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High-pressure mafic granulites in the Trans-North China Orogen: Tectonic significance and age

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Abstract

High-pressure mafic granulites (including retrograded eclogites) have been reported from the Trans-North China Orogen, a Paleoproterozoic orogenic belt along which two discrete continental blocks, referred to as the Eastern and Western Blocks, were amalgamated to form the North China Craton. Extensive metamorphic investigations and geochronology carried out over the last few years provide important insights into the age and significance of these high-pressure granulites, which are critical in understanding of the timing and tectonic processes involved in the assembly of the North China Craton.

Most high-pressure mafic granulites in the Trans-North China Orogen preserve the high-pressure granulite facies assemblage garnet + plagioclase + clinopyroxene + quartz, the medium-pressure granulite facies assemblage garnet + plagioclase + clinopyroxene + orthopyroxene ± quartz, the low-pressure granulite facies assemblage orthopyroxene + clinopyroxene + plagioclase ± quartz, and the amphibolite facies assemblage hornblende + plagioclase. Minor high-pressure granulites preserve the early eclogite facies mineral assemblage of garnet + quartz + omphacite pseudomorph (clinopyroxene + Na-rich plagioclase), indicating that they are retrograded eclogites. These mineral assemblages and their P–T estimates define a clockwise P–T path involving near-isothermal decompression and cooling following the peak high-pressure metamorphism, which suggests that they formed during continent–continent collision. Field mapping and geochronology indicate that the precursors of these high-pressure granulites were mafic dykes which were emplaced at ~1915 Ma and underwent high-pressure granulite facies metamorphism at ~1.85 Ga. Taken together, the high-pressure granulites in the Trans-North China are considered to have resulted from final collision between the Eastern and Western Blocks to form the North China Craton at ~1.85 Ga, not at ~2.5 Ga as recently proposed by some authors.

Keywords: High-pressure granulite; Trans-North China Orogen; P–T paths; North China Craton; Paleoproterozoic tectonics

1. Introduction

One of the main arguments against the operation of plate tectonic processes in the early Precambrian has been the apparent lack of high-pressure rock assemblages. In recent years, however, such rocks of Paleo- to Mesoproterozoic age have been discovered in the Canadian Shield (Snoeyenbos et al., 1995; Baldwin et al., 2003; Indares, 2003), NW Scotland (Baba, 1998), North China (Zhai et al., 1992, 1993, 1995, Dirks et al., 1997; Guo et al., 1993, 2001, 2002; Guo and Zhai, 2001; Zhao et al., 2001a; O'Brien et al., 2005), Tanzania (Möller et al., 1995; Boven et al., 1999), India (Bhowmik and Roy, 2003), Brazil (Del Lama et al., 2000), Siberia (Smelov and Beryozkin, 1993) and the Baltic Shield (Möller, 1998, 1999). Studies of the metamorphic and structural evolution of such high-pressure rocks occurring in former mountain belts provides valuable information on possible subduction and collision events as well as on the subsequent exhumation and cooling processes (Carswell, 1990; O'Brien, 2001; O'Brien and Rotzler, 2003; Carswell et al., 2003).

High-pressure mafic granulites (including retrograded eclogites) have been widely reported in the Trans-North China

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Orogen, a collisional belt along which two discrete continental blocks, referred to as the Eastern and Western Blocks, were amalgamated to form the North China Craton (Zhao, 2001; Zhao et al., 2001b). The presence of high-pressure granulites, together with fragments of ancient oceanic crust, mélanges and large-scale thrusts in the Trans-North China Orogen, is considered to be important evidence for the collision between these blocks (Zhao et al., 2001b; Guo et al., 2002; Wilde et al., 2002). However, controversy has surrounded the age and tectonic nature of the high-pressure rocks, with one school of thought believing that they formed in the late-Archean and underwent high-pressure metamorphism and subsequent exhumation at ~2.5 Ga (Li et al., 2000; Kusky and Li, 2003), whereas others consider that these rocks formed in the Paleoproterozoic and experienced high-pressure metamorphism and exhumation during a ~1.85 Ga collisional event that led to the final amalgamation of the North China Craton (Zhao et al., 2000a, 2001b; Wilde et al., 2002, Guo et al., 2001, 2002; Guo and Zhai, 2001; Kröner et al., 2005, in press). In the last few years, geologists from China, Australia, Germany, USA and other countries have carried out extensive metamorphic and geochronological investigations on these high-pressure granulites and related rocks in the Trans-North China Orogen and produced numerous new geological data and interpretations (e.g. Wang et al., 1996, 1997; Wilde et al., 1997, 1998, 2002, 2004, 2005; Wu and Zhong, 1998; Zhao et al., 1998, 1999a, 2000a, 2001a, 2002, 2005; Guo et al., 2001, 2002, 2005; Halls et al., 2000; Liu et al., 2000, 2002a,b, 2004, 2005; Zhai et al., 2000, 2003, 2005; Guo and Zhai, 2001; Zhai and Liu, 2003; Wang et al., 2003, 2004a,b; Kusky and Li, 2003; Kröner et al., 2005, in press; O'Brien et al., 2005; Wu et al., 2005). In this contribution, we review and analyze these new data and present our current understanding of the tectonic setting and age of high-pressure granulites in the Trans-North China Orogen, which provide important insights into the evolution of the North China Craton.

2. Regional setting

The North China Craton refers to the Chinese part of the Sino-Korea Craton, covering most of north China, the southern part of northeast China, Inner Mongolia, Bohai Bay and the northern part of the Yellow Sea. It is triangular in shape, with an area of approximately 1,500,000 km^2 (Fig. 1). The craton is bounded by faults and younger orogenic belts. The Early Paleozoic Qilianshan Orogen and the Late Paleozoic Tianshan–Inner Mongolia–Daxinganling Orogen bound the craton to the west and north, respectively, and in the south, the Qinling–Dabie–Su–Lu ultrahigh-pressure metamorphic belt separates the craton from the Yangtze Block (Fig. 1). Tectonically, the North China Craton can be divided into the Archean to Paleoproterozoic Eastern and Western Blocks, separated by the Paleoproterozoic Trans-North China Orogen (Fig. 2; Zhao et al., 2001b, 2005).

The Eastern Block consists of early Archean to Paleoproterozoic basement, partially overlain by Paleoproterozoic to

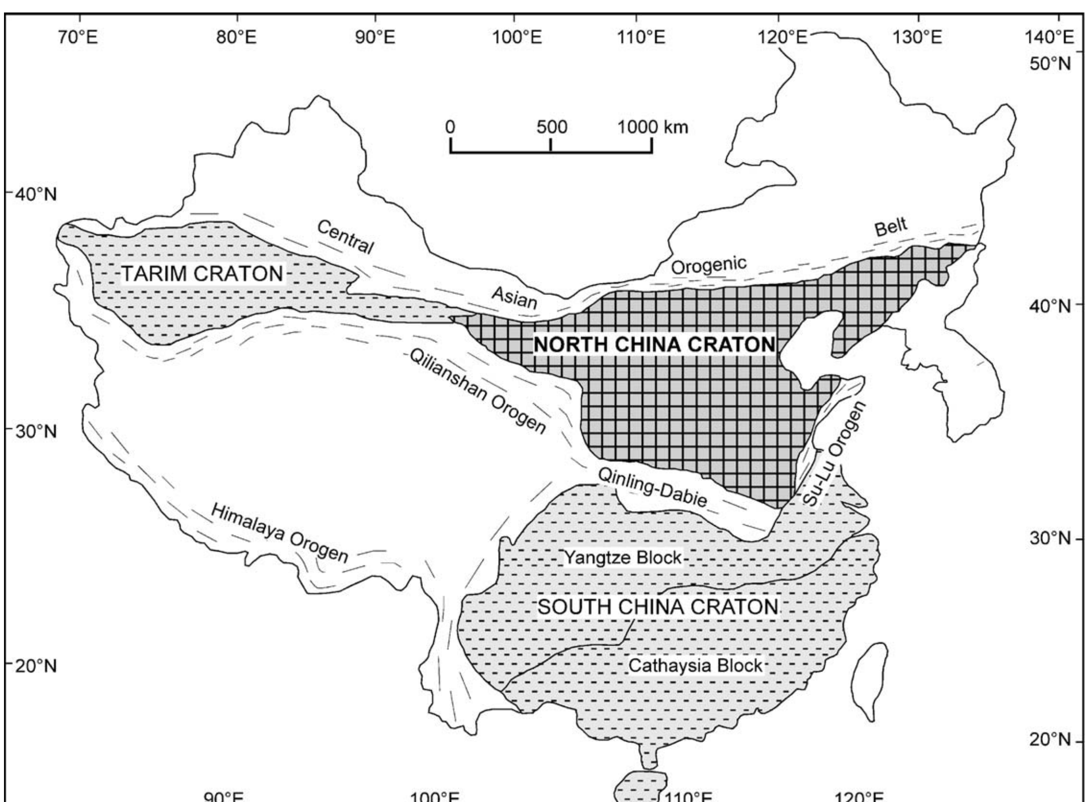

Fig. 1. Tectonic map of China showing cratons and younger orogens (Zhao et al., 2001b).

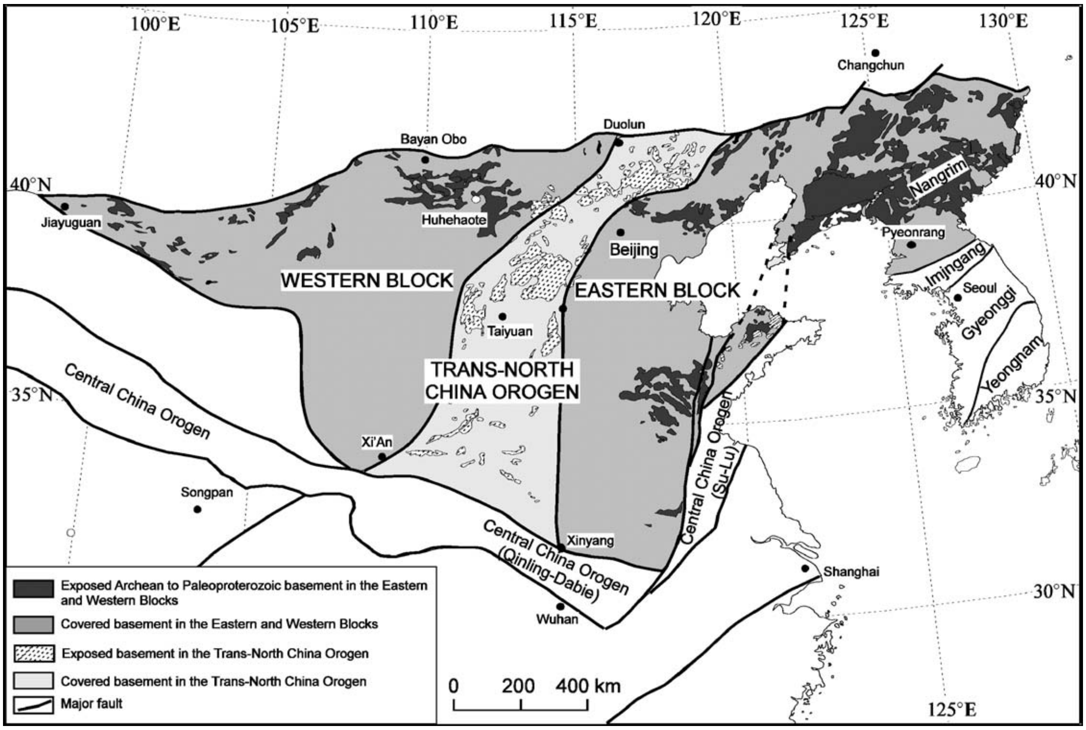

Fig. 2. Three-fold tectonic subdivision of the North China Craton proposed by Zhao et al. (1998, 2001b).

