies and are confined to the Bakchar bottom formation [3].

Since the ore finding and up to the present day numerous researchers, such as A. Babin, I. Nikolaev, N. Belous, A. Kondakov, U. Kazanski, A. Mazurov, V. Domarenko, A. Pshenichkin, L. Rikhvanov, E. Asochakova and others, have been exploring and surveying the iron ore deposits in the West-Siberian basin [1, 2, 4, 5]. However, despite the significant contribution of the above-mentioned researchers, the outstanding Bakchar ore valuation still remains an open problem.
Based on mineral composition and ore specifications the following ore types were distinguished by these researchers [1, 2, 4, 5]: hydrogoethite oolitic loose ore; gothite-hydrogoethite with siderite cement; leptochlorite-hydrogoethite oolitic ore with chlorite-argillaceous cement; gothite-hydrogoethite oolitic ore with hydromica cement; glauconite-hydrogoethite oolitic ore with siderite-chlorite cement. The ore components of these types are gothite-hydrogoethite and chlorite-hydrogoethite oolites, while the difference includes the nature and composition of the cement itself, which, in its turn, is determined by the facies environment. The classification of the above-mentioned ore types can be identified only in laboratory conditions by applying the detailed optical microscopic method. In this case, it is impossible to perform ore geometrization by type during geological prospecting and exploration, thus the identification of only 5-7 ore types is impractical and of little importance.

As a result of the detailed investigation of material composition and ore texture-structure specifications three natural ore types were identified: “loose”, medium and poorly cemented (or continuous) and closely cemented (sideritic). These ore types macroscopically contour ore sequence cross-sections as observed in drill-hole core samples.

Figure 1. Map of West-Siberian iron-ore basin [2, 4]: 1 – Cretaceous-Paleogene sea area; 2 – occurrence zone of coastal-marine iron ores; 3 – area of vast iron ore clusters (deposits).

2. Data Sources and Methodology

Based on the results of optical observations, X-ray fluorescence and electron microscopy, infrared spectroscopy (IR – spectroscopy) and mass-spectroscopy with inductive-coupled plasma (ICP-MS) the mineral and elemental composition characteristic features of “loose” oolitic ores have been considered. Cores were retrieved from the lower Bakchar formation (“loose” ore deposits) of the
western and eastern ore cluster areas. The core samples were divided into the following granulometric grades: more than 1mm; -1 - +0.5 mm; -0.5 - +0.2 mm; -0.2 - +0.1mm and less than 0.1mm. The testing of these core sample groups was performed by the “wet” screening method and further investigated under ore microscopy. Next, polished pressed blocks were made from above-mentioned fractions, then investigated in reflected X-ray fluorescene (HORIBA XGT-7200) and electron (Hitachi S-3400N) microscopy. Fraction mineral composition of less than 0.1mm was investigated on the infrared spectroscopy (IR-Fourier IR Prestige-21). The sample elemental composition was determined by ICP-MS method at the premises of Tomsk Polytechnic University (TPU).

3. Results and Discussion

In view of the results the granulometric composition of “loose” ores within the ore cluster area was determined as consistent. The following grade yields were determined: fraction more than 1mm-6.3%; -1 - +0.5 mm – 13.6%; -0.5 - +0.2 mm – 60.7%; -0.2 - +0.1mm – 12% and less than 0.1mm-7.3%. The highest grade yield was for fraction (-0.5 - +0.2 mm), which indicates that the bulk of ore components is concentrated here.

Based on optical and microscopic investigations the Bakchar cluster oolites can be classified as chlorite-hydrogoethite and hydrogoethite grains being of relatively consistent mineral composition. The average elemental composition of chlorite-hydrogoethite and hydrogoethite grains was determined on the X-ray fluorescene microscope. Due to the alumino-silicate mineral predominance, the first group is distinguished by reduced iron and phosphate content, but by increased silica, aluminum and potassium content. Hydrogoethite grains are characterized by the following elemental composition (based on X-ray fluorescene analysis-XFA data): Fe – 58.59 %, Si – 2.73 %, P – 1.17 %, Al – 3.17 %, K – 0.15 %, Mg – 0.15 %, Ca – 0, 16 %, Ti – 0.09 %, V – 0.16 %, O – 33.23 % and others.

