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Age, geochemistry and tectonic setting of the Neoproterozoic (*ca* 830 Ma) gabbros on the southern margin of the North China Craton

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ABSTRACT

Many studies have addressed the Paleozoic to Triassic collisional processes along the southern margins of the North China Craton (NCC), but little is known about the evolution of this margin during Precambrian time. This paper examines the geochronology and geochemistry of gabbros from the Luanchuan Group, which is located on the southern margin of the NCC. These gabbros are dated at *ca* 830 Ma by SHRIMP and LA–ICP-MS zircon U–Pb methods. They are characterized by high contents of TiO_2 (2.21–4.45 wt%) and light-REEs (rare earth elements) ($(La/Yb)_N = 9.54–7.71$). The gabbros have overall OIB (ocean island basalts)-like trace element patterns, without the positive Pb and Sr anomalies and negative Nb–Ta anomalies. In addition, they have low La/Nb (<1.5) and La/Ta (<30) ratios, indicating an origin in the asthenospheric mantle. The depletions of HFSEs (high field strength elements) (e.g. Zr–Hf and Ti) probably suggest that their source has been metasomatized by carbonates. The gabbros show negative $\varepsilon_{Nd}(t)$ (−1.5 to −3.0), suggesting crustal contamination or mixing with metasomatized lithospheric mantle. However, the low Th and U contents, constant incompatible-element ratios (e.g. Zr/Nb, La/Nb, La/Sm) and the absences of correlations of $\varepsilon_{Nd}(t)$ with MgO, Nb/Nb*, SiO_2 or 1/Nd preclude significant crustal contamination. Alternatively, the wide range of Hf–isotope ratios in zircons ($\varepsilon_{Hf}(t)$ from −3.6 to +6.3) may imply the interaction between asthenosphere-derived melts and the metasomatized lithospheric mantle. Petrological modeling suggests that the gabbros may have been generated from the low-degree (2–3%) partial melting of lherzolite with 2% garnet at depths greater than 85 km. The gabbros may have been generated in a within-plate rift setting. The gabbros may best be correlated with the Neoproterozoic magmatic rocks in the NQB (North Qinling Belt), representing the relicts onto the southern margin of the NCC following the Neoproterozoic rifting between the NCC and the NQB. Therefore, the NCC and NQB may have been connected at *ca* 830 Ma. Moreover, the occurrence of the gabbros implies that the present southern margin of the NCC may have been mixed with late Mesoproterozoic to Neoproterozoic crustal materials from the NQB. The new findings imply that the southern margin of the NCC has been the locus of at least three extension-convergence cycles, and the reactivation of such tectonic margins may be more common in the geological record than previously recognized.

1. Introduction

Cratons, which were dominantly formed before late Archean time, have roots of rigid, cold and refractory lithospheric mantle, commonly extending to depths of 150–250 km. After their final stabilization, these cratonic areas generally remained stable, with weak tectonic activity and few intrusions of magmatic rocks until decratonization took place with the loss of the roots, as documented in the North China Craton (e.g., Yang et al., 2008). However, the edges of these lithospheric blocks represent major discontinuities in composition and rheology, and thus are critical for the evolution of continents (e.g., Begg et al., 2009). Therefore, we need to understand the margins of cratons and find how they develop during continental rifting and assembly.

The North China Craton (NCC), which initially developed around 3.8 Ga, is a part of Asia that has been built up through the complex convergence of continental blocks and micro-blocks, and represents a natural laboratory for understanding the role of passive