Cenozoic platform cover. The early Archean (>3.4 Ga) basement is extremely limited in extent, represented by ~3.8 Ga trondhjemitic gneisses in the Anshan area and 3.6–3.4 Ga supracrustal rocks in Eastern Hebei (Jahn et al., 1987; Ernst, 1989; Liu et al., 1992, Song et al., 1996; Wu et al., 1998); their original extent and tectonic history are unknown, owing to extensive reworking by a major ~2.5 Ga tectonothermal event. The middle Archean (3.4–2.9 Ga) basement is also limited, represented by the Lower Anshan, Qianxi and Longgang Groups and associated granite plutons (e.g. Tiejiashan granite). The Late Archean (2.9–2.5 Ga) basement is more widespread, making up 80% of the total exposure of Archean rocks in the Eastern Block. It consists of 2.6–2.5 Ga tonalitic–trondhjemitic–granodioritic (TTG) gneisses with minor supracrustal rocks ranging in age from 2.8 to 2.5 Ga (Ernst, 1988; Ernst et al., 1988). These rocks were intruded by syn-tectonic granite/charnockite and experienced greenschist to granulite facies metamorphism at ~2.5 Ga (Pidgeon, 1980; Compston et al., 1983; Jahn and Zhang, 1984; Jahn and Ernst, 1990; Kröner et al., 1998; Zhao et al., 1998, 2003; Ge et al., 2003). The Paleoproterozoic (>1.8 Ga) basement comprises I-type and A-type granites, and bimodal volcanic and sedimentary rocks, most of which are interpreted to have developed in intracontinental rift basins (Li et al., 1995, 1996, 2001a,b; 2005).

Much of the basement in the Western Block underlies deeply subsided Mesozoic to Cenozoic basins, with exposures largely restricted to the northern portion of the block. The exposed basement rocks are poorly constrained in terms of modern geochronology and are generally considered to be composed of a Late Archean terrane in the north, referred to as the Yinshan Terrane, flanked to the south by a belt of Paleoproterozoic high-grade supracrustal rocks, named the Khondalite Belt, which separates the Yinshan Terrane from the Ordos Basin (Zhao et al., 2005). Like those in the Eastern Block, the Late Archean basement rocks in the Western Block are also composed predominantly of TTG gneisses with minor supracrustal rocks, metamorphosed from greenschist to granulite facies at ~2.5 Ga (Zhao et al., 1999b). The Paleoproterozoic supracrustal rocks consist of graphite-bearing, sillimanite-garnet gneisses, garnet quartzites, calc-silicate rocks and marbles, representing stable continental margin deposits (Condie et al., 1992; Lu, 1991; Lu and Jin, 1993; Lu et al., 1996), with a maximum depositional age of ~2.3 Ga and a metamorphic age of 2.0–1.9 Ga (Zhao et al., 1999b, 2005).

Between the Eastern and Western Blocks is the Trans-North China Orogen, a nearly south–north-trending zone, ~1200 km long and 100–300 km wide (Figs. 2 and 3). It includes the Chengde, Northern Hebei, Xuanhua, Huai'an, Hengshan, Wutai, Fuping, Zanhuang, Lüliang, Zhongtiao, Dengfeng and Taihua Complexes (Fig. 3). The main lithotectonic features of the Trans-North China Orogen include dominant Late Archean to Paleoproterozoic juvenile crust with minor reworked basement rocks (Kröner et al., 1988; Sun et al., 1992; Wan et al., 2000; Zhao et al., 2000a), linear structural belts defined by strike–slip ductile shear zones, large-scale thrusting and folding, and transcurrent tectonics (Li and Qian, 1991), sheath folds and strong mineral lineations (Wu and Zhong, 1998), high-pressure granulites and retrograded eclogites (Zhai et al., 1993; Guo et al., 1993, 2002; Guo and Zhai, 2001; Zhao et al., 2001a,b), clockwise metamorphic P–T paths involving near-isothermal decompression (Zhao et al., 2000a,b; Guo et al., 2002), ancient oceanic fragments and ophiolitic mélange (Li et

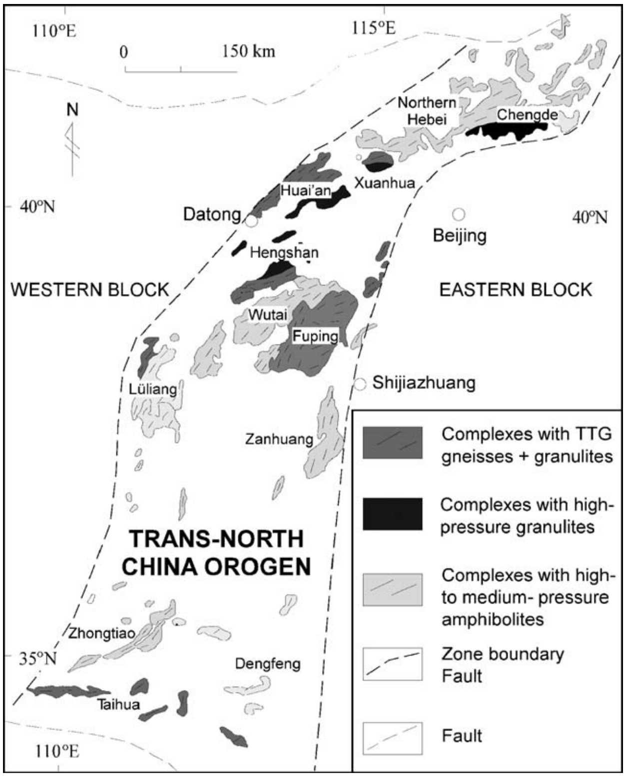

Fig. 3. Simplified tectonic map showing the distribution of metamorphic complexes in the Trans-North China Orogen (after Zhao et al., 2000a).

al., 1990; Bai, 1986; Bai and Dai, 1998; Wang et al., 1996; Wu and Zhong, 1998), syn- or post-tectonic granites (Liu et al., 2000, 2005), and post-collisional mafic dyke swarms (Halls et al., 2000; Zhao et al., 2001b). Most of these lithotectonic elements are classical indicators of collision tectonics, supporting the model that the Trans-North China Orogen is a collisional belt along which the Eastern and Western Blocks amalgamated to form the North China Craton (Zhao et al., 1999c, 2000a, 2001b, 2005).

3. High-pressure granulites in the Trans-North China Orogen

High-pressure mafic granulites are those granulite facies metabasic rocks that contain the main (peak) mineral assemblage clinopyroxene+plagioclase+garnet+quartz. They are distinguished from eclogites by the presence of plagioclase and from medium-pressure mafic granulites by the lack of orthopyroxene, although orthopyroxene may occur in high-pressure mafic granulites as symplectites or coronas formed during post-peak decompression. Recent geological mapping reveals that high-pressure mafic granulites in the Trans-North China Orogen occur along a northeast–southwest trending zone that extends from the Hengshan Complex (Zhao et al., 2001a, O'Brien et al., 2005), through the Huai'an (Zhai et al., 1993, 1995; Guo et al., 1993, 1996, 2002) and Xuanhua Complexes (Wang et al., 1994; Guo et al., 2002), into the Chengde Complex (Li et al., 1998; Mao et al., 1999). They constitute a northeast–southwest trending high-pressure granulite belt, tens of kilometers wide and up to 500 km long, in the northern segment of the Trans-North China Orogen (Fig. 3). The southern segment of the Trans-North China Orogen is occupied by a high-pressure amphibolite belt in which 10–14 kbar garnet amphibolites and kyanite–staurolite–anthophyllite mafic schist occur (Wang et al., 1997; Zhao et al., 1999c, 2000a). This high-pressure amphibolite belt seems to be the tectonic counterpart of the high-pressure granulite belt in the northern segment of the orogen, and together they constitute a large-scale Paleoproterozoic high-pressure belt that traverses the orogen and represents an important terrane boundary.

In the field, the high-pressure mafic granulites outcrop as boudins and sheets, ranging from 0.1 to 2 m in width and 0.1 to 50 m in length, within heterogeneous, migmatitic and deformed upper amphibolite to granulite facies TTG gneisses (Fig. 4). In most cases, the high- and medium-pressure mafic granulites crop out separately. In some places, however, they can be observed within the same outcrop, but they are never in contact with each other. In the field, the high-pressure mafic granulite boudins can be distinguished from the medium-pressure mafic granulites by their coarse-grained textures and the lack of large brown orthopyroxene crystals, which are ubiquitous in the medium-pressure granulite boudins. On the outcrop scale, it can be observed that coarse-grained garnet porphyroblasts in the high-pressure granulite are surrounded by symplectic plagioclase and pyroxene (Fig. 5a). Although there are sharp contacts between the high-pressure mafic granulites and the host TTG gneisses, no obvious intrusive relationships have been observed between them. The long axes of the granulite boudins are always parallel to the regional strike of the foliations of the TTG gneisses. In rare cases, and especially in low-strain zones, the high-pressure granulites occur as dykes which can be traced up to several hundred meters in length (Fig. 5b). This is convincing evidence that the high-pressure granulites in the Trans-North China Orogen were derived from mafic dykes. Ductile deformation has later

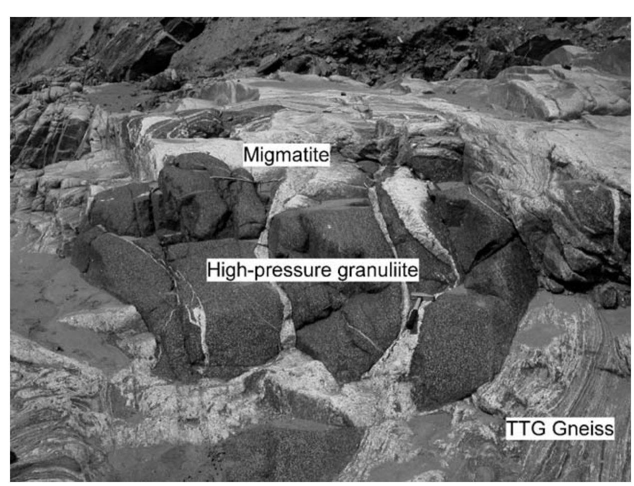

Fig. 4. Large boudins of high-pressure mafic granulites enclosed within heterogeneous and migmatitic TTG gneisses in the Hengshan Complex.

