UDC 549 : 553.31 (477.63)

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EPIGENETIC MINERALIZATION OF HIGH GRADE IRON ORES OF SAKSAGAN IRON ORE REGION, THE KRYVYI RIH BASIN

Description of epigenetic minerals forming cement of porous high grade hematite ores from Saksagan iron ore deposits located in Kryvbas such as quartz, specularite, goethite, carbonates, silicates, apatite, and iron sulfides is given. Regularities of paragenetic associations alterability of epigenetic minerals to the depth and along the strike of iron ore deposits and of the region in whole is defined.

High grade ores of martite, specularite-martite, less often of dispersed hematite-martite, martite-dispersed hematite, dispersed hematite, kaolinite-dispersed hematite content that are known under the designation of ores of the "Saksagan type" have always been a huge part of saleable output of the Kryvyi Rih basin mines. They are connected genetically and spacely with banded iron formation mass to which relate all the main world reserves of iron.

Ore deposits are located in Central (Saksagan) region of the Kryvyi Rih basin and are mostly worked out by underground mining methods. At present their output is at the rate of 10-12 million tons of saleable ore per year at iron content of 50-54 mas.% in the extracted ore, which is much lower than in the saleable ore from other iron ore mining countries in the world (60-67,0 mas.%).

Comparatively low quality of iron ore won by Ukrainian underground mines is conditioned by the high content of impurities, especially of silica, that explains prices to be 1,5-2 times less than worldwide average ones in rigorous market conditions.

It is necessary to note that geological exploration data show iron content in the ore to be quite high, it is more than 58-60 mas.%. But obtaining raw material having iron content verging to the natural one is not practically achievable: in the process of mining mixing of ores of various texture-mineral varieties takes place, as well as their dilution with enclosing rocks represented by ferruginous quartzites and schists of various compositions. Their epigenetic cementation by non-metallic minerals, especially their silification carries its weight into decrease in quality of high grade iron ore in Kryvbas.

Ores of the Saksagan type are characterized by a range of peculiarities, the most important of which are the following:

– locaton of steeply dipping ore bodies at the eastern wing of the Saksagan anticline, more exactly at its flexurally complicated areas having elevated jointing; it has conditioned ore clusters (deposits) formation, separated by massifs of enclosing ferriferous rocks including hypergene-unaltered ones;

– confinedness mostly to the sixth and fifth ferruginous horizons, and, in the southern part of the region, to the fourth ferruginous, fourth, fifth and sixth schistose horizons;

– inheritance of texture and structure characteristics of original ferruginous rocks;

– simplicity of chemical composition, represented by practically two components that are Fe_2O_3 and SiO_2 in martite and specularite-martite ores to which Al_2O_3 and LoI are added in dispersed hematite and martite-dispersed hematite ores;

– practically bimineral content: hematite and quartz, and in ores of schistose horizons there occurs kaolinite, intergrowths of which form basic structures of ore;

– limited quantity (from 3 to 5) of textural-mineral varieties;

– high porosity, up to 30-40%;

– low hardness (from 1-2 to 6-8 points on Protodiakonov scale) conditioning ore flow rate;

– duration and complexity of formation processes including accumulation of ferruginous-cherty sediments, their regional metamorphism, and not less than three stages of hypergenesis, including abyssal, occurring in the conditions of elevated temperature (up to 90-150ºC) and pressure.

It should be added that favorable combination of Saksagan ore enclosing structure and large, possibly planetary scale tectonic displacements has led not only to formation of enormous banded iron formations crusts of weathering but also to cementation of porous hematite ores with many epigenetic minerals. In this regard Kryvyi Rih is a unique phenomenon among analogous deposits in the world.

At the present moment the following epigenetic minerals occur in the Saksagan type ores: pyrite, marcasite, barite, hematite, goethite, quartz, siderite, ankerite, dolomite, magnesite, apatite, chlorite, kaolinite, serpentine and talc.

