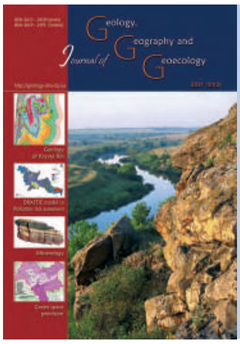

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Mineralogical justification for potentiality of producing marketable hematite products

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Abstract. Hematite quartzites are a product of weathering of magnetite quartzites, which make up the ferruginous horizons of deposits of the Precambrian banded-iron formation. They occur all over the planet. The largest deposits are found in the iron-producing areas and basins of Central Kazakhstan, the Kursk magnetic anomaly, the Karelian-Kola region, Western Australia, Southeastern India, Brazil, the United States, and Canada. The geological and mineralogical issues of hematite quartzites as raw materials for producing concentrate and sinter ore have been studied most deeply and comprehensively for the deposits of the Kryvyi Rih basin and Central Kazakhstan. However, when developing an effective scheme for producing high-quality metallurgical raw materials, the mineralogical features of hematite ores have been taken into account insufficiently. The aim of the authors of the present work was to study the localization, structure of deposits and mineral composition of hematite quartzites as raw materials for sinter ore and concentrate production. Data from geological observations and mineralogical studies were used as source material. Proven geological, mineralogical, petrochemical methods were used. In accordance with the obtained results, the hematite quartzites are composed of ore-forming (quartz, hematite) and secondary (relict and newly formed) minerals. The total content of the hematite and quartz exceeds 90 mass %. The peculiarity of Ushkatyn III deposit ores is the high content of manganese oxides. The depth of distribution of the weathering crust composed of hematite quartzites varies from 200 to 1000 m. The hematite quartzites' bodies are characterized by a zonal structure. Their central parts are represented by martite-micaceous hematite, micaceous hematite-martite quartzites; intermediate ones by martite quartzites; peripheral parts – by dispersed hematite-martite, kaolinite-martite-dispersed hematite quartzites. The horizons differ in the quantitative ratio of these varieties. The quantitative ratio of mineral varieties of hematite quartzites, morphology of individuals and aggregates of ore-forming and secondary minerals, their chemical composition and physical properties must be taken into account when developing the optimal technology for the production of high-quality hematite concentrate.

Key words: Precambrian banded-iron formation, hypergenesis, hematite quartzite deposits, mineralogical zonation

Мінералогічне обгрунтування можливості виробництва гематитових товарних продуктів

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Анотація. Розглянуті питання локалізації, будови та складу гематитових кварцитів Валявкинського родовища (Криворізький басейн) та родовища Ушкатин ІІІ (залізорудний район Каражал) як первинної сировини для виробництва високоякісних товарних гематитових продуктів. Охарактеризовані процеси мінералогічних перетворень вихідних метаморфогенних магнетитових кварцитів, поклади яких у поточний час розробляються гірничозбагачувальними комбінатами Центрального Казахстану, Курської магнітної аномалії, Карело-Кольського району, Криворізького басейну та інших регіонів планети. Показано, що найбільш глибоко та всебічно питання мінералогічного обгрунтування збагачуваності гематитових кварцитів розглянуті для родовищ Криворізького басейну. Потужність кори вивітрювання їх залізорудних товщ, складеної гематитовими кварцитами, коливається від 50 до понад 2500 м. Автори виконали детальні геологічні, мінералогічні дослідження покладів гематитової сировини. Встановлено, що поклади гематитових кварцитів зосереджені, головним чином, в корі вивітрювання четвертого, п'ятого, шостого залізистих горизонтів саксаганської світи Валявкинського родовища та залізорудної товщі родовища

Ушкатин ІІІ. Для всіх їх властива мінералогічна зональність, проявлена закономірною зміною в напрямку від центральних до периферійних частин горизонтів верств гематитових кварцитів наступного мінерального складу: мартит-залізнослюдкові – залізнослюдко-мартитові – мартитові – дисперсногематит-мартитові – каолініт-мартит-дисперсногематитові. Гіпергенна зональність наслідує первинну аутигенну метаморфогенну зональність цих залізистих горизонтів. Мінеральний склад зазначених п'яти різновидів гематитових кварцитів аналогічний в розрізах усіх досліджених рудних покладів. Відміна полягає в різному кількісному співвідношенні мінеральних різновидів у розрізах залізистих горизонтів. Рудоутворювальні мінерали гематитових кварцитів – кварц і гематит, представлений трьома морфологічними різновидами (мартит, залізна слюдка, дисперсний гематит). Їх загальний вміст перевищує 90 мас.%. Другорядними є реліктові (магнетит, матаморфогенні силікати, карбонати, сульфіди) та новоутворені (гетит, каолініт) мінерали. Мінералогічні особливості гематитової сировини та хімічні, фізичні показники рудоутворювальних і другорядних мінералів необхідно враховувати при розробці оптимальної схеми виробництва високоякісної металургійної сировини.