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margins during the evolution of cratons. It is generally recognized that the NCC was involved in the middle Paleozoic to late Triassic assembly processes with the South China Block (SCB) (Mattauer et al., 1985; Zhao and Coe, 1987; Li, 1994; Meng and Zhang, 1999; Wu et al., 2009). The Triassic collision event led to the formation of the Dabie-Sulu ultra-high-pressure (UHP) metamorphic belt. Recently, more and more geochronological data suggest significant early- to middle-Neoproterozoic magmatism in the Qinling and Dabie-Sulu orogenic belts (e.g., Zheng et al., 2004; Chen et al., 2006). However, the accepted model for the pre-Neoproterozoic evolution of the Qinling-Dabie orogenic belt leaves several unanswered questions (e.g., Meng and Zhang, 1999): What was the Precambrian evolution of the southern margin of the NCC? What was the relationship between it and the terranes of the Qinling Belt before 800 Ma? Did it ever connect with North Qinling Belt (NQB) during the Precambrian? Resolving these questions will improve our understanding of the Neoproterozoic margin of the NCC, the evolution of the Qinling-Dabie orogenic belt, and the petrogenesis of the protoliths of the UHP metamorphic rocks.

Neoproterozoic magmatic rocks are widespread in the SCB (e.g., Zhou et al., 2002a, 2004, 2006, 2007, 2009; Li et al., 2003; Wang et al., 2006, 2007; Zhao and Zhou, 2009a,b; Zheng et al., 2008) with a possible correlation with the Rodinia supercontinent. However, it has been unclear whether the NCC was also involved in the global Neoproterozoic magmatic events, because 830–740 Ma magmatism is very rare. Therefore, identifying magmatic rocks within this age span in the NCC is critical to understanding the Neoproterozoic history on its southern margin and the possible connections with other continents and micro-blocks to the south. In this paper, we present new geochronological and geochemical data for the gabbros from the Luanchuan Group on the southern margin of the NCC, and conclude that they have been generated in a within-plate rifting setting, representing the relicts of the NQB to the southern margin of the NCC following the rifting between the NQB and NCC. This finding suggests that the NQB and NCC may have been connected during the early Neoproterozoic.

2. Geological setting

The North China Craton (Fig. 1a) was formed by the amalgamation of the eastern and western blocks at *ca* 1.85 Ga (Zhao et al., 2001, 2002, 2005; Wilde and Zhao, 2005; Kröner et al., 2006; Zhang et al., 2006), which was followed by the eruption of the *ca* 1.80–1.75 Ga Xiong'er volcanic rocks (Zhao et al., 2004, 2009; He et al., 2008, 2009, 2010a,b; Wang et al., 2010) and the formation of the *ca* 1.63 Ga alkali granites (Bao et al., 2009) along the southern margin. The EW-trending Qinling orogenic belt (Fig. 1a), which connects with the Dabie UHP metamorphic belt to the east and lies between the NCC and SCB, is one of the most important orogenic belts in China. It is the best place to study the amalgamation between the NCC and the SCB. The collision of the two blocks led to the formation of the Shangdan and Mianlue suture zones within the orogenic belt (Fig. 1b; Meng and Zhang, 1999). The Qinling orogenic belt can be further subdivided into the North and South Qinling belts (Fig. 1b). However, the geological evolution of the two sub-orogens is complex, and the boundary between the NCC and the NQB (North Qinling Belt) may have been in different places at different stages (Meng and Zhang, 1999). Some pieces of the southern margin of the NCC may then have been involved in the formation and evolution of the NQB (Zhang et al., 2000) during Mesoproterozoic to Paleozoic time, making the tectonic situation of the NQB an open question. Despite the Paleozoic and later tectonic overprinting, Precambrian strata and volcanic rocks on the current southern margin of the NCC show close affinities to the NCC (Gao et al., 1996), such as the Taihua Group, the Guandaokou Group and the volcanic rocks of the Xiong'er Group. This geological evidence has led many geologists to believe that the southern margin of the NCC was separated from the Qinling Orogenic Belt by the Zhu–Xia (Zhuyangguan–Xiaguan) Fault (Lu et al., 2006; Fig. 1c).