Epigenetic pyrite occurs as fine automorphic, usually octahedral, less often cubical, pentagon-dodecahedral crystals forming veinlets in ores as well as druses at the walls of pores and fissures.

Markasite sometimes occurs in kaolinite-dispersed hematite ores as oval micro concretions having size less than 0,04 mm.

Barite was found in high grade ores from "Gigant-Glyboka" Mine of the former F.E.Dzerginskiy Mine Administration as druses of quite big (up to 2 cm) plate crystals having thickness from parts of a millimeter up to 2 mm. Colorless and grey transparent crystals of barite are often dusted with dispersed hematite, covered with zonal growths and sinter aggregates of goethite. Habitus of crystals is a pinacoid, the main shapes are pinacoid and rhombic prism. The face surface of the pinacoid is dull, it has traces of resorption; the surface of other habitus shapes is glance and plane.

Epigenetic specularite is common for all varieties of the Saksagan ores but it does not make up noticeable concentrations. In martite and specularite-martite ores its crystals predominantly occur at pores as sort of swab-like, stellar formations on the surface of martite aggregates. In addition, crystals of newly-formed specularite usually have similar optical alignment to individuals of specularite building up martite, they seem to be their prolongation out of the limits of martite aggregates. Crystals of epigenetic specularite, unlike tabular crystals of original (metamophogenic) specularite, are characterized by platelet shape and have perfect faceting. In plane section they are spindly shaped, the size varies from 0,02 to 0,25 mm. When cementation is intensive, crystals of epigenetic specularite form net structure completely filling ore pores. In polarized light structure of crystals may sometimes be zonal. In dispersed hematite ores, that are marked by very thin porosity, epigenetic specularite occurs mostly as a result of accumulative recrystallization of dispersed hematite that involves the increase in pore size in ore.

Iron hydroxides are represented by goethite and dispersed goethite (hydrogoethite). Two morphological varieties of cementing goethite play the major role, they are relatively automorphic stampy crystals having length of 0,02-0,2 mm, and dripstones of concentric zonal and divergent structures. Both varieties of goethite mold on pore walls often filling them and forming ore cement of basal type. Dispersed goethite often accompanies colloform goethite buildups. Goethite commonly replaces relicts of magnetite in martite aggregates.

Epigenetic quartz occurs as two morphological varieties which are spherolitic and poikilitic ones. Spherolitic chalcedonic quartz forms petaloid individuals of maximum size 0,2-0,4 mm that form aggregates of sectorial extinction. Presence of finest (0,1-10 um) two-phase gassy-liquid inclusions of round, oval or elongated shapes having branches that are often exposed when making sections, is a characteristic feature of spherolitic quartz. Inclusions are located in quartz crystals irregularly or in a fan-shaped way. Moving gas bubbles usually make up 10-25% of vacuole volume. Submicroscopical studies (carbon replica) show gassy-liquid inclusions as bug holes of various shapes and sizes as well as prints of hexagonal kaolinite crystals in individuals in this variety of quartz. Besides, chalcedonic quartz crystals contain small inclusions of martite, specularite, prismatic crystals of goethite. Underlined features of spherolitic quartz make it possible to assume colloidal nature of original solutions.

Poikilitic quartz is represented by coarse (0,5-2 mm) individuals of polygonal shape having regular extinction and distinct poikilitic structure. Separate short-prismatic crystals of this variety of quartz having size from parts of a millimeter up to 2 cm occur in pores, micro fractures and big cavities of ores. The major habitus shapes are trigonal prism and a rhombohedral. Crystals width-to-length ratio is generally 1:3. During the growth process crystals absorbed partially or in full buildups of martite or specularite. It resulted in appearing of cement intergrowth structure. Frequently it is possible to observe regeneration phenomena in sections when individuals of relict metamorphogenic quartz form nuclei inside crystals of poikilitic quartz recognizable after their annular includings of iron hydroxides. Gassy-liquid inclusions in this variety of quartz crystals are smaller and occur less often comparing to idividuals of spherolitic quartz. Generally, they are zonal and underline the shape of a seed crystal. Sometimes there occur dust inclusions of dolomite. Using the method of gassy-liquid inclusions homogenization for studying well faceted crystals of poikilitic quartz it has been defined that they had been formed from low-mineralized solutions under pressure of less than 300-400 atm. within temperature range of 95-135°C.