Ключові слова: докембрійська залізисто-кремниста формація, гіпергенез, поклади гематитових кварцитів, мінералогічна зональність

Introduction

Hematite (martite) quartzites are the product of weathering of magnetite quartzites, which are currently mined in many regions of the world as a raw material for producing iron ore (magnetite) concentrate. Industrial deposits of hematite quartzites occur in the iron ore strata of most deposits of the Precambrian banded-iron formation. Their distribution is mainly controlled by two factors: 1) the effective action of hypergenic factors on primary magnetite quartzites; 2) the intensity of erosion of iron ore strata weathering crust under formation. The most significant reserves and resources of hematite raw materials were identified at the Karazhal deposit (Central Kazakhstan), Lebedinsky, Mikhailovsky and other deposits of the Kursk magnetic anomaly, Olenegorsk deposit of the Kola iron ore district, Kryvyi Rih basin (Ukraine), Hamersley deposits (Western Australia), the Quadrilátero Ferrífero (Brazil), the Upper Lakes (USA), etc. In the CIS countries, the problem of the use of hematite quartzites has been studied most deeply and comprehensively for the Kryvyi Rih basin deposits (Demchenko, 2018; Evtekhov, 2016; Prilepa, 2019; Tsypin, 2015).

Currently, the problem of the use of hematite raw materials at the mining and beneficiation enterprises of Kryvbas is being studied in connection with the increase in the level of integrated use of the mineral mass extracted from the subsoil. The priority directions involve the operation of deposits of hematite (oxidized) quartzites in order to produce sinter ore and concentrate . In the course of mining operations, hematite quartzites are extracted as overburden and accumulated at specially organized stockpiles (Southern Mining and Beneficiation Plant (YUGZK), ArselorMittal Kryvyi Rih (AMKR) Mining and Beneficiation Complex, or are stocked at waste dumps (Inhulets, Central, Nothern GZKs).

The depth of the weathering crust of different Kryvbas deposits varies from less than 50 m in areas of crust distribution to more than 2,500 m in areas of linear weathering crust along discontinuous faults (Dodatko, 1973; Yurk, 1960). .

The Skeliuvatka (Southern GZK) and Valyavkinske (AMKR GZK) hematite quartzite deposits belonging to the Southern iron ore region of the Kryvbas are recognized to be the priority for the development. The explored reserves of hematite raw materials here exceed 2 billion tons. The deposits were considered to be the raw material base for oxidized ores GZK (GZKOR).

The authors studied the bodies of hematite quartzites of the Valyavkinske deposit in detail, the explored reserves of which make up about 25 mass % of its productive stratum. The depth of distribution of the weathering crust of magnetite quartzites varies from 200-250 m in the southern part to 700-800 m in the northern part of the deposit. A significant part of the hematite raw material (about 400 million tons) was extracted from the subsoil and is stored in two stockpiles. Reserves in the subsoil are about 500 million tons. The average iron content in hematite quartzites is about 37 mass %.

Since the 1960s attempts have been made to use hematite raw materials on a commercial scale. Concentration plants were designed and built on the basis of magnetic technology for beneficiating low grade hematite ores: roasting-magnetic plant for beneficiating hematite quartzites of Central GZK, Kryvyi Rih GZKOR, section №10 of the beneficiation plant #2 of AMKR GZK. The obtained results showed that it is impossible to obtain hematite concentrate with an iron content of more than 60-61 mass % in industrial conditions by the method of wet magnetic separation. The suggested repreparation of the rough concentrate by the method of reverse flotation contributed to the increase of the iron content in the final concentrate to 64-65 mass %. Thus, flotation recovery does not allow a high quality concentrate to be obtained (67-69 mass %).

The technology of wet gravitational beneficiation with the use of conical and spiral separators has proved to be the most effective. In the Kryvbas, it is implemented in three industrial plants with a capacity of up to 1 million tons of raw materials per year, it allows hematite concentrate to be obtainined with iron content of not less than 65 mass %. Semi-industrial tests were also conducted for the ores of the Karazhal, Ushkatyn III deposits.

The results of laboratory and industrial tests of the authors of the present work showed the fact that it is possible to produce the end-product with various iron content from hematite quartzite deposits of Karazhal iron ore region, Southeast India, Kursk magnetic anomaly, Kryvyi Rih basin and similar deposits from other regions depending on the selected technologies for ore preparation and beneficiation: low-grade sinter ore (total iron content 55-57 mass %), ordinary sinter ore (58-60%), high-quality sinter ore (60-62%), sinter concentrate (62-64%), ordinary concentrate (64-66 %), high-quality concentrate (67-69%).

The **goal** of the authors of this work was to study the localization, structure of deposits and mineral composition of hematite quartzites as raw materials for the production of sinter and concentrate using the example of the Valyavkynske deposit in the Kryvbas and the Ushkatyn III deposit in Central Kazakhstan.

Source material and research methods

The results of geological observations and mineralogical studies of hematite quartzites of these deposits were used as source material. Proven geological and mineralogical methods were used.

Research results

The *Valyavkinske deposit* of ferruginous quartzites is located in the southwestern part of the Kryvyi Rih structure (Fig. 1). The rocks of the Skeliuvatka, Saksagan and Hdantsivka suites of the Kryvyi Rih Paleoproterozoic series occur in its structure. The Novokryvorizka and Hleyuvatka suites within the deposit boundaries have not been opened up (Belevtsev, 1962; Svital'skyi, 1932; Shcherbak, 1988).