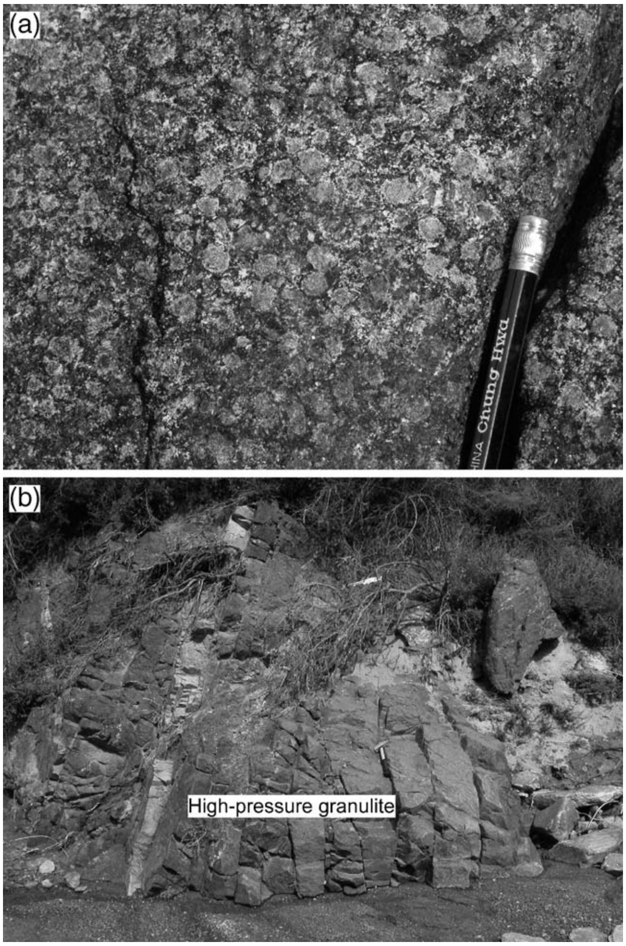

Fig. 5. (a) Coarse-grained garnet porphyroblasts surrounded by symplectic plagioclase and pyroxene in high-pressure granulite; (b) high-pressure granulites occurring as dykes can be traced up to several hundred meters in the Hengshan Complex.

rotated these dykes into parallelism with the layering in the enclosing gneisses and, at the same time, caused boudinage (Kröner et al., 2005, in press).

4. P–T paths of the high-pressure granulites and tectonic implications

As shown in Fig. 3, high-pressure mafic granulites in the Trans-North China Orogen are mainly exposed in the Hengshan, Huai'an, Xuanhua and Chengde Complexes. In the past few years, numerous metamorphic investigations have been carried out on the high-pressure mafic granulites in these complexes and detailed metamorphic histories have been reconstructed. In the following, we summarize the mineral assemblages, reaction relations and P–T paths of the high-pressure mafic granulites in these complexes in order to discuss their tectonic significance.

4.1. High-pressure granulites in the Hengshan Complex

The Hengshan Complex is situated in the central part of the Trans-North China Orogen (Fig. 3) and is composed of four major rock units: (1) the Hengshan granitoid gneisses, (2) the Hengshan mafic granulites, (3) the Yixingzhai gneisses, and (4) the Zhujiafang supracrustal assemblage (Fig. 6; Tian, 1991; Li and Qian, 1994; Zhao et al., 2001a; Kröner et al., 2005, in press). The Hengshan granitoid gneisses are strongly deformed high-grade orthogneisses of dioritic–tonalitic–trondhjemitic–granodioritic–granitic composition, which are extensively migmatized, and some of the migmatized zones show evidence of in situ melting and advanced anatexis, generating reddish granites. Within the Hengshan granitoid gneisses, there are discontinuous lenses or layers of amphibolite and high- and medium-pressure mafic granulite, ranging from 0.1 to 5 m in width and 0.1 to 50 m in length and interpreted as boudinaged gabbroic dykes (Kröner et al., in press). The Yixingzhai gneisses occur in the southern part of the Hengshan Complex, and are chemically similar to the Hengshan granitoid gneisses, but are only metamorphosed to lower amphibolite facies and are less deformed, locally preserving igneous textures. The Zhujiafang assemblage consists predominantly of amphibolite, felsic gneiss, mica schist, BIF and quartzite, and is distinctively

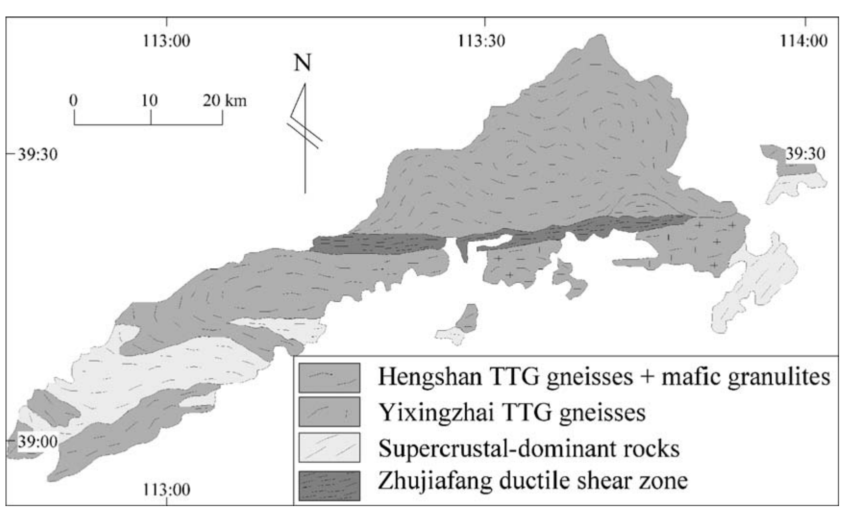

Fig. 6. Overview map of the Hengshan Complex showing major rock units (after Zhao et al., 2001a).

lower in metamorphic grade than the Hengshan granitoid gneisses. Most Chinese authors have considered the Zhujiafang assemblage to be the equivalent of the Wutai greenstones in the Hengshan area (Tian, 1991; Li and Qian, 1994).

Zhao et al. (2001a) recognized four distinct metamorphic assemblages from the high-pressure mafic granulites in the Hengshan Complex. The early prograde assemblage (M_1) is represented by quartz and rutile inclusions within the cores of garnet porphyroblasts, and omphacite pseudomorphs that are indicated by clinopyroxene + sodic plagioclase (An_{10-20}) symplectic intergrowths of which the exsolution-like sodic plagioclases make up to 30–40 vol.% (Fig. 7a). This texture is thought to indicate the replacement of omphacite by plagioclase and clinopyroxene through the following solid–solid reactions during the retrogration from eclogite facies to high-pressure granulite facies (Rubie, 1990; Möller, 1998; Zhao et al., 2001a):

$$\text{omphacite} + \text{quartz} \rightarrow \text{sodic plagioclase} + \text{clinopyroxene} \quad (1)$$

The peak assemblage (M_2) consists of clinopyroxene + garnet + sodic plagioclase + quartz ± hornblende, most of which occur as matrix minerals. The post-peak near-isothermal decompression assemblage (M_3) represents the development of plagioclase + orthopyroxene ± clinopyroxene symplectites and coronas surrounding embayed garnet grains. The symplectic texture consists of intergrowths of fine-grained, worm-like orthopyroxene + plagioclase ± magnetite around embayed garnet grains (Fig. 7b). The corona textures consist of very elongate plagioclase, clinopyroxene and/or orthopyroxene, separating garnet and quartz (Fig. 8a). The symplectic or coronitic orthopyroxene, plagioclase and clinopyroxene may be produced by the following decompressional reactions (Zhao et al., 2001a):

$$\text{garnet} + \text{quartz} \rightarrow \text{orthopyroxene} + \text{plagioclase} \quad (2)$$

$$\text{garnet} + \text{quartz} \pm O_2 \rightarrow \text{orthopyroxene} + \text{plagioclase} \pm \text{magnetite} \quad (3)$$

$$\text{garnet} + \text{quartz} \rightarrow \text{clinopyroxene} + \text{plagioclase} \quad (4)$$

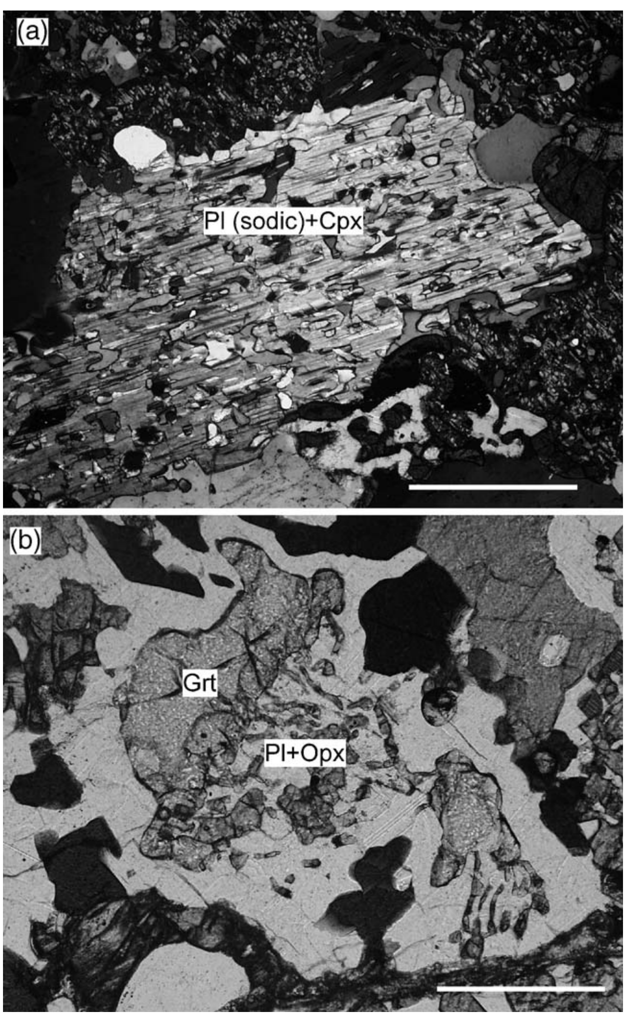

Fig. 7. Photomicrographs showing (a) Omphacite pseudomorph indicated by sodic plagioclase + clinopyroxene symplectic intergrowths (Hengshan), and (b) Plagioclase + orthopyroxene symplectite around garnet (Hengshan). Scale bar: 0.5 mm. Mineral symbols are after Kretz (1983).

