

## Facies and sedimentation model of iron-ore sequence in Bakchar deposit

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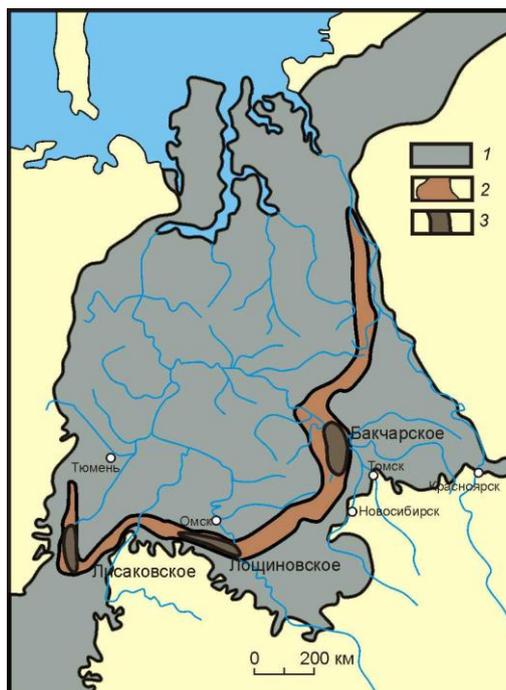
**Abstract.** This article describes the investigation in the behavior and structure features of the iron-ore sequence in Bakchar ore deposit. Five facies characterizing the typical sedimentation environments were identified based on the analysis of typomorphic attributes of ore-bearing and barren deposits. The facies where oolitic ores are localized have been determined. A conceptual sedimentation model of the Bakchar ore mineralization has been proposed. Two facies- littoral argillo-arenaceous ferriferous sediments and mobile shallow alluvium oolitics were proposed as prospecting indicators of oolite hydrogoethite ore deposits.

### 1. Introduction

The Bakchar ore deposit is located in the south-eastern West Siberian Iron Ore Basin (figure 1), i.e. 200 km NW of Tomsk. Iron occurrences in the West Siberian Iron Ore Basin have been traced within an area of 150 km wide and extending approximately 2000 km (from the Turukhan and Bolshaya Kheta River basin in the NE and to the Tobol river upstream in the SW). The ore-bearing sediments of the Bakchar ore cluster include typical sediments of coastal-marine facies: gravelites, oolite ores, sandstones, siltstones and clays. The iron ores are characteristic of goethite-hydrogoethite and chloride-hydrogoethite oolite composition and are confined to three horizons: Narym, Kolpashevo and Bakchar [1–2].

The first findings on the facies environments in iron ore sequences of the Bakchar ore occurrence and the West Siberian Basin were published by A Kondakov, I Nikolaeva and N Belous in 1964-1967 [3, 4]. The point is that facies differentiation of Bakchar ore-hosting sequences has not been furthered. The problem of ore formation has been addressed in several conference proceedings, however, positive findings have not been discussed [5, 6]. In this case, the conclusions about the typical Bakchar ore formation environments stated in the 1960s of the last century are the only and major ones available. Without doubt, ore sequence sediments are commonly considered to be coastal-marine ones. The prospecting-evaluating survey data of 2006-2014 provided up-dated information on the geological structure aspects of Bakchar area itself. The analysis of data and its correlation with modern understanding of sedimentary iron-ore deposit formation conditions (V Kholodov, R Nedoumov, Ye Golubovskaya et al. [7, 8]) provides the possible identification of facial features of Bakchar ore-hosting sequence.





**Figure 1.** Map of West Siberian iron-ore basin [2, 9]: 1 – areal limits of Cretaceous–Paleogene sea; 2 – zone of coastal-marine iron-ore sediments; 3 – areas of the largest iron-ore clusters.

## 2. Factual Material and Research Methods

The facies analysis data source included graphics of the 1960s, as well as physical and geological maps plotted on the results of prospecting–evaluating survey data of 2006–2008 and 2006–2014 in Bakchar ore deposits and occurrences. Therefore, integrated exploration embraced geological plans, cross-sections, borehole logging and core samples. To investigate sample substance composition the optical and electron microscopy methods were applied.

