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Formation age and genesis of the banded iron formations from the Guyang Greenstone Belt, Western North China Craton

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ABSTRACT

Previous studies focused on banded iron formations (BIFs) from the eastern North China Craton (NCC), few were conducted on those of the western NCC. This paper concentrates on two BIFs, Sanheming and Gongyiming, from the Guyang Greenstone Belt (GB), western NCC. SIMS U–Pb analyses of zircons from the amphibolite interlayers of Sanheming and Gongyiming BIFs gave upper intercept ages of 2562 ± 14 Ma and 2569 ± 78 Ma, respectively, coupled with 2555 ± 56 Ma for the tonalite with BIF xenoliths, the formation age of the BIFs is inferred to be 2.56–2.57 Ga. Protolith reconstruction based on geochemistry and field occurrence of the amphibolites shows that they are originally basaltic. Trace elements reveal that the basalts of Sanheming and Gongyiming are T-MORB and N-MORB, respectively. Metabasites from other locations of the Guyang GB in previous studies display island arc geochemical characteristics. Plus the lithologic assemblage of komatiite, basaltic komatiite, boninite, tholeiite, high-Mg andesite and Nb-enriched basalt identified by previous work, the geodynamic setting of the BIFs from Guyang GB is deduced to be a mantle plume erupting into the subduction zone and they were deposited in arc-related basins. Relatively low contents of Al_2O_3, TiO_2 and HFSE for the BIFs indicate negligible detritus involvement. PAAS-normalized REY profiles are characterized by LREE depletion and HREE enrichment, positive La, Gd, Y and Eu anomalies, weak negative Ce anomalies and Y/Ho weight ratios of 26–41, indicating a mixture of submarine high-temperature hydrothermal fluids and seawater. Chondrite-normalized REE patterns for the BIFs are similar to those of the komatiites occurring at the bottom of the GB. Collectively, it is speculated that submarine high-temperature hydrothermal fluids leached out the Fe and Si of oceanic volcanics during circulation, and they deposited due to the changed physiochemical conditions when the fluids mixed with the seawater. The hydrothermally altered amphibolites proximal to the Gongyiming upgraded iron ores are enriched in various elements added by the hydrothermal fluids. Plus the $\delta^{18}O$ values of magnetites and quartzs, the genesis of the Gongyiming upgraded iron ores is proposed to be hydrothermal interaction with low-grade BIF.

1. Introduction

Banded iron formations (BIFs) are widely distributed in the North China Craton (NCC), and they are mainly Algoma-type BIF occurring in Greenstone Belts (GB), e.g., Shuichang and Shirengou BIFs in the Zunhua GB, Wuyang BIF in the Dengfeng GB, Gongyiming and Sanheming BIFs in the Guyang GB. Unlike BIFs from other parts of the world such as Hamersley BIFs in Western Australia and Transvaal BIFs in South Africa, which host world-renown large-scale high-grade iron ore deposits, the majority of BIF-type iron ore deposits in NCC are of low grade, and only a small proportion of them have been locally enriched to high-grade iron ores, nevertheless, such type of iron ore deposits play a dominant role in the supply of iron resource in China, accounting for 55.2% of the total iron reserve (Jiao and Jiang, 2009).

Previous work concentrated on the formation age and genesis of BIF, as well as the mechanism from BIF to high-grade iron ores. Indirect dating of the interlayers of BIFs showed that the formation ages of BIFs from NCC were largely Late Neoarchean, corresponding well with the peak period for the formation of BIFs worldwide (Klein, 2005), for instance, the ages of Shuichang, Shirengou, Sijiaying and Zhoutaizi BIFs from the Zunhua GB were 2547 Ma, 2541–2553 Ma, 2537–2543 Ma and 2512 Ma, respectively (Cui, 2012; Xiang et al., 2012; Zhang et al., 2011, 2012), Gongchangling, Qidashan and Waitoushan BIFs from Anshan–Benxi were formed at 2550 Ma, 2533 Ma and 2533 Ma, respectively (Dai et al., 2012; Wan, 1993; Wang and Zhang, 1995), Sanheming BIF from the Guyang GB has a formation age of 2562 Ma (L. Liu et al., 2012). In light of the geochemical characteristics of wall rocks such as amphibolite, plagioclase–amphibole gneiss, amphibole plagiogneiss, the tectonic settings for the deposition of BIFs in the NCC have been mostly speculated to be arc-related basins (Cui, 2012; Dai et al., 2012; L. Liu et al., 2012; Zhang et al., 2011, 2012), which are compatible with those of the typical Algoma-type BIFs from the Isua GB (Haugaard et al., 2013). In terms of the source of Fe and Si components