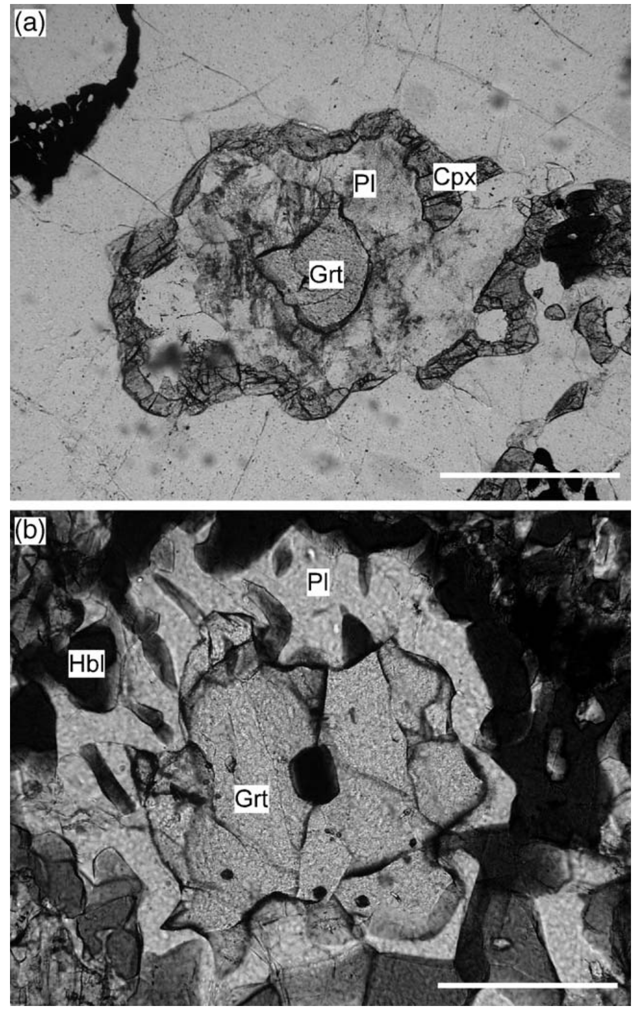

Fig. 8. Photomicrographs showing (a) Plagioclase + clinopyroxene + orthopyroxene corona surrounding garnet (Hengshan), and (b) Hornblende + plagioclase symplectite around garnet (Xuanhua). Scale bar: 1 mm. Mineral symbols are after Kretz (1983).

The cooling retrogression assemblage (M_4) is represented by hornblende + plagioclase symplectites which occur as worm-like intergrowths adjacent to garnet (Fig. 8b). Their formation has been related to the following reaction by Zhao et al. (2001a):

$$\text{garnet}^1 + \text{plagioclase}^1 + \text{quartz} + H_2O \rightarrow \text{garnet}^2 + \text{plagioclase}^2 + \text{hornblende} \quad (5)$$

Another possibility for the formation of the M_4 assemblage is a simple hydration of already formed orthopyroxene + plagioclase symplectites.

The P–T conditions of the early prograde assemblage (M_1) cannot be quantitatively estimated because of the absence of representative high-pressure minerals (e.g. omphacite). The THERMOCALC (Holland and Powell, 1998) program yields P–T conditions of 13.4–15.5 ± 1.5 kbar and 770–840 ± 50 °C for the peak mineral assemblage (M_2), based on the core composition of garnet, matrix clinopyroxene, hornblende and plagioclase. The P–T conditions of orthopyroxene + plagioclase ± magnetite symplectite and clinopyroxene + orthopyroxene + plagioclase corona (M_3) were estimated at c. 6.5–8.0 ± 1.0 kbar and 750–830 ± 40 °C, and hornblende + plagioclase symplectite (M_4) at 4.5–6.0 ± 1.2 kbar and 680–790 ± 60 °C. The combination of petrographic textures, mineral compositions and thermobarometric data defines a near-isothermal decompressional clockwise P–T path for the Hengshan high-pressure granulites (Fig. 9; Zhao et al., 2001a).

4.2. High-pressure granulites in the Huai'an and Xuanhua Complexes

North of the Hengshan Complex is the Huai'an Complex where the first high-pressure mafic granulites in the Trans-North China Orogen were discovered (Fig. 3; Zhai et al., 1993). High-pressure granulites were also found in the Xuanhua Complex (Wang et al., 1994), which is only ~50 km northeast of the Huai'an Complex (Fig. 3). Both the Huai'an and Xuanhua Complexes consist predominantly of high-grade granitoid gneisses, with minor charnockites, Al-rich gneisses (khondalites) and high-pressure mafic granulites (Zhai et al., 1993; Guo et al., 1993; Zhang et al., 1994; Guo and Zhai, 2001; Guo et al., 2002). High-pressure granulites in the two complexes occur as small sheets and boudins within the granitoid gneisses (Zhai et al., 1993; Guo et al., 1993, 2002; Wang et al., 1994; Zhang et al., 1994).

The metamorphic P–T evolution of high-pressure granulites in the Huai'an and Xuanhua Complexes has been studied by a number of authors (e.g. Wang et al., 1994; Zhang et al., 1994; Guo et al., 2002). They show mineral assemblages similar to those of the high-pressure granulites in the Hengshan Complex, although omphacite pseudomorphs indicated by clinopyroxene+ sodic plagioclase (An_{10-20}) symplectic intergrowths in the Hengshan high-pressure granulites (Zhao et al., 2001a), have not been found in the Huai'an and Xuanhua high-pressure granulites. Guo et al. (2002) recognized prograde (M_1), peak (M_2), post-peak decompression (M_3), and later cooling (M_4)

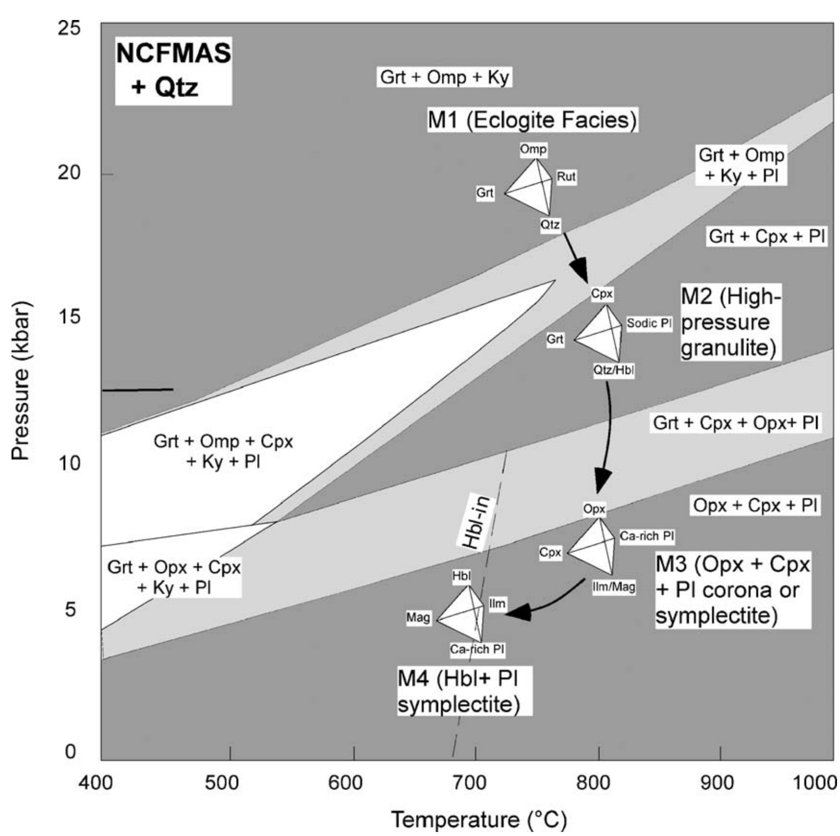

Fig. 9. Metamorphic P–T path of the Hengshan high-pressure granulites in the Trans-North China Orogen (after Zhao et al., 2001a).

assemblages from high-pressure granulites in the Huai'an and Xuanhua Complexes. The prograde assemblage (M_1) is represented by low-Ca cores in growth-zoned garnets and associated inclusions of clinopyroxene, plagioclase and quartz, which formed under P–T conditions of ~10 kbar and 700 °C. The peak assemblage (M_2) comprises high-Ca domains in garnet interiors and inclusions of clinopyroxene, plagioclase and quartz, yielding 11–14.5 kbar and 750–870 °C (Guo et al., 2002). The post-peak decompression assemblage (M_3) is represented by coronas and kelyphites (symplectites) of orthopyroxene + plagioclase + magnetite around garnet porphyroblasts, produced at conditions around 8.5–10.5 kbar and 770–830 °C (Guo et al., 2002). The cooling assemblages (M_4) include hornblende + plagioclase kelyphites around garnet and formed at about 5.5–8 kbar and 500–650 °C (Guo et al., 2002). These mineral assemblages and their P–T estimates define a clockwise P–T path involving isothermal decompression (ITD) and cooling following peak metamorphism (Fig. 10), suggesting a continent–continent collisional environment (Guo et al., 2002).

4.3. High-pressure granulites in the Chengde Complex

The Chengde Complex is located in the northernmost part of the Trans-North China Orogen (Fig. 3). It consists of amphibolite facies supracrustal rocks and granitoid gneisses in the north and granulite facies granitoid gneisses and minor high-grade supracrustal rocks in the south, where high-pressure mafic granulites have also been reported (Li et al., 1998). The high-pressure granulites occur as sheets and boudins (<2 m wide) within the high-grade granitoid gneisses.

The mineral assemblages, reaction relations and P–T conditions of the high-pressure mafic granulites in the Chengde Complex have not been clearly defined. Li et al. (1998) recognized three mineral assemblages from the Chengde high-pressure mafic granulites: clinopyroxene + garnet + quartz (M_1), orthopyroxene + clinopyroxene + plagioclase ± magnetite (M_2), and hornblende + plagioclase (M_3). Recently, we re-examined these high-pressure granulites and recognized four distinct mineral assemblages: high-pressure granulite facies (M_1), medium-pressure granulite facies (M_2), low-pressure granulite facies (M_3), and amphibolite facies (M_4) assemblages (Zhao et al., unpublished data). The high-pressure granulite–facies assemblage (M_1) is represented by garnet (core) + clinopyroxene + Na-rich plagioclase + quartz, which occur as mineral inclusions within garnet porphyroblasts. The medium-pressure granulite facies assemblage (M_2) is indicated by garnet + clinopyroxene + orthopyroxene + plagioclase ± quartz, of which garnet occurs as porphyroblasts and the rest occur as matrix minerals. The low-pressure granulite facies assemblage is defined by orthopyroxene + clinopyroxene + Ca-rich plagioclase ± magnetite, which occur as symplectites or coronas around the embayed garnet grains. The amphibolite facies assemblage is hornblende + Ca-rich plagioclase, which also occur as symplectites around garnet grains.