Oolites and chlorite-hydrogoethite peas have a rather diverse mineral composition, being of 0.5mm. Such grains have consistent ilmenite impurities (figure 2), phosphate minerals and, rarely, zircon. The impurity size of titanite minerals is from 1 to 80-100 microns, including ilmenites and, presumably, pseudobrookites (TiO₂ – 20-30 %; Fe₂O₃ – 65-70 %). In some cases, tens of titanite impregnations can be found in one ore grain. Besides, there is zircon impregnation of 30-100microns in chlorite-hydrogoethite peas. According to the elemental composition, titanite and zircon mineral impregnations in oolites and peas are similar to those of ore minerals in Tugan ilmenite-zircon placer deposit (40km north-eastward from Tomsk). This assumes the fact that the source area for these components is common.

Consistent phosphate minerals of 1-2 to 50 microns are found in ferrous oolites and peas. There are different phosphates in composition: kularite, anapaite and monazite, whereas only anapaite impregnation is of 20-50 microns, while the remaining phosphates are abundant in ore components as micro-inclusions, concentric zones (figure 3A) and dendritic aggregates. However, the latter can only be found in chlorite-hydrogoethite pea composition. Rare-earth phosphates (kularite) which form either micro-inclusions or single interrupted circular zones (figure 3) are predominant in hydrogoethite oolitic with regularly zonal structure. In some cases, significantly disintegrated grains of prismatic habitus can be found, which, in composition correspond to monazitet with an increased content of La, Ce (18-20 % for each). Not only quartz, feldspar, glauconite, leptochlorite, magnetite, sphalerite and rutile (figure 3C), but also zircon, brazilite and galenite (figure 3B) can be found in oolite ores. Different terrigenous fragments (quartz, feldspar, goethite, hydrogoethite, magnetite, glauconite and clay mineral concentrations) act as “seed” components of oolite kernels.
According to the IF-spectroscopy results, characteristic sample wavelength frequency of less than 0.1 mm was obtained. The mineral composition fraction has a continuous behavior within the ore cluster area. Visible divergence could be observed only in those samples which are confined to the Kolpashevsk formation. This divergence can be explained by the occurrence of carbonate mineral in the sample itself and this fact is based on the specific IF spectrum frequency peak of 1420 and 877 cm$^{-1}$. Specifying the fraction less than 0.1 mm of “loose” Bakchar formation ores, it should be noted that these samples are of heterogeneous composition, which, in its turn, significantly impedes the precise and detailed diagnostics of the mineral phases. However, all the samples are approximately of one and the same composition.

Based on the IF-spectroscopy results, the following minerals can be found in the samples: ferrum oxides (hydrogoethite, lepidocrocite), clay minerals of the nontronite-beidellite group, purpurite and hisingerite. Ferrum oxides are determined by the specific frequency peaks of 912, 800..796, 488 cm$^{-1}$, clay minerals - maximum double peaks of 1032, 1008 cm$^{-1}$, as well as 912 cm$^{-1}$. The double peak of 1032, 1008 cm$^{-1}$ indicates the presence of aluminosilicate anion in the sample; however, this could superpose anion peak PO$_4^{3-}$, which impedes the identification of phosphate minerals. Purpurite is identified in some spectrums of double peak 796, 777 cm$^{-1}$. Carbonate minerals with wave frequency of 1420 and 877 cm$^{-1}$, which are probably ankerite, can be found in Kolpashevsk formation samples [6]. Carbonate minerals were also identified on the basis of X-ray structural analysis.

Elemental composition of “loose” ores are characterized by an average content of the following: iron - 35 and 38 %, phosphate - 0.41 and 0.32 %; vanadium – 0.16 and 0.18 % within the western and eastern areas, respectively. In this case, the iron content increases up to 5…8 % in a fraction of maximum yield percentage (fraction 0.5…0.2 mm).
The granulometric grade 1…0.2 mm within the western area includes a total yield of about 80 %, whereas the average content of iron, phosphate and vanadium would be 37,5, 0.49 and 0.17 % respectively, which, in its turn, simplifies the further treatment process of these ores. The granulometric grade 1…0.1 mm within the eastern area includes a total yield of about 86,2 %, whereas the average content of iron, phosphate and vanadium would be 39,4, 0.35 and 0.19 %, respectively, thus, regarding these ores as high grade ones.

**Figure 3.** Micro-inclusions in hydrogoethite oolites of fraction 0.5…0.2 mm (backscattered electron image): A- concentric zones and micro-inclusion of rare-earth phosphates (kularite); B- galenite in rare-earth phosphate within micro-cracks; C- sinige rutile impregnation.