Geology of hematite raw material deposits. Geologically, the deposits of hematite raw materials of the Kryvbas and Central Kazakhstan are similar, represented by layers, lenses of hematite quartzites, which alternate with layers of low-ore, ore-free rocks. They differ in age - Paleoproterozoic deposits of the Kryvbas, Paleozoic - Central Kazakhstan and mineral composition: the deposits of Central Kazakhstan are characterized by manganese-iron ore specialization. The genesis of both iron ore basins is volcanic-sedimentary.

As the main object, the authors have chosen the more deeply and comprehensively studied deposits of the Saksagan suite of the Kryvbas.

The Saksagan suite is represented by six schistose and six ferruginous horizons. The thickness of the weathering crust of the first, second and third ferruginous and first, second, third, fourth schistose horizons does not exceed 50-70 m. The main deposits of hematite ores belong to the fourth, fifth, sixth ferruginous horizons.

The fourth ferruginous horizon is characterized by a thickness of 260 to 540 m, 392 m on average. Up to a depth of 200 to 400 m it is composed of hematite quartzites, below it – of magnetite quartzites, which are currently mined as raw materials for producing magnetite concentrate. The horizon is characterized by the heterogeneity of the mineral composition, structural and textural features of the ores, corresponding to the features of the authigenic mineralogical zonation of ferruginous horizons (Evtekhov, 1971; Lazarenko, 1977; Strakhov, 1962). The central zones of the horizon are represented by micaceous hematite-magnetite, the intermediate ones – by magnetite, peripheral zones – by cummingtonite-magnetite and magnetite-cummingtonite quartzites. In this direction, the texture of ores naturally changes, from thin-bedded to medium-bedded and wide-bedded. The average value of the total iron content ($Fe_{tot.}$) is about 37 mass %, the iron content in the magnetite ($Fe_{magn.}$) makes up about 32 mass %.

There was a change in the mineral composition of ores in the weathering crust due to iron oxidation. The section of the horizon here in the same direction is as follows: micaceous hematite-martite → martite → dispersed hematite-martite → kaolinite-martite-dispersed hematite quartzites. In the upper parts of the weathering crust there is an intense goethitization of ferruginous quartzites to a depth of 30 m. The textural features of the ores are preserved. The average value of the total iron content due to its poor mobility in the weathering crust is almost unchanged, it makes up 37.2 mass %, the iron content in the magnetite varies from less than 1 mass % (in the upper part of the weathering crust) to 15 mass % (in the lower part).

The fifth schistose horizon is composed of alternating layers of barren quartzites and graphite-containing schists of muscovite-chlorite-cummingtonite-quartz-biotite composition. The thickness of the horizon varies from 20 to 50 m.

The fifth ferruginous horizon for the entire depth of deposit development (up to 700 m) is composed of weathering products of magnetite-micaceous hematite, micaceous hematite-magnetite, magnetite, cummingtonite-magnetite and magnetite-cummingtonite quartzites. The presence of powerful layers of magnetite-micaceous hematite quartzites in the central parts of the fifth ferruginous horizon is dissimilar

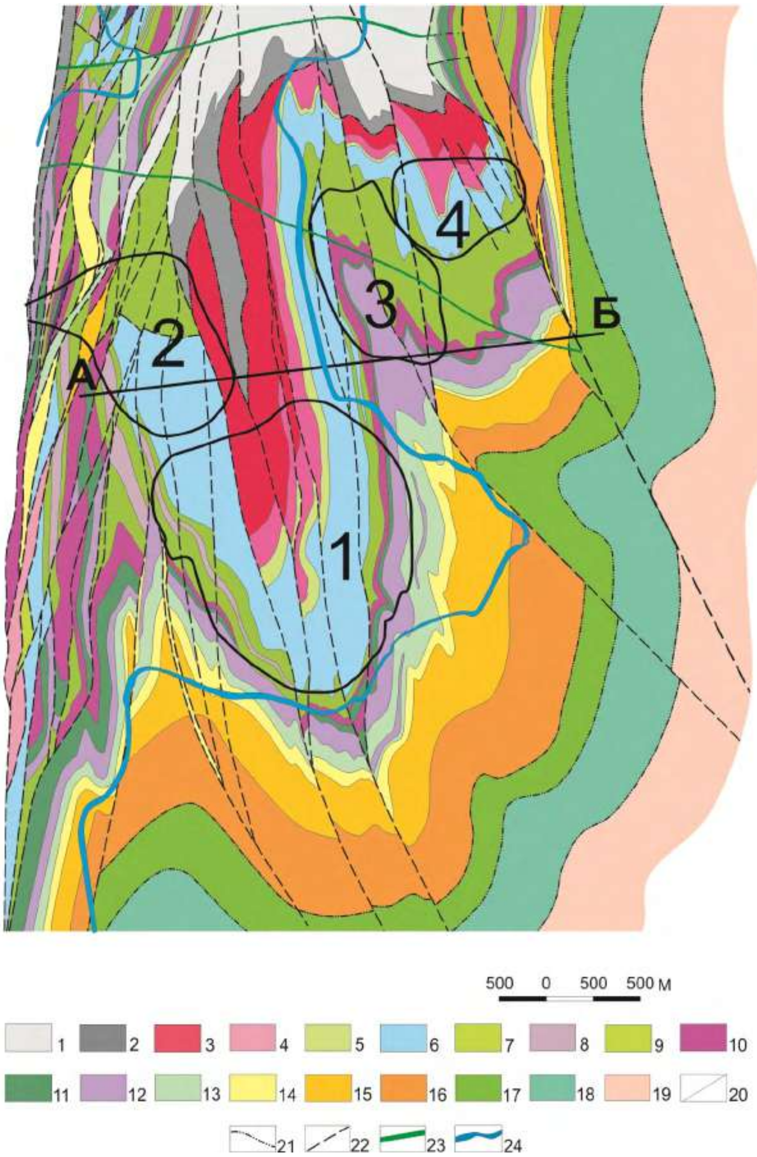

Fig. 1. Geological map of the area of the Skeliuvatka and Valyavkynske deposits.

