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Mesoproterozoic high Fe–Ti mafic magmatism in western Shandong, North China Craton: Petrogenesis and implications for the final breakup of the Columbia supercontinent

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ABSTRACT

High Fe–Ti basic rocks (FeOt > 12 wt% and TiO_2 > 2 wt%) are rare in the geological record and display a different evolutionary trend (the 'Fenner' trend) from the normal 'Bowen' trend of SiO_2 enrichment. In this paper, we present geochronological, geochemical and Sr–Nd isotopic data for the Fe–Ti-rich gabbros from western Shandong within the Eastern Block of the North China Craton. Zircon U–Pb dating indicates that they were emplaced at ~1.21 Ga. All high Fe–Ti gabbros are characterized by low MgO (<7 wt%) and Mg numbers (<50), and high FeOt (>12 wt%), TiO_2 (>2 wt%) and P_2O_5 (mostly >0.4 wt%). Geochemically, they can be divided into two different series (the alkaline series for the Yishui gabbros and the sub-alkaline series for the Feixian gabbros). Both series of Fe–Ti-rich gabbros show similar depletion in Th, U, Nb and Ta, and have positive Eu anomalies. The main difference is that the alkaline series displays slightly more fractionated REE patterns and more depleted Sr–Nd isotopic compositions than the sub-alkaline series; it also lacks positive P anomalies. Elemental geochemistry indicates that both series were likely generated by the partial melting of lherzolitic mantle, with different proportions of garnet in their sources. The mantle sources were re-enriched through varying degrees of hybridization of lower crustal materials prior to partial melting. The results of modeling based on the Sr–Nd isotopic compositions show that their mantle sources could have formed from the hybridization of N-MORB-like depleted mantle through involvement of around 1% lower crustal components for the alkaline series and 2% for the sub-alkaline series: this accounts for their geochemical signatures, especially for the marked depletion in Th and U, and weak negative Nb and Ta anomalies. A combination of Fe-rich mantle source and subsequent fractional crystallization, coupled with low fO_2 during magmatic evolution, likely resulted in the Fe–Ti enrichment trend in both series of gabbros. In combination with regional and global studies, their generation could be related to a prolonged superplume that led to the final breakup of the Columbia supercontinent during Mesoproterozoic time.

1. Introduction

High Fe–Ti basic rocks (FeOt > 12 wt% and TiO_2 > 2 wt%; Clague and Bunch, 1976; Clague et al., 1981; Perfit and Fornari, 1983), show a different evolutionary trend (the 'Fenner' trend toward high FeOt and low SiO_2) from the more typical 'Bowen' differentiation trend (evolving to silica-rich and iron-poor rhyolitic products, Hunter and Sparks, 1987); but are rather rare in the geological record. Excluding the oceanic setting, such as propagating spreading centers at mid-ocean ridges (Clague et al., 1981; Perfit and Fornari, 1983; Sinton et al., 1983) and in back-arc basins (Pearce et al., 1994; Harper, 2003), several studies have demonstrated that high Fe–Ti basic igneous rocks are also generated in continental settings, such as in the Afar Rift of Ethiopia (Barberi et al., 1975) and in the northern and southern sections of the Red Sea Rift (Juteau et al., 1983; Cocherie et al., 1994). Moreover, most of the Fe–Ti-rich compositions are found in plutonic environments and only rare cases are known for erupted rocks (Clague et al., 1981; Perfit and Fornari, 1983; Sinton et al., 1983; Hunter and Sparks, 1987; Pearce et al., 1994; Hooper, 2000; Harper, 2003; Zhang et al., 2012). Some of these intrusions host world class Fe–Ti oxide deposits, such as the Skaergaard Intrusion in East Greenland (e.g., Nielsen, 2004; Jakobsen et al., 2005, 2011), the Sept Iles layered intrusion in Canada (e.g., Namur et al., 2011), the Bushveld Complex in South Africa

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(e.g., VanTongeren and Mathez, 2012), the Panzhihua intrusive complex in southwestern China (e.g., Zhou et al., 2005, 2008a,b) and the Damiao complex in North China (e.g., Zhao et al., 2009). However, the mechanism by which they achieved their enrichment in Fe–Ti contents, especially for those developed in a continental regime, remains controversial. Thus, probing further into their petrogenesis will allow us to understand Fe–Ti enrichment in high Fe–Ti basic magma in different tectonic environments.