## 3. Facial Features of Bakchar Ore-Hosting Sequences

Based on investigation results of the Bakchar ore occurrences, the following ore-hosting sequence facies (according to Logvinenko classification, 1980 [10]) were identified: sand beach sediments in aggradation terraces and bars; argillic-ferrous silts in isolated stagnant depressions; oolite sands in mobile shallows – barriers and bars; sand–argillic–ferrous sediments in coastal bay zones; silt clays in the shallow marine shelf. It should be noted that the climate and sea-floor relief are important factors in facies differentiation. N Strakhov [11] stated that "... oolite ores are most commonly found the gulf, bay and island sea areas involving complex shoreline contours..."; "such ores usually accumulated in distinctly contoured submarine pits (potholes)..." (based on the investigation of oolite iron ores in Lotharingian and Kerch basins, as well as Ayat deposit). The lithological feature of the ore sequence correlated with the established concepts indicated the fact that these sediments had formed under humid climate.

### *Facies of sand beach sediments in aggradation terraces and bars*

Facies of sand beach sediments in aggradation terraces and plains (sea depth of up to several meters) are light–gray (often greenish) fine-grained sands, silts and poorly cemented fine–grained gray sandstones. The amount of ore oolites in these facies sediments rarely exceeds 10%.

These facies sediments formed in the ore occurrence area within Ipatovskaya suite top as a result of regression having formed the Narym ore horizon. The facies is exposed in the south-eastern part of the ore occurrence (figure 2–A). The facies on the map is of a NW trending offshore bar, pinching out in the central part of the ore occurrence. This bar was enclosed by a depression in which there was a sharp transition of predominating argillic–ferrous silt facies in isolated stagnant depressions.

#### *Facies of argillic-ferrous silts in isolated stagnant depressions*

Facies of argillic-ferrous silts in isolated stagnant depressions is related to coastal–marine facies with sea depth of up to 10 meters. Under the conditions of relatively calm wave dynamics and aleurolitic material denudation, gray thin clay layers with oolite inclusions formed.

The clays of this facies were abundant throughout the ore occurrence area within Ipatovskaya suite top (figure 2–A) isolated by a sand bar, which, in its turn, was washed out after subsequent transgression. Therefore, due to indistinct unconformity these sediments are superposed by sediments of shallow marine shelf silt clay facies. In the W and NW trending of the Ipatovsk suite top the facies of clay–iron silt facies grade to facies of sand–argillic–ferrous sediments in coastal bay zones.

#### *Facies of sand–argillic–ferrous sediments in coastal bay zones*

Facies of sand–argillic–ferrous sediments in coastal bay zones (sea depth between 10 and 40 m) includes the following lithogenetic types: cemented hydrogoethite–chlorite oolite ores, well–cemented hydrogoethite oolite ores, argillic chlorite and hydromicaceous cemented sandstones and greenish–gray aleurolites and clays. As a result of erosion caused by regression, weak (up to 2 m) gravelite lenses are observed. Sediment continuity is observed towards the shoreline. Gray, greenish sandstones change to oolite ores with argillic, chlorite–argillic and sometimes hydrogoethite cements, then to well–cemented siderite–chlorite and siderite cement at the bay bottom. Such a sequence could be explained by the regular succession of autigenous minerals in marine sedimentary iron ores in humid climate [11]. The sediments of this facies can be divided into two subfacies: aleurolite–clay–iron sediments on the bay slope and sand–iron sediments on the bay bottom.

(1) Subfacies of aleurolite–clay–iron sediments on the bay slope includes sandy aleurolites, sandstones with argillic and chlorite–argillic cement, oolite hydrogoethite–chlorite ores with argillic, argillic–chlorite and chlorite cement. The sediments of this facies formed on the bay slope where the environment reduction potential gradually increased progressively to depth, resulting in the formation of corresponding authigenic minerals (glauconite, montmorillonite, nontronite, leptochochlorite, iron sulfides–pyrite framboids. Hydrogoethite–chlorite grains are similar to irregular–shaped spheric oolites, peas with inner homogeneous structure of numerous micron–sized terrigenous debris, as a result of relatively constant and unidirectional geochemical and hydrodynamic mode. Conventionally, ore accumulated at times of pH changing from 5.0 to 6.5.