1-17 – Kryvyi Rih series: 1-2 – Hdantsivka suite: 1 – metaclastolites and dolomite marbles of the upper subsuite; 2 – metaclastolites and high-grade iron ores of the lower subsuite; 3-13 – Saksagan suite: 3, 4 – hematite quartzites of the sixth (3) and fifth (4) ferruginous horizons; 5, 7, 9, 11, 13 – schists with interlayers of barren quartzites of the fifth (5), fourth (7), third (9), second (11) and first (13) schistose horizons; 6 – magnetite quartzites of the fourth ferruginous horizon; 8, 10, 12 – magnetite-silicate and silicate-magnetite quartzites of the third (8), second (10) and first (12) ferruginous horizons; 14-16 – Skelyuvatka suite: 14 – talc-containing schists of the upper subsuite; 15 – quartz-muscovite schists (phyllites) of the middle subsuite; 16 – muscovite quartzites, metaconglomerates (arcoses) of the lower subsuite; 17 – metaclastolites with interlayers of amphibolites of the Novokryvorizka suite; 18 – amphibolites with interlayers of metaclastolites of the Konka series; 19 – granitoids of the Dnipropetrovsk complex; 20 – contact lines of stratigraphically conformably occurring strata; 21 – contact lines stratigraphically inconsistent with the strata; 22 – faulting; 23 – diabase dykes; 24 – the bed of the river Ingulets.

Iron ore quarries: 1 - Skelyuvatsky of the Southern GOK; 2, 3, 4 - (respectively) Valyavkynsky, Novokryvorizhsky-2, Novokryvorizhsky -1 GOK of the AMKR plant.

AB is the line of the reference section of the productive stratum of the Southern iron ore district of Kryvbas.

to the fourth and sixth ferruginous horizons. In the weathering crust, these magnetite-containing ferruginous quartzites are transformed into martite-micaceous hematite, micaceous hematite-martite, martite, dispersed hematite-martite, and kaolinite-martite-dispersed hematite quartzites. The ores of the fifth ferruginous horizon are characterized by a micro- (less than 2 mm) and thin-bedded (2-5 mm) texture. The average iron content in ferruginous quartzites of the weathering crust is slightly higher than the corresponding indicators of the fourth and sixth ferruginous horizons making up about 38 mass %. The average iron content in the magnetite is about 4 mass %. The thickness of the horizon varies from 50 to 150 m.

The sixth schistose horizon is also composed of hypergenically altered ferruginous rocks – low-ore dispersed hematite-martite, martite, and ore-free quartzites, which are often intensely marshalitized. Silicate, quartz-silicate interlayers of initial rocks have been converted into kaolinite-dispersed hematite-quartz ones. The thickness of the horizon varies from 10 to 50 m.

The sixth ferruginous horizon completes the section of the Saksagan suite of the deposit. Its section is similar to the section of the fourth ferruginous horizon. At a depth of up to 700 m, the original magnetite-containing ferruginous quartzites are replaced by hematite varieties. Its constituent rocks are also intensely hypergenically altered. The texture of ores is medium-bedded, more rarely thin-bedded and wide-bedded. The average content of $Fe_{tot.}$ is 36.7 mass %, that of $Fe_{magn.}$ is 0.8% in hematite quartzites of the horizon. The thickness of the horizon within the boundaries of the deposit is from 200 to 500 m.

The mineral composition of hematite quartzites of the fourth, fifth and sixth ferruginous horizons of the Valyavkinske deposit is relatively simple due to the hypergenic replacement of polymineral associations of primary metamorphogenic magnetite quartzites by their hypergenic hematite varieties:

– magnetite has been replaced by hematite (martite);

– iron-free carbonates (calcite, dolomite, etc.) have been completely dissolved;

– iron-containing carbonates (siderite, sideroplesite, pistomessite, etc.) have partially been dissolved (calcium, magnesium components), the iron component has been replaced by dispersed hematite or dispersed goethite;

– iron sulfides (pyrite, pyrrhotine, etc.) have been replaced by dispersed hematite or dispersed goethite; sulfur in the form of sulfur dioxide passed into solution;

– alumina-free silicates (cummingtonite, ferrous talc (minnesotaite), celadonite, etc.) have been replaced by an aggregate of fine-crystalline quartz (chalcedony, opal) and dispersed hematite (dispersed goethite); the calcium and magnesium ions, which are a part of them, passed into solution;

– alumina-containing silicates have been replaced by fine crystalline aggregate of quartz, dispersed hematite (dispersed goethite) and kaolinite (Lazarenko, 1977; Martynenko, 1971; Yurk, 1960).