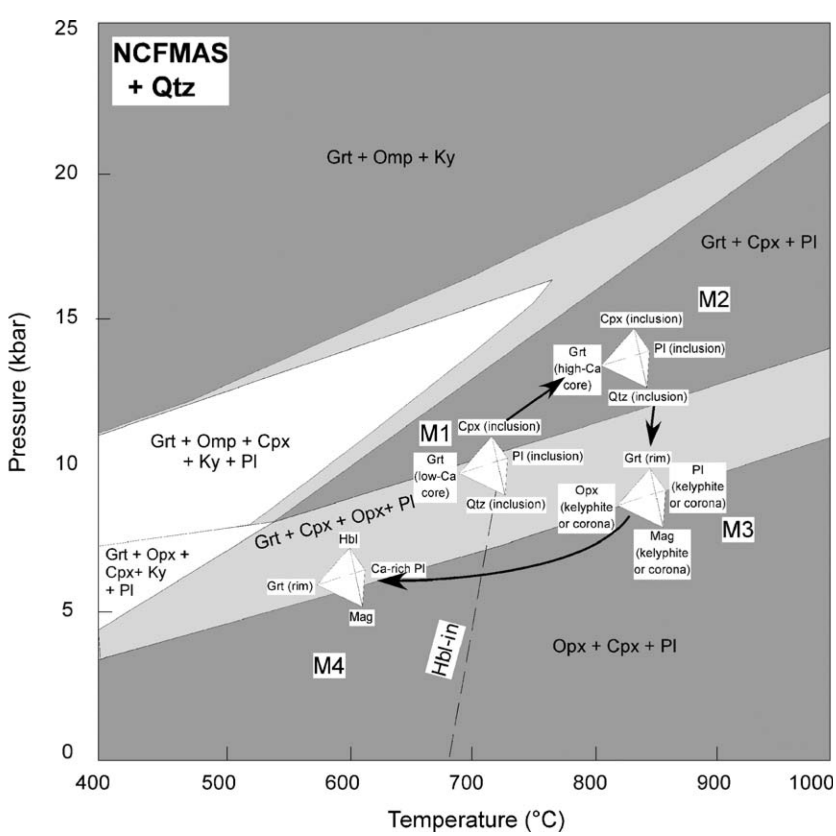

Fig. 10. Metamorphic P–T paths of high-pressure granulites from the Huai'an and Xuanhua Complexes (Modified after Guo et al., 2002).

The P–T path of these assemblages can be qualitatively defined by a P–T pseudosection of the NCFMAS grid of Holland and Powell (1998), with a low-temperature extension in order to take into account the hornblende+plagioclase symplectite assemblage (M_4) (Fig. 11). This NCFMAS (+quartz) grid was built up for a silica-saturated aluminous basalt bulk composition (wt.%, SiO_2=54.5, Al_2O_3=19.2, CaO=8.4, MgO=6.0, FeO=8.2, Na_2O=3.7) with less than 0.5% normative quartz. Compared with the chemical compositions of the Chengde high-pressure granulites, this model NCFMAS composition is higher in SiO_2, Al_2O_3 and Na_2O. Despite these compositional variations, the calculated P–T pseudosection of the NCFMAS grid shows a sequence of mineral assemblages similar to those observed in the Chengde high-pressure granulites, except for the presence of kyanite which is not present in the Chengde high-pressure granulites, probably because of their lower Al_2O_3 contents or relatively lower pressures. For example, the fields garnet+clinopyroxene+plagioclase, garnet+clinopyroxene+orthopyroxene+plagioclase, clinopyroxene+orthopyroxene+plagioclase and hornblende+plagioclase in the pseudosection, each of which is with quartz in excess, can be used to show the high-pressure granulite facies (M_1), medium-pressure granulite facies (M_2), low-pressure granulite facies (M_3) and amphibolite facies (M_4) assemblages in the Chengde high-pressure granulites, respectively (Fig. 11). Taken together, a clockwise P–T path has been qualitatively inferred according to the sequence of mineral assemblages in the Chengde high-pressure mafic granulites (Fig. 11). The quantitative P–T trajectory cannot be defined from this P–T pseudosection because of the lack of sufficient reactions and the difference between the model and actual chemical compositions.

4.4. Summary

Most high-pressure mafic granulites in the Trans-North China Orogen preserve the high-pressure granulite facies assemblage of garnet+plagioclase+clinopyroxene±quartz (M_1), medium-pressure granulite facies assemblage of garnet+plagioclase+clinopyroxene+orthopyroxene±quartz (M_2), low-pressure granulite facies assemblage of orthopyroxene+clinopyroxene+plagioclase±quartz (M_3), and amphibolite facies assemblage of hornblende+plagioclase (M_4). In addition, minor high-pressure granulites (e.g. those in the Hengshan Complex) preserve the early eclogite facies mineral assemblage of garnet+quartz+omphacite pseudomorphs (clinopyroxene+Na-rich plagioclase). These mineral assemblages and their thermobarometric estimates define clockwise P–T paths involving near-isothermal decompression and cooling following peak metamorphism (Figs. 9–11). The reconstructed P–T paths are compatible with a tectonothermal process characterized by initial crustal thickening, subsequent near-isothermal

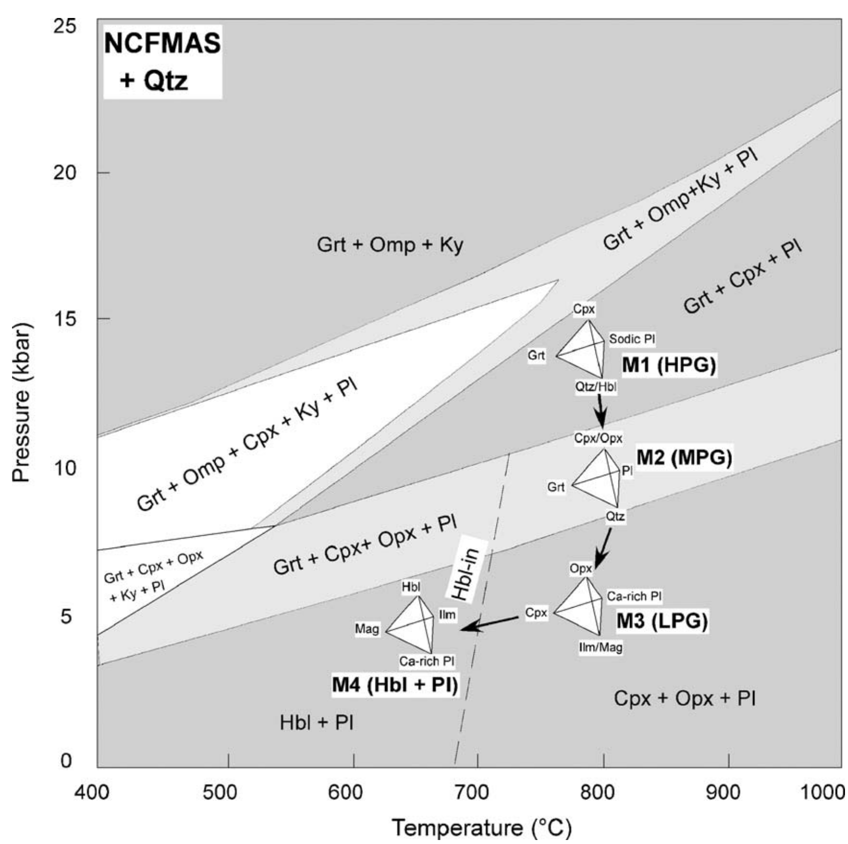

Fig. 11. P–T pseudosection for a portion of the NCFMAS system (after Holland and Powell, 1998) showing the qualitative P–T path of the Chengde high-pressure granulites constrained by the sequence of mineral assemblages. See text for details. Divariant fields are in white, trivariant fields in light grey, quadrivariant fields in dark grey. Mineral symbols are after Kretz (1983).

exhumation and final cooling, a sequence of tectonothermal events typical of continent–continent collision (England and Thompson, 1984; Thompson and England, 1984). Consequently, these high-pressure granulites are considered to have resulted from final collision between the Eastern and Western Blocks to form the coherent North China Craton. However, there is debate on when this collision occurred (Zhao et al., 2000a, 2001b, 2005, Li et al., 2000, Guo and Zhai, 2001; Guo et al., 2002; Liu et al., 2002a; Kusky and Li, 2003; Zhai and Liu, 2003; Zhai et al., 2003; Kröner et al., 2005, in press).

5. Protolith and metamorphic ages of the high-pressure granulites

As mentioned earlier, field data show that the precursors of the high-pressure mafic granulites in the Trans-North China Orogen are chiefly mafic dykes (Kröner et al., 2005, in press). The precise determination of protolith and metamorphic ages of the high-pressure granulites is critical to understanding when the final collision between the Eastern and Western Blocks occurred. Two contrasting views have been proposed as to the protolith and metamorphic ages of the high-pressure granulites in the orogen. One view proposes that the precursors of these high-pressure granulites formed in the Late Archean and underwent high-pressure granulite facies metamorphism and subsequent exhumation at ~2.5 Ga (Li et al., 2000; Kusky and Li, 2003). Another school of thought believes that the precursors of the high-pressure granulites were emplaced in the Paleoproterozoic and experienced high-pressure metamorphism and subsequent exhumation during a ~1.85 Ga collisional event that led to the final amalgamation of the North China Craton (Zhao et al., 2000a, 2001a,b, 2005; Wilde et al., 2002, Guo et al., 2001, 2002; Guo and Zhai, 2001; Kröner et al., 2005, in press). To resolve this controversy, extensive geochronological investigations on the high-pressure granulites and related rocks in the Trans-North China Orogen have been carried out in the last few years and numerous new data are now available (Mao et al., 1999; Chang et al., 1999; Guo et al., 2001, 2002, 2005; Guo and Zhai, 2001; Zhao et al., 2002; Guan et al., 2002; Kröner et al., 2005, in press). These new data now enable resolution of the protolith and metamorphic ages of the high-pressure granulites in the Trans-North China Orogen.

5.1. Protolith age of the high-pressure mafic granulites

Several geochronological studies attempted to resolve the age of emplacement of the mafic granulite precursors, but there is often disagreement as to whether the protolith age has been determined. Tian et al. (1992) reported two Sm–Nd whole-rock isochron ages for Hengshan high-pressure mafic granulites of 2851 ± 76 Ma and 2818 ± 86 Ma, which were interpreted as the protolith ages (Tian et al., 1992). However, Kröner et al. (2005) have demonstrated that the majority of gneisses in the Hengshan were emplaced between ~2500 and ~2520 Ma, and the mafic dykes that have been metamorphosed to high-pressure are clearly intrusive into these gneisses. Therefore, the Sm–Nd ages are too old to represent the protolith age of the high-pressure mafic granulites. Chang et al. (1994) have already noted this and pointed out that the individual Sm–Nd analyses come from samples of different dykes and yielded a combined 8-point isochron age of 2860 ± 135 Ma with $\varepsilon_{Nd(T)}$ of 6.1, a value which these authors considered too high. Chang et al. (1994) tentatively ascribed the anomalous values to a heterogeneous mantle source, but also considered crustal contamination as a potential contributing factor.