Aleurolite–argillic–ferrous sediments on the bay slope extend throughout the ore sequence. The sediments of this subfacies are 65–70% of the ore occurrence area in the Ipatovsk suite top (figure 2–A); 25–30 % in the Gankinskaya suite base (figure 2–B); 80–85% in the Gankinsk suite top (figure 2–C); and 10% in the Lulinvorskaya suite base (figure 2–D).

During the formation of the Ipatovsk suite top (70–80 million years ago), these sediments were located in the central part of the ore occurrence (figure 2–A), whereas, unstable underwater elevations were located in the southern and northern parts. Sandstones and oolite ores formed an inclined dipping elevation trending W–E towards the bay floor where the sediments of sandy–ferrous subfacies were extensive. A successive facies substitution of argillic cement sandstones to silt sandstones with chlorite–argillic cement, then, oolite ores with argillic–chloride and chlorite cement was observed from the central elevation areas to the bay bottom.

During the formation of the Gankinsk suite bottom as a result of the pre-Kolpashevo transgression within ore occurrence area, the shallow–water shelf environment with a NW trending underwater bar with aleurolite–argillic–ferrous sediments and ores with glauconite–chlorite cement was predominate (figure 2–B).

Then, during the final stages of the Kolpashev horizon formation in the Gankinsk suite top, the sediments of this subfacies embrace maximum distribution (figure 2–D). Within this area two depressions in the north and south were observed, where sediments of the sandy–ferrous subfacies were predominate on the bay bottom.

During the formation of the Lulinvorsk suite (50 million years ago), the sediments on the bay slope had subordinate occurrence. They occupied a narrow zone (figure 2–C) where shallow water bars separated oolite sands and shallow water shelf - aleuritic clays.

(2) Subfacies of sand–iron sediments on the bay bottom is mainly characterized by hydrogoethite oolite ores with chlorite–siderite, argillic–siderite and siderite cement. Such oolites usually have a concentric inner zone structure and show a significant disintegration. The cleavage of oolites indicates the fact of their transportation by wave currents and parallel oxidation of chlorite minerals. The ores formed on the bay bottom silt sediment at times of pH changing from 6 to 7. As a result of reduction potential increase during diagenesis, sphalerite microspherulites, as well as chlorite and carbonate minerals (e. g. siderite) formed and cemented by transported oxidized oolites. These sediments have been lithified due to profound diagenetic changes, which, in its turn, furthered the development of the sea bottom environment.

These facies sediments extensively accumulated in the top of Ipatovsk (figure 2–A) and Gankinsk (figure 2–C) suites throughout the ore occurrence area and occupied 15–20% of this area, in the Lulinvorsk suite basement (figure 2–D) -not more than 2%. During ore formation these sediments were the result of facial sediment replacement in associated facies. The sediments on the bay slope, as a rule, successively grade to bottom sediments.

#### *Facies of oolite sands in mobile shallows – barriers and bars*

Facies of oolite sands in mobile shallows – barriers and bars (sea depth -10–20 m) is characterized by loose hydrogoethite oolite ores, poorly- cemented ores with argillic cement, fine–grained dark gray sands. Hydrogoethite oolites have a contrasting concentric zoned inner structure which could be the result of oscillating geochemical (pH change within the range of 4–5) and hydrodynamic formation environment conditions. The sediments formed in shallow bar conditions. Due to wave action argillic fractions were transported from the upper bar zones, resulting in sediment succession. Consequently, the bars have the following structure: upper zone is composed of loose poorly-sorted hydrogoethite oolite ores gradually grading to fine–grained sands with argillic cement or poorly cemented ores in the middle or lower zones.

These facies sediments extensively accumulated in the Lulinvorsk suite bottom throughout the ore occurrence area and occupied 15–20% of this area. These sediments formed two shallow bars in the western and eastern areas of the ore occurrence, which, in its turn, are associated with loose ore-bodies.