There is a transition from spherolitic quartz to poikilitic one in silicificated ores (M.V.Frunze and “Yubileyna” Mines), poikilitic qurtz predominates further to the north.

Epigenetic carbonates, content of which in studied ores is from 7 to 25%, occur inside pores and cement ore grains. **Siderite** as well as cementing quartz is defined as spherolitic and poikilitic varieties. Crystal size of the latter is from 0,2 to 2 mm. **Dolomite, magnesite and ankerite** were found in ores occurring at the depth of more than 1700 m; the two first were found at V.I. Lenin Mine, ankerite was found in ores from M.V.Frunze and “Bilshovyk” Mines. Dolomite and magnesite as large individuals (from 0,02 to several mm) fill the whole pores volume in the ore partings of 0,2-0,3 mm thickness that interlay with partings where ore minerals are cemented by magnesia silicates such as serpentine and talc. Studies of fractions enriched in carbonates showed alteration of CaO:MgO ratio from 0,7:1 to 1,5:1 at complete absence of FeO. Ankerite forms basal cement in ores, it occasionally occurs as short interrupted partings having thickness up to 0,02 mm. Individuals size in cement is from 0,01-0,08 to 0,2-0,6 mm. Paragenetic associations with ankerite form quartz, serpentine, talc, and occasionally, chlorite.

Apatite, similar to other epigenetic minerals, is characterized by variety of manifestation shapes starting from separate hexagonal-prismatic crystals and their aggregates in the form of nests and incrustations to fine grained aggregates forming basal type cement in ore partings having thickness up to 2 cm. Well faceted apatite crystals are stampy or tabular. Sections often have zonal structure with zone width up to 0,02 mm underlined by two-phase gassy-liquid inclusions having size less than 5 um. In cross-sections of crystals inclusions have rounded or hexagonal shape, in longitudinal sections they are elongated, tubicolous. Chemical analysis of fraction material enriched with apatite showed presence of fluorine up to 1,0 and CO_2 up to 0,39 mas.%. X-ray pattern of ore cemented by apatite (“Yubileyna” Mine) confirmed diagnostics of the mineral and defined it to be fluorapatite.

Epigenetic silicates have maximum abundance in deep horizons ores; in the limits of the deposit of “Gigant-Glyboka” Mine they occur at the depth of about 1000 m (the level of ore deposit attenuation), in ore deposits located further to the north they are at the depth from 1500 to 2300 m. Chlorite, kaolinite, talc and serpentine are found there. **Chlorite** is represented by light-green, greyish-green cryptocrystalline aggregates making pores in ores. Interference tint are grey with bluish and lilac tones. Data of XD and thermographic analysis show chlorite to be subsumed as chamosite. **Kaolinite** is abundant in deep horizons ores, its content reaches 10 vol.%. It forms incrustations, films on the surface of ore built-ups, cement in porous ores. Hummocky, nodular surface of incrustations specific for dripstones can often be observed under a binocular microscope. Kaolinite aggregates are cryptocrystalline ones, maximal individual size is 1-2 um, sometimes it is up to 5 um. Electron-microscopic study showed their pseudo-hexagonal shape. Diagnostics of kaolinite was confirmed by optical, X-ray diffraction, thermographic methods. **Serpentine and talc** are quite common for ores from deep horizons. They occur either separately or together, their total content in ore reaches 15-20 vol.%. Serpentine forms fine scaly, fibrous aggregates making pores and forming incrustations (of 10-15um in thickness), and rosette-like build-ups. Serpentine is of green color in sections. Undulatory extinction is specific for the fibrous variety. Electron-microscopic studies defined serpentine crystals to be fibrous and tubicolous. Diagnostics of serpentine have been fulfilled after the data of optical, thermographic and XD studies. Similar to serpentine, talc cements porous ores. Its fine scaly aggregates are of white color and pearly lustre. It is colorless in sections, sometimes it has brownish tint. Scaly and platy talc crystals having size from less than 1 um to 20-30 um form scattered and rosette-like aggregates. Diagnostics of talc has been confirmed by results of XD and thermographic analysis. Chemical analysis of talc has showed noticeable content of ferrous iron in it, e.g. presence of ferrous minal – minnesotaite.