Most recently, the SHRIMP U–Pb zircon dating technique has been applied to determination of protolith and metamorphic ages of the Hengshan high-pressure mafic granulites (Kröner et al., in press; Guo et al., 2005). Kröner et al. (in press) dated two high-pressure granulite facies mafic dykes that include magmatic zircons with clear oscillatory zoning and yielded mean $^{207}Pb/^{206}Pb$ ages of 1915 ± 4 Ma and 1914 ± 2 Ma, respectively. These ages were interpreted as reflecting the time of emplacement of the gabbroic dykes (Kröner et al., in press). Excellent agreement in the rock-formation ages for the two mafic dykes leaves little doubt that the precursors (mafic dykes) of the Hengshan high-pressure granulites were emplaced at ~1915 Ma, much later than previously considered and only shortly before being subjected to high-pressure granulite facies metamorphism (see the following discussion). The protolith ages of high-pressure mafic granulites in the Huai'an, Xuanhua and Chengde Complexes have not been precisely determined, but the high-pressure granulite precursors in these complexes are assumed to have been emplaced coevally with those in the Hengshan Complex, since they have nearly same geological occurrence.

5.2. Timing of metamorphism of the high-pressure granulites

Several dating methods, including SHRIMP U–Pb metamorphic zircon and mineral Sm–Nd and $^{39}Ar/^{39}Ar$ techniques, have been applied to determining the timing of metamorphism of the high-pressure granulites in the Trans-North China Orogen (Mao et al., 1999; Chang et al., 1999; Guo et al., 2001, 2002, 2005; Guo and Zhai, 2001; Kröner et al., 2005, in press).

In the Hengshan Complex, SHRIMP and evaporation zircon studies, combined with cathodoluminescence images and U–Th chemistry, confirm the existence of both magmatic and metamorphic zircons in the high-pressure mafic granulites and Late Archean TTG gneisses (Kröner et al., 2005, in press). The metamorphic zircons occur as either overgrowth rims surrounding older magmatic zircon cores or as single grains that are structureless, highly luminescent and very low in Th and U contents. These features make them distinct from magmatic zircons, which are generally characterized by oscillatory zoning, low luminescence and comparatively high Th and U contents (e.g. Zhao et al., 2002, Kröner et al., in press). SHRIMP and evaporation zircon dating shows that the major TTG bodies in the Hengshan Complex were emplaced between 2.52 Ga and 2.48 Ga, whereas the emplacement of minor granitoid rocks continued through the early Paleoproterozoic, particularly at ~2360–2330 Ma, 2250 Ma and 2115 Ma (Kröner et al., 2005).

It is important to note that the granitoids emplaced at 2360–2330 Ma in the Hengshan Complex possess the same deformational features as the older gneisses and thus unambiguously demonstrate that the main deformational event is not Archean but Proterozoic in age (Kröner et al., 2005). Metamorphic zircons from two high-pressure granulite facies mafic dykes (with peak metamorphic P–T conditions of 13–15.5 kbar and 780–840 °C; Zhao et al., 2001a) yielded SHRIMP $^{207}Pb/^{206}Pb$ ages of 1850±3 Ma and 1867±23 Ma (Kröner et al., in press). Metamorphic zircons from another two high-pressure granulite facies mafic dykes were evaporated and produced mean $^{207}Pb/^{206}Pb$ ages of 1859.7±0.5 Ma and 1881.3±0.4 Ma (Kröner et al., in press), similar to the SHRIMP results. These data show that the high-pressure granulite facies metamorphic event in the Hengshan Complex occurred at ∼1.85 Ga. This conclusion is further supported by the metamorphic zircon ages of 1848±5 Ma and 1881±8 Ma obtained from the Hengshan granitoid gneisses (Kröner et al., 2005, in press).

Similar metamorphic ages have also been obtained from high-pressure granulites in other metamorphic complexes of the Trans-North China Orogen. In the Huai‘an Complex, Guo et al. (1993) obtained a garnet–clinopyroxene–orthopyroxene Sm–Nd isochron age of 1824±18 Ma and a U–Pb zircon age of 1833±23 Ma from the high-pressure mafic granulites, interpreted as the age of the high-pressure metamorphic event. More recently, Guo et al. (2005) obtained a SHRIMP U–Pb zircon of 1817±12 Ma for metamorphic zircons from the Huai‘an high-pressure granulites. In the Xuanhua Complex, Guo and Zhai (2001) obtained a garnet–pyroxene Sm–Nd isochron age of 1842±38 Ma from the high-pressure granulites, interpreted as the age of the high-pressure metamorphic event. Guo et al. (2005) also obtained SHRIMP U–Pb zircon ages of 1872±16 Ma and 1819±16 Ma from metamorphic zircons in the high-pressure mafic granulites of the Xuanhua Complex. In the Chengde Complex, Mao et al. (1999) obtained a zircon U–Pb lower intercept age of 1817±17 Ma from a high-pressure granulite, also interpreted as the age of the high-pressure metamorphic event. All these data indicate that the high-pressure metamorphic event in the Trans-North China Orogen occurred at about 1.85 Ga, not at ∼2.5 Ga as proposed by Kusky and Li (2003), supporting the model that the final amalgamation of the North China Craton was completed at ∼1.85 Ga (Zhao, 2001; Wilde et al., 2002; Zhao et al., 2001b, 2005; Kröner et al., 2005, in press).

6. Conclusions

Recent field mapping, metamorphic investigations and geochronology on the high-pressure granulites in the Trans-North China orogen have produced a large amount of new data which provide important insights into the tectonic setting and timing of the high-pressure granulite facies event. Major conclusions from these investigations are summarized as follows:

(1) Geological mapping has revealed that the high-pressure mafic granulites in the Trans-North China Orogen are mainly exposed along a northeast–southwest trending belt in the northern segment of the orogen, extending from the Hengshan Complex, through the Huai‘an and Xuanhua Complexes, into the Chengde Complex. Field evidence also reveals that the high-pressure granulites were derived from metamorphosed mafic dykes.

(2) Metamorphic investigations show that most high-pressure mafic granulites contain high-, medium- and low-pressure granulite facies and amphibolite facies assemblages. Minor high-pressure granulites preserve an early eclogite facies assemblage represented by symplectic clinopyroxene+sodic plagioclase after omphacite. These assemblages and their P–T calculations define a clockwise P–T path involving near-isothermal decompression and cooling following peak high-pressure metamorphism. This tectonothermal path is considered to record the collision between the Eastern and Western Blocks, which resulted in the final assembly of the North China Craton.

(3) Recent geochronological data indicate that the precursors (mafic dykes) of the high-pressure granulites in the Trans-North China Orogen were emplaced at ∼1915 Ma and underwent the high-pressure granulite facies event at ∼1.85 Ga, not at ∼2.5 Ga as some authors have proposed. All these data support the recently proposed tectonic model that the amalgamation of the Western and Eastern Blocks to form the North China Craton occurred at ∼1.85 Ga.

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References

Baba, S., 1998. Proterozoic anticlockwise P–T path of the Lewisian Complex of South Harris, Outer Hebrides, NW Scotland. Journal of Metamorphic Geology 16, 819–841.

Bai, J., 1986. The Precambrian crustal evolution of the Wutaishan area. In: Bai, J. (Ed.), The Early Precambrian Geology of Wutaishan. Tianjin Science and Technology Press, Tianjin, pp. 376–383 (in Chinese).

Bai, J., Dai, F.Y., 1998. Archean crust of China. In: Ma, X.Y., Bai, J. (Eds.), Precambrian Crust Evolution of China. Springer-Geological Publishing House, Beijing, pp. 15–86.

Baldwin, J.A., Bowring, S.A., Williams, M.L., 2003. Petrological and geochronological constraints on high pressure, high temperature metamorphism in the Snowbird tectonic zone, Canada. Journal of Metamorphic Geology 21, 81–98.

Bhowmik, S.K., Roy, A., 2003. Garnetiferous metabasites from the Sausar Mobile Belt: petrology, P–T path and implications for the tectonothermal evolution of the Central Indian Tectonic Zone. Journal of Petrology 44, 387–420.

Boven, A., Theunissen, K., Sklyarov, E., 1999. Timing of exhumation of a high-pressure mafic granulite terrane of the Paleoproterozoic Ubende belt (West Tanzania). Precambrian Research 93, 119–137.

Carswell, D.A., 1990. Eclogite Facies Rocks. Blackie, Glasgow.

Carswell, D.A., Brueckner, H.K., Cuthbert, S.J., Mehta, K., O'Brien, P.J., 2003. The timing of stabilisation and the exhumation rate for ultra-high pressure rocks in the Western Gneiss Region of Norway. Journal of Metamorphic Geology 21, 601–612.

Chang, X.Y., Zhu, B.Q., Fan, S.K., Xie, G.H., 1994. High abnormal εNd(T) value and its possible explanation on Archean mantle of northern Shanxi Province. Chinese Science Bulletin 39, 1351–1355.

Chang, X.Y., Chen, Y.D., Zhu, B.Q., 1999. U–Pb zircon isotope age of metabasites from Hengshan grey gneiss. Acta Mineralogica Sinica 19, 263–266 (in Chinese with English abstract).

Compston, W., Zhang, F.P., Foster, J.J., Collerson, K.D., Bai, J., Sun, D.Z., 1983. Rubidium–strontium geochronology of Precambrian rocks from the Yanshan Region, North China. Precambrian Research 22, 175–202.

Condie, K.C., Boryta, M.D., Liu, J.Z., Qian, X.L., 1992. The origin of khondalites–geochemical evidence from the Archean to early Proterozoic granulite belt in the North China Craton. Precambrian Research 59, 207–223.

Del Lama, E.A., Zanardo, A., Oliveira, M.A.F., Morales, N., 2000. Exhumation of high-pressure granulites of the Guaxupe Complex, southeastern Brazil. Geological Journal 35, 231–249.

Dirks, P.H.G.M., Zhang, J.S., Passchier, C.W., 1997. Exhumation of high-pressure granulites and the role of lower crustal advection in the North China Craton near Datong. Journal of Structural Geology 19, 1343–1358.

England, P.C., Thompson, A.B., 1984. Pressure–temperature–time paths of regional metamorphism: I. Heat transfer during the evolution of regions of thickened continental crust. Journal of Petrology 25, 894–928.

Ernst, W.G., 1988. Element partitioning and thermobarometry in polymetamorphic Late Archean and Early–Mid Proterozoic rocks from eastern Liaoning and southern Jilin Provinces, People's Republic of China. American Journal of Science 288-A, 293–340.