Thus, polymineral aggregates of initial metamorphogenic magnetite ores have been replaced by bimineral (hematite + quartz) or trimineral (hematite + quartz + kaolinite) associations of hypergenic hematite ores; in the upper parts of the weathering crust – by trimineral (hematite + quartz + goethite) or four-mineral (hematite + quartz + kaolinite + goethite) associations.

Due to incomplete substitution, relic magnetite has been preserved in hematite ores in an amount of from less than 1 to 15 mass %. The average content of $Fe_{magn.}$ as a part of hematite raw materials of all three studied ferruginous horizons is 4.2 mass %.

Hematite is represented by three morphological varieties: martite (a granular variety), iron mica (a lamellar, scaly variety) and dispersed hematite (a fine-crystalline, pulverized variety); goethite – by two of them: proper goethite (dripstone metacolloid aggregates) and dispersed goethite (fine-crystalline, pulverized variety). Occasionally lepidocrocite is present in goethitized hematite quartzites. The magnetite content, as noted above, increases with depth. Its relict sharply xenomorphic buildups are usually present in the central parts of martite aggregates (Martynenko, 1971; 1932; Yurk, 1960).

Quartz is the leading nonmetallic mineral. The amount of relict silicates (cummingtonite, biotite, chlorite, celadonite, etc.) and iron carbonates (sideroplesite, pistomesite, ferrodolomite, dolomite, calcite, aragonite, etc.) gradually increases with depth. Accessory minerals include sulfides (pyrite and less commonly pyrrhotine and cellular pyrite), zircon, apatite, tourmaline, garnet, etc.

Hematite quartzites of all three ore bodies are also divided according to the main textural feature – the thickness of the interlayers into: microbedded (jaspilite-like ones) (the thickness of the interlayers is less than 2 mm); thin-bedded (2-5 mm); medium-bedded (5-10 mm); wide-bedded (10-20 mm); coarsely-bedded (20-50 mm); giant-bedded (more than 50 mm).

The quantitative ratio of mineral varieties of hematite quartzites in the ore bodies of the three ferroginous horizons, which has been determined from detailed geological exploration data, operational exploration data and topomineralogical studies conducted by the authors, of the faces of the Valyavkynskyi open-pit, is given in Table. 1.

Fig. 2 shows schematic sections of the fourth, fifth and sixth ferruginous horizons. As can be seen, they are represented by the same mineral varieties of hematite quartzites, but differ in quantitative ratio. The fifth ferruginous horizon is characterized by the maximum prevalence of micaceous hematite-containing varieties, and the fourth and sixth ones are characterized by prevalence of martite varieties.

The ore mined in the open-pit and accumulated in stockpiles contains mineral varieties of low-grade hematite ores of the three studied ferruginous horizons in the amount determined not only by the natural ratio

Table 1. Quantitative ratio (mass %) of mineral varieties of hematite quartzites in the ore bodies of the fourth, fifth and sixth ferruginous horizons

Mineral varieties of ferruginous quartzites	Stratigraphic horizons		
	the fourth ferruginous	the fifth ferruginous	the sixth ferruginous
martite-micaceous hematite	2.9	12.7	8.5
micaceous hematite-martite	12.8	26.8	20.7
martite	44.1	35.3	37.9
dispersed hematite-martite	29.0	18.1	23.6
martite-dispersed hematite, kaolinite-martite-dispersed hematite	11.2	7.2	9.3

of hematite raw materials in the subsoil, but also by the dynamics of stripping conducted in different directions of open-pit development. Petrographic study of the material of hematite quartzite stockpiles showed that the following quantitative ratio of the main mineral varieties of low-grade hematite ores (volume %) can be expected in the primary hematite quartzite raw material of the beneficiation plant of the Valyavkynske deposit: martite-micaceous hematite quartzites; micaceous hematite-martite quartzites – 19.3; martite quartzites – 36.9; dispersed hematite-martite quartzites – 23.9; martite-dispersed hematite quartzites – 8.1. The average content of diluting non-metallic impurities (schists of different composition, silicate quartzites) in the ore material is 4.8% by volume.

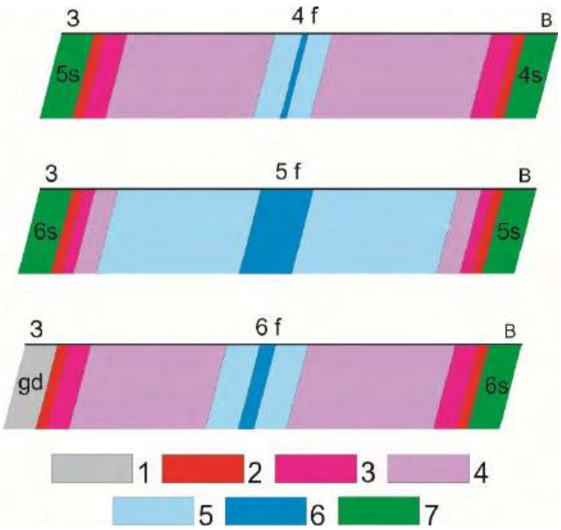

Fig. 2. The scheme of horizontal zonation of hematite quartzite deposits of the fourth, fifth and sixth ferruginous horizons of the Valyavkynske deposit.

Stratigraphic horizons of the Saksagan suite: 4s – the fourth schistose; 4f – the fourth ferruginous; 5s – the fifth schistose; 5f – the fifth ferruginous; 6s – the sixth schistose; 6f – the sixth ferruginous; gd – Hdantsivska suite.