Epigenetic minerals form mono- or polymineral ores cement that may contain up to six mineral species which is more specific for deep horizons ores. Cementing minerals content varies from 2-3 to 30-35% of total amount of ore. Manifestation of epigenetic mineralization in ores is more often observed at flanks of the deposits, near natural aquacludes, for example, near contacts with granites of ore field at "Gigant-Glyboka" Mine, near the contact with dyke of diabase within limits of "Yubileyna" Mine ore field.

There exist certain regularities in the distribution of mineral varieties participating in epigenetic cementation of porous ores. Iron hydroxides occur mostly as far as a depth of 300-500 m, rarely at zones of faultings to a depth of 1700 m ("Gvardiyska" Mine). Cementing hematite occurs at various depths but its quantity noticeably increases with depth. Ferriferous carbonates are the most common at a depth of 800-1000 m. Magnesium containing carbonates are specific for 1700-2000 m depth, they notably occur in ores of the northern part of Saksagan iron ore region; at "Gigant-Glyboka" Mine they were found at a depth of about 1000 at the area of ore body attenuation. Magnesia silicates (chlorite, talk, serpentine) occur at the deepest horizons; maximal content of kaolinite has been noticed al a level of 1200-1500 m.

Epigenetic mineralization of high grade iron ores of Pre-Cambrian banded iron formation has been defined for many deposits in the world, but every case has its own intensity and different set of mineral species. Specularite is a cementing mineral for Bilozerske deposit of the Ukranian Shield porous ores, for Kremenchuh iron ore region of the Ukranian Shield they are siderite and iron hydroxide, for the Kursk Magnetic Anomaly deposits they are siderite and pyrite. Iron and aluminum hydroxides and silicate, that are close to chlorite after their composition, serve as cementing materials in high grade specularite-martite ores of India (Singhbhum basin).

Conclusions

1. Epigenetic cementing mineralization is specific for porous hematite ores from deep hypsometric horizons of Saksagan iron ore region located in the Kryvyi Rih basin.

2. Cement contains pyrite, cellular pyrite, barite, hematite, goethite, quartz, siderite, ankerite, dolomite, magnesite, apatite, chlorite, kaolinite, serpentine, talc. After its mineral composition cement can be mono- or polymineral, the latter may contain up to six mineral species.

3. Epigenetic minerals content in ores change from 1 to 35 vol.%. Depending on their amount, contact, porous and basal cements are distinguished.

4. There exist regularities in distribution of epigenetic minerals according to the depth of ore deposits and along the strike of high grade iron ores in Saksagan region.

5. Epigenetic minerals differ from analogous minerals of metamorphic and other origins after morphological and optical characteristics.

8. Cementation of porous high grade ores with epigenetic minerals comes amid changing their mineral and chemical composition, physical, technical and technological properties.

9. Epigenetic mineralization is one of the last stages of hypergene changes in high grade iron ores of Pre-Cambrian banded iron formation. At the Kryvyi Rih basin it is specific abyssal hypergenesis caused by combination of ore enclosing structure and intensive tectonic dislocations providing penetration of meteoric waters to the depth of several kilometers at zones of higher temperatures (up to 90-150ºC) and pressure. It seems that this explains extent of cementation and variability of epigenetic minerals in porous high grade iron ores.