The North China Craton (NCC) is the largest known cratonic block in China and consists of the Eastern and Western blocks, and an intervening Trans-North China Orogen (Zhao et al., 2001). It is also one of the oldest cratons in the world, with crustal rocks as old as 3.8 Ga (Liu et al., 1992; Wu et al., 2008; Zhao and Zhai, 2013; Zheng et al., 2013). Its final cratonization took place in the Paleoproterozoic at around 1.85–1.80 Ga (e.g., Zhao, 2001; Zhao et al., 2001, 2002a,b, 2008a,b, 2010; Wilde and Zhao, 2005; Kröner et al., 2006; Liu et al., 2006, 2011a,b, 2012a,b; Zhang et al., 2006, 2007, 2009a,b; Xiao et al., 2011). In recent years, numerous high Fe–Ti basic intrusive rocks have been documented in the NCC, such as the ~1.77 Ga mafic dykes (Peng et al., 2004; Wang et al., 2004, 2008) and the Damiao complex (Zhao et al., 2009 and references therein) in the Trans-North China Orogen, and the ~1.93 Ga Xuwujia gabbronorites (Peng et al., 2010) and ~1.31 Ga diabase sills (Zhang et al., 2012) in the Western Block. The occurrence of these high Fe–Ti mafic intrusive rocks likely reveals that an iron-rich mantle source was present beneath the Trans-North China Orogen and the Western Block in the Precambrian, particularly in the Paleoproterozoic, as pointed out by Wang et al. (2004, 2008). In the Eastern Block, although some Paleoproterozoic (~1.84 Ga) mafic dykes have been reported by Wang et al. (2007), these rocks do not possess a high Fe–Ti signature. On the contrary, they originated from a depleted rather than an enriched mantle source (Wang et al., 2007). Hence, the recent identification of Mesoproterozoic (~1.21 Ga) high Fe–Ti basic magmatic rocks in western Shandong within the Eastern Block of the NCC, will provide a significant new insight into the nature of the lithospheric mantle beneath the NCC and also offer an opportunity to better understand the mechanism of Fe–Ti enrichment of basic magma.

In this contribution, we present new geochronological, elemental and Sr–Nd isotopic data for the Mesoproterozoic high Fe–Ti gabbros in western Shandong. Our aims are to: (1) determine the petrogenesis of these high Fe–Ti gabbros and the nature of their mantle source; (2) probe the mechanism for their Fe–Ti enrichment, and (3) enhance our understanding of the final breakup of the Columbia supercontinent in the time interval of 1.3–1.2 Ga.

2. Geological setting and petrography

The North China Craton formed by the amalgamation of the Eastern and Western blocks along the Trans-North China Orogen at ~1.85 Ga (Fig. 1a; Zhao et al., 1999a,b, 2000, 2001, 2005, 2006, 2007, 2008a,b; Trap et al., 2007; Liu et al., 2006; Zhang et al., 2006, 2007, 2009a,b; Li et al., 2010b; Wang et al., 2010a,b). The Western Block is further subdivided into the Yinshan Block in the north and the Ordos Block in the south, which amalgamated along the Khondalite Belt at ~1.95 Ga (Fig. 1a; Zhao et al., 2003a, 2010; Xia et al., 2006a,b, 2008, 2009; Zhao, 2009; Yin et al., 2009, 2011; Zhou et al., 2010). In contrast, the Eastern Block experienced rifting at ~1.90 Ga and subsequent collision between the Longgang and Langrim Blocks, forming the Jiao-Liao-Ji Belt (Fig. 1a; Luo et al., 2004, 2008; Li et al., 2006; Zhou et al., 2008a,b; Tam et al., 2011, 2012a,b). The Eastern Block is dominated by ~2.7–2.6 Ga TTG gneisses, and mafic–ultramafic igneous rocks, ~2.52 Ga diorite, granodiorite, monzogranite and K-feldspar granite plutons, and ~2.5 Ga syntectonic charnockites, with minor 2.55–2.50 Ga bimodal volcanics and sedimentary supracrustal rocks (Zhao et al., 1998, 2001, 2005; Wu et al., 2005b, 2008; Yang et al., 2008; Jiang et al., 2010; Li et al., 2010c). Also, the oldest known basement within the craton is located in the Eastern Block, which has been dated at 3.8 Ga (Liu et al., 1992; Wu et al., 2005a).