#### *Facies of silt clays in the shallow marine shelf*

This facies belongs to the group of neritic facies (sea depth of over 40 m) and marks the transition to shallow marine environment. The sediments are gray (often greenish) parallel–layered clays and aleurolites. The clays comprise montmorillonite, nontronite, chlorites and other terrigenous minerals. During the ore sequence formation, the silty clay sediment facies extensively accumulated in the Gankinsk (figure 2–B) and Lulinvorsk (figure 2–C) suite basements and occupied about 70–75% of the ore occurrence area. Greenish–gray clays of this facies, as a rule, superpose iron–hosting sediments, indicating the closing ore sequence formation.

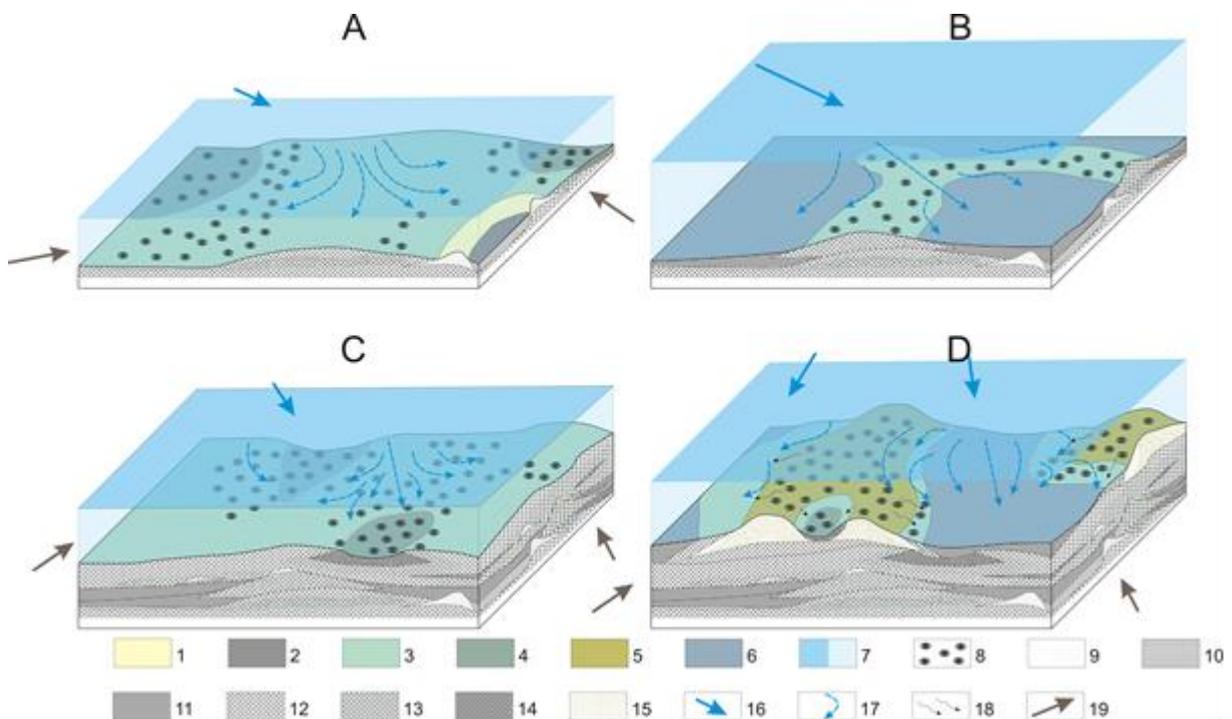
The sandy–argillic–ferrous sediments of coastal bay zones gradually grade to silty clays of the shallow shelf with depth increase. Observed cross–sections of such transitions showed that this was the result of transgression and normally have sharp boundaries indicating the formation of thin gravelite lenses after the rewashing of underlying sediments.