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ЗИМА С.М. Епігенетична мінералізація багатих залізних руд Саксаганського залізорудного району Криворізького басейну.

Резюме. *Епігенетична цементаційна мінералізація характерна для пористих багатих гематитових руд глибоких гіпсометричних горизонтів родовищ Саксаганського залізорудного району Криворізького басейну. В складі цементу присутні пірит, марказит, барит, гематит, гетит, кварц, сидерит, анкерит, доломіт, магнезит, апатит, хлорит, каолініт, серпентин, тальк. Вміст епігенетичних мінералів у складі руд змінюється від 1 до 35 об'ємн.%. Існують закономірності в розподілі епігенетичних мінералів за глибиною (від 300 м до понад 2000 м) и за простяганням рудних покладів. Цементація руд обумовлює зміну їх мінерального, хімічного складу, фізичних, технічних, технологічних властивостей.*

Ключові слова: залізисто-кремниста формація, Криворізький басейн, багаті залізні руди, мінералогія, епігенетичні мінерали.

ЗИМА С.Н. Эпигенетическая минерализация богатых железных руд Саксаганского железорудного района Криворожского бассейна.

Резюме. *Богатые железные руды Криворожского бассейна, генетически и пространственно связанные с толщей железисто-кремнистой формации, имеют мартитовый, железнослюдко-мартитовый, реже дисперсногематит-мартитовый, мартит-дисперсногематитовый, дисперсногематитовый, каолинит-дисперсногематитовый состав. Характеризуются повышенной пористостью, низкой крепостью. Практически все их залежи расположены в Центральном (Саксаганском) железорудном районе Криворожского бассейна, отрабатываются, в основном, подземным способом. На протяжении последних лет добывается 10-12 млн. т. товарной руды в год. Содержание железа в руде, извлекаемой из недр, составляет 50-54 мас.%, что значительно ниже соответствующего показателя руд, добываемых в других государствах (60-67 мас.%). Относительно низкое качество железных руд Кривбасса обусловлено высоким содержанием примесей, особенно кремнезема, из-за чего цены на них в 1,5-2 раза ниже среднемировых.*

Одной из основных причин повышенного содержания в составе пористых богатых гематитовых руд кремнезема и других балластных и вредных химических компонентов является цементация руд гипергенным кварцем и другими эпигенетическими минералами. В этом отношении Кривой Рог представляет собой уникальное явление среди аналогичных месторождений мира. К наиболее хорошо изученным эпигенетическим минералам руд относятся: пирит, который встречается в виде прожилков или щеток мелких (до 1 мм) идиоморфных кристаллов на стенках трещин и пор; марказит, иногда присутствующий в каолинит-дисперсногематитовых рудах в виде сферолитовых стяжений размером до 0,04 мм; барит, выявленный в богатых рудах шахты «Гигант-Глубокая» в виде щеток довольно крупных (до 2 см) кристаллов пинакоидального габитуса; апатит, образующий отдельные короткостолбчатые или таблитчатые кристаллы размером до 0,1 мм или щетки в порах и трещинах руд; карбонаты, представленные сидеритом, доломитом, магнезитом, анкеритом, содержание которых составе руд достигает 25 объемн.% и которые присутствуют в виде отдельных кристаллов, щеток в порах и трещинах, цементируют индивиды и агрегаты рудных минералов; силикаты, представленные хлоритом, каолинитом, серпентином, железистым тальком (миннесотаитом), мелкие (до 0,1 мм) пластинчатые индивиды и спутанно-чешуйчатые агрегаты которых выполняют трещины и поры в рудах и которые максимальным распространением пользуются в рудах глубоких (более 1000 м) гипсометрических горизонтов, где их суммарное количество достигает 20-25 объемн.%; гидроксиды железа, представленные, преимущественно, гетитом и дисперсным гетитом («гидрогетитом»), концентрически-зональные, радиально-лучистые, землистые агрегаты которых выполняют полости, цементируют агрегаты рудных минералов, реже их метасоматически замещают; железная слюдка, присутствующая в составе руд всех минеральных разновидностей, но не образующая заметных концентраций, обычно представленная хорошо ограненными пластинчатыми кристаллами размером от 0,02 до 0,25 мм, агрегаты которых часто образуют сетчатые структуры, выполняющие поры руд.

