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Zircon growth and ages of migmatites in the Algoma-type BIF-hosted iron deposits in Qianxi Group from eastern Hebei Province, China: Timing of BIF deposition and anatexis

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ABSTRACT

Algoma-type BIFs and associated volcanic suites of the Qianxi Group in eastern Hebei Province have undergone high-grade metamorphism and anatexis. The anatectic event is genetically related to high-grade magnetite ores, but the age of the anatectic melting has not been well constrained. We present detailed textural relationship and internal structures of zircon grains and their age data from eight samples of migmatitic rocks representing the different Algoma-type BIF-hosted iron deposits to constrain the formation age of BIF deposition and subsequent anatexis. Six continuous zircon growth stages are distinguished by a series of low-CL and high-CL zones outside from center to edge: inherited magmatic zircon, bright-CL resorption domain, dark-CL recrystallization front, dark-gray-CL diffusion domain, light-gray-CL overgrowth and bright-CL resorption edge. The overgrowths are interpreted as a solid-state diffusion of Zr of primary zircon during interaction with anatectic melt, which resulted in different stages of chemical re-equilibration of primary domains and local re-deposition of newly grown domains on the suitable isostructural substrate of residual magmatic zircon. SHRIMP zircon U–Pb dating of inherited magmatic cores and discrete magmatic grains constrains the peak BIF-deposition age at 2520 Ma, which is different from the peak at 2.75–2.70 Ga for Algoma-type BIFs elsewhere in the world. Zircon U–Pb dating of light-gray-CL rims and newly grown homogeneous grains indicates that the anatectic event lasted from 2511 to 2485 Ma at least, immediately following the BIF deposition. The BIF depositional event is consistent with widespread late Neoarchean magmatism, and the anatectic event is consistent with regional metamorphic events in the eastern part of the North China Craton.

1. Introduction

Precambrian banded iron formations (BIFs) are Fe-rich marine sedimentary rocks which are composed of alternating bands of iron oxides, silicates or carbonates and chert (James, 1954). BIFs are classified as Algoma- and Superior-type (Gross, 1965). Superior-type BIFs are generally large in size and were deposited in a shelf environment with rare volcanic assemblages. In contrast, the Algoma-type BIFs are usually small in size and associated with synchronous volcanic suites. The BIFs in China are mainly distributed in North China Craton (NCC) and are closely associated with greenstone belts (Zhai and Santosh, 2011, 2013; Zhang et al., 2012a). Most of them belong to Algoma-type (Zhai and Windley, 1990; Zhai et al., 1990; Zhai and Santosh, 2013; Li et al., 2010, 2014; Zhang et al., 2014).

Dating of the synchronous volcanic rocks in the hanging wall, footwall or interlayer helps to constrain the BIF depositional event. Globally, the formation ages of Algoma-type BIFs reached a peak at 2.75–2.70 Ga (Huston and Logan, 2004; Klein, 2005). However, SHRIMP U–Pb ages obtained in recent years indicate that the dominant BIFs depositional events in the NCC occurred in late Neoarchean (2.55–2.50 Ga) (Dai et al., 2012; Zhang et al., 2011, 2012b; Wan et al., 2012a for an overview). The deposition of the ~2.7 Ga Algoma-type BIFs in the NCC remains unclear.

Most of the BIF-hosted ores mined today worldwide are high-grade hematite ores with TFe (total Fe) > 60% which are considered to be formed by leaching of gangue minerals from BIFs during

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supergene process (e.g. Morris, 1985; Beukes et al., 2008; Ramanaidou, 2009; Angerer and Hagemann, 2010). In China, the majority of BIF-hosted ores is of low-grade type and is largely composed of coarse-grained magnetite ores which formed during various grades of metamorphism and deformation (Zhou, 1994; Shen et al., 2005). High-grade ores with TFe (total Fe) $\geqslant$ 50% are less than 2% of the total ore reserves of China and occur as lenses or veins in the BIFs. Some high-grade ores resulted from metamorphism and deformation of the iron-rich BIFs, which led the iron oxides transforming to coarse-grained magnetites (Cheng et al., 1978; Wang, 1986). Others are magnetite ores that have been widely interpreted as the product of hydrothermal replacement of protore, mainly related to migmatization (Cheng, 1957; Ren, 1981; Qian et al., 1985; Zhao, 2013). This type of high-grade ores mainly occurs in the fracture zones or in the axis of folds, such as those in the Gongchangling iron deposit and eastern Hebei Province. However, the age of the anatectic event is not well understood.