Mineral varieties of ferruginous quartzites and other rocks: 1 – metaclastolites of the Hdantsivska suite; 2 – martite-micaceous hematite quartzites; 3 – micaceous hematite-martite quartzites; 4 – martite quartzites; 5 – dispersed hematite-martite quartzites; 6 – martite-dispersed hematite, kaolinite-martite-dispersed hematite quartzites; 7 – cummingtonite-siderite-chlorite-quartz-biotite schists of the fourth, fifth and sixth schistose horizons.

Mineralogy of ores. *Martite-micaceous hematite quartzites* are the product of weathering of the original magnetite-micaceous hematite quartzites (Fig. 3a). They form layered, less often lenticular bodies which are up to 50 m thick, spatially tend to the central zones of the studied ferruginous horizons. The ores are strong, relatively easily cleave along lamination. The structure is microcryptocrystalline and fine-crystalline. The texture is micro-bedded, rarely thin-bedded and medium-bedded. The quantitative ratio of ore-forming and secondary minerals is given in Table 2.

Micaceous hematite-martite quartzites are the product of weathering of the original micaceous hematite -magnetite quartzites. They are represented by embedded bodies, which are up to 50 m thick, spatially tend to the central zones of the studied ferruginous horizons. The ores are strong, in the areas of marshalitization the strength decreases significantly, the ore becomes loose. The structure is microcryptocrystalline and fine-crystalline. The texture is thin-bedded, rarely micro- and medium-bedded.

Table 2. The average mineral composition (vol.%) of hematite quartzites of the fourth, fifth and sixth ferruginous horizons

Minerals	Mineral varieties of hematite quartzites				
	MrMhs	MhsMr	Mr	DhMr	MrDh
quartz	51.4	51.1	50.2	49.7	48.8
martite	19.5	27.1	3,3	29.2	16.2
micaceous hematite	2.8	12.4	2.5	0.3	0.0
dispersed hematite	0.6	0.8	2.1	8.1	17.1
magnetite	2.7	2.9	3.0	2.9	2.5
goethite	2.9	3.1	3.4	3.5	3.9
dispersed goethite	0.5	0.7	1.1	2.0	3.8
carbonates	0.8	0.9	1.1	1.3	0.9
apatite	0.1	0.1	0.1	0.2	0.2
kaolinite, beidellite	0.1	0.2	0.5	1.9	5.4
pyrite, cellular pyrite	0.1	0.1	0.1	0.1	0.2
other minerals	0.5	0.6	0.6	0.8	1.0
Total	100.0	100.0	100.0	10.,0	10.,0

Other minerals: hydromicas, chlorite, cummingtonite, celadonite, stilpnomelane, Fe-talc (minnesotaite), garnet, zircon, tourmaline, chloritoid, gypsum, jarosite, lepidocrocite, chalcedony, opal.

Mineral varieties of hematite quartzites: MrMhs – martite-micaceous hematite; MhsMr – micaceous hematite-martite; Mr – martite; DhMr – dispersed hematite-martite; MrDh – martite-dispersed hematite.

Martite quartzites are the product of weathering of the original magnetite quartzites (Fig. 3b). They form embedded bodies with a thickness of up to 70 m in the sections of the fifth and sixth ferruginous horizons and up to 150-200 m of the fourth ferruginous horizon. In the primary magnetite quartzites micaceous hematite or silicates (cummingtonite, chlorite, biotite) occurred in an amount of up to 5 mass %. In this regard, martite quartzites contains both weathering-resistant micaceous hematite and dispersed hematite, which is the product of hypergenic changes of silicates. The ore is strong, cleaves poorly along lamination. The structure is microcryptocrystalline and fine-crystalline. The texture is bedded, due to the alternation of ore (quartz-martite) and non-ore (quartz, micaceous hematite-quartz, dispersed hematite-quartz) interlayers. The medium-bedded texture predominates, thin- and wide-bedded texture is less common. Manifestations of coarse- and giant-bedded texture are rare.

Dispersed hematite-martite quartzites were formed as a result of hypergenic changes of the initial silicate-magnetite quartzites. They form layered bodies with a thickness of up to 30 m in the section of the fifth ferruginous horizon, up to 50 m in the section of the sixth ferruginous horizon and up to 80 m in the section of the fourth ferruginous horizon. They spatially tend to the peripheral zones of the horizons. The ores have reduced strength, cleave well along lamination due to the layer-by-layer presence of dispersed hematite. The structure is microcryptocrystalline and fine-crystalline. The texture is wide-bedded, less often medium- and coarsely bedded. Manifestations of thin- and giant-bedded texture are rare.

Martite-dispersed hematite quartzites are the product of weathering of the original magnetite silicate quartzites. In the layers that prior to weathering contained up to 30% or more by volume of chlorite, biotite and other alumina-containing silicates, kaolinite is present in an amount of more than 5% by volume. Martite-dispersed hematite quartzites form layered bodies, which are up to 10 m thick in the section of the fifth ferruginous horizon, up to 15 m in the section of the sixth ferruginous horizon and up to 20 m in the section of the fourth ferruginous horizon. They compose the extreme peripheral zones of the horizons. The ores have medium strength, cleave well along lamination. The structure is microcryptocrystalline and fine-crystalline. The texture is wide-bedded, less often coarse- and medium-bedded.