Ernst, W.G., 1989. Petrochemical comparison of 3.5 Ga old mafic amphibolite inclusions from eastern Hebei Province, with Archean mafic–ultramafic supracrustals of uncertain antiquity, southern Jilin/eastern Liaoning Provinces, China. Chinese Journal of Geochemistry 8, 97–111.

Ernst, W.G., Cao, R.L., Jiang, J.Y., 1988. Reconnaissance study of Precambrian metamorphic rocks, northeastern Sino-Korean shield, People's Republic of China. Geol.. Bulletin of the Geological Society of America 100, 692–701.

Ge, W.C., Zhao, G.C., Sun, D.Y., Wu, F.Y., Lin, Q., 2003. Metamorphic P–T path of the Southern Jilin complex: implications for tectonic evolution of the Eastern block of the North China Craton. International Geology Review 45, 1029–1043.

Guan, H., Sun, M., Wilde, S.A., Zhou, X.H., Zhai, M.G., 2002. SHRIMP U–Pb zircon geochronology of the Fuping Complex: implications for formation and assembly of the North China Craton. Precambrian Research 113, 1–18.

Guo, J.H., Zhai, M.G., 2001. Sm–Nd age dating of high-pressure granulites and amphibolites from Sanggan area, North China Craton. Chinese Science Bulletin 46, 106–111.

Guo, J.H., Zhai, M.G., Zhang, Y.G., 1993. early Precambrian Manjinggou high-pressure granulites melange belt on the southern edge of the Huaian Complex, North China Craton: geological features, petrology and isotopic geochronology. Acta Petrologica Sinica 9, 329–341.

Guo, J.H., Bian, A.G., Shi, X., 1996. High-pressure granulites, retrograded eclogites and granites in the early Precambrian Sanggan structural belt. In: Zhai, M.G. (Ed.), Granulites and Lower Continental Crust in the North China Craton. Seismological Press, Beijing, pp. 21–54.

Guo, J.H., Wang, S.S., Sang, H.Q., Zhai, M.G., 2001. Ar-40–Ar-39 age spectra of garnet porphyroblast: implications for metamorphic age of high-pressure granulite in the North China Craton. Acta Petrologica Sinica 17, 436–442.

Guo, J.H., O'Brien, P.J., Zhai, M.G., 2002. High-pressure granulites in the Sangan area, North China Craton: metamorphic evolution, P–T paths and geotectonic significance. Journal of Metamorphic Geology 20, 741–756.

Guo, J.H., Sun, M., Zhai, M.G., 2005. Sm–Nd and SHRIMP U–Pb zircon geochronology of high-pressure granulites in the Sanggan area, North China Craton: timing of Paleoproterozoic continental collision. Journal of Asian Earth Sciences 24, 629–642.

Halls, H.C., Li, J.H., Davis, D., Hou, G., Zhang, B.X., Qian, X.L., 2000. A precisely dated Proterozoic palaeomagnetic pole from the North China Craton, and its relevance to palaeocontinental reconstruction. Geophysical Journal International 143, 185–203.

Holland, T.J.B., Powell, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. Journal of Metamorphic Geology 16, 309–343.

Indares, A., 2003. Metamorphic textures and P–T evolution of high-P granulites from the Lelukuau terrane, NE Grenville Province. Journal of Metamorphic Geology 21, 35–48.

Jahn, B.M., Ernst, W.G., 1990. Late Archean Sm–Nd isochron age for mafic–ultramafic supracrustal amphibolites from the northeastern Sino-Korean Craton, China. Precambrian Research 46, 295–306.

Jahn, B.M., Zhang, Z.Q., 1984. Archean granulite gneisses from eastern Hebei Province, China: rare earth geochemistry and tectonic implications. Contributions to Mineralogy and Petrology 85, 224–243.

Jahn, B.M., Auvray, B., Cornichet, J., Bai, Y.D., Shen, Q.H., Liu, D.Y., 1987. 3.5 Ga old amphibolites from eastern Hebei Province, China: field occurrence, petrography, Sm–Nd isochron age and REE geochemistry. Precambrian Research 34, 311–346.

Kretz, R., 1983. Symbols for rock-forming minerals. American Mineralogist 68, 277–279.

Kröner, A., Compston, W., Zhang, G.W., Guo, A.L., Todt, W., 1988. Ages and tectonic setting of Late Archean greenstone–gneiss terrain in Henan Province, China, as revealed by single-grain zircon dating. Geology 16, 211–215.

Kröner, A., Cui, W.Y., Wang, W.Y., Wang, C.Q., Nemchin, A.A., 1998. Single zircon ages from high-grade rocks of the Jianping Complex, Liaoning Province, NE China. Journal of Asian Earth Sciences 16, 519–532.

Kröner, A., Wilde, S.A., Li, J.H., Wang, K.Y., 2005. Age and evolution of a Late Archaean to early Palaeozoic upper to lower crustal section in the Wutaishan/Hengshan/Fuping terrain of northern China. Journal of Asian Earth Sciences 24, 577–595.

Kröner, A., Wilde, S.A., Zhao, G.C., O'Brien, P.J., Sun, M., Liu, D.Y., Wan, Y.S., Liu, S.W., Guo, J.H., in press. Zircon geochronology of mafic dykes in the Hengshan Complex of northern China: evidence for late Palaeoproterozoic rifting and subsequent high-pressure event in the North China Craton. Precambrian Research.

Kusky, T.M., Li, J.H., 2003. Paleoproterozoic tectonic evolution of the North China Craton. Journal of Asian Earth Sciences 22, 23–40.

Li, J.H., Qian, Q.L., 1991. A study on the Longquanguan shear zone in the northern part of the Taihang Mountains. Shanxi Geology 6, 17–29 (in Chinese).

Li, J.H., Qian, X.L., 1994. The early Precambrian Crustal Evolution of Hengshan Metamorphic Terrain, North China Craton. Shanxi Science and Technology Press, Taiyuan.

Li, J.L., Wang, K.Y., Wang, C.Q., Liu, X.H., Zhao, Z.Y., 1990. An Early Proterozoic collision belt in the Wutaishan area, China. Scientia Geologica Sinica 25, 1–11 (in Chinese).

Li, S.Z., Yang, Z.S., Liu, Y.J., 1995. Paleoproterozoic tectonic framework of the eastern North China Craton. Journal of Changchun University of Science and Technology 25, 2514–2521 (in Chinese).

Li, S.Z., Yang, Z.S., Liu, Y.J., 1996. Preliminary analysis on the uplift-delamination structure of the Paleoproterozoic orogenic belt in Liaodong Peninsular, China. Journal of Changchun University of Science and Technology 26, 305–309 (in Chinese).

Li, J.H., Zhai, M.G., Li, Y.G., Zhan, Y.G., 1998. Discovery of Late Archean high-pressure granulites in Luanping–Chengde area, Northern Hebei Province: tectonic implications. Acta Petrologica Sinica 14, 34–41.

Li, J.H., Kröner, A., Qian, X.L., O'Brien, P., 2000. Tectonic evolution of an early Precambrian high-pressure granulite belt in the North China Craton. Acta Geologica Sinica 74, 246–258.

Li, S.Z., Han, Z.Z., Liu, Y.J., Yang, Z.S., 2001a. Geological and geochemical constraints on Paleoproterozoic pre-Orogenic deep processes in the Jiao-Liao Block. Scientia Geologica Sinica 36, 184–194.

Li, S.Z., Han, Z.Z., Liu, Y.J., Yang, Z.S., Ma, R., 2001b. Regional metamorphism of the Liaohe Group: implications for continental dynamics. Geological Review 47, 9–18.

Li, S.Z., Zhao, G.C., Sun, M., Wu, F.Y., Hao, D.F., Han, Z.Z., Luo, Y., Xia, X.P., 2005. Deformational history of the Paleoproterozoic Liaohe Group in the Eastern Block of the North China Craton. Journal of Asian Earth Sciences 24, 659–674.

Liu, D.Y., Nutman, A.P., Compston, W., Wu, J.S., Shen, Q.H., 1992. Remnants of 3800 crust in the Chinese part of the Sino-Korean Craton. Geology 20, 339–342.

Liu, S.W., Liang, H.H., Zhao, G.C., Hua, Y.G., Jian, A.H., 2000. Isotopic chronology and geological events of Precambrian complex in the Taihangshan region. Science in China, Series D 43, 386–393.

Liu, S.W., Pan, P.M., Li, J.H., Li, Q.G., Zhang, J., 2002a. Geological and isotopic geochemical constraints on the evolution of the Fuping Complex, North China Craton. Precambrian Research 117, 41–56.

Liu, S.W., Li, J.H., Pan, Y.M., Zhang, J., Li, Q.G., 2002b. An Archean continental block in the Taihangshan and Hengshan regions: constraints from geochronology and geochemistry. Progress of Nature Science 12, 568–576.

Liu, S.W., Pan, Y.M., Xie, Q.L., Zhang, J., Li, Q.G., 2004. Archean geodynamics in the Central Zone, North China Craton: constraints from geochemistry of two contrasting series of granitoids in the Fuping and Wutai Complexes. Precambrian Research 130, 229–249.

Liu, S.W., Pan, Y.M., Xie, Q.L., Zhang, J., Li, Q.G., 2005. Geochemistry of the Paleoproterozoic Nanying granitoid gneisses: constraints on the tectonic setting of the Central Zone, North China Craton. Journal of Asian Earth Sciences 24, 643–658.

Lu, L.Z., 1991. Metamorphic P–T–t path of the Archean granulite–facies terrains in Jining area, Inner Mongolia and its tectonic implications. Acta Petrologica Sinica 8, 1–12.

Lu, L.Z., Jin, S.Q., 1993. P–T–t paths and tectonic history of an early Precambrian granulite facies terrane, Jining district, southeastern Inner Mongolia, China. Journal of Metamorphic Geology 11, 483–498.

Lu, L.Z., Xu, X.C., Liu, F.L., 1996. early Precambrian Khondalite Series in North China. Changchun Publishing House, Changchun.

Mao, D.B., Zhong, C.T., Chen, Z.H., Lin, Y.X., Li, H.M., Hu, X.D., 1999. Isotopic ages and geological implications of high-pressure mafic granulites in the northern Chengde area, Hebei Province, China. Acta Petrologica Sinica 15, 524–534.

Möller, C., 1998. Decompressed eclogites in the Sveconorwegian (-Grenvillian) orogen of SW Sweden: petrology and tectonic implications. Journal of Metamorphic Geology 16, 641–656.

Möller, C., 1999. Sapphirine in SW Sweden: a record of Sveconorwegian (-Grenvillian) late-orogenic tectonic exhumation. Journal of Metamorphic Geology 17, 127–141.

Möller, A., Appel, P., Mezger, K., Schenk, V., 1995. Evidence for a 2 Ga subduction zone: eclogites in the Usagaran belt of Tanzania. Geology 23, 1067–1070.

O'Brien, P.J., 2001. Subduction followed by collision: Alpine and Himalayan examples. Physics of the Earth and Planetary Interiors 127, 277–291.