Zircon geochronology in high-grade metamorphic and anatectic rocks is challenging, particularly where the zircons generally have complex external morphology and internal texture (Black et al., 1986; Corfu and Stott, 1998; Whitehouse et al., 1999). However, modern in-situ techniques have been widely applied to derive information on the timings of magmatism and metamorphism (Claoué-Long et al., 1991; Kröner and Willner, 1998; Pidgeon et al., 2000; Kröner et al., 2014; Nutman et al., 2014). It is important to carefully discriminate metamorphic/recrystallized, relict magmatic, and detrital zircon domains or grains (Vavra et al., 1996, 1999; Schaltegger et al., 1999; Hoskin and Ireland, 2000; Kröner et al., 2000; Kelly and Harley, 2005; Harley et al., 2007; Grant et al., 2009). Zircon imaging techniques such as cathodoluminescence (CL) or backscattered electron (BSE) have been widely used to evaluate the internal texture and crystal evolution of zircons (Schaltegger et al., 1999; Corfu et al., 2003; Hoskin and Schaltegger, 2003; Wu and Zheng, 2004; Zhou and Chen, 2007). Furthermore, some investigators have proposed that detailed textural relationships between the zircons and the host rock are also crucial in revealing zircon behavior in metamorphic/anatectic processes within the rock (Dirks and Hand, 1991; Jian et al., 2001, 2012a,b; Dempster et al., 2008).

BIFs in the Qianxi Group of the eastern Hebei Province (EHP) were traditionally considered to have formed in Mesoarchean by many geologists (Qian et al., 1985; Liu et al., 1990; Shen, 1998; Shen et al., 2005). Almost all of the BIF-hosting volcanic suites of the Qianxi Group have undergone upper amphibolite facies to granulite facies metamorphism and anatectic melting event (Yang et al., 2014a,b; Yao et al., 2014). Widespread migmatite and K-rich granites occur parallel to or cross-cutting the BIFs. In-situ U–Pb dating of complex zircons in these wall rocks of BIFs can provide age constraints to evaluate the anatectic melting event as well as BIF depositional event (Foster et al., 2001; Keay et al., 2001). In this study, we present integrated studies on zircon morphology, internal texture, textural relationship with other minerals in the host rock, and U–Pb age data for eight samples of migmatitic rocks from different Algoma-type BIF-hosted iron deposits in the Qianxi Group of the EHP. The study aims to provide detailed age data on the depositional and anatectic melting events.

2. Geological background

The NCC, one of the oldest continental nuclei on Earth, has been considered to be composed of an Archean to Paleoproterozoic crystalline basement and an overlying Mesoproterozoic to Cenozoic cover (Jahn et al., 1987; Jahn, 1990; Zhai et al., 2005; Zhai, 2014). Tectonically, the basement has been divided into Eastern and Western Blocks, separated by the NS-trending Trans-North China Orogen (TNCO) (Zhao et al., 1998; Zhai and Santosh, 2011; Zhao and Zhai, 2013). The NCC formed by amalgamation of the Eastern and Western Blocks along the TNCO (Zhao et al., 1998, 2001; Kusky and Li, 2003), but the timing of the final collision remains controversial with different views as 1850 Ma (Wilde and Zhao, 2005; Kröner et al., 2006; Santosh et al., 2006, 2013; Zhao et al., 2012; Zhao and Zhai, 2013; Yang and Santosh, 2014; Zhai, 2014) or as 2.5–2.3 Ga (Kusky and Li, 2003; Kusky, 2011). The Western Block formed by amalgamation of the Yinshan and Ordos Blocks along the Khondalite Belt at ca. 1950 Ma (Zhao et al., 2005). The Eastern Block is separated by Jiao-Liao-Ji Belt into the Longgang and Langrim Blocks at ca. 1900 Ma (Zhao et al., 2011; Zhao and Zhai, 2013; Wu et al., 2013).