Diluting non-metallic impurities. Due to the suboptimality of drilling-and-blasting and mining technologies, low-ferruginous rocks are present in the material of hematite raw material stockpiles. The most common are chlorite-cummingtonite-quartz-biotite (Fig. 3c) schists and monomineral silicate quartzites of the fourth, fifth, and sixth schistose horizons. Fragments of vein quartz in monomineral form or in intergrowth with hematite quartzites are noticed less often (Fig. 3d).

The Ushkatyn III deposit is part of the Zhairem ore district (Brusnitsyn, 2018). In terms of mineral and petrographic composition of the productive stratum, it

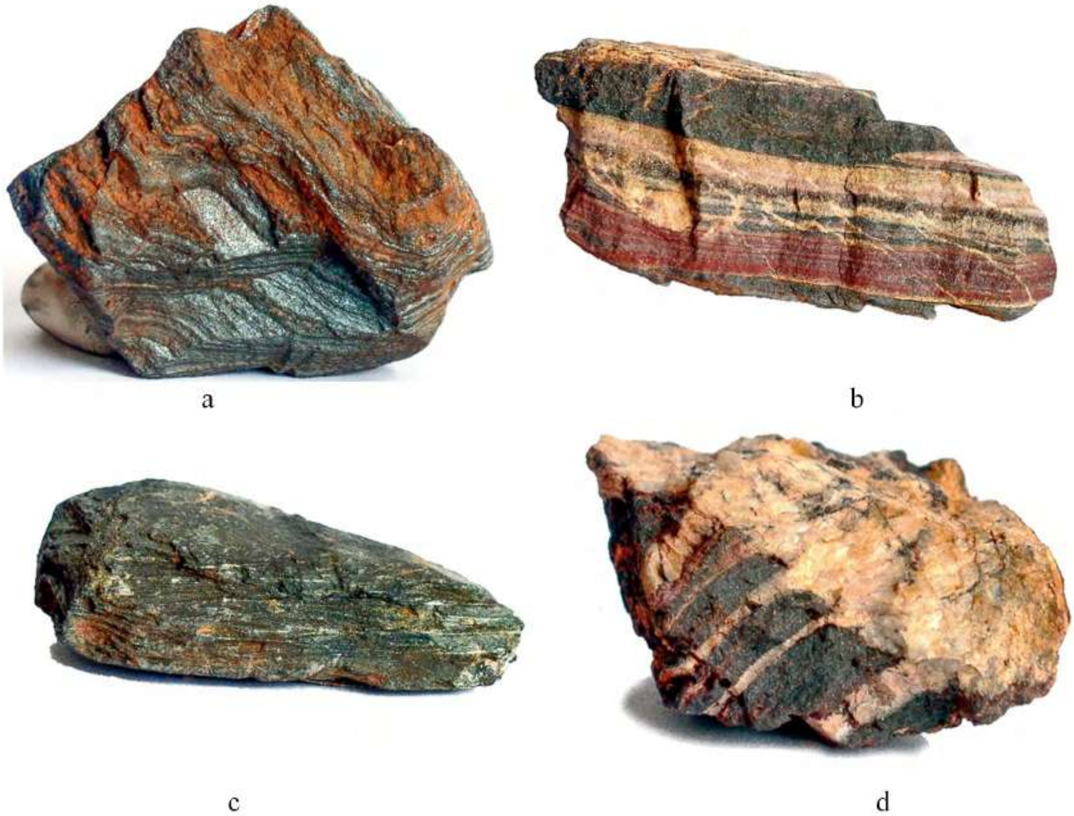

Fig. 3. Low-grade hematite ores and diluting rocks of ore stockpiles.

a – martite-micaceous hematite quartzite (jaspilite) of the fifth ferruginous horizon; b – martite quartzite of the fourth ferruginous horizon; c – chlorite-cummingtonite-quartz-biotite schist of the fourth schistose horizon; d – vein quartz from martite quartzite of the sixth ferruginous horizon.

The maximum size of samples is 10 cm.

is similar to the Valyavkynske deposit of the Krivbas. The increased content of manganese oxides (from 1 to 20 mass %) is the difference between them. Iron-containing minerals are represented by hematite of three morphological varieties: martite, micaceous hematite (specularite, dispersed hematite) (Fig. 4). A characteristic feature of individuals and aggregates of hematite is their much smaller size in comparison with the ores of the Kryvyi Rih deposits. In this regard, the same degree of grinding (0.05-0.06 mm), allows a full release of hematite from the Valyavskinske deposit, the hematite of the Ushkatyn III deposit retains intergrown pieces with non-metallic minerals – quartz, carbonates, silicates.

Thus, the ore-forming minerals of hematite raw materials of the studied deposits are represented by hematite (martite, micaceous hematite, dispersed hematite), quartz. Their total content in all mineral varieties of hematite quartzites exceeds 90 mass %. Secondary minerals include relict (magnetite, metamorphogenic silicates, carbonates, sulfides, etc.) and newly formed (iron hydroxides, clay minerals, etc.) minerals. Their quantitative ratio, morphology of individuals and aggregates, chemical composition and physical properties must be taken into account when developing an optimal technology for the production of high-quality hematite concentrate.

