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Fluid types and their genetic meaning for the BIF-hosted iron ores, Krivoy Rog, Ukraine

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ABSTRACT

This paper contributes to the understanding of the genesis of epigenetic, hypogene BIF-hosted iron deposits situated in the eastern part of Ukrainian Shield. It presents new data from the Krivoy Rog iron mining district (Skelevatske–Magnetitove deposit, Frunze underground mine and Balka Severnaya Krasnaya outcrop) and focuses on the investigation of ore genesis through application of fluid inclusion petrography, micro-thermometry, Raman spectroscopy and baro-acoustic decrepitation of fluid inclusions. The study investigates inclusions preserved in quartz and magnetite associated with the low-grade iron ores (31–37% Fe) and iron-rich quartzites (38–45% Fe) of the Saksaganskaya Suite, as well as magnetite from the locally named high-grade iron ores (52–56% Fe). These high-grade ores resulted from alteration of iron quartzites in the Saksaganskiy thrust footwall (Saksaganskiy tectonic block) and were a precursor to supergene martite, high-grade ores (60–70% Fe). Based on the new data two stages of iron ore formation (metamorphic and metasomatic) are proposed.

The metamorphic stage, resulting in formation of quartz veins within the low-grade iron ore and iron-rich quartzites, involved fluids of four different compositions: CO_2-rich, H_2O, H_2O–CO_2($\pm N_2$–CH_4)–NaCl($\pm NaHCO_3$) and H_2O–CO_2($\pm N_2$–CH_4)–NaCl. The salinities of these fluids were relatively low (up to 7 mass% NaCl equiv.) as these fluids were derived from dehydration and decarbonation of the BIF rocks, however the origin of the nahcolite ($NaHCO_3$) remains unresolved. The minimum P–T conditions for the formation of these veins, inferred from microthermometry are $T_{min} = 219$–246 °C and $P_{min} = 130$–158 MPa. The baro-acoustic decrepitation analyses of magnetite bands indicated that the low-grade iron ore from the Skelevatske–Magnetitove deposit was metamorphosed at T = ~530 °C.

The metasomatic stage post-dated and partially overlapped the metamorphic stage and led to the upgrade of iron quartzites to the high-grade iron ores. The genesis of these ores, which are located in the Saksaganskiy tectonic block (Saksaganskiy ore field), and the factors controlling iron ore-forming processes are highly controversial. According to the study of quartz-hosted fluid inclusions from the thrust zone the metasomatic stage involved at least three different episodes of the fluid flow, simultaneous with thrusting and deformation. During the 1st episode three types of fluids were introduced: CO_2–CH_4–N_2($\pm$C), CO_2($\pm N_2$–CH_4) and low salinity H_2O–N_2–CH_4–NaCl (6.38–7.1 mass% NaCl equiv.). The 2nd episode included expulsion of the aqueous fluids H_2O–N_2–CH_4–NaCl($\pm CO_2$, $\pm$C) of moderate salinities (15.22–16.76 mass% NaCl equiv.), whereas the 3rd event involved high salinity fluids H_2O–NaCl($\pm$C) (20–35 mass% NaCl equiv.). The fluids most probably interacted with country rocks (e.g. schists) supplying them with CH_4 and N_2. The high salinity fluids were most likely either magmatic–hydrothermal fluids derived from the Saksaganskiy igneous body or heated basinal brines, and they may have caused pervasive leaching of Fe from metavolcanic and/or the BIF rocks. The baro-acoustic decrepitation analyses of magnetite comprising the high-grade iron ore showed formation T = ~430–500 °C. The fluid inclusion data suggest that the upgrade to high-grade Fe ores might be a result of the Krivoy Rog BIF alteration by multiple flows of structurally controlled, metamorphic and magmatic–hydrothermal fluids or heated basinal brines.

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1. Introduction

Iron ore deposits within Precambrian banded iron formations (BIFs) are the most profitable sources of iron making them very attractive exploration targets (Duuring et al., 2012). However there are many aspects of their genesis and evolution that are controversial and not fully understood, not least the mechanisms of iron ore enrichment, which have been a subject of recent intense research (e.g. Rosière and Rios, 2004; Hagemann et al., 2006; Belykh et al., 2007; Beukes et al., 2008; Spier et al., 2008; Thorne et al., 2009; Angerer et al., 2012; Figueiredo e Silva et al., 2013).