O'Brien, P.J., Rotzler, J., 2003. High-pressure granulites: formation, recovery of peak conditions and implications for tectonics. Journal of Metamorphic Geology 21, 3–20.

O'Brien, P.J., Walte, N., Li, J.H., 2005. The petrology of two distinct granulite types in the Hengshan Mts, China, and tectonic implications. Journal of Asian Earth Sciences 24, 615–627.

Pidgeon, R.T., 1980. Isotopic ages of the zircons from the Archean granulite facies rocks, Eastern Hebei, China. Geological Review 26, 198–207.

Rubie, D.C., 1990. Role of kinetics in the formation and preservation of eclogites. In: Carswell, D.A. (Ed.), Eclogite Facies Rocks. Blackie, Glasgow, pp. 111–140.

Smelov, A.P., Beryozkin, V.I., 1993. Retrograded eclogites in the Olekma granite–greenstone region, Aldan Shield, Siberia. Precambrian Research 62, 419–430.

Snoeyenbos, D.R., Williams, M.L., Hanmer, S., 1995. Archean high-pressure metamorphism in the western Canadian Shield. European Journal of Mineralogy 7, 1251–1272.

Song, B., Nutman, A.P., Liu, D.Y., Wu, J.S., 1996. 3800 to 2500 Ma crustal evolution in Anshan area of Liaoning Province, Northeastern China. Precambrian Research 78, 79–94.

Sun, M., Armstrong, R.L., Lambert, R.St.J., 1992. Petrochemistry and Sr, Pb and Nd isotopic geochemistry of early Precambrian rocks, Wutaishan and Taihangshan areas, China. Precambrian Research 56, 1–31.

Thompson, A.B., England, P.C., 1984. Pressure–temperature–time paths of regional metamorphism: II. Their influences and interpretation using mineral assemblages in metamorphic rocks. Journal of Petrology 25, 929–955.

Tian, Y.Q., 1991. Geology and Gold Mineralization of Wutai–Hengshan Greenstone Belt. Shanxi Science and Technology Press, Taiyuan.

Tian, Y.Q., Liang, Y.F., Fan Sikun, Zhu, B.Q., Chen, Y.W., 1992. Geochronology of the Hengshan Complex in special reference to Nd isotopic evolution. Geochimica 9, 255–264 (in Chinese with English abstract).

Wan, Y.S., Geng, Y.S., Shen, Q.H., Zhang, R.X., 2000. Khondalite series–geochronology and geochemistry of the Jiehekou Group in the Lüliang area, Shanxi Province. Acta Petrologica Sinica 16, 49–58.

Wang, R.M., Lai, X.Y., Dong, W.D., Ma, J., Tang, B., 1994. Some evidence for the Late Archean collisional belt in the western Hebei Province. In: Qian, X.L., Wang, R. (Eds.), Geological Evolution of the Granulite Terrains in the Part of the North China Craton. Seismological Press, Beijing, pp. 7–20.

Wang, K.Y., Li, J.L., Hao, J., Li, J.H., Zhou, S.P., 1996. The Wutaishan mountain belt within the Shanxi Province, Northern China: a record of Late Archean collision tectonics. Precambrian Research 78, 95–103.

Wang, K.Y., Li, J.L., Hao, J., Li, J.H., Zhou, S.P., 1997. Late Archean mafic–ultramafic rocks from the Wuatishan, Shanxi Province: a possible ophiolite melange. Acta Petrologica Sinica 13, 139–151.

Wang, Y.J., Fan, W.M., Zhang, Y., Guo, F., 2003. Structural evolution and $^{40}Ar/^{39}Ar$ dating of the Zanhuang metamorphic domain in the North China Craton: constraints on Paleoproterozoic tectonothermal overprinting. Precambrian Research 122, 159–182.

Wang, Y.J., Fan, W.M., Zhang, Y., Guo, F., 2004a. Geochemical, $^{40}Ar/^{39}Ar$ geochronological and Sr–Nd isotopic constraints on the origin of Paleoproterozoic mafic dikes from the southern Taihang Mountains and implications for the ca. 1800 Ma event of the North China Craton. Precambrian Research 135, 55–77.

Wang, Z.H., Wilde, S.A., Wang, K.Y., YU, L.J., 2004b. A MORB–arc basalt–adakite association in the 2.5 Ga Wutai greenstone belt: Late Archean magmatism and crustal growth in the North China Craton. Precambrian Research 131, 323–343.

Wilde, S.A., Cawood, P., Wang, K.Y., 1997. The relationship and timing of granitoid evolution with respect to felsic volcanism in the Wutai Complex, North China Craton. Proceedings of the 30th IGC. Precambrian Geology and Metamorphic Petrology 17, 75–88.

Wilde, S.A., Cawood, P.A., Wang, K.Y., 1998. SHRIMP U–Pb data of granites and gneisses in the Taihangshan–Wutaishan area: implications for the timing of crustal growth in the North China Craton. Chinese Science Bulletin 43, 144.

Wilde, S.A., Zhao, G.C., Sun, M., 2002. Development of the North China Craton during the Late Archaean and its final amalgamation at 1.8 Ga; some speculations on its position within a global Palaeoproterozoic Supercontinent. Gondwana Research 5, 85–94.

Wilde, S.A., Zhao, G.C., Wang, K.Y., Sun, M., 2004. First precise SHRIMP U–Pb zircon ages for the Hutuo Group, Wutaishan: further evidence for the Palaeoproterozoic amalgamation of the North China Craton. Chinese Science Bulletin 49, 83–90.

Wilde, S.A., Cawood, P.A., Wang, K.Y., Nemchin, A.A., 2005. Granitoid evolution in the Late Archean Wutai Complex, North China Craton. Journal of Asian Earth Sciences 24, 597–613.

Wu, C.H., Zhong, C.T., 1998. The Paleoproterozoic SW–NE collision model for the central North China Craton. Progr. Precambrian Research 21, 28–50 (in Chinese).

Wu, J.S., Geng, Y.S., Shen, Q.H., Wan, Y.S., Liu, D.Y., Song, B., 1998. Archean Geological Characteristics and Tectonic Evolution of China–Korea Paleo-Continent. Geological Publishing House, Beijing.

Wu, F.Y., Zhao, G.C., Wilde, S.A., Sun, D.Y., 2005. Nd isotopic constraints on the crustal formation of the North China Craton. Journal of Asian Earth Sciences 24, 523–545.

Zhai, M.G., Liu, W.J., 2003. Paleoproterozoic tectonic history of the North China Craton: a review. Precambrian Research 122, 183–199.

Zhai, M.G., Guo, J.H., Yan, Y.H., 1992. Discovery and preliminary study of the Archean high-pressure granulites in the North China. Science in China 12B, 1325–1330.

Zhai, M.G., Guo, J.H., Yan, Y.H., Li, Y.G., Han, X.L., 1993. Discovery of high-pressure basic granulite terrain in the North China Archean Craton and preliminary-study. Science in China, Series B 36, 1402–1408.

Zhai, M.G., Guo, J.H., Li, H.H., Yan, Y.H., Li, Y.G., 1995. Discovery of retrograded eclogites in the Archaean North China Craton. Chinese Science Bulletin 40, 1590–1594.

Zhai, M.G., Gong, B.L., Guo, J.H., Liu, W.J., Li, Y.G., Wang, Q.C., 2000. Sm–Nd geochronology and petrography of garnet pyroxene granulites in the northern Sulu region of China and their geotectonic implication. Lithos 52, 23–33.

Zhai, M.G., Guo, J.H., Li, Y.G., Liu, W.J., Peng, P., Shi, X., 2003. Two linear granite belts in the central–western North China Craton and their implication for Late Neoarchaean–Palaeoproterozoic continental evolution. Precambrian Research 127, 267–283.

Zhai, M.G., Guo, J.H., Liu, W.J., 2005. Neoarchaean continental evolution and tectonic history of the North China Craton: a review. Journal of Asian Earth Sciences 24, 547–561.

Zhang, J.S., Dirks, H.G.M., Passchier, C.W., 1994. Extensional collapse and uplift in a polymetamorphic granulite terrain in the Archean and Paleoproterozoic of North China. Precambrian Research 67, 37–57.

Zhao, G.C., 2001. Palaeoproterozoic assembly of the North China Craton. Geological Magazine 138, 87–91.

Zhao, G.C., Wilde, S.A., Cawood, P.A., Lu, L.Z., 1998. Thermal evolution of the Archaean basement rocks from the eastern part of the North China Craton and its bearing on tectonic setting. International Geology Review 40, 706–721.

Zhao, G.C., Cawood, P.A., Lu, L.Z., 1999a. Petrology and P–T history of the Wutai amphibolites: implications for tectonic evolution of the Wutai Complex, China. Precambrian Research 93, 181–199.

Zhao, G.C., Wilde, S.A., Cawood, P.A., Lu, L.Z., 1999b. Tectonothermal history of the basement rocks in the western zone of the North China Craton and its tectonic implications. Tectonophysics 310, 37–53.

Zhao, G.C., Wilde, S.A., Cawood, P.A., Lu, L.Z., 1999c. Thermal evolution of two types of mafic granulites from the North China Craton: implications for both mantle plume and collisional tectonics. Geological Magazine 136, 223–240.

Zhao, G.C., Cawood, P.A., Wilde, S.A., Lu, L.Z., 2000a. Metamorphism of basement rocks in the Central Zone of the North China Craton: implications for Paleoproterozoic tectonic evolution. Precambrian Research 103, 55–88.

Zhao, G.C., Wilde, S.A., Cawood, P.A., Lu, L.Z., 2000b. Petrology and P–T path of the Fuping mafic granulites: implications for tectonic evolution of the central zone of the North China Craton. Journal of Metamorphic Geology 18, 375–391.

Zhao, G.C., Cawood, P.A., Wilde, S.A., Lu, L.Z., 2001a. High-pressure granulites (retrograded eclogites) from the Hengshan Complex, North China Craton: petrology and Tectonic implications. Journal of Petrology 42, 1141–1170.

Zhao, G.C., Wilde, S.A., Cawood, P.A., Sun, M., 2001b. Archean blocks and their boundaries in the North China Craton: lithological, geochemical, structural and P–T path constraints and tectonic evolution. Precambrian Research 107, 45–73.

Zhao, G.C., Wilde, S.A, Cawood, P.A., Sun, M., 2002. SHRIMP U–Pb zircon ages of the Fuping Complex: implications for accretion and assembly of the North China Craton. American Journal of Science 302, 191–226.

Zhao, G.C., Sun, M., Wilde, S.A., 2003. Major tectonic units of the North China Craton and their Paleoproterozoic assembly. Science in China, Series D 46, 23–38.

Zhao, G.C., Sun, M., Wilde, S.A., Li, S.Z., 2005. Late Archean to Paleoproterozoic evolution of the North China Craton: key issues revisited. Precambrian Research 136, 177–202.