The EHP is located in the northern part of the Eastern Block (Fig. 1a). The Precambrian terrain in the EHP consists of Neoarchean gneisses with subordinate amounts of Eoarchean gneisses. Rocks that preserve Eoarchean record are exposed rarely in the Caozhuang area. Sm–Nd isotopic analyses of amphibolites confirmed an isochron age of 3.5 Ga (Jahn et al., 1987; Huang et al., 1986; Liu et al., 1990), and detrital zircon U–Pb dating of fuchsite-bearing quartzites (Liu et al., 1992; Wu et al., 2005; Wilde et al., 2008) and paragneisses (Liu et al., 2013) gave an age range of 3.8–3.4 Ga. The basement rocks of the EHP comprise mainly of Neoarchean trondhjemite–tonalite–granodiorite (TTG) gneisses (more than 80% of the total exposure), gabbroic intrusive rocks, BIF-bearing supracrustal rocks which have been metamorphosed to granulite, amphibolite and epidote–amphibolite facies rocks. The overlying cover rocks comprise mainly of middle-upper Proterozoic and Quaternary sedimentary sequences and a small volume of Paleozoic and Mesozoic sequences. On the basis of metamorphic facies, migmatization and protolith formation, BIF-bearing sequences of the EHP have been subdivided into three Groups, namely Qianxi Group, Luanxian Group and Zhuzhangzi Group (Fig. 1b) (Sun, 1984; Qian et al., 1985).

The Qianxi Group constitutes more than 90% Archean outcrop of the EHP with an area ca. 700 km^2. The supracrustal rocks have undergone upper amphibolite to granulite facies metamorphism and anatectic melting, and comprise mainly of two-pyroxene granulites, pyroxene amphibolites, pyroxene–biotite bearing plagioclase gneisses, migmatites, magnetite quartzites, and some subordinate amounts of garnet–sillimanite gneisses, cordierite–plagioclase gneisses, clinopyroxene–hornblende–plagioclase granulites and garnet-bearing fayalite peridotites. The protoliths of these rocks are basalts and intermediate–felsic tuffs with subordinate tuffaceous greywacke (Qian et al., 1985; Jahn et al., 1987; Geng et al., 2006). Recent high-precision in-situ zircon dating shows that most of the supracrustal rocks in the Qianxi Group formed in Neoarchean (Geng et al., 2006; Yang et al., 2008; Zheng, 2009; Li et al., 2010; Nutman et al., 2011; Zhang et al., 2011, 2012b; Lv et al., 2012; Wan et al., 2012a; Guo et al., 2013; Bai et al., 2014). The Qianxi Group comprises abundant BIFs and hosts the clusters of iron deposits in the EHP. There are eight >100 Mt BIF-hosted iron deposits distributed in the Qianxi Group, such as the Shuichang, Shirengou, Malanzhuang and Xingshan (Li et al., 2012; Li and Li, 2013). Anatectic melting is common in these iron deposits, showing widespread migmatite and K-rich granite parallel to or in sheared contact with BIFs.

The Luanxian Group is distributed in Luan County–Lulong County–southern Qianan County and comprises supracrustal rocks that have undergone amphibolite facies metamorphism. Supracrustal rocks comprise mainly of plagioclase amphibolites, biotite leptynites, plagioclase–amphibole gneisses and magnetite quartzites. Their protoliths are dominantly basalts, intermediate–felsic tuffs and tuffaceous greywacke. Migmatization in the Luanxian Group is less common than that in the Qianxi Group. Supracrustal