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Discovery and geological significance of high-pressure mafic granulites in the Pingdu–Anqiu area of the Jiaobei Terrane, the Jiao–Liao–Ji Belt, the North China Craton

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ABSTRACT

High-pressure (HP) mafic granulites in the Pingdu–Anqiu area of the Jiaobei Terrane, in the southwestern segment of the Jiao–Liao–Ji Belt of the North China Craton, occur as irregular lenses or deformed dike swarms within the Paleoproterozoic graphite-bearing paragneisses and marbles. Petrographic examination has revealed three distinct metamorphic mineral assemblages: a peak HP granulite-facies assemblage (M_1) that consists of garnet + clinopyroxene + plagioclase + quartz ± amphibole ± Fe–Ti oxides, a post-peak decompression assemblage (M_2) that is characterized by symplectites of orthopyroxene + clinopyroxene + plagioclase ± amphibole ± Fe–Ti oxides, and a late cooling assemblage (M_3) represented by symplectites of amphibole + plagioclase + Fe–Ti oxides. Pseudosection modeling using THERMOCALC in the NCFMASHTO system and conventional thermobarometers constrained the *P–T* conditions of the M_1, M_2 and M_3 assemblages to P = 1.28–1.44 GPa and T = 757–805 °C, P = 0.50–0.80 GPa and T = 780–840 °C, and P = 0.55–0.73 GPa and T = 665–730 °C, respectively. An integrated study involving laser Raman spectroscopy and scanning electron microscope analysis of mineral inclusions, cathodoluminescence imaging, and *in-situ* U–Pb dating of zircons showed that the protolith ages of the HP mafic granulites are mainly 2200–2000 Ma and that the timing of the peak HP granulite-facies metamorphism ranges from 1950 to 1900 Ma, as recorded by the cores of metamorphic zircons. The medium- to low-pressure amphibolite- to granulite-facies retrogression occurred mainly at 1900–1800 Ma, as recorded by the rims of some zircon grains as well as zircon grains that contain inclusions of clinopyroxene + orthopyroxene + plagioclase + amphibole + sphene. Comprehensive petrographic, mineralogical, and geochronological investigations of the HP mafic granulites defined a clockwise *P–T–t* path involving near-isothermal decompression and near-isobaric cooling, which further suggests that the Jiaobei Terrane had underwent initial crustal thickening during 1950–1900 Ma, followed by relatively rapid exhumation, cooling, and retrogression in the period 1900–1800 Ma. This *P–T–t* path was probably generated by the Paleoproterozoic collisional orogenesis of the North China Craton.

1. Introduction

The North China Craton (NCC) is one of the oldest cratonic blocks in the world, containing rocks as old as ca. 3850 Ma (Liu et al., 1992; Song et al., 1996). In recent years, researchers from various countries have carried out extensive field-based structural, metamorphic, geochemical, geochronological, and geophysical investigations on the basement rocks of the NCC, which have led to major improvements in our understanding of the Precambrian history of the NCC. The most important achievement has been the recognition of three Paleoproterozoic orogenic/mobile belts: the Khondalite Belt (KB) in the western part of the NCC, the Trans-North China Orogen (TNCO) in the center of the NCC, and the Jiao–Liao–Ji Belt (JLJB) in the eastern part of the NCC (for a summary, see Zhao et al., 2012; Zhao and Zhai, 2013; Fig. 1).

The JLJB, also called the Liaoji Belt (Zhai and Santosh, 2011; Fig. 1), is one of the most important Paleoproterozoic orogenic/mobile belts within the NCC. It records a long and complicated history of sedimentation, magmatism, tectonic deformation, multi-metamorphic evolution, and crustal growth. In recent years,

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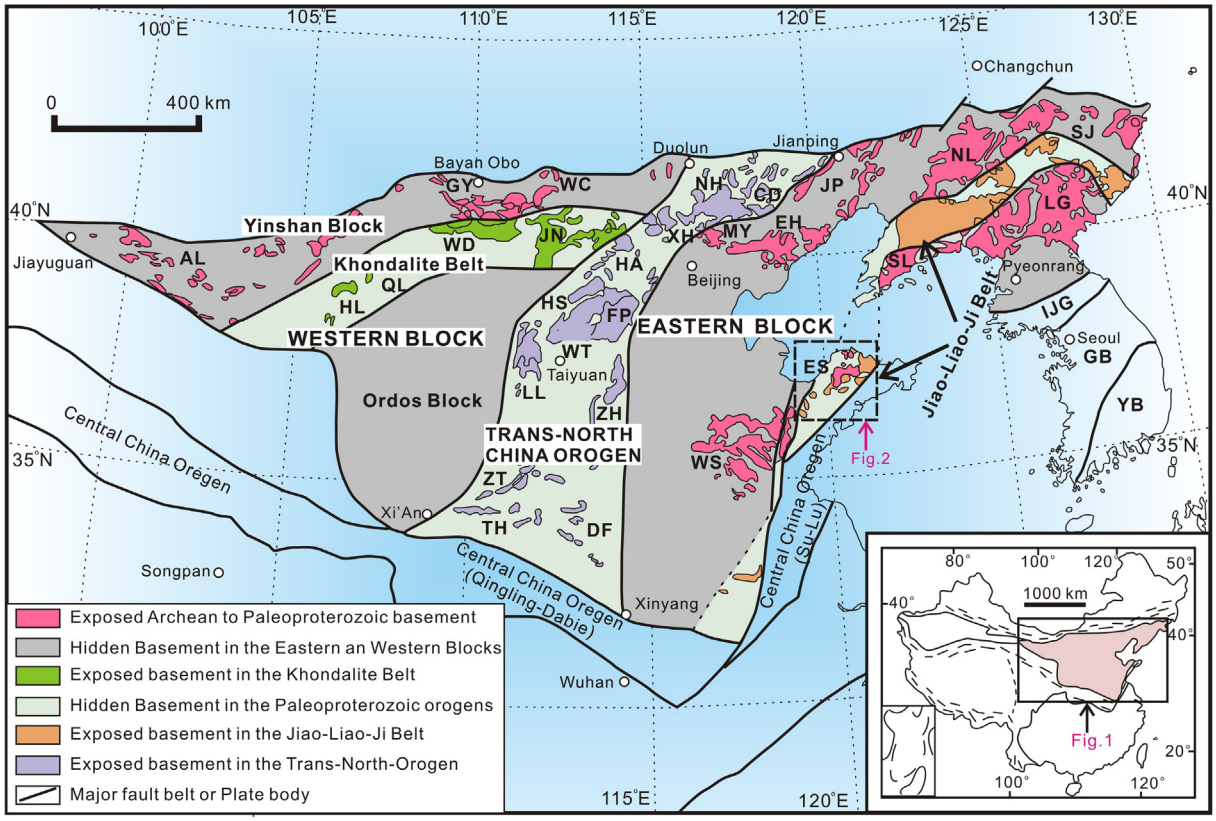

Fig. 1. Tectonic framework of the NCC showing the Jiaobei terrane in the Eastern Block (Zhao et al., 2005). Abbreviations of metamorphic complexes after Zhao et al. (2005).

metamorphic evolution, geochemistry, and U–Pb dating of various metamorphic rocks from the JLJB have been well documented (e.g., Zhao et al., 2012), but the tectonic setting of the JLJB remains debated, and different geodynamic models have been proposed, including arc–continent collision (Bai, 1993; Bai and Dai, 1998; Faure et al., 2004; Lu et al., 2006) and opening and closing of an intra-continental rift (Zhang and Yang, 1988; Peng and Palmer, 1995; Luo et al., 2004, 2008; Li and Zhao, 2007).

The Jiaobei Terrane is the southwestern part of the JLJB (Figs. 1 and 2) that underwent amphibolite- to granulite-facies metamorphism (e.g., Zhao et al., 2012). Since the discovery of high-pressure (HP) mafic and pelitic granulites in the terrane (Liu et al., 1998; Zhou et al., 2004, 2008; Liu et al., 2010b, 2012, 2013c; Tam et al., 2012a,c), extensive investigations of their petrology, genetic mineralogy, geochemistry, metamorphism, tectonic deformation, and geochronology have been carried out. In particular, the *P–T–t* paths for the HP mafic and pelitic granulites are well constrained (Liu et al., 1998, 2010b, 2013c; Zhou et al., 2008; Wang et al., 2010; Tam et al., 2011, 2012a,c). However, most of these studies were restricted to the Laixi–Laiyang–Qixia area, the central part of the Jiaobei Terrane, and few studies have examined the southwestern segment of the terrane (Wang et al., 1998b; Lan et al., 2015), thus hampering our understanding of the spatial distribution, metamorphic evolution, and petrogenesis of the HP granulites.

In this paper, we first present detailed textural and compositional data for the mineral assemblages in the Pingdu–Anqiu HP mafic granulites in the southwestern segment of the Jiaobei Terrane. Then, we use pseudosection modeling and traditional thermobarometers to estimate the *P–T* conditions of the different stages of metamorphism. In addition, we present the results of a detailed geochronological investigation, which included identification of mineral inclusions hidden zircons, CL images of zircons, and precise LA–ICP–MS zircon U–Pb dating. Finally, taking into account the field relationships of the HP mafic granulites and adjacent rocks, we use our results to place new constraints on the nature of the HP granulite-facies metamorphism and on the tectonic evolution of the Jiaobei Terrane in the JLJB.

2. Geological setting

2.1. Regional setting

The Archean to Paleoproterozoic basement of the NCC can be divided into the Eastern, Yinshan, and Ordos blocks and three Paleoproterozoic orogenic/mobile belts (the JLJB, KB and TNCO; Fig. 1; Zhao et al., 2005). The Yinshan and Ordos blocks are considered to have amalgamated along the KB to form the Western Block at ca.1950 Ma (Zhao et al., 2005, 2012; Yin et al., 2009, 2011, 2014), and then the united Western Block collided with the Eastern Block along the TNCO at ca. 1850 Ma (Fig. 1; Zhao et al., 2005, 2012).

The JLJB is located in the Eastern Block, and subdivides the block into the Longgang and Langrim blocks (Fig. 1; Zhao et al., 2005, 2012). The JLJB is a nearly north–south trending zone that is 100–200 km wide and extends for 1200 km from southern Jilin, through Liaodong Peninsula, into Jiaodong Peninsula. It consists of greenschist- to lower amphibolite-facies and rarely granulite-facies meta-sedimentary and meat-volcanic successions, with associated granitic and mafic intrusions. The sedimentary and volcanic successions include the Macheonayeong Group in North Korea, the Ji'an and Laoling groups in southern Jilin, the North and South Liaohe groups in the eastern Liaoning Peninsula, the Fenzishan and Jingshan groups in the Jiaobei Terrane, and the Wuhe Group in Anhui Province (Fig. 1; Zhao et al., 2012). These groups have similar transitional stratigraphic successions from a

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