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Neoarchean to Paleoproterozoic continental evolution and tectonic history of the North China Craton: a review

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Abstract

Rocks of Archean age are widely distributed in the North China Craton (NCC) and can be divided into high-grade regions and granite-greenstone belts, even though most underwent amphibolite to granulite facies metamorphism. Quartzo-feldspathic gneisses occupy 70 to 85% of the total exposure of Archean rocks in the craton. Supracrustal rocks commonly consist of intercalated volcano-sedimentary rocks, including metabasites, meta-intermediate to acid rocks, banded iron formations, metapelites and minor marbles. The oldest rocks outcrop over a small area of $\sim 4\ km^2$ and are a quartzite–amphibolite sequence that yield 3.8–3.5 Ga isotopic ages. Chemical and geochronological data constrain the earliest main crust-forming episode at ca. 2.9–2.7 Ga, when most rocks were metamorphosed to upper amphibolite or granulite facies at moderate pressures. Mafic granulites can be classified into two textural types, referred to as near-isobaric cooling (IBC) and near-isothermal decompression (ITD) types. High-pressure granulites and retrograded eclogites occur mainly near the junction of the provinces of Hebei, Shanxi and Inner Mongolia in the central NCC, and in eastern Shandong Province of the eastern NCC, as well as locally in Henan Province in the southern NCC. These high-pressure rocks show clockwise P–T paths, indicating decompression from >14 kb to 5–6 kb. An exposed section, interpreted as representing Precambrian continental lower crust has also been identified in the northern part of the craton. Although some mafic–ultramafic metamorphic rocks have been interpreted as remnants of ancient oceanic crust and mantle by a number of geologists, geochemical and petrological evidence demonstrates that many supracrustal/orthogneiss associations have island arc affinities. Therefore, several tectonic models have been proposed, including continent–continent collision and island arc terrain accretion achieved by arc–arc or arc–microcontinent collision. The NCC underwent multiple high-grade metamorphic events of which the two most important took place during the intervals 2600–2450 Ma and 1950–1750 Ma, which are considered to be related to early Precambrian supercontinental cycles.

Keywords: North China Craton; Archean; Tectonic evolution

1. Introduction

The North China Craton (NCC) is the Chinese portion of what has also been referred to as the Sino-Korean Craton, and encompasses nearly all of the North China Plateau, a part of northeastern China and the northern portion of the Korean peninsula (Zhai, 1997). Early Precambrian rocks crop out extensively and constitute the metamorphic basement of the craton (Fig. 1). Proterozoic, Paleozoic and younger rock sequences partially cover this basement and Zhao et al. (1993) have referred to the whole sequence as the Sino-Korean Paraplatform. Nearly all Archean rocks in the NCC underwent high-grade metamorphism at amphibolite or granulite facies and these high-grade rocks commonly have a multi-stage metamorphic history. For example, upper amphibolite and granulite facies rocks are commonly overprinted by low- to mid-amphibolite facies assemblages. Isotopic data from the NCC are mainly concentrated in two age ranges: 2600–2450 Ma and 1950–1750 Ma, representing the two most important tectonothermal events in the craton (Zhai et al., 2000; Zhao et al., 2001a).

The oldest supracrustal rocks and orthogneisses are located at Caozhuang in eastern Hebei Province (Fig. 2) and near Tiejiashan in Liaoning Province (Fig. 1) (Liu et al., 1994; Huang et al., 1983; Jahn and Zhang, 1984). The main supracrustal rocks are amphibolites, fuchsite quartzites, banded magnetite quartzites, diopsidites and serpentinized

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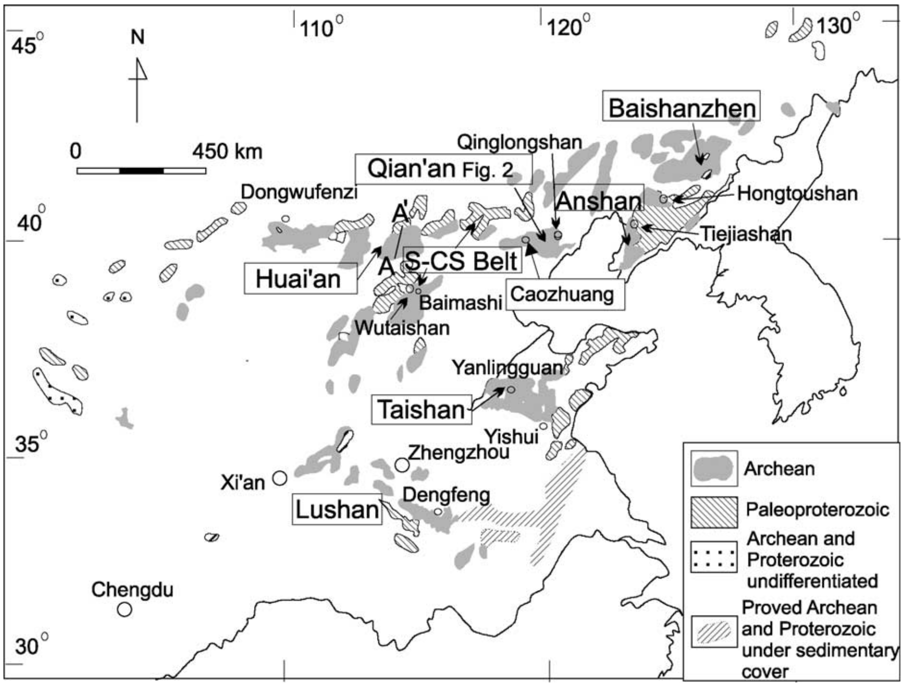

Fig. 1. Distribution of Archean and Paleoproterozoic rocks in the NCC S-CS Belt is Sanggar-Chengde structural belt. The location of Fig. 2 is also indicated.

marbles. The protoliths of the amphibolites were probably basalts and diabases, which yield whole rock Sm–Nd isochron ages of ~3.5 Ga. Based on geochemistry, the protoliths of the fuchsite quartzites and diopsidites have been considered to be clastic sedimentary rocks and evaporates, respectively, deposited in a continental or shoreline environment (Yan et al., 1991; Yan and Wu, 2002). Zircons from