Наиболее распространен эпигенетический кварц, который представлен двумя основными морфологическими разновидностями – сферолитовой и пойкилитовой. Сферолитовый (халцедоновидный) кварц образует лепестковидные индивиды максимальным размером 0,2-0,4 мм, образующие агрегаты с секториальным погасанием. Пойкилитовый кварц представлен крупными (0,5-2 мм) полигональными индивидами. В трещинах и полостях руд наблюдаются отдельные короткопризматические кристаллы кварца этой разновидности размером от десятых долей миллиметра до 2 см. В процессе роста кристаллы кварца этой разновидности частично или полностью захватывали индивиды и агрегаты мартита и железной слюдки, в результате чего формировалась цементационная структура руд. Методом гомогенизации газово-жидких включений, присутствующих в хорошо ограненных кристаллах пойкилитового кварца, было установлено, что их образование происходило из слабо минерализованных растворов под давлением не выше 300-400 атм. в интервале температур 95-135^{o}C.

Эпигенетические минералы образуют моно- или полиминеральный (до 6 минеральных видов) цемент руд, суммарное содержание их колеблется от 1 до 35% от общего объема руды. Установлены следующие особенности их распределения: гидроксиды железа встречаются обычно до глубины 300-500 м, изредка по зонам разрывных нарушений до глубины 1700 м (шахта «Гвардейская»); железная слюдка отмечается на разных глубинах, но в общем случае ее количество с глубиной заметно возрастает; железистые карбонаты наиболее характерны для глубин 800-1000 м; магний-содержащие их разновидности – для глубин 1000-2000 м; каолинит тяготеет к глубинам 1200-1500 м; магнезиальные силикаты (хлорит, тальк, серпентин) – к наиболее глубоким частям рудных залежей.

Эпигенетическая минерализация характерна для богатых руд железисто-кремнистой формации докембрия многих месторождений мира, но отличается разной интенсивностью и разным составом минеральных видов. Для богатых руд Белозерского месторождения Украинского

щита (УЩ) отмечается цементация, в основном, железной слюдкой; для руд Кременчугского железорудного района УЩ – сидеритом и гидроксидами железа, для руд месторождений Курской магнитной аномалии – сидеритом и пиритом. В богатых железнослюдко-мартитовых рудах Индии (бассейн Сингхбум) в качестве цементационных минералов присутствуют гидроксиды железа, гидроксиды алюминия и силикаты, близкие по составу к хлориту.

Ключевые слова: железисто-кремнистая формация, Криворожский бассейн, богатые железные руды, минералогия, епигенетические минералы.

ZYMA S.M. Epigenetic mineralization of high grade iron ores of Saksagan iron ore region, the Kryvyi Rih basin.

Summary. *Epigenetic cementing mineralization is specific to porous high grade hematite ores from deep hypsometric horizons of the Saksagan iron ore region deposits at the Kryvyi Rih basin. The cement contains pyrite, cellular pyrite, baryte, hematite, goethite, quartz, siderite, ankerite, dolomite, magnesite, apatite, chlorite, kaolinite, serpentine, talc. Epigenetic minerals content in ores varies from 1 to 35 vol.%. There are some regularities in epigenetic minerals distribution according to the depth (from 300 m to more than 2000 m) and along the strike of iron ore bodies. Cementation of ores causes changes in their mineral, chemical composition, physical, technical and technological properties.*

Key words: banded iron formation, the Kryvyi Rih basin, high grade iron ores, mineralogy, epigenetic minerals.

The article was recieved by editorials 15 september 2012.
It was recommended for publishing by professor V.D.Evtekhov.