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RAPID COMMUNICATION

Tectonic affinity and reworking of the Archaean Jiaodong Terrane in the Eastern Block of the North China Craton: evidence from LA-ICP-MS U–Pb zircon ages

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Abstract

The Archaean Jiaodong Terrane is located in the southern segment of the Palaeoproterozoic Jiao-Liao-Ji Belt, which separates the Eastern Block of the North China Craton into the Longgang and Langrim blocks. Controversy has long surrounded the issue of whether the Jiaodong Terrane is part of the North China Craton or an exotic terrane. This study presents new zircon U–Pb ages for the major lithologies of the Jiaodong Terrane, and the results indicate that the terrane underwent two main magmatic events at ~ 2.89 Ga and 2.62–2.56 Ga and two metamorphic events at ~ 2.5 Ga and 1.9–1.8 Ga. These ages are consistent with those of other metamorphic complexes in the Eastern Block, suggesting that the Jiaodong Terrane was part of the Neoarchaean basement of the Eastern Block, which was reworked at 1.9–1.8 Ga in association with the development of the Palaeoproterozoic Jiao-Liao-Ji Belt.

Keywords: zircon ages, metamorphism, crustal reworking, Jiaodong Terrane, North China Craton.

1. Introduction

Most recent investigations on the Precambrian basement of the North China Craton (NCC) have identified three Palaeoproterozoic mobile belts, namely the Trans-North China Orogen (TNCO), the Khondalite Belt and the Jiao-Liao-Ji Belt (JLJB) (e.g. Zhao *et al*. 2001, 2005, 2012; Zhao & Cawood, 2012; Fig. 1a). The TNCO subdivides the NCC into the Western and Eastern blocks, whereas the Khondalite Belt separates the Western Block into the Yinshan and Ordos blocks, and the JLJB separates the Eastern Block into the Longgang and Langrim blocks (Zhao *et al*. 2001, 2005; Zhao & Cawood, 2012). Most of the basement rocks within the Western and Eastern blocks are characterized by the widespread ~ 2.5 Ga tectonothermal event with anticlockwise *P–T* paths (Zhao *et al*. 1998; Geng, Liu & Yang, 2006; Wu *et al*. 2012, 2013), whereas the basement rocks within the three mobile belts are characterized by the 1.9–1.8 Ga tectonothermal events with clockwise *P–T* paths (Zhao *et al*. 2005; Yin *et al*. 2009, 2011; Tam *et al*. 2011, 2012*a,b,c*; Zhang *et al*. 2012). Particularly, the basement rocks exposed in the Eastern Shandong Province in the Eastern Block have records of both ~ 2.5 Ga and 1.9–1.8 Ga tectonothermal events, making this area critical to understanding the relationship between these two events and the Precambrian evolution of the NCC. However, most of the previous studies were focused on the Palaeoproterozoic JLJB with high-pressure (HP) granulite facies metamorphism in the Eastern Shandong Province (Zhou *et al*. 2008*a,b*; Tam *et al*. 2011, 2012*b,c*), but less work has been done on the Archaean Jiaodong Terrane that was located within the JLJB. Several models about the Jiaodong Terrane have been proposed, with some suggesting that the Jiaodong Terrane was part of the Archaean Eastern Block in the NCC (Tang *et al*. 2007; Jahn *et al*. 2008; Zhou *et al*. 2008*a*), while others argued that the Jiaodong Terrane has affinities to the South China Craton (SCC) (Faure, Lin & Le Breton, 2001; Faure *et al*. 2003; Wu, Zheng & Zhou, 2004). Moreover, some scholars speculate that the Jiaodong Terrane was an exotic terrane that was accreted to the NCC in the Mesozoic (Cai, 1989; Shang, 1989; Li *et al*. 2013). In this paper, we carried out laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) U–Pb zircon dating on the major lithologies of the Jiaodong Terrane, and the results will provide important insights into understanding the affinity of the Jiaodong Terrane and the relationship between the Jiaodong Terrane and the Palaeoproterozoic JLJB.

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2. Regional geology

The Precambrian basement rocks of the Eastern Block are composed mainly of trondhjemitic–tonalitic–granodioritic (TTG) gneisses, granites and minor supracrustal rafts, exposed in the Southern Jilin, Northern Liaoning, Anshan–Benxi, Western Liaoning, Eastern Hebei, Miyun, Southern Liaoning, Eastern Shandong and Western Shandong domains (Fig. 1a; Zhao *et al*. 2005). Previous geochronological studies show that most basement rocks were formed in the period of 2.55–2.50 Ga (Zhao *et al*. 1998; Geng, Liu & Yang, 2006; Yang *et al*. 2008; Wang *et al*. 2013*a*; Peng *et al*. 2013; Wu *et al*. 2013), with minor Early Neoarchaean rocks of ~ 2.7 Ga age reported from the Western and Eastern Shandong domains (Tang *et al*. 2007; Jahn *et al*. 2008; Wan *et al*. 2011; Wang *et al*. 2013*b*). All the Archaean basement rocks experienced the strong regional metamorphism at ~ 2.5 Ga, characterized by anticlockwise *P–T* paths (Geng, Liu & Yang, 2006; Yang *et al*. 2008; Wu *et al*. 2012, 2013).

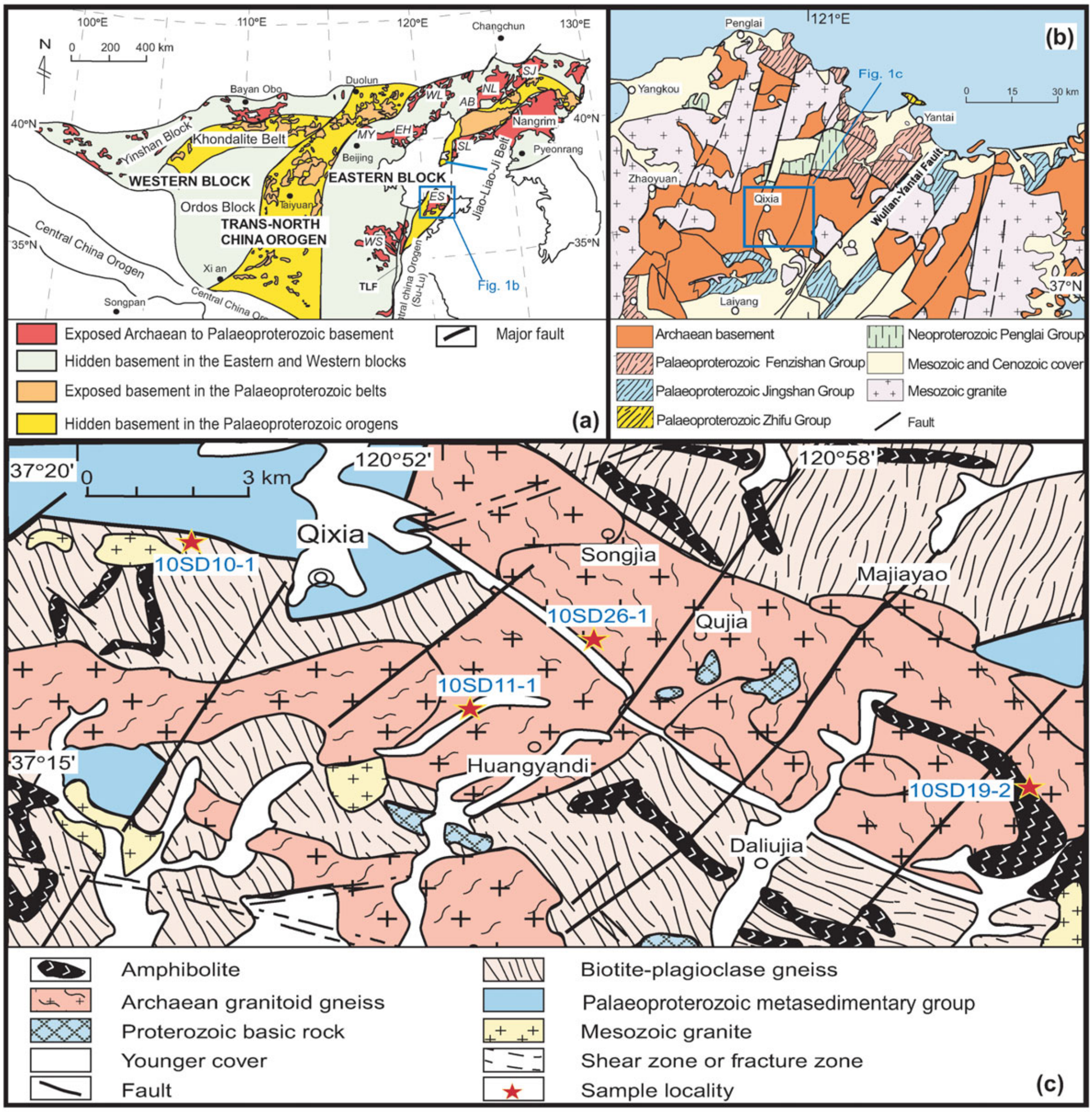

Figure 1. (Colour online) (a) Tectonic subdivision of the North China Craton (revised after Zhao *et al*. 2005). (b) Geological sketch map of the Eastern Shandong Complex (revised after Tam *et al*. 2011). (c) Geological sketch map of the Jiaodong Terrane (revised after Jahn *et al*. 2008). Abbreviations: AB – Anshan-Benxi; EH – Eastern Hebei; ES – Eastern Shandong; MY – Miyun; NL – Northern Liaoning; SL – Southern Liaoning; SJ – Southern Jilin; WL – Western Liaoning; WS – Western Shandong; TLF – Tancheng–Lujiang Fault.

The Precambrian basement exposed in the northeastern part of the Shandong Province is traditionally named the Eastern Shandong Complex, separated from the Western Shandong Complex by the famous Tancheng–Lujiang Fault zone (TLF) (Fig. 1a). It is composed of the Archaean Jiaodong Terrane, the uncomformably overlying Palaeoproterozoic Jingshan, Fenzishan and Zhifu groups and the Neoproterozoic Penglai Group (Fig. 1c). The Archaean Jiaodong Terrane is composed predominately of granitoid gneisses with minor supracrustal rocks, metamorphosed to amphibolite facies and locally granulite facies (Wan *et al*. 2006; Tang *et al*. 2007; Fig. 1c). The granitoid gneisses mainly include TTG gneisses and minor granitic rocks, while the supracrustal rocks, traditionally named the 'Jiaodong Group', consist of amphibolites and biotite-plagioclase gneisses, occurring as enclaves or tectonic lenses enclosed in the granitoid gneisses (Fig. 1c). The overlying Jingshan and Fenzishan groups were metamorphosed from amphibolite facies to granulite facies (Zhai & Liu, 2003; Zhai, Guo & Liu, 2005; Zhao *et al*. 2005; Wan *et al*. 2006; Tang *et al*. 2007), while the Zhifu and Penglai groups were metamorphosed from upper greenschist facies to amphibolite facies (SBGMR, 1991; Faure, Lin & Le Breton, 2001; Faure *et al*. 2003).

Available geochronological data show that the protoliths of the granitoid gneisses and supracrustal rocks from the Jiaodong Terrane were formed in the period of 2.9–2.5 Ga (Tang *et al*. 2007; Jahn *et al*. 2008; Zhou *et al*. 2008*a*; Liu *et al*. 2013*a*). Available zircon ages obtained for the Fenzishan and Jingshan groups suggest that the two groups were formed coevally at 2.2–1.9 Ga and experienced metamorphism around 1.9–1.8 Ga (Wan *et al*. 2006; Zhou *et al*. 2008*b*; Tam *et al*. 2011; Zhao *et al*. 2012). The dating results of detrital zircons from the Penglai and Zhifu groups indicate two major age populations of 2.45–2.1 Ga and 2.0–1.7 Ga (Zhou *et al*. 2008*a*; Liu *et al*. 2013*b*), suggesting that their sources

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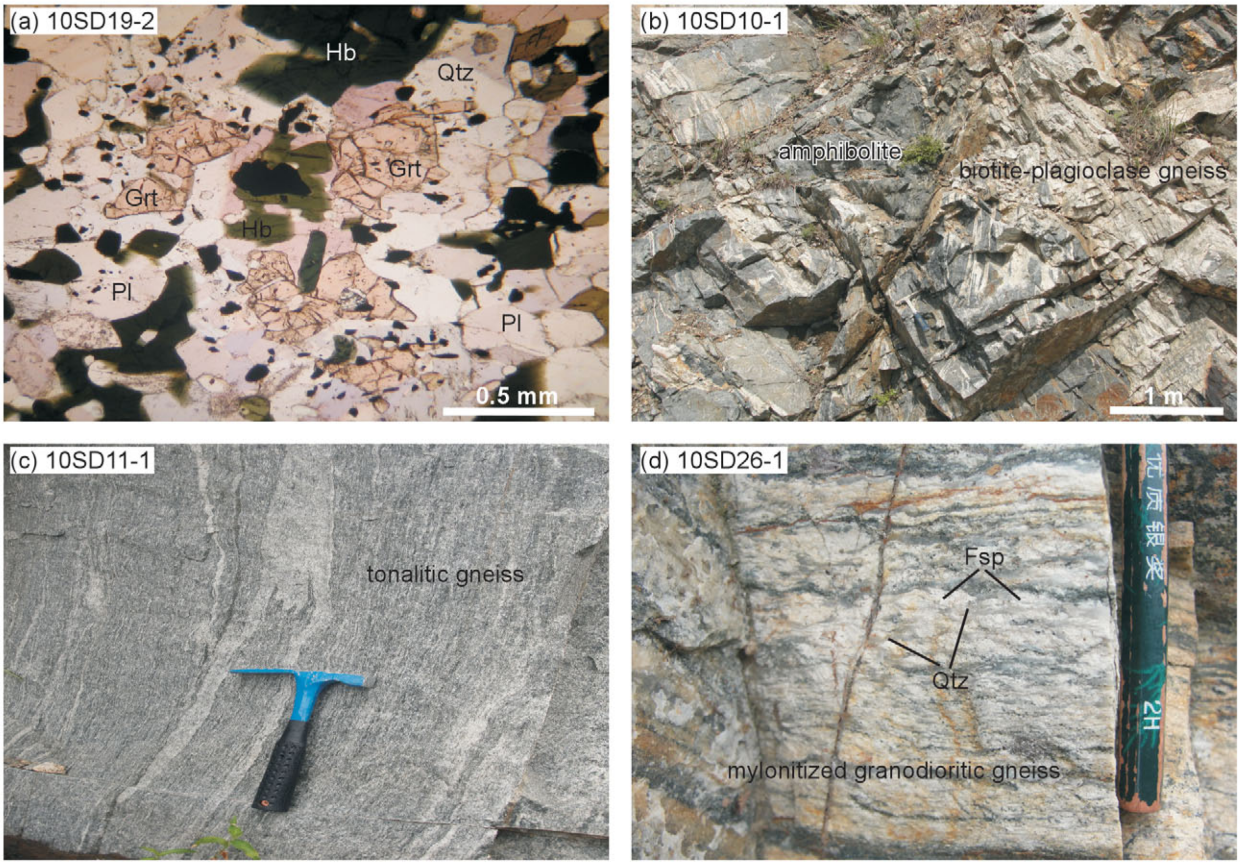

Figure 2. (Colour online) Field photographs or microphotographs of (a) amphibolite (10SD19-2), (b) biotite-plagioclase gneiss (10SD10-1), (c) tonalitic gneiss (10SD11-1) and (d) granodioritic gneiss (10SD26-1), collected from the Jiaodong Terrane. The length of the hammer is 30 cm and the width of the pencil is 6 mm. Abbreviations: Grt – garnet; Pl – plagioclase; Hb – hornblende; Qtz – quartz; Fsp – feldspar.

were most likely from the Palaeoproterozoic Jingshan and Fenzishan groups.

3. Sample selection and methodology

Four representative samples of different lithologies from the Jiaodong Terrane were selected for zircon U–Pb dating, including amphibolite (10SD19-2) and biotite-plagioclase gneiss (10SD10-1) from the supracrustal rocks, tonalitic gneiss (10SD11-1) and granodioritic gneiss (10SD26-1).

Zircons were extracted from samples through standard heavy liquid and magnetic separation techniques, and then hand-picked and mounted into epoxy resin and polished to half of their thickness. Cathodoluminescence (CL) imaging and zircon dating were both carried out at the State Key Laboratory of Continental Dynamics, Northwest University (Xi'an), China. Zircon U–Th–Pb isotopes were analysed by a LA-ICP-MS method, of which the laser-ablation system includes an Agilent 7500a ICP-MS instrument equipped with a 193 nm ArF excimer laser. A laser beam of 32 μm in diameter and repetition rate of 7 Hz was adopted during the whole analyses, and the more detailed analytical procedures were similar to those described by Wu *et al*. (2013). The U–Th–Pb isotopic ratios were calculated using the GLITTER 4.0 program (Macquarie University, Sydney, Australia), and then corrected by using the standard zircon 91500 as an external standard. Concordia plots and weighted mean U–Pb age calculations were made using the ISOPLOT 3 program with a 1σ error and 95 % confidence level (Ludwig, 2003). All zircon U–Th–Pb data are presented in online Supplementary Table S1 available at http://journals.cambridge.org/geo.

4. Results

4.a. Amphibolite

10SD19-2 is a coarse-grained garnet-bearing amphibolite sample collected at a locality 18 km southeast of Qixia City (Fig. 1c), with a mineral assemblage of garnet (~ 10 %) + hornblende (~ 35 %) + plagioclase (~ 40 %) + quartz (~ 10 %) + opaque minerals (~ 5 %) (Fig. 2a). Zircons grains from this sample are subhedral to euhedral stubby and prismatic in shape with their lengths ranging from 30 to 200 μm. The CL imaging shows that most zircon grains have inherited magmatic oscillatory-zoned cores surrounded or truncated by narrow high-luminescent metamorphic overgrowth rims, and some grains have metamorphic structureless cores (Fig. 3a). Nineteen analyses were carried out on magmatic and metamorphic zircons from this sample and the results were plotted in Figure 4a. Of 15 analyses on magmatic zircons, 9 concordant analyses yield a weighted mean average ^{207}Pb–^{206}Pb age of 2555 ± 11 Ma (MSWD = 1.09), interpreted as the age of the magmatic provenance of the amphibolites. Two analyses on metamorphic overgrowth rims and one analysis on a dark structureless core give apparent ^{207}Pb–^{206}Pb ages of 2506–2459 Ma, approximating the timing of metamorphism. In addition, one analysis on a high-luminescent structureless core gives a ^{207}Pb–^{206}Pb age of

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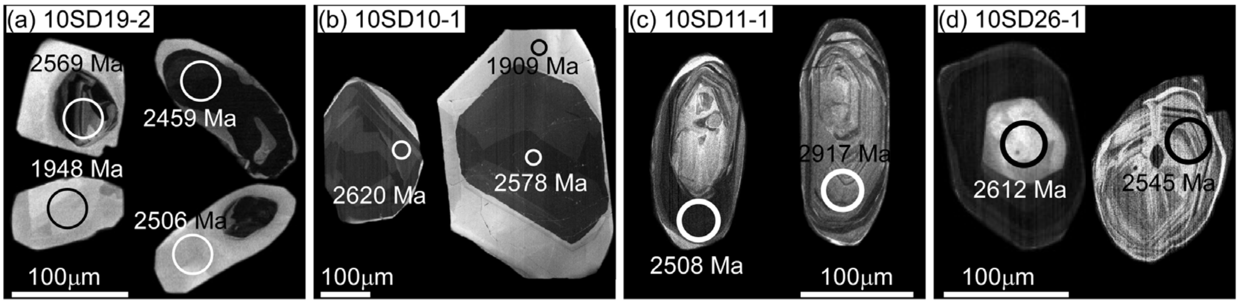

Figure 3. Cathodoluminescence images (CL) of representative zircons from (a) amphibolite (10SD19-2), (b) biotite-plagioclase gneiss (10SD10-1), (c) tonalitic gneiss (10SD11-1) and (d) granodioritic gneiss (10SD26-1), collected from the Jiaodong Terrane. The open circles represent the U–Pb analytical positions and each circle is 32 μm in diameter.

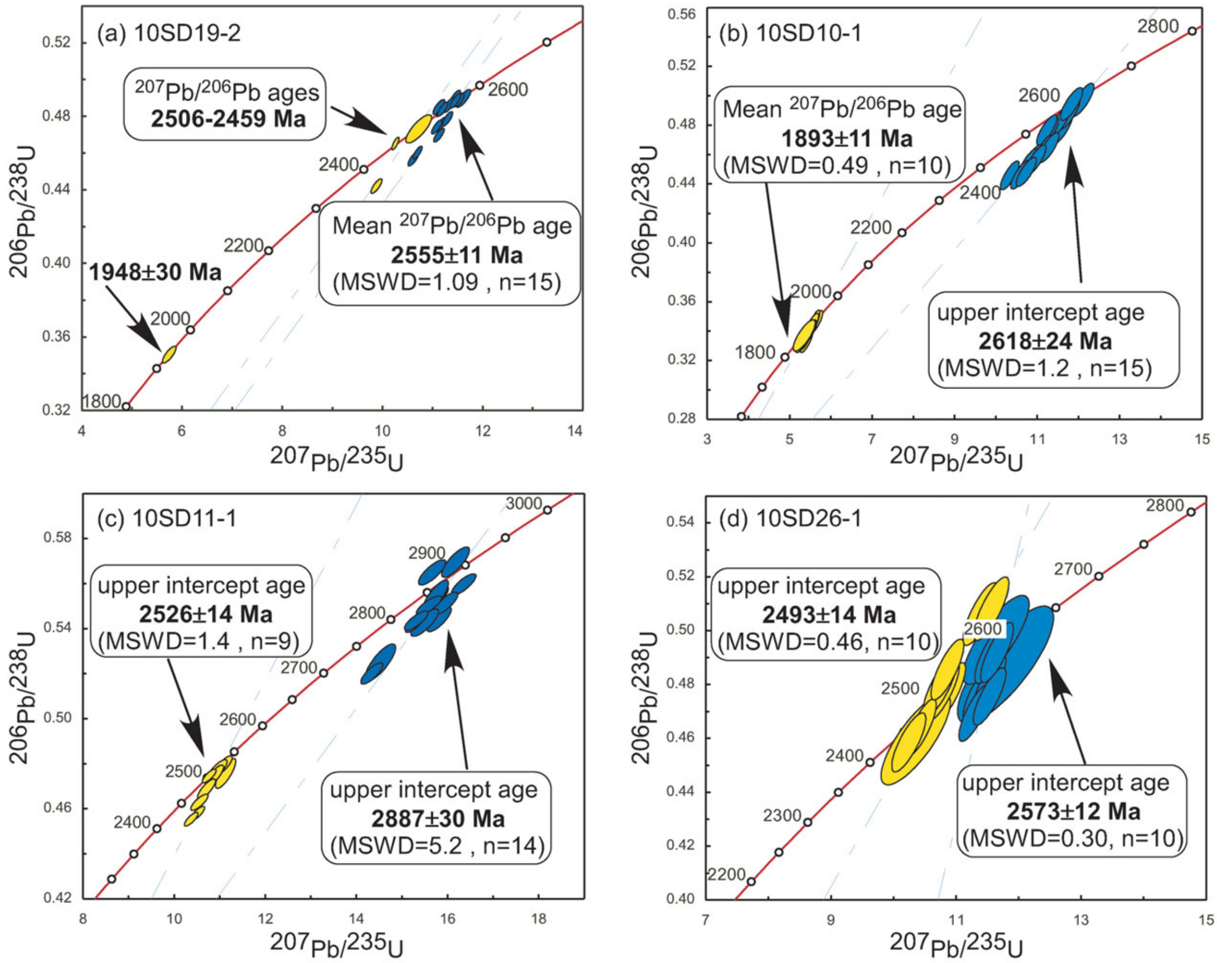

Figure 4. (Colour online) Concordia diagrams of zircon U–Pb data from (a) amphibolite (10SD19-2), (b) biotite-plagioclase gneiss (10SD10-1), (c) tonalitic gneiss (10SD11-1) and (d) granodioritic gneiss (10SD26-1), collected from the Jiaodong Terrane. The blue circles represent magmatic zircon domains. The yellow circles represent metamorphic zircon domains. Analytical errors are depicted at the 1 sigma level.

1948 ± 30 Ma, which is interpreted as the timing of a second metamorphic event.

4.b. Biotite-plagioclase gneiss

10SD10-1 is a biotite-plagioclase gneiss sample collected on an outcrop 3 km northeast of Qixia City (Fig. 1c). The sample shows a moderate gneissic structure, and consists of quartz (∼ 30 %), plagioclase (∼ 50 %) and biotite (∼ 10 %), with minor hornblende and K-feldspar (Fig. 2b). Zircon grains in this sample are mainly subhedral stubby or rounded grains with sizes ranging from 150 to 400 μm, and are characterized by clear core–rim textures (Fig. 3b). Most of the cores show blurred sector zoning, probably suggesting recrystallization (Fig. 3b). The high-luminescent overgrowth rims surrounding the cores (Fig. 3b) are typical of metamorphic origin. Of 25 analyses on zircons from this sample, 15 made on the cores form a discordant line, intercepting the concordia at 2618 ± 24 Ma (MSWD = 1.2; Fig. 4b), interpreted as the crystallization age of the magmatic protoliths. The remaining ten analyses made on overgrowth rims give concordant

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^{207}Pb–^{206}Pb apparent ages of 1909–1871 Ma, which yield a weighted mean average age of 1893 ± 11 Ma (MSWD = 0.49), in agreement with the timing of the Palaeoproterozoic metamorphism recorded by the amphibolite.

4.c. Tonalitic gneiss

10SD11-1 is a tonalitic gneiss sample collected from an outcrop 5 km southeast of Qixia City (Fig. 1c). The sample shows a strong gneissosity (Fig. 2c) and a medium- to fine-grained texture, with a mineral assemblage of plagioclase (~ 60 %) + quartz (~ 15 %) + biotite (~ 15 %) ± hornblende ± K-feldspar. Zircons from this sample are mainly prismatic grains with rounded terminations, with sizes ranging from 100 to 250 μm (Fig. 3c). Most zircons show typical magmatic oscillatory zoning with narrow (< 10 μm) highly luminescent rims, which are considered to be of metamorphic origin (Fig. 3c). Some zircons have relatively wide (10–50 μm) low-luminescent rims between the magmatic cores and narrow highly luminescent rims (see the lower left grain in Fig. 3c), which are considered to form by metamorphic recrystallization. Of 23 analyses carried out for this sample, 14 made on magmatic domains give variable apparent ^{207}Pb–^{206}Pb ages from 2917 to 2821 Ma and form a discordant line with an upper intercept age of 2887 ± 30 Ma (MSWD = 5.2; Fig. 4c), which is interpreted as the crystallization age of the tonalite. The remaining nine analyses made on those wide metamorphic rims give variable apparent ^{207}Pb–^{206}Pb ages of 2549–2498 Ma and form a discordant line with an upper intercept age of 2526 ± 14 Ma (MSWD = 1.4; Fig. 4c), which approximates the timing of the end-Neoarchaean regional metamorphism.

4.d. Granodioritic gneiss

10SD26-1 is a fine-grained granodioritic gneiss sample collected from an outcrop 8 km southeast of Qixia City (Fig. 1c). The rock shows a moderate gneissic structure with local mylonitization, where quartz grains are flattened and stretched to form a lineation (Fig. 2d). The major mineral phases of the sample are plagioclase (30 %), K-feldspar (25 %), quartz (30 %), biotite (10 %) and minor accessory minerals. Zircons from this sample are subhedral stubby grains with rounded terminations, and their sizes vary from 100 to 150 μm. CL imaging reveals that most zircons have oscillatory-zoned cores surrounded by structureless or patchy-zoned rims (10–60 μm wide; Fig. 3d). The oscillatory-zoned cores are typical of a magmatic origin, whereas the structureless and patchy-zoned rims are considered to be formed during metamorphic recrystallization. Of 20 analyses carried out for this sample, 10 made on magmatic domains form a discordant line with an upper intercept age of 2573 ± 12 Ma (MSWD = 0.30; Fig. 4d), interpreted as the crystallization age of the protolith of the granodioritic gneiss. The remaining ten analyses made on metamorphic domains form a discordant line with an upper intercept age of 2493 ± 14 Ma (MSWD = 0.46; Fig. 4d), interpreted as the timing of the end-Neoarchaean regional metamorphism. Some zircon grains possess outermost thin rims with high-luminescence (Fig. 3d), which are too narrow to be analysed.

5. Discussion

Controversy has surrounded the tectonic affiliation of the Jiaodong Terrane for a long period. Some researchers proposed that the Jiaodong Terrane was an exotic terrane that was accreted to the Western Shandong domain in the NCC owing to the sinistral movement of the Tan-Lu Fault at the end of the Mesozoic (Cai, 1989; Shang, 1989; Li *et al.* 2013). Recently, some scholars have even suggested that the Jiaodong Terrane belonged to the SCC and considered the northern margin of the Jiaodong Terrane as the boundary between the NCC and SCC (Faure, Lin & Le Breton, 2001; Wu, Zheng & Zhou, 2004). However, new results presented in this study and previous geochronological data do not support these two models. Magmatic zircon ages obtained from this study suggest that the protoliths of the metamorphosed supracrustal rocks of the Jiaodong Terrane were formed in the period of 2.62–2.56 Ga, while the protolithic TTG magmas of the granitoid gneisses were emplaced at ~ 2.89 Ga and ~ 2.57 Ga. Metamorphic dating results indicate that, like most metamorphic basement complexes in the Eastern Block of the NCC, the Jiaodong Terrane experienced regional metamorphism at ~ 2.5 Ga, though it encountered widespread reworking at 1.9–1.8 Ga in association with the development of the Palaeoproterozoic JLJB. These data are in good concordance with previous magmatic zircon ages of ~ 2.9–2.5 Ga and metamorphic ages of ~ 2.5 Ga and ~ 1.9–1.8 Ga obtained for different lithologies of the Jiaodong Terrane (Faure *et al.* 2003; Zhang *et al.* 2003; Tang *et al.* 2007; Jahn *et al.* 2008; Zhou *et al.* 2008*a*; Liu *et al.* 2013*a*). All these geochronological data suggest that the Jiaodong Terrane is neither an exotic terrane accreted to the NCC at the end of the Mesozoic nor a part of the SCC where the Neoarchaean magmatism was minor but Neoproterozoic (700–800 Ma) magmatism was dominant (Zhao & Guo, 2012).

Our results and previous data support models proposing that the Jiaodong Terrane is part of the NCC (Tang *et al.* 2007; Jahn *et al.* 2008; Zhou *et al.* 2008*a*). Based on distinct geochronological, geochemical, and Nd and oxygen isotopic data on both sides of the N–S-trending Wulian–Yantai Fault (Fig. 1b), Tang *et al.* (2007) divided the Eastern Shandong domain into the eastern and western parts, of which the former is considered as an extension of the Sulu-Dabie orogen in the SCC, whereas the western part, regarded as the Jiaodong Terrane in this paper, belongs to the NCC. Our data further support this model, as the Neoarchaean magmatism and metamorphism of the Jiaodong Terrane were consistent with those of other Neoarchaean metamorphic terranes in the Eastern Block of the NCC (e.g. Zhao *et al.* 1998, 2001; Geng, Liu & Yang, 2006; Zhao & Cawood, 2012; Wu *et al.* 2013).

Previous studies indicate that mafic supracrustal rocks (mainly amphibolites) from the Jiaodong Terrane only preserve 1.9–1.8 Ga metamorphic zircon ages (Tang *et al.* 2007; Zhou *et al.* 2008*a*; Liu *et al.* 2013*a*), without ~ 2.5 Ga metamorphic zircon ages, which are only obtained from granitoid gneisses from the Jiaodong Terrane (Faure *et al.* 2003; Tang *et al.* 2007; Jahn *et al.* 2008; Liu *et al.* 2013*a*; this study). In this study, however, we show that one amphibolite sample (10SD19-2) preserves both metamorphic ages of ~ 2.5 Ga and ~ 1.9 Ga, suggesting that the Archaean Jiaodong Terrane experienced two discrete metamorphic events at the end of the Neoarchaean and the Palaeoproterozoic. This is further supported by zircon CL images that show some ~ 2.5 Ga metamorphic zircon domains (rims) surrounded by very thin metamorphic rims (see left grain in Fig. 3c), which are considered to be the products of the ~ 1.9 Ga metamorphic reworking, although these thin metamorphic rims are too narrow to be analysed. Moreover, the Palaeoproterozoic metamorphic ages of 1.95–1.89 Ga reported from the Jiaodong Terrane are well consistent with the timing of metamorphism reported from the JLJB. Previous geochronological and metamorphic studies on the JLJB have shown that the belt experienced peak HP granulite facies metamorphism at ~ 1.95 Ga and post-peak medium-pressure granulite facies metamorphism at ~ 1.85 Ga (Zhou *et al*. 2008*a,b*; Wan *et al*. 2006; Tam *et al*. 2011; Liu *et al*. 2013*c*), which are interpreted as ages of the continent–continent collision between the Longgang and Langrim blocks to form the Eastern Block and the subsequent exhumation, respectively (Zhou *et al*. 2008*a,b*; Tam *et al*. 2011, 2012*a,b,c*). Considering the close spatial and temporal relationships between the Jiaodong Terrane and the JLJB, we believe that the Archaean Jiaodong Terrane was part of the Neoarchaean basement in the Eastern Block of the NCC, which was involved in the subduction and collision to form the JLJB in the Palaeoproterozoic.

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