### 4. Conclusions

In this paper the Bakchar cluster “loose” ores have been investigated. The results suggest that:

1. “Loose” oolitic ores are of medium-grained structure. The average yield of fraction more than 1mm includes 6.3 %; fraction of 1…0.5mm – 13.6 %; fraction of 0.5…0.2 mm – 60.7 %; fraction of 0.2…0.1 mm – 12 %; fraction of less than 0.1mm – 7.3 %. The highest grade yield was for fraction (-0.5 - +0.2 mm), which indicates that the bulk of ore components is concentrated here.

2. “Loose” ore-types include hydrogoethite and chlorite-hydrogoethite oolites, lepidocrocite-clay grains, lepidocrocite, hisingerite, clay minerals, siderite, glauconite, quartz fragments, opal and feldspar. Inter-mineral impregnations in oolites and peas include quartz, feldspar (orthoclase), sphalerite, rutile, zircon, beidellite, magnetite, calcium phosphates (anapaite), phosphates of rare-earth elements (monazite, kularite). Different terrigenous fragments - quartz, feldspar, goethite, magnetite, glauconite and clay mineral concentrations- act as “seed” components. The major hydrogoethite oolite bulk is concentrated in fraction 0.5…0.2mm with characteristic impregnation- minerals- kularite, ilmenite, rutile and galenite. The most significant group (more than 0.5mm) involves an equal distribution of chlorite-hydrogoethite and hydrogoethite oolites and a rather impregnation diversity. Fraction less than 0.1mm includes clay minerals (nontronite-beidellite group), hydroxysilicate minerals (hisingerite) with subordinate quantity of lepidochlorite (cronstedtite), purpurite, siderite, oolite ore
fragments and glauconite.

3. The basic "loose" ore mineral is hydrogoethite, where the iron content is 70%, while the remaining ferrous minerals include goethite, lepidocrocite, lepidochlorite, siderite and hisingerite. The harmful phosphate impurities can be consistently found in the ores. The minerals associated with phosphate impurities are calcium phosphates (anapaite) of 5…60 microns and phosphates of rare-earth elements (monazite, kularite) of nor more than 10 microns. Calcium phosphates are impregnations in fractions of more than 0.5mm, the average yield of which is not more than 20%. In the productive fraction 0.5…0.2 mm the phosphate impurities is associated with kularite which is observed as concentric zones and microscopic impregnations of 5microns in oolite structure. Microscopic phosphate inclusions in the productive fraction significantly affect processing results due to the fact that it is impossible to extract such inclusions mechanically. The remaining quantity of harmful impurities such as arsenic, copper, zinc, lead and tin, does not exceed allowable value for oolite ores. Besides phosphate there are also such impurities as vanadium and manganese, the content of which is up to 0.35 % and 0.3 %, respectively, in ore components. The content of titanium in ores is 0.8% and is associated with the following mineral impregnations: ilmenite, rutile and their fragments. The size of ilmenite and rutile impregnations is up to 80…100 microns, which means that it is possible to reveal them in association with quartz and feldspar impurities, if the coarseness is less than 0.2…0.1 mm.

4. Based on the sample analysis, the “loose” ore-types, retrieved from different areas and formations, are continuous in mineral composition, both in area and cross-section throughout the Bakchar ore cluster.

5. The elemental composition of “loose” ores within the western area includes the following average content: iron-35 %, phosphate-0.41 % and vanadium-0.16%, whereas within the eastern area, the average content includes: iron- 38 %, phosphate- 0.32 % and vanadium-0.18 %. The most productive granulometric grade 1…0.2 mm, within the western area, under conditions of 80% yield includes the following average content: iron- 37.5%, phosphate-0.49% and vanadium- 0.17%. The most productive granulometric grade 1…0.1 mm, within the eastern area, is about 86.2% yield. The average content of iron, phosphate and vanadium in this group is 39.4 %, 0.35 % and 0.19 %, respectively. Thus, the fraction 1…0.2 mm (in the western area) and the fraction 1…0.2 mm (in the eastern area) are the most promising ones in future processing.

6. It can be concluded that the basic process in oolite ore formation is oxidation of previously formed chloritic and hydromicaceous minerals with a high iron content, as well as microbiological processes and colloidal exsolution. In general, the formation of iron-ore oolites can be characterized as a multi-phase and heterogenous process.

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