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of BIFs around the world, it remains controversial whether they were derived from the continental sources or originated from hydrothermal fluids (Alexander et al., 2008; Frei and Polat, 2007; Garrels et al., 1973; Jacobsen and Pimentel-Klose, 1988). However, all the PAAS-normalized REY profiles of BIFs in the NCC display both manifest seawater and high-temperature hydrothermal fluid signatures, on the grounds of which a conclusion that a mixture of high-temperature hydrothermal fluids and seawater provided Fe and Si for these BIFs was drawn (Dai et al., 2012; Li et al., 2008, 2010; W.J. Li et al., 2012; L. Liu et al., 2012; Yang et al., 2012; Zhang et al., 2011). As for the mechanism of transforming BIF to high-grade iron ores in the NCC, three main views have been put forward: (1) the primary siderite was decomposed into graphite and magnetite via metamorphism (Li, 1983), (2) the primary BIF was of high grade (Wan, 1993), and (3) the primary unmineralised BIF was upgraded thereby the interaction with hydrothermal fluids (H.M. Li et al., 2012; Liu and Jin, 2010; M.J. Liu et al., 2012; Shi and Li, 1980; Yang et al., 2012; Zhao and Li, 1980), or owing to the structural deformation of the Fe bands (Chen et al., 2012). In this respect, other classic models proposed on the basis of studies on the large-scale BIF-hosted iron ore deposits from Western Australia, South Africa, Brazil and India include: supergene enrichment (Harmsworth et al., 1990; Morris, 1980, 1988), interaction of BIF with hydrothermal fluids (Barley et al., 1999; Duuring and Hagemann, 2013; Powell et al., 1999; Thorne et al., 2009) and two stage hydrothermal-supergene model (Taylor et al., 2001; Thorne et al., 2004).

A vast amount of research has been conducted into BIFs from the eastern and central NCC, by stark contrast, BIFs of the western NCC have rarely been studied (L. Liu et al., 2012), which, consequently, restricts the understanding of the genesis of BIFs in NCC as a whole and hinders the development of new exploration targets for concealed iron orebodies in the western NCC. The Sanheming and Gongyiming deposits are two typical BIFs from the Guyang GB, additionally, there are some upgraded iron ores in Gongyiming. This paper focuses on the two BIFs and upgraded iron ores. Based on SIMS zircon U–Pb dating, geochemistry and oxygen isotope analyses, we provide constraints on the formation age, geodynamic setting and source of the BIFs from Guyang GB, coupled with proposing the genesis of upgraded iron ores.

2. Geological background

The North China Craton is one of the oldest cratons in the world, with crustal rocks up to 3.8 Ga (D.Y. Liu et al., 1992). During the initial period of 3.8–3.0 Ga, about five to ten nuclei were generated (Bai et al., 1993; Deng et al., 1999; Wu et al., 1998; Zhai et al., 2005). After that, voluminous continental crust accretion developed surrounding these ancient nuclei at ca. 2.9–2.7 Ga, forming several micro-blocks, seven of which have been identified, i.e., Jiaoliao Block (JL), Xuchang Block (XCH), Qianhuai Block (QH), Ordos Block (OR), Xuhuai Block (XH), Jining Block (JN) and Alashan Block (ALS) (Zhai and Bian, 2000). Subsequently, the most significant tectonic evolving stage, Late Neoarchean (2.6–2.5 Ga), saw the amalgamation of the seven micro-blocks, welded by the Greenstone Belts, including the Wutaishan GB, Guyang GB, Dengfeng GB, Houtoushan GB, Zunhua GB and Yanlingguan GB (Fig. 1a). Accompanied by the amalgamation were the widespread intrusions of granites and TTG, which were derived from partial melting of continental crust and mafic crust, respectively, resulting in pervasive amphibolite to granulite facies metamorphism. Additionally, granitic–pegmatitic and mafic dykes extensively intruded into the Archean rocks, indicating the accomplishment of Late Archean cratonization of the North China block (Zhai and Santosh, 2011). After a stable period of approximately 150 Ma (2.50–2.35 Ga), the NCC underwent an orogenic cycle from rifting to subduction–collision during 2.35–1.97 Ga and an extensive tectonic event inducing widespread regional high-grade metamorphism during 1.95–1.82 Ga (Zhai and Peng, 2007), the latter is commonly proposed to be the final amalgamation at ca. 1.85 Ga along a high-pressure metamorphic belt between a western block (amalgamated previously from two sub-blocks at 2.0–1.9 Ga) and an eastern block, within which a rift opened and closed at 2.2–1.9 Ga (Guo et al., 2005; Kröner et al., 2005, 2006; Santosh et al., 2007; Wilde et al., 2002; Zhao et al., 2001, 2002, 2005, 2008). After the Paleoproterozoic orogenies, the NCC experienced reworking during a period between 1.82 Ga and 1.60 Ga, e.g., the whole-scale uplifting of metamorphic basement at 1.82–1.80 Ga, intrusion of ~1.78 Ga mafic dyke swarms with radial distribution and 1.8–1.6 Ga aulacogens and rift basins, all of which were ascribed to mantle–plume tectonics (Zhai, 2011). From ~1.6 Ga on, the NCC had been a stable platform until the Mesozoic Era.