The gabbros studied here are located just north of the Zhu–Xia Fault, adjacent to the L–L (Luonan–Luanchuan) Fault (Fig. 1c), and thus have been regarded as part of the southern margin of the NCC (Wang, 2000; Lu, 2009; Song et al., 2009; Wang et al., 2009; Yan et al., 2009). In fact, the *ca* 10 km-wide L–L Fault belt and the *ca* 30 km-wide strongly deformed zone to the north are rather complex (Song et al., 2009) and may better be considered as a transitional zone between the NCC and the NQB (Hu and Zhang, 1990). In this transitional zone, the Precambrian sequences are mainly composed of four stratigraphic units: the Taihua Group, the Xiong'er Group, the Guandaokou Group and the Luanchuan Group, from bottom to top (HIGS, 1990). All of them have been thrust to the south (Fig. 1d). The 2.5–2.3 Ga (Xu et al., 2009) sequences of the Taihua Group are metamorphosed to amphibolite facies, and represent the basement along the southern margin of the craton. The Xiong'er Group consists mainly of volcanic rocks (including basaltic andesites, andesites, rhyolitic lavas and minor pyroclastic rocks) with SHRIMP zircon U–Pb ages of 1.80–1.75 Ga (Zhao et al., 2004; He et al., 2009). The late-Mesoproterozoic Guandaokou Group, which unconformably overlies the Xiong'er Group, is mainly composed of sandstones, mudstones, clays and dolomites, representing the cover strata in the area. The Luanchuan Group is generally considered to be formed in the Neoproterozoic (BGMRHNP, 1989; Zhang et al., 2000). It can be subdivided into four formations: the Sanchuan Formation, the Nannihu Formation, the Meiyaogou Formation and the Dahongkou Formation.

As the upper part of the Luanchuan Group, the Dahongkou Formation is mainly composed of trachytes, trachy-andesites, trachy-tuffs and interlayered slates and quartz-phyllites. Zhang et al. (1991) obtained a whole-rock Sm–Nd isochron age of 682 ± 60 Ma and an Rb–Sr isochron age of 660 ± 27 Ma for the meta-trachytes of the Dahongkou Formation. Concurrently with the eruption of the volcanic rocks of the Dahongkou Formation, co-magmatic intrusive rocks were emplaced, including gabbros, syenitic porphyries and syenites (HIGS, 1990; Jiang, 1993; Wang, 2000). The gabbros generally occur near Luanchuan county, intruding into the Guandaokou Group, and have a total outcropping area of *ca* 25 km^2 (BGMRHNP, 1989). Some of the gabbro dykes host later Cu–Zn mineralization.

The gabbros of the Luanchuan Group generally have been altered to some extent. Fresh mafic minerals (such as pyroxenes) have been replaced by tremolite, calcite, chlorite, zoisite and epidote. The plagioclase crystals are relatively fresh and have An_{30-34} compositions. To minimize the influence of alteration, we have tried to select the freshest samples for geochronological and geochemical studies.

3. Analytical methods

Three representative gabbro samples were selected for zircon U–Pb dating. Zircons from two samples (07CTD-08 and 07CTD-09; N33°50′34.1″, E111°32′25.8″) were dated by LA–ICP-MS, and zircons from the third sample (07CTD-18; N33°54′44.9″, E111°21′13.8″) were analysed by both LA–ICP-MS and SHRIMP. U–Pb isotopic results are listed in Supplementary Table 1. Zircons were separated using conventional heavy liquid and magnetic techniques, mounted in epoxy resin and polished down to expose grain centers. Cathodoluminescence (CL) images (Fig. 2a) of zircons were acquired with a Mono CL3+ (Gatan, USA) attached to a scanning electron microscope (Quanta 400 FEG) at the State Key Laboratory of Continental Dynamics, Northwest University (NWU), Xi'an.

LA–ICP-MS zircon U–Pb dating was carried out at the State Key Laboratory for Mineral Deposits Research (MiDeR), Nanjing University (NJU), using an Agilent 7500a ICP–MS attached to a New Wave