#### 4. Formation Model of Bakchar Ore–Hosting Sequence

The analysis of obtained data on the structure and facies features of the Bakchar ore sequence indicated the fact that the above- described environments have co-occured from the very beginning of the formation itself and changed during the transgressive–regressive cycles. Some authors have forwarded [4, 12] such a theory that well–cemented and loose ores are the products of oxidation and alteration of lepto chlorides with different cements. However, it should be noted that such oxidation processes occurred during the ore formation but were predominate in the formation of hydrogoethite ores which could be proved by their geochemical differentiation [13]. Therefore, a conceptual sedimentary model is proposed to explain the formation of the Bakchar ore occurrence (figure 2).

Initially, (Ipatovsk suite top (figure 2–A)) there were two silty depressions within the ore occurrence area where material was transported from the land and then transported by bottom wave currents resulting in the formation of a slightly north–north–west elevation, composed of aleurolite–argillic–ferrous sediments. Hydrogoethite ores with argillic–chlorite cement were formed on the elevation slope, while hydrogoethite ores with siderite cement formed on the bay bottom. In the south–east area, as a result of sand material deposition, south–west offshore bar was formed partitioning off the stagnant depression where gray and dark gray layered clays and aleurolites were deposited.

Further, during the post–Narym wave action transgression [2] (Gankinsk suite basement) resulted in the formation of an underwater bar (figure 2–B) extending from SW to NE, where shallow–water silty clays were formed on both sides. This bar was composed of oxidized hydrogoethite–chlorite ores of early generation and glauconite sandstones.



**Figure 2.** Conceptual sedimentation model of Bakchar iron ore occurrence. A – Ipatovsk suite top; B – Gankinsk suite basement; C – Gankinsk suite top; D – Lulinvorsk suite basement; 1 –facies of

sand beach sediments in aggradation terraces and bars; 2 – facies of argillic-ferrous silts in isolated stagnant depressions; facies of sand–argillic–ferrous sediments in coastal bay zones: 3 – subfacies of aleurolite–clay–iron sediments on the bay slope; 4 – subfacies of sand–iron sediments on the bay bottom; 5 -facies of oolite sands in mobile shallows – barriers and bars; 6 - facies of silt clays in the shallow marine shelf; 7 -diagrammatic sea level; 8 - oolite ore formation area (scheme view); 9 - gray sands, silts and poorly-cemented sandstones; 10 - aleurolites and clays of argillic-ferrous silt stagnant depression facies; 11– aleurolites and clays of silt clay shallow marine shelf facies; 12 - cemented barren sandstones; 13 - cemented hydrogoethite–leptochlorite ores; 14 - closely–cemented hydrogoethite ores; 15 - loose hydrogoethite ores; 16 - sea movement direction; 17 - supposed directions of bottom waves; 18 - direction of material denudation in the bottom; 19 - direction of material input.

As a result of successive regressions (Gankinsk suite top), two silt depressions (figure 2–C) formed within the N-S ore occurrence areas, where the transported ore material was found. Subfacies of sandy–ferrous sediments predominated in such depressions where ores with siderite cement were mainly formed. Chlorite–goethite oolite ores and sandstones deposited on the bottom slope. After the following transgression, the sea advanced from the north, "heading" towards the southern bay depression, resulting in the formation of two underwater bars in consequence of dubottom wave action in the shallow zone (figure 2–D). The oolites transported from the bar sediments formed ores with siderite cement in the bay bottom, which, in its turn, graded to shallow-water clays. After a significant post–Bakchar transgression [2], aleurite clay sediments overlapped these ore deposits after which ore genesis did not proceed.

## 5. Conclusion

The proposed sedimentation model does not fully exclude the existing problem, i.e. the sources of ore matter ( for example, ancient crust weathering or catagen- connate waters in oil and gas bearing basins). Nevertheless, the analysis of the obtained data showed that the facies factor is predominating in determining the shape and location of ore substance. The singled out facies in the ore occurrence area only rarely develop lateral succession from the central part of the bay (silt depressions) to the coastal beach zone, which could be explained by the frequent transgression–regression cycles.

Facies of sand–argillic–ferrous sediments in coastal bay zones and facies of oolite sands in mobile shallows could be considered as a prospecting tool for oolite hydrogoethite deposits in different areas of the West–Siberian iron–ore basin.

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