2.1. Geologic setting of the Guyang Greenstone Belt

The Guyang Greenstone Belt is located in the northern margin of the western NCC, with the Paleoproterozoic Bayan Obo tectonic belt to the north and the Paleoproterozoic khondalite series along Helanshan–Daqingshan to the south. The Guyang GB, along with the eastern high-grade granulite terrain, constitutes the most widely distributed Archean basement of the western NCC (Jin et al., 1991; Li et al., 1987; X.S. Liu et al., 1992). The EW-striking, elongated belt (Fig. 1b) is exposed as a residual basin, with its boundaries defined by Paleoproterozoic and Phanerozoic strata (Li et al., 1987).

The Guyang Greenstone Belt is hosted in the Neoarchean Seertengshan Group, which is a volcanic–sedimentary sequence that has undergone greenschist to low-amphibolite facies metamorphism. On the basis of distinct rock assemblages, the group is divided into four formations: the Dongwufenzi Formation, the Liushugou Formation, the Beizhaogou Formation and the Dianlisutai Formation. The lower section of Dongwufenzi Formation is characterized by BIF, amphibolite, serpentinized amphibololite, amphibole pyroxenite, marble and biotite chlorite-schist, while the upper section is quartz schist, leptynite and marble. The Liushugou Formation consists predominantly of quartz schist, albite schist, actinolite schist, and overlain by tremolite marble on the top. The Beizhaogou Formation is dominated by schist and intercalated with minor tremolite marble. The uppermost Dianlisutai Formation comprises mainly quartzite and marble with leptynite interlayers. According to the protolith reconstruction of the Seertengshan Group, the lower part of the sequence contains primarily mafic volcanic rocks interlayered with silicalite and BIF, overlying ultramafic volcanics. Intermediate and acid volcanics are increasingly abundant upwards, and are overlain by clastic rocks and carbonatite at the top of the sequence (Li et al., 1987).

The Seertengshan Group was subsequently intruded by the Late Neoarchean TTG, high-Mg diorite and granite, which are distributed roughly along a EW-striking belt (Fig. 1b; Jian et al., 2005, 2012; Ma, 2011; Ma et al., 2010; Tao, 2003; Zhang et al., 2000). Within these plutons, xenoliths of amphibolite, BIF, amphibole schist, serpentinized amphibololite and amphibole pyroxenite from the Seertengshan Group are commonly observed (Fig. 5c; Jian et al., 2005; Ma, 2011; Ma et al., 2010). Both the Seertengshan Group and the Late Neoarchean plutons were once again intruded by Proterozoic and Phanerozoic intrusions (Fig. 1b).

A four-stage deformation sequence has been proposed for the Seertengshan Group and the Late Neoarchean intrusions within it. D1 was bed-parallel deformation, including rootless folds and folding layers. Subsequent D2 compression induced tight isoclinal folds, the axial planes of which were north-dipping, parallel to the regional foliation. The regional large-scale sinistral ductile shear D3 was intense and extensive, producing structures such as NW mineral stretching lineation, NW rodding structure and mylonite foliation. D4 was NS intense compression, forming the inverted synclines and conjugate kink bands. Apart from that, faults of various ages and types are rather common in this region, previous work has identified two groups of faults: the EW-striking and the NE-striking (Fig. 1b), the former are mostly