The production of hematite sinter ores and concentrates is not associated with fundamental technological difficulties for deposits of different scales. The first results of the search for an effective technology for the enrichment of hematite raw materials were obtained during the 1960s. Technological schemes based on the use of magnetic, gravitational, flotation units were considered. To date, the optimal technology has not been determined. Reducing the explored volumes of magnetite quartzites helps to intensify its search. According to the authors of this publication, the least energy-consuming, the most technologically efficient is gravity technology.

This also applies to the ores of Central Kazakhstan, the feature of which is the presence of a wide range of minerals ; manganese and other metals. Effective involvement of the latter in the operation can be achieved by updating the ore preparation (Demchenko, 2018; Evtekhov, 2016; Prilepa, 2019; Tsypin, 2015), including utilization of the lump sorting module of mineral raw materials produced by scientific production enterprise “Gamayun”. The module provides a significant reduction in energy

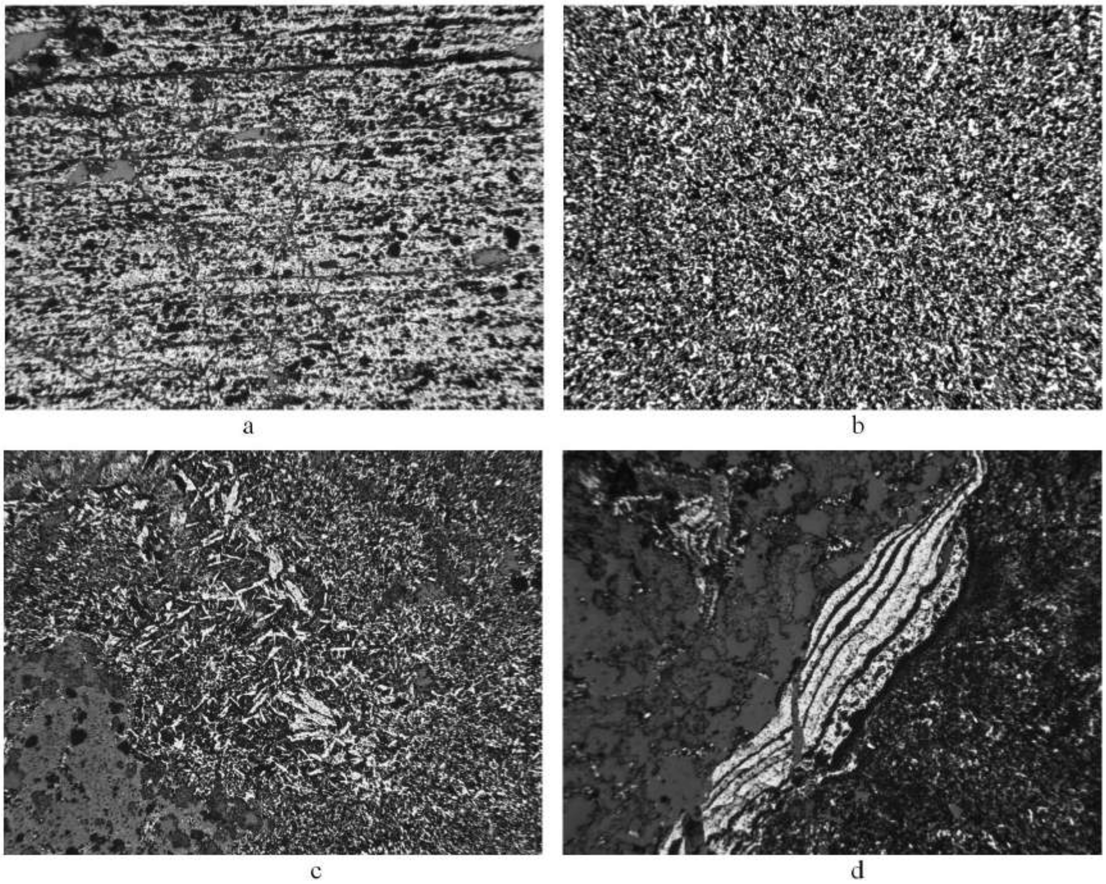

Fig. 4. Mineral composition, structure and texture of hematite ores of the Ushkatyn III deposit.

a – layer-by-layer oriented aggregates of fine-crystalline martite; b – finely-impregnated aggregate of micaceous hematite; c – an alpine streak of macrolaminar micaceous hematite (specularite); d – alpine hematite vein of rhythmic structure.

Reflected light; without analyzer; magnification 30ˣ.

consumption, mobility, efficiency of integration with existing structures. It was tested at the Atasui ore deposits of Central Kazakhstan (Karazhal, Ushkatyn III, Zhairem).

Conclusions

1. Hematite quartzites belong to the types of iron ore which commonly occur all over the planet. Depending on the technologies of ore preparation and beneficiation, it is possible to produce metallurgical raw materials with different iron content (from 55 to 69 mass %).

2. The optimal technology for hematite quartzite beneficiation for ores of most deposits has not been developed due to insufficient mineralogical justification.

3. Bi- (hematite + quartz) or trimineral (hematite + quartz + kaolinite) composition is typical for hematite ores.

4. The results of geological and mineralogical research must be taken into account when drawing up effective technological schemes for ore preparation and beneficiation of hematite quartzites in order to produce metallurgical raw materials with different iron content.

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