The western Shandong area is also referred to as the Luxi granite-greenstone belt (Cao et al., 1996; Hou et al., 2008b) or the Taishan granite-greenstone terrane (TSGT) (Fig. 1a). It covers a total area of >10,000 km^2 and extends in a northwest–southeast direction, being truncated by the major Tanlu Fault in the east (Fig. 1b). Its basement gneisses are Mesoarchean to Paleoproterozoic in age, and are partially overlain by Mesoproterozoic to Cenozoic platform cover. Neoarchean (2.9–2.5 Ga) basement crops out widely and is dominated by ~2.7–2.6 Ga TTG gneisses and gneissic monzogranites, accounting for 80% of the total Precambrian basement in the TSGT (Jahn et al., 1988; Zhang et al., 2001). Minor ~2.7–2.6 Ga ultramafic to felsic volcanic and sedimentary rocks, collectively referred to as the Taishan greenstone belt, occur as lenses within the TTG gneisses (Fig. 1b; Xu et al., 1992; Cao et al., 1996; Zhang et al., 2001). The ultramafic–mafic volcanics were metamorphosed up to amphibolite facies and some of them show fault-bounded contacts with the ~2.7 Ga TTG gneisses, whereas others form lenses or boundins in the TTG gneisses (Jahn et al., 1988). In addition, a number of Late Archean pyroxenite, gabbro, diorite, granodiorite, and granite plutons intrude the TTG gneisses (Jahn et al., 1988; Cao et al., 1996; Wu et al., 1998); field observations suggest that these later plutons were metamorphosed at lower grades than the gneissic country rocks. Recent precise zircon U–Pb dates show that they were emplaced at ~2.54 Ga (Hou et al., 2008b; Shen et al., 2004, 2007; Zhao et al., 2008; Wang et al., 2009).

Paleoproterozoic mafic dykes, previously dated at ~1.84 Ga, extensively crop out over the whole area (Wang et al., 2007), and thus pre-date the ~1.75 Ga mafic dykes found in the Trans-North China Orogen (Wang et al., 2004, 2008). Moreover, their low FeOt contents and depleted $\varepsilon_{Nd}(t = 1.84\,Ga)$ values are distinctly different from the latter, which display enriched characteristics and mostly have a Fe–Ti-rich affinity (Wang et al., 2004, 2008). Additionally, Mesozoic basic magmatism also occurred in the area, including gabbroic intrusions (Huang et al., 2012) and diabase dykes (Liu et al., 2008), both of which do not possess high Fe–Ti abundances.

Several minor gabbroic intrusions also occur within ~2.55 Ga gneisses and are distributed across a wide area (Figs.1b, 2a and b). A clear intrusive contact can be observed between them in the field. Previous field investigations suggested these were emplaced in the Paleoproterozoic; synchronous with the Taoke metabasic rocks (Fig. 1b; SDGMRB, 1990). However, the Taoke metabasic rocks were recently dated at ~2.54 Ga by Wang et al. (2009). Moreover, unlike the Taoke metabasic rocks, these gabbroic intrusions are unmetamorphosed and not deformed; instead they are massive, greenish to black in color (Fig. 3a and b) and medium- to coarse-grained. The main mineralogy is plagioclase and clinopyroxene, without olivine (Fig. 3c and d). Accessory minerals are apatite, zircon and ilmenite. The gabbro samples for this study were collected from the Yishui (samples 08YS-61–08YS-71; Fig. 2a) and Feixian areas (samples 08YS-123–08YS-126; Fig. 2b). Gabbro sample 08YS-61 for U–Pb zircon dating was collected along the Caiu-Niuxinguanzuang road (35°51.094 N, 118°42.707 E) in the Yishui area (Fig. 2a).

3. Analytical techniques

Zircons for SHRIMP U–Pb dating were separated using conventional heavy liquid and magnetic techniques, followed by handpicking under a binocular microscope. The zircon grains were mounted in epoxy resin, polished and reduced to half their grain size. They were then gold coated and photographed in transmitted