Recently improved genetic models for Fe deposits hosted by BIFs worldwide, e.g. Kursk Group, KMA, Russia (~2.39 Ga), Brockman Iron Formation, Hamersley Basin, Australia (~2.46 Ga), itabirites of the Cauê Formation, Brazil (~2.45 Ga) or Serra Norte Carajás BIF, Brazil (~2.7 Ga) are primarily focused on a direct transition from a BIF-protolith to the high-grade (>58% Fe) martite and hematite ores (e.g. Belykh et al., 2007; Spier et al., 2008; Thorne et al., 2009; Figueiredo e Silva et al., 2013). According to these models the ore-forming fluids, interacting with the BIF-protolith, played a crucial role in the iron ore enrichment (Belykh et al., 2007; Spier et al., 2008; Thorne et al., 2009; Figueiredo e Silva et al., 2013). For instance, martite and specular hematite–martite, high-grade ores from Fe deposits of the KMA region, which are hosted by BIF similar in age and tectonostratigraphic setting to the Krivoy Rog BIF, were upgraded during the introduction of meteoric waters and unknown hypogene fluids derived from deep-seated sources (Belykh et al., 2007). The most recent fluid flow models worldwide also propose multiple interactions of BIF with fluids of various origins, e.g. hypogene and supergene meteoric fluids in Fe deposits of the Quadrilátero Ferrífero region, Brazil (Spier et al., 2008), supergene and modified hydrothermal fluids in deposits of the Iron Ore Group, India (Beukes et al., 2008), basinal brines and meteoric fluids in Hamersley-type deposits, Australia (Hagemann et al., 2006; Thorne et al., 2009) or modified magmatic and meteoric fluids in the Carajás Fe deposits, Brazil (Figueiredo e Silva et al., 2013).

The study by Rosière and Rios (2004) indicated that the ore-forming processes preceding formation of the final product, i.e. high-grade hematite Fe ore, were also not restricted to a single fluid alteration event affecting a parent BIF. They proposed that in Fe deposits of the Quadrilátero Ferrífero district, Brazil, magnetite mineralization predating the transformation to a high-grade hematite ore, resulted from contraction accompanied by influx of reduced metamorphic fluids and connate water (Rosière and Rios, 2004). Belevtsev et al. (1991) describe epigenetic, magnetite, quartz-absent BIF (52–56% Fe) as a proto-ore for the porous, dispersed-hematite–martite, high-grade Fe ores (60–70% Fe) hosted by the BIF of the Krivoy Rog Belt (KRB). This paper aims to unravel the processes behind the formation of Fe ore precursors generated before the enrichment to the supergene dispersed-hematite–martite, high-grade ores. Fe ore precursors include metamorphosed low-grade Fe ore (31–37% Fe) and iron-rich quartzites (38–45% Fe) as well as compacted, quartz-absent Fe ore (52–56% Fe), which is locally named massive, high-grade ore (Belevtsev et al., 1991). These ore types are actively exploited in the KRB in numerous mines, even at depths exceeding 1.3 km. The rocks of KRB have undergone a very complex evolution with multiple metamorphic, metasomatic and magmatic–hydrothermal events, extensive deformation and supergene alteration (Bobrov et al., 2002). Consequently, the generation of high-grade iron ores in this region is not fully understood. The current genetic model relies on the assumption that contraction and partial BIF leaching by hydrothermal fluids of metamorphic origin were responsible for the hypogene iron ore upgrade to epigenetic, compacted high-grade ore, 52–56% Fe (Belevtsev et al., 1991), however an influence of fluids from other sources has been neither confirmed nor excluded (Lazarenko et al., 1977). Unraveling the fluid evolution within the Fe deposits at Krivoy Rog is crucial to understanding the origin of these ore bodies and could lead to improved genetic models and increased exploration success in the area.

The purpose of this study is to characterize the fluids that formed the iron ores at Krivoy Rog through analysis of fluid inclusions. We use microthermometry and laser Raman techniques on a series of quartz veins and breccias from the low-grade and high-grade iron ores as well as acoustic decrepitometry on ore minerals in order to constrain the composition and source of fluids involved in formation of the iron ores.

2. Geology of the Krivoy Rog Belt

The KRB is situated within the Ukrainian Shield close to the border between two geological units, the Paleoproterozoic Kirovogradskiy terrane and the Archean Middle Dniprean (Dnyepropyetrovskiy) terrane (Bobrov et al., 2002; Yesipchuk et al., 2004) (Fig. 1A). The KRB forms an elongated structure, which is constrained by the deep-seated Krivoy Rog–Kremenchug fault zone to the west and the Saksaganskiy and Demurinskiy granitoid massifs to the east (Fig. 1B). The Mesoarchean age of the Saksaganskiy granitoids is 3.067 ± 0.081 Ga (Yesipchuk et al., 2004; Stepanyuk et al., 2010), however the time span of their formation is unknown. The currently valid stratigraphy of the region and of the Krivoy Rog Belt itself is constantly under debate and requires actualization (Paranko et al., 2005; Khudur, 2006; Paranko et al., 2011).

The KRB hosts the Paleoproterozoic Krivoy Rog Series (equivalent of the Supergroup), which comprises six Suites (corresponding to Groups): the Novokrivorozhskaya Suite, the Skelevatskaya Suite, the metakomatiite rock association, the iron ore-bearing Saksaganskaya Suite, the Gdantsevskaya Suite and the Gleyevatskaya Suite (Figs. 1B, 2a, b) (Bobrov et al., 2002; Yesipchuk et al., 2004). The Krivoy Rog Series is underlain by the oldest metavolcanic rocks of the KRB, the Konkskaya Series (Figs. 1B, 2a, b) (Bobrov et al., 2002).

The Novokrivorozhskaya and Skelevatskaya Suites (Figs. 1B, 2a, b) represent metaconglomerate-schist and metaconglomerate-sandstone–schist rock associations, respectively (Bobrov et al., 2002). The metakomatiite rock association (Figs. 1B, 2a, b) is represented by fissure type rocks, and effusive ultramafic lava flows, which were metamorphosed to talc-carbonate schists (Paranko and Mikhnitskaya, 1991; Paranko, 1993; Paranko et al., 1993; Khudur, 2006; Pieczonka et al., 2011). This suite has a thickness of up to 150 m and extends throughout the entire length of the KRB, yet its origin is still unclear (Paranko and Mikhnitskaya, 1991). Its contact with the Skelevatskaya Suite is gradational, whereas the upper boundary is associated with thrust zones (Paranko and Mikhnitskaya, 1991). The Saksaganskaya Suite (Figs. 1B, 2a, b) of a thickness up to 1500 m (Shcherbak and Bobrov, 2005) comprises seven sets of alternating schist and BIF horizons (Fig. 3) (Bobrov et al., 2002). The former are composed of ferruginous schists and barren quartzites, whereas the latter consist of banded ferruginous quartzites (e. g. silicate–magnetite quartzites, jaspilites, locally containing tiger-eye variety) and high-grade iron ores (Paranko and Mikhnitskaya, 1991; Bobrov et al., 2002) (Fig. 4). In the late Paleoproterozoic the rocks of the Saksaganskaya Suite underwent extensive deformation including folding, faulting, metamorphism, thrusting and metasomatism (Bobrov et al., 2002). The metamorphic grades vary from garnet zone greenschist facies at T = 430–550 °C in the central part of the KRB and staurolite-bearing epidote–amphibolite facies at T = 510–600 °C in the southern and northern parts of the KRB (Belevtsev et al., 1983, 1991). The Saksaganskaya Suite is unconformably overlain by the Gdantsevskaya Suite (1400 m) and the Gleyevatskaya Suite (1500–2000 m) (Figs. 1B, 2a, b) (Paranko and Mikhnitskaya, 1991; Paranko, 1993, 1997; Bobrov et al., 2002).

The Archean Konkskaya Series and Paleoproterozoic Krivoy Rog Series (Novokrivorozhskaya–Saksaganskaya Suites) dip to the west and form a monoclinal structure, which is crosscut by thrust zones (Kalyayev et al., 1984; Paranko, 1993; Reshetnyak, 1993; Bobrov