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EARTH SCIENCE FRONTIERS

WHEN DID PLATE TECTONICS BEGIN ON THE NORTH CHINA CRATON? INSIGHTS FROM METAMORPHISM*

从变质作用观看板块构造何时在华北克拉通开始

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Zhao Guochun. When did plate tectonics begin on the North China Craton? Insights from metamorphism. *Earth Science Frontiers*, 2007, 14(1): 019-032

Abstract: Understanding when and why plate tectonics began on Earth is one of the most important unresolved problems in earth sciences. As a final result of plate tectonics, continental collisional orogens are formed, and the identification of such orogens is regarded as a milestone in recognizing the operation of plate tectonics in Earth's history. Metamorphism of continental collisional belts is generally characterized by clockwise *p*–*T* paths, especially for those involving isothermal decompression following the peak metamorphism. Therefore, clockwise *p*–*T* paths involving isothermal decompression are considered one of the important indicators for recognition of plate tectonics, especially in the early history of the earth. As one of the oldest continental blocks in the world, the North China Craton is considered a promising area for applying the large-scale synthesis approach of metamorphic *p*–*T* paths to understand tectonic settings or processes since extensive investigations have been undertaken on the *p*–*T*–*t* evolution of the basement rocks over the craton. Tectonically, the North China Craton is composed of three small continental blocks (Eastern Block, Yinshan Block, and Ordos Block) and three Paleoproterozoic mobile belts (Trans-North China Orogen, Khondalite Belt, and Jiao–Liao–Ji Belt). Metamorphism of Late Archean basement rocks in the Eastern and Yinshan Blocks is characterized by anticlockwise *p*–*T* paths, mostly involving isobaric cooling, suggesting that the heating source of the metamorphism was related to the underplating or intrusion of large volumes of mantle-derived magmas. Although theoretically such mantle-derived magmas form under continental magmatic arc, mantle plume or continental rift environments, only a mantle plume model can reasonably explain spatial and temporal distribution, lithological association, and structural features of the Late Archean basement rocks in the Eastern and Yinshan Blocks. Therefore, mantle plumes may be the major tectonic mechanism that governed the formation and evolution of the Late Archean crust in the Eastern and Yinshan Blocks, and plate tectonics may not have operated in the two blocks during Late Archean period. Metamorphism of the basement rocks in the Paleoproterozoic Khondalite Belt and the Trans-North China Orogen is both characterized by clockwise *p*–*T* paths involving isothermal decompression following peak metamorphism, which suggests that the two orogens underwent initial crustal thickening followed by rapid exhumation/uplift tectonic processes. Such tectonic processes are typical indicators of collisional orogens that accommodate plate tectonics. The Paleoproterozoic Jiao – Liao – Ji Belt can be divided into the southern and northern zones, of which the former is characterized by anticlockwise *p*–*T* paths, whereas the latter is characterized by clockwise *p*–*T* paths, also indicating a regime of plate tectonics. The time of the initiation of plate tectonics in the North China Craton can be approximated by the age of the earliest ju-

收稿日期: 2006 – 12 – 06; **修回日期**: 2006 – 12 – 20

基金项目: 香港 RGC 项目(7055/03P, 7058/04P, 7055/05P, 7063/06P)

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* 本文出版得到中国地质大学(北京)地质过程与矿产资源国家重点实验室资助。

venile crustal components in the three Paleoproterozoic tectonic belts. So far, the convincing oldest, subduction-related, juvenile crustal component in the North China Craton is the 2.56 Ga Wutai granitoids in the Trans-North China Orogen, which can be used to approximate the timing of the onset of plate tectonics in the North China Craton.

Key words: Archean; North China Craton; plate tectonics; Paleoproterozoic; metamorphism; *p-T* paths

CLC number: P588.3; P542.4 **Document Code**: A **Article ID**: 1005-2321(2007)01-0019-14

摘 要: 了解板块构造在地球上何时和怎样开始的是地球科学领域还没有解决的重要问题之一。作为板块运动的最终结果,大陆碰撞造山带是识别地球历史演化中板块构造机制起主导作用的重要标志。大陆碰撞带变质作用一般以顺时针 *p-T* 轨迹演化为特征,尤其伴有峰期变质之后的等温减压过程。这样,具有峰后等温减压过程的顺时针 *p-T* 轨迹是识别地球早期的板块构造作用的重要标志之一。作为世界上最古老的克拉通陆块之一,华北克拉通基底岩石变质作用 *p-T* 演化在过去几年已得到广泛深入的研究,使得该克拉通可能成为应用大规模变质作用 *p-T* 轨迹途径来探讨构造环境和构造演化过程的最佳场所。构造上,华北克拉通可划分为三个小的陆块(东部陆块、阴山陆块和鄂尔多斯陆块)和三个古元古代活动带(华北中部碰撞带、孔兹岩带和胶—辽—吉带)。东部陆块和阴山陆块新太古代基底岩石变质作用具有等压冷却型逆时针 *p-T* 演化轨迹特征,反映变质作用热源与大量地幔岩浆底板垫托或侵位有关。尽管理论上这样大规模的地幔岩浆可形成在大陆岩浆弧、地幔柱或大陆裂谷环境,只有地幔柱模式才能合理地解释东部陆块和阴山陆块新太古代基底岩石时空分布、岩石组合和构造特征。这样,地幔柱可能是主导东部陆块和阴山陆块新太古代地壳形成和演化的主要构造机制,而板块构造在晚太古宙并不是其主要的构造机制。古元古代孔兹岩带和华北中部碰撞带基底岩石变质作用均具有等温减压型顺时针 *p-T* 演化特征,反映两造山带都经历地壳加厚和随后的隆升剥蚀构造过程。这样的构造过程是板块构造体制下的碰撞造山带的典型标志。古元古代胶—辽—吉带可进一步划分为南部带和北部带,其中南部带基底岩石具有逆时针 *p-T* 演化特征,而北部带基地岩石具有顺时针 *p-T* 演化特征,也反映板块构造机制下的产物。现代规模的板块构造在华北克拉通上的启动时间可以由三个活动带中最老的与板块俯冲有关的新生地壳形成时间来大致标定。目前,华北克拉通内部三个活动带中可识别出来的最老的与板块俯冲有关的新生地壳是华北中部碰撞带 2.56 Ga 五台花岗岩,它们的形成可能大致标志着现代样式的板块构造在华北克拉通大规模作用的开始。

关键词: 太古宙; 华北克拉通; 板块构造; 古元古代; 变质作用; *p-T* 轨迹

1 Introduction

Earth is the only planet with plate tectonics, and the question of when plate tectonics began on Earth still remains controversial, with one school of thought believing that plate tectonics already operated during Archean periods, whereas others argue that it operates only much later. Consequently, understanding when and why plate tectonics began has become one of the most important unresolved problems in our understanding of the Earth, and progress toward resolving it will require creative, interdisciplinary, and international efforts. On June 13-18, 2006, 65 geologists from different countries gathered in Lander (Wyoming, USA) to hold a Penrose conference entitled "When did plate tectonics begin on Earth?" to discuss this important issue. Alexandra Witze, a journalist of *Nature*, wrote an interesting report on some of the details about this conference, which was published in the *Nature* 13 July 2006 issue (v. 442, p. 128-138).

To know when planet tectonics was initialized on Earth, we must know the hallmarks of plate tectonics. Although the 65 attendees at the Lander Penrose conference proposed 18 different definitions of plate tectonics to support their own arguments for or against the operation of plate tectonics during a certain period of Earth's history, most participants agreed that three components were the key for the plate tectonics, as Witze (2006) summarized: there must be rigid plates at the surface of the Earth; those plates must move apart through ocean spreading, with new crust being formed where the sea floor pulls apart; and the plates must on occasion dive beneath each other at subduction zones. Of three hallmarks for plate tectonics, only the last one, subduction, could form

products with some unique characteristics that were preserved and distinct from those generated by other tectonic mechanisms (e. g. mantle plumes). As pointed out by Brown (2006), one of the most important hallmarks of plate tectonics is the development of two contrasting but linked thermal regimes where plates converge—these are the subduction zones. For example, subduction often produces special igneous lithologies (e. g. adakites, boninites, sunukites) in subduction zones. Subduction can also causes the movement of slabs into the deep level of the crust or mantle where high- to ultrahigh-pressure metamorphism occurs. More importantly, subduction will finally result in the complete consumption of an oceanic floor, leading to collision between two continental blocks that were originally bordered on the sides of the ocean, forming a continent-continent collisional orogen, the identification of which is regarded as a milestone in recognizing the operation of plate tectonics in Earth's history. Continent-continent collisional orogens are generally characterized by a series of unique features that are different from other types of orogenic belts (e. g. accretionary belts), including the presence of large-scale thrusting structures, multiphase isoclinal folds, crustal-scale ductile shear zones, mineral stretch lineations, sheath folds, high- and ultrahigh-pressure rocks (blueschist, high-pressure granulites, eclogites, etc), mélange, ophiolites, etc. In terms of metamorphic evolution, rocks in continental collisional belts are generally characterized by clockwise p–T paths, especially for those involving isothermal decompression (ITD) following the peak metamorphism (England and Thompson, 1984; Thompson and England, 1984; Harley, 1989; Brown, 1993). In contrast, metamorphic rocks with anticlockwise p–T paths, especially for those involving isobaric cooling (IBC), can either form under magmatic arc and back-arc basin environments (Bohlen, 1987, 1991; Brown, 2006) or in any other extensional settings such as intracontinental rifts (Sandiford and Powell, 1986) or continental mantle plumes (Zhao et al., 1999a). Therefore, rocks with anticlockwise p–T paths involving isobaric cooling (IBC) cannot be used to infer plate tectonics since they can also form under those tectonic settings that are beyond plate tectonics (e. g. mantle plumes), whereas clockwise p–T paths, especially for those involving isothermal decompression (ITD) following the peak metamorphism, have been recognized only in those metamorphic rocks formed in subduction zones or continent-continent collisional belts (Brown, 1993, 2006). Therefore, clockwise p–T paths involving isothermal decompression (ITD) are considered one of the important indicators for recognition of plate tectonics, especially in the early history of the earth.

As one of the oldest continental blocks in the world, the North China Craton is a promising area for applying the large-scale synthesis approach of metamorphic p–T paths to understand tectonic settings or processes and especially the question of when plate tectonics began on Earth, since numerous studies on the tectonothermal evolution of basement rocks have been undertaken throughout the craton over the past 15 years (Cui et al., 1991; Jin et al., 1991; Lu, 1991; Li, 1993; Liu et al., 1993; Lu and Jin, 1993; Sun et al., 1993; Chen et al., 1994; Zhao et al., 1999b, 2000a, 2001a; Ge et al., 2003, Zhang et al., 2006). The detailed features of p–T paths of the basement rocks in the North China Craton and their tectonic implications have been discussed by Zhao et al. (1998, 1999c, 2000b, 2001b). This article aims to present a summary on the differences in metamorphic assemblages and p–T paths between the Archean and Paleoproterozoic basement rocks in the North China Craton, which provide important insights into understanding when the plate tectonics began on this craton.

2 Tectonic architecture of the North China Craton

The North China Craton is tectonically divisible into two major Archean to Paleoproterozoic blocks, named the Eastern Block and Western Block, which amalgamated at ~1.85 Ga along a Paleoproterozoic orogen, named the Trans-North China Orogen (Fig. 1; Zhao et al., 2001b). The detailed lithological, structural, metamorphic, and geochronological differences between the Trans-North China Orogen and the Eastern and Western Blocks have been summarized by Zhao et al. (1998, 1999c, 2000b, 2001b) and Wu and Zhao (2005) and are not repeated here.

Recently, the above three-fold subdivision and tectonic model of the North China Craton have been further refined and modified by new structural, petrological, and geochronological data obtained over the past few years (Fig. 2; Zhao et al., 2003a, 2005). These new data indicate that the Western Block is formed by amalgamation of the Ordos Terrane in the south and the Yinshan Terrane in the north along the east-west-trending Khondalite Belt during a certain period of time, prior to the collision of the Western and Eastern

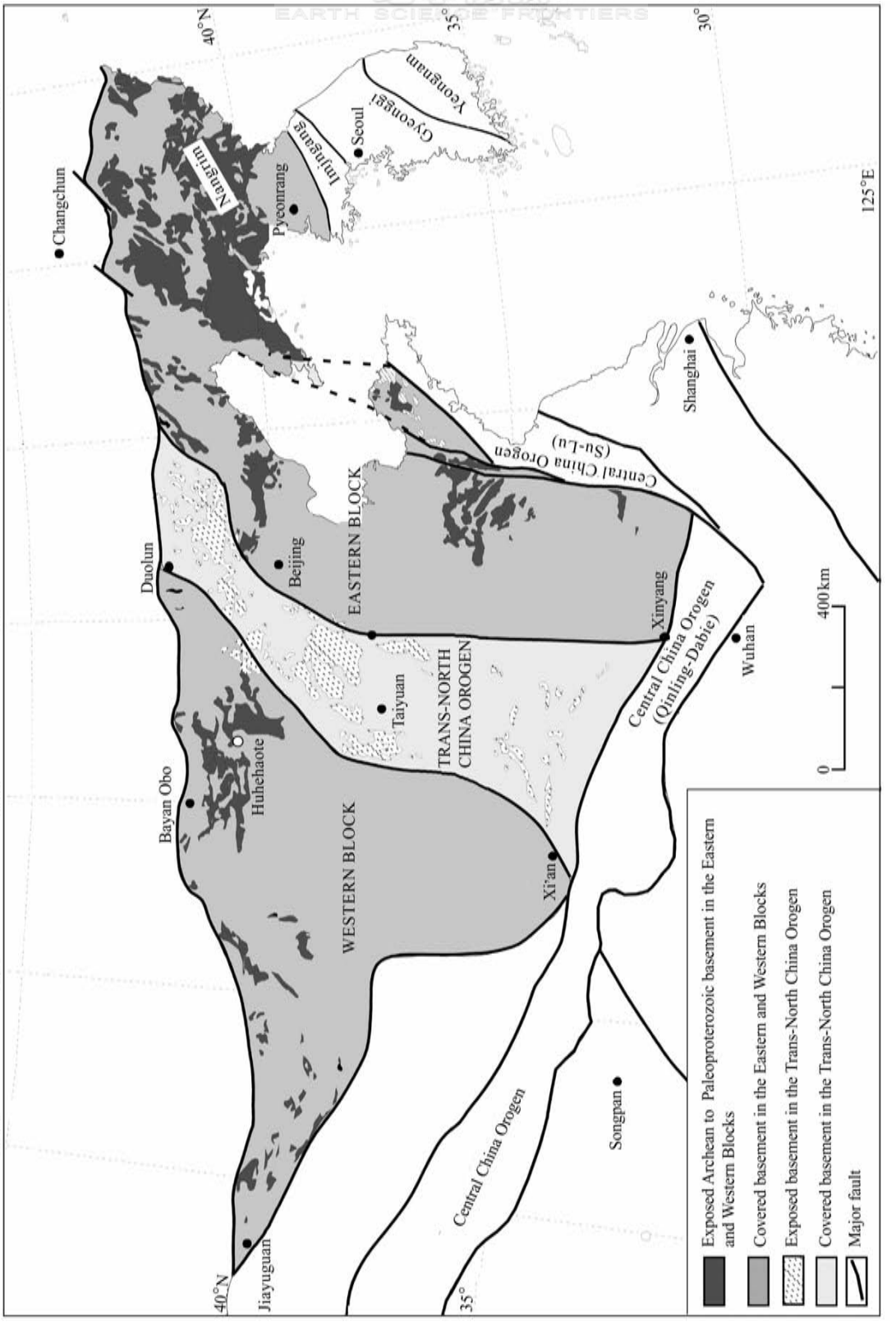

Fig. 1 Three-fold tectonic subdivision of the North China Craton proposed by Zhao et al. (1998; 2001b)

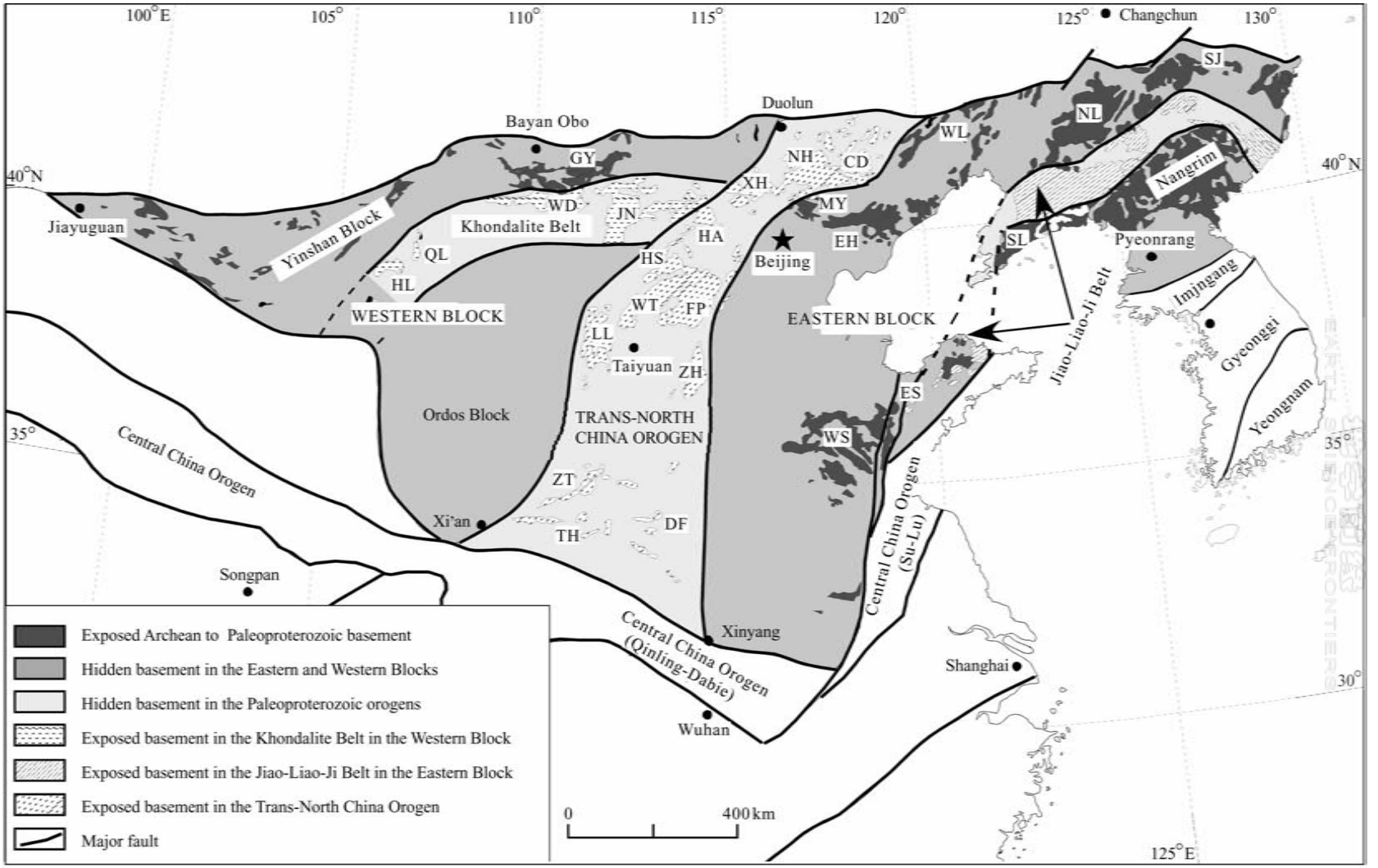

Fig. 2 Tectonic subdivision of the North China Craton modified by Zhao et al. (2005)

Abbreviations for metamorphic complexes: CD, Chengde; DF, Dengfeng; EH, Eastern Hebei; ES, Eastern Shandong; GY, Guyang; HA, Huai'an; HL, Helanshan; JN, Jining; LL, Lüliang; MY, Miyun; NH, Northern Hebei; NL, Northern Liaoning; QL, Qianlishan; SJ, Southern Jilin; ; SL, Southern Liaoning; TH, Taihua; WD, Wulashan-Daqingshan; WL, Western Liaoning; WS, Western Shandong; WT, Wutai; XH, Xuanhua; ZH, Zanhuang; ZT, Zhongtiao

Blocks (Fig. 2; Zhao et al., 2005; Xia et al., 2006a, 2006b). The data also suggest that the Eastern Block underwent Paleoproterozoic rifting along its eastern continental margin in the period 2.2–1.9 Ga, which was accompanied by the deposition of the Fenzishan and Jingshan Groups in Eastern Shandong, the South and North Liaohe Groups in Liaoning, the Laoling and Ji'an Groups in Southern Jilin, and possibly the Macheonayeong Group in North Korea (Li et al., 2004, 2005, 2006; Luo et al., 2004; Lu et al., 2006). The closure of the rift basin at ~1.9 Ga led to the formation of the Jiao-Liao-Ji Belt (Fig. 2). In the Late Archean to early Paleoproterozoic period, toward the western margin of the Eastern Block lay a major ocean, and eastward-directed subduction beneath the western margin of the Eastern Block led to the formation of magmatic arcs or island arcs that were subsequently incorporated into the Trans-North China Orogen during the collision between the Eastern and Western Blocks to form the North China Craton at ~1.85 Ga (Zhao et al., 2005).

Therefore, the tectonic framework of the North China Craton is composed of three small continental blocks (Eastern Block, Yinshan Block and Ordos Block) and three large Paleoproterozoic mobile belts (Trans-North China Orogen, Khondalite Belt and Jiao-Liao-Ji Belt). Of the three continental blocks, the Yinshan and Ordos Blocks were amalgamated along the Khondalite Belt at ~1.9 Ga to form the Western Block, which then collided with the Eastern Block along the Trans-North China Orogen to form the coherent North China Craton at ~1.85 Ga. Therefore, the Khondalite Belt and the Trans-North China Orogen represent two typical Paleoprotoerozoic continent-continent collisional belts (Zhao et al., 2001b; 2005, Guo et al., 2002, 2005; Wilde et al., 2002; Kröner et al., 2005, 2006; Wilde and Zhao, 2005, Liu et al., 2006). In contrast, the Paleoproterozoic Jiao-Liao-Ji belt represents an intracontinental rift which commenced about 2.3 Ga ago, represented by the widespread emplacement of the Liaoji Granitoids and the deposition of the South and North Liaohe Groups in Liaoning, Fenzishan and Jingshan Groups in Shandong, Laoling and Ji'an Groups in Jilin, and the rift was closed at ~1.93 Ga (Li et al., 2004, 2005, 2006; Luo et al., 2004).

3 Contrasting p–T paths between the Archean and Paleoproterozoic basement rocks

Over the past 15 years, extensive research has been undertaken on the p–T–t evolution of the basement rocks in the North China Craton (Cui et al., 1991; Jin et al., 1991; Lu, 1991, Zhai et al., 1992; Li, 1993; Sun et al., 1993; Liu et al., 1993; Lu and Jin, 1993; Chen et al., 1994; Zhao et al., 1999b, 2000a, 2001a; Ge et al., 2003). The detailed data for metamorphic stages, mineral assemblages, p–T conditions, and p–T path patterns of different metamorphic domains in the Eastern and Western Blocks and the Trans-North China Orogen have been re-evaluated by Zhao et al. (1998, 1999c, 2000b, 2001b, 2005). These data highlight some significant differences in metamorphic evolution between the Archean and Paleoproterozoic basement rocks in the North China Craton.

3.1 p–T paths of Late Archean basement rocks in the Eastern and Yinshan Blocks

The Late Archean basement rocks in the Eastern Block consists of 2.6 – 2.5 Ga tonalitic-trondhjemitic-granodioritic (TTG) gneisses with minor supracrustal rocks, with ages ranging from 2.8 to 2.5 Ga. These rocks were intruded by syntectonic granites/charnockites and underwent greenschist to granulite facies metamorphism at ~2.5 Ga (Pidgeon, 1980; Compston et al., 1983; Kröner et al., 1998; Zhao et al., 1998; Zhai and Liu, 2003; Zhai et al., 2005). Similar to those in the Eastern Block, the Late Archaean basement rocks in the Western Block is also composed predominantly of TTG gneisses with minor supracrustal rocks, metamorphosed from greenschist to granulite facies at ~2.5 Ga (Zhao et al. 1999c, 2003, 2005).

The metamorphic evolution of the Late Archean basement rocks of the Eastern Block and Yinshan Block (Western Block), regardless of high-grade terrains or low-grade granite-greenstone belts, is characterized by anticlockwise p–T paths involving near-isobaric cooling (Fig. 3a and 3b). Mafic granulites, amphibolites and pelitic gneisses in the Eastern Block preserve prograde, peak, and post-peak mineral assemblages. The prograde assemblage is indicated by inclusions within minerals of the peak stage, represented by the assemblages of hornblende + plagioclase + quartz ± biotite in mafic granulites, chlorite + actinolite + epidote + plagioclase + quartz in amphibolites and biotite

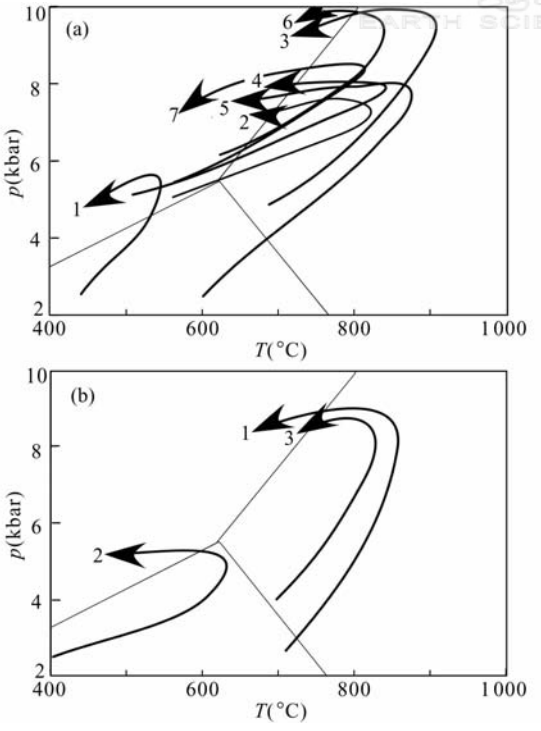

Fig. 3 (a) Metamorphic p-T paths of basement rocks in the Eastern Block; (b) Metamorphic p-T paths of basement rocks in the Yinshan Block
(a): 1—Western Shandong Complex (Zhao et al., 1998); 2—Eastern Hebei Complex (Zhao et al., 1998); 3—Western Liaoning Complex (Cui et al., 1991); 4—Northern Liaoning Complex (Sun et al., 1993); 5—Eastern Shandong Complex (Li, 1993); 6—Miyun-Chengde Complex (Chen et al., 1994); 7—Southern Jilin Complex (Ge et al., 2003). (b): 1—Guyang-Wuchuan Complex (Jin, 1989); 2—Sheerteng Complex (Jin, 1989); 3—Daqingshan-Ulashan Complex (Archean TTG gneisses and mafic granulites; Jin et al., 1991; Liu et al., 1993)

+ plagioclase + quartz ± andalusite in pelitic gneisses (e. g. the presence of relict andalusites within planar sillimanite crystals from the Caozhuang pelitic gneiss, Eastern Hebei; Zhao et al., 1998). The peak assemblage is shown by the assemblages of orthopyroxene + clinopyroxene + garnet + plagioclase + quartz in mafic granulites, hornblende + plagioclase + quartz + garnet in garnetiferous amphibolites and garnet + sillimanite + plagioclase + quartz + biotite in pelitic gneisses. The post-peak assemblage is characterized by garnet + quartz symplectic coronas in mafic granulites, actinolite + garnet retrogressive rims around garnet or hornblende grains in amphibolites, and kyanite replacing sillimanite or staurolite replacing sillimanite + garnet in pelitic gneisses (e. g. Ge et al., 2003). These mineral assemblages and their p-T estimates define nearly isobaric cooling, anticlockwise, p-T paths (Fig. 3a and 3b).

3.2 p-T paths of Paleoproterozoic khondalites in the Khondalite Belt

The Paleoproterozoic khondalites in the Khondalite Belt of the Western Block are dominated by graphite-bearing sillimanite-garnet gneiss, garnet quartzite, felsic paragneiss, calc-silicate rock and marble, which have previously been referred to as "khondalite series" in the Chinese literature and are considered to represent stable continental margin deposits (Jin et al., 1991; Liu et al., 1993; Lu and Jin, 1993). Associated with the khondalites are minor TTG gneisses, mafic granulites, syntectonic charnockites, and S-type granites. It has long been considered that the khondalites were deposited and metamorphosed in the Archean period (Lu, 1991; Qian and Li, 1999; Li et al., 1999; Yang et al., 2000). However, the available isotopic data suggest that the khondalites were deposited and metamorphosed in the Paleoproterozoic period, with depositional ages ranging from 2.3 to 1.9 Ga and a metamorphic age of 2.0-1.9 Ga (Xia et al., 2006a, 2006b).

The khondalites in the Paleoproterozoic Khondalite Belt preserve four distinct mineral assemblages (M_1-M_4). M_1 is represented by inclusions of plagioclase + biotite + quartz ± kyanite ± rutile within M_2 garnet porphyroblasts; M_2 represents the growth of garnet porphyroblasts and matrix plagioclase + biotite + quartz + sillimanite ± ilmenite; M_3 is represented by cordierite coronas and cordierite + orthopyroxene or cordierite + spinel symplectites, surrounding garnet porphyroblasts; and M_4 represents retrograde minerals biotite + chlorite replacing garnet, K-feldspar + sericite + chlorite replacing cordierite, and andalusite + muscovite dissecting the main foliation (Lu, 1991, Lu and Jin, 1993; Zhao et al., 1999c). These mineral assemblages and their thermobarometric estimates define clockwise p-T paths involving near-isothermal decompression (Fig. 4).

3.3 p-T paths of Paleoproterozoic rocks in the Jiao-Liao-Ji Belt

The Jiao-Liao-Ji Belt is considered to be a Paleoproterozoic rifting zone lying at the eastern margin of the Eastern Block, with its northern segment intervening between the Northern Liaoning-Southern Jilin Complex and the Southern Liaoning-Nangrim Complex and its southern segment extending across the Bohai Sea into the Eastern Shandong Complex (Fig. 5). The belt consists of

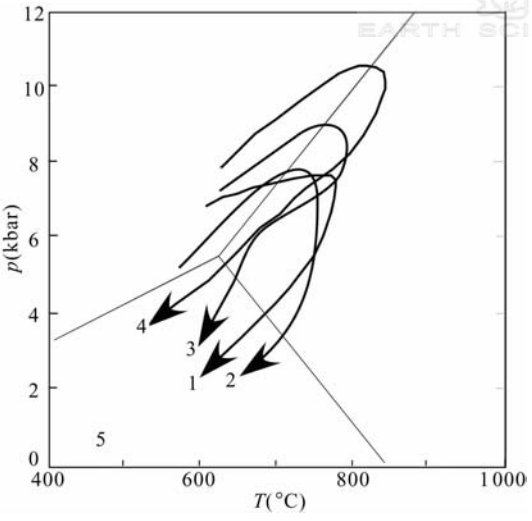

Fig. 4 Metamorphic p–T paths of basement rocks in the Khondalite Belt of Western Block
1—Helanshan-Qianlishan domain (Zhao et al., 1999c); 2—Daqingshan-Ulashan Complex (Paleoproterozoic knondalite series; Jin et al., 1991; Liu et al., 1993); 3—Jining Complex (khondalite series; Lu and Jin, 1993); 4—Jining Complex (mafic granulites; Lu and Jin, 1993)

greenschist to lower amphibolite facies sedimentary and volcanic successions and associated granitic and mafic intrusions. The sedimentary and volcanic successions, including the Fengzishan and Jingshan Groups in eastern Shandong, the South and North Liaohe Groups in eastern Liaoning, the Ji'an and Laoling Groups in southern Jilin, and possibly the Macheonayeong Group in North Korea, are transitional from a basal clastic-rich sequence and a lower bimodal-volcanic sequence, through a middle carbonate-rich sequence, to an upper pelite-rich sequence (Li et al., 2005). Stratigraphically, the Fenzishan Group in eastern Shandong is well correlated with the North Liaohe Group in Liaoning and the Laoling Group in southern Jilin (Luo et al., 2004; Li et al., 2005; Zhao et al., 2005; Lu et al., 2006). Similarly, the Jingshan Group in eastern Shandong can also be stratigraphically correlated with the South Liaohe Group in Liaoning and the Ji'an Group in southern Jilin (Zhao et al., 2005). Therefore, the Jiao-Liao-Ji Belt itself can be further subdivided into a northern zone, which comprises the Fenzishan, North Liaohe and Laoling Groups, and a southern zone that consists of the Jingshan, South Liaohe and Ji'an Group (Fig. 5). Separating the two belts are ductile shear zones and faults (Li et al., 2005; Zhao et al., 2006). The metamorphic evolution of the two belts is characterized by different metamorphic p–T paths: clockwise p–T paths reconstructed for the northern zone, and anticlockwise p–T paths for the southern zone (Lu et al., 1996; He and Ye, 1998).

Microstructures and mineral reaction relations reveal that both the northern and southern zones of the Jiao-Liao-Ji Belt underwent four distinct metamorphic stages (M_1 to M_4), and they have a similar M_1 mineral assemblage that is represented by fine-grained (0.1–0.2 mm) metamorphic minerals (white mica, chlorite, biotite, quartz and albite) present in some undeformed or weakly deformed domains or microlithons which occur as lenses wrapped by the S_1 schistosity. The M_2 assemblage is quartz + plagioclase + muscovite + biotite + garnet + staurolite + kyanite for the northern zone and quartz + plagioclase + muscovite + biotite + garnet + andalusite ± staurolite for the southern zone. The M_3 assemblage is sillimanite + garnet + plagioclase + quartz + biotite + muscovite for the northern zone and sillimanite + cordierite + plagioclase + quartz + biotite + muscovite for the southern zone. The M4 assemblage is chlorite + sericite for both the northern and southern zones, representing later retrograde metamorphism. Lu et al. (1996) and He and Ye (1998) showed that the mineral assemblages and their p–T calculations define a clockwise p–T path for the northern zone and an anticlockwise p–T path for the southern zone (Fig. 5).

Li et al. (2005) interpreted development of the clockwise and anticlockwise p–T paths of the Jiao-Liao-Ji Belt as follows. At about 1.9 Ga, the rift basin underwent lithospheric uplift, probably associated with asthenospheric upwelling, resulting in the initial greenschist facies metamorphism (M_1) and subsequent extensional deformation D_1. Concurrent with D_1 was the M_2 metamorphism that occurred before D_2 and produced lower-pressure assemblages in the areas near the center of upwelling-thinning (the southern zone) and medium-pressure assemblages in the areas where the thrust stacking and thickening of the sedimentary sequences occurred (the northern zone). D_1 extension was followed by a compressive event at 1.90–1.87 Ga, leading to closure of the rift basin to form the Jiao-Liao-Ji Orogen. Associated with this compressive event was D_2 deformation and subsequent M_3 metamorphism, producing sillimanite + cordierite in low-pressure-type rocks in the southern zone and kyanite + staurolite in medium-pressure-type rocks in the northern zone. Finally, both the northern and southern zones in the Jiao-Liao-Ji Orogen underwent exhumation, associated with the D_3 deformation and subsequent retrograde met-

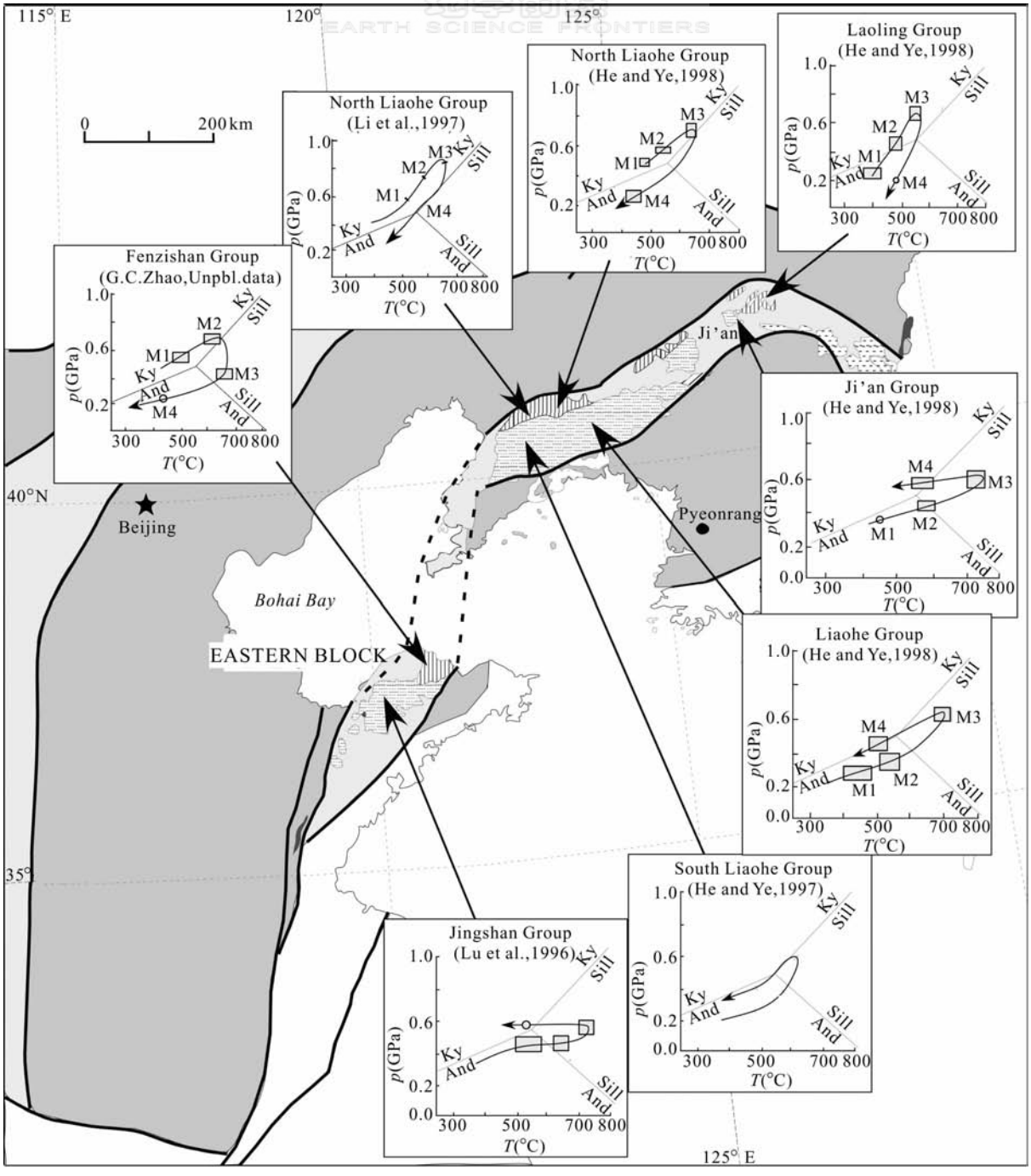

Fig. 5 Metamorphic *p*–*T* paths of basement rocks in the Paleoproterozoic Jiao-Liao-Ji Belt of the Eastern Block

amorphism (M_4), together with the emplacement of rapakivi granite at (1 875±10) Ma[increase a reference about the age of rapakivi granite].

3.4 *p*–*T* paths of the basement rocks in the Trans-North China Orogen

The main lithotectonic features of the Trans-North China Orogen include: (1) dominant Late Archean to Paleoproterozoic arc-related juvenile crust with minor reworked basement rocks (Kröner et al., 1988; Sun et al., 1992; Zhao et al., 2000b; Liu et al., 2002, 2005); (2) linear structural belts defined by strike-slip ductile shear zones, large-scale thrusting and folding, and transcurrent tectonics (Li and Qian, 1991; Zhao et al., 1999a); (3) sheath folds and mineral lineations (Wu and Zhong, 1998); (4) high-pressure granulites and retrograde eclogites (Zhai et al., 1992; Guo et al., 2002, 2005; Zhao et al., 2001a;

O'Brien et al., 2005; Zhang et al., 2006); (5) clockwise metamorphic p–T paths involving near-isothermal decompression (Zhai et al., 1992; Zhao et al., 2000a, 2001a; Guo et al., 2005); (6) ancient oceanic fragments and ophiolitic mélange (Wang et al., 1996; Wu and Zhong, 1998); (7) syn- or post-tectonic granites; and (8) post-collisional mafic dyke swarms (Peng et al., 2005) [However, Peng et al., 2005 did not consider the mafic dyke swarms as post-collisional but intracontinental rift products]. Most of these lithotectonic elements are classical indicators of collision tectonics.

The basement rocks in the Trans-North China Orogen preserve the peak, post-peak decompression and later cooling mineral assemblages. The representative peak assemblages, which occur as porphyroblasts or matrix minerals, include garnet + quartz + omphacite pseudomorph (clinopyroxene + Na-rich plagioclase) in retrograded eclogites, garnet + quartz + plagioclase + clinopyroxene in high-pressure granulites, garnet + quartz + plagioclase + clinopyroxene + orthopyroxene in medium-pressure granulites, garnet + hornblende + plagioclase + quartz ± rutile in amphibolites, and garnet + plagioclase + K-feldspar + quartz + biotite + sillimanite/kyanite in medium-pressure pelitic gneisses. The post-peak decompressional assemblages occurred as coronas or symplectites surrounding the peak minerals. In retrograded eclogites, the decompression assemblage is represented by symplectite clinopyroxene + Na-rich plagioclase, which has been found in many other retrograded eclogite terrains and is considered to have formed from the breakdown of omphacite during the transformation of eclogites to high-pressure granulites. In high- and medium-pressure granulites, the decompression assemblage is represented by symplectite orthopyroxene + Ca-rich plagioclase or corona orthopyroxene + clinopyroxene + Ca-rich plagioclase surrounding the embayed garnet grains. In amphibolites, the decompression assemblage is the hornblende/cummingtonite + plagioclase symplectite surrounding the embayed garnet grains, and in pelitic gneisses, the decompression assemblage is represented by cordierite coronas or cordierite + orthopyroxene/spinel symplectites. The later cooling assemblages include the hornblende + plagioclase symplectite in high- and medium-pressure granulites, chlorite + biotite replacing garnet in amphibolites, and biotite + K-feldspar ± muscovite replacing cordierite, garnet or sillimanite in pelitic gneisses. These mineral assemblages and their thermobarometric estimates define a clockwise p–T path involving near-isothermal decompression and cooling following the peak metamorphism (Fig. 6), suggesting a continent-continent collision environment for the Trans-North China Orogen.

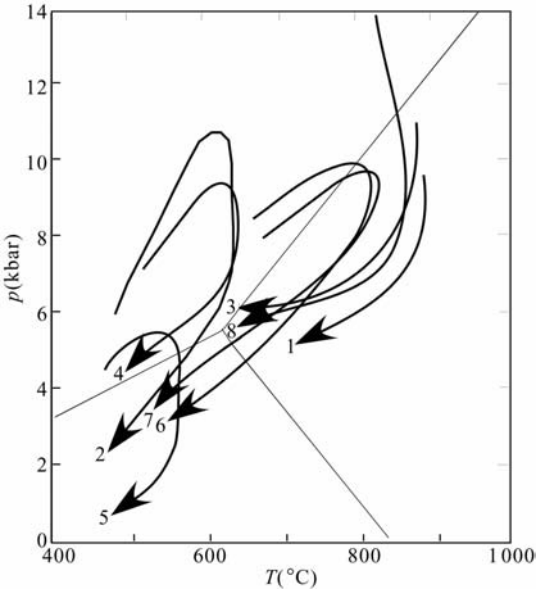

Fig. 6 Metamorphic p–T paths of basement rocks in the Trans-North China Orogen

1—Hengshan Complex (Zhao et al., 2001a); 2—Wutai Complex (Zhao et al., 1999a); 3—Fuping Complex Zhao et al., 2000a); 4—Lüliang Complex (Zhao et al., 2000b); 5—Zhongtiao domain (Zhao et al., 2000b); 6—Huaian Complex (Zhao et al., 2000b); 7—High-pressure granulite (Zhai et al., 1992; Zhao et al., 2001a)

4 Discussion

As discussed above, the metamorphism of Late Archean rocks in the Eastern Block and the Yinshan Block, regardless of high-grade terrains or low-grade granite-greenstone belts, is characterized by anticlockwise p–T paths involving near-isobaric cooling (Fig. 3a and 3b), which suggests that the origin of metamorphism was related to the underplating or intrusion of a large volume of mantle-derived magmas (Bohlen, 1987, 1991). Emplacement of sufficient volumes of mantle-derived magmas through underplating, thereby leading to granulite facies metamorphism involving anticlockwise isobaric cooling paths, may occur in continental magmatic arc regions (Bohlen, 1987), above hot spots driven by mantle plumes (Bohlen, 1991), and in continental rift environments (Sandiford and Powell, 1986). Of these potential tectonic settings in which substantial magmatic activity

occurs, a continental rift environment is considered inappropriate for the formation of Late Archaean basement rocks in the Eastern Block of the North China Craton, as it cannot explain the extensive exposure of 2.6–2.5 Ga TTG granitoid intrusions over a width of more than 800 km, dominant domal structures, and lack of intrusion of abundant alkali rocks commonly associated with rifting (Zhao et al., 1998). Both mantle plume and continental magmatic arc models can explain a close temporal relationship between the primary emplacement of TTG granitoid magmas and subsequent regional metamorphism involving anticlockwise $p-T-t$ paths. However, Zhao et al. (1998, 1999a, 2001b) favored a mantle plume model for the Eastern Block because this model can also reasonably interpret: (1) the exceptionally large exposure of granitoid intrusions that were formed over a short time period (2.6–2.5 Ga), without systematic age progression across a ~800 km wide terrain; (2) affinities of mafic rocks to continental tholeiitic basalts; (3) dominant diaprism-related domal structures; and (4) bimodal volcanic assemblages (basaltic rocks on the one hand, and dacitic, rhyodacitic, and rhyolitic rocks on the other), which are different from Phanerozoic magmatic arc assemblages where andesites are the peak volcanic-rock types. On the basis of these facts, Zhao et al. (2001b) presented a specific scenario describing the upswelling of Late Archean (2.6–2.5 Ga) mantle plumes beneath the Eastern Block and massive heat transfer resulting in widespread melting of the upper mantle and lower crust to form voluminous granitoid (TTG) magmas and the granulite facies metamorphism involving anticlockwise, isobaric cooling, p–T paths. The same arguments also stand for a mantle plume tectonic setting for the regional metamorphism involving anticlockwise p–T–t paths in the Yinshan Block. Therefore, we believe that mantle plumes were major tectonic mechanism that governed the formation and evolution of the Late Archean crust in the Eastern and Yinshan Block, whereas plate tectonics may not have operated in the two blocks during Late Archean period.

Clockwise p–T paths involving isothermal decompression reconstructed for the metamorphic rocks in the Khondalite Belt in the Western Block and the Trans-North China Orogen suggest that the development of these two Paleoproterozoic orogenic belts must have been the products of plate tectonics. This is also consistent with structural, lithological, and geochemical considerations, including widespread presence of large-scale thrusting, isoclinal folds, sheath folds, mineral stretching lineations, arc-related igneous associations, high-pressure rocks, etc. Recent studies show that the Paleoproterozoic Khondalite Belt in the Western Block developed by the collision between the Yinshan Block in the north and the Ordos Block in the south to form the Western Block at ~1.9 Ga (Zhao et al., 2003, 2005), whereas the Trans-North China Orogen resulted from the collision between the Western and Eastern Blocks to form the coherent North China Craton at ~1.85 Ga (Zhao et al., 2001b, 2005). The Paleoproterozoic Jiao–Liao–Ji Belt is a little more complicated than the Khondalite Belt and Trans-North China Orogen in terms of metamorphism since both clockwise and anticlockwise p–T paths have been found in this belt. However, it is certain that the Jiao–Liao–Ji Belt was the product of plate tectonics since the metamorphism with clockwise p–T paths was involved in its northern zone, and other aspects show that the belt represents a Paleoproterozoic rift zone.

The time of the initiation of plate tectonics in the North China Craton can be approximated by the age of the earliest juvenile crustal components in the three Paleoproterozoic tectonic belts. In contrast, the reworked crustal components in the three tectonic belts cannot be used to define the onset of plate tectonics since these crustal materials may have come from the early crust that was formed by other tectonic mechanism (e.g. mantle plumes). Available data show that the oldest juvenile crustal components in the Paleoproterozoic Jiao–Liao–Ji Belt is the 2.2–2.1 Ga Liaoji granites, which are most likely the sedimentary sources of the Liaohe Group and its equivalents in the belt (Luo et al., 2004). In the Paleoproterozoic Khondalite Belt, we have not found any juvenile crustal material older than 2.5 Ga. In the Trans-North China Orogen, the oldest, arc-related, and juvenile crustal component is the ~2.56 Ga Wutai granitoids (Wilde et al., 2005), which may be the oldest arc-related products so far found in the North China Craton. Thus, it is no doubt that Phanerozoic-style plate tectonics was operated in the North China Craton at 2.56 Ga.

5 Conclusions

(1) Metamorphism of Late Archean basement rocks in the Eastern and Yinshan Blocks is characterized by anticlockwise p–T paths, mostly involving isobaric cooling, suggesting that the heating source of the metamorphism was related to the un-

derplating or intrusion of large volumes of mantle-derived magmas. Although theoretically such mantle-derived magmas form under continental magmatic arc, mantle plume, or continental rift environments, only a mantle plume model can reasonably explain spatial and temporal distributions, lithological association and structural features of the Late Archean basement rocks in the Eastern and Yinshan Blocks. Therefore, mantle plumes may be the major tectonic mechanism that governed the formation and evolution of the Late Archean crust in the Eastern and Yinshan Block, and plate tectonics may not have operated in the two blocks during Late Archean period.

(2) Metamorphism of the basement rocks in the Paleoproterozoic Khondalite Belt and the Trans-North China Orogen is both characterized by clockwise p–T paths involving isothermal decompression following peak metamorphism, which suggests that the two orogens underwent initial crustal thickening followed by rapid exhumation/uplift tectonic processes. Such tectonic processes are typical indicators of collisional orogens that accommodate plate tectonics. The Paleoproterozoic Jiao-Liao-Ji Belt can be divided into the southern and northern zones, of which the former is characterized by anticlockwise p–T paths, whereas the latter is characterized by clockwise p–T paths, also indicating a regime of plate tectonics.

(3) So far, the convincing oldest, magmatic arc-related, juvenile crustal component in the North China Craton is the 2.56 Ga Wutai granitoids in the Trans-North China Orogen, which can be used to approximate the timing of the occurrence of plate tectonics in the North China Craton.

Acknowledgments *We thank Lifei Zhang (Peking University) and Zhengdong You for inviting me to write this article. This research was financially supported by Hong Kong RGC grants (7063/06P, 7055/05P, 7048/04P, 7055/03P, and 7048/03P) and a HKU Seed Funding for Basic Research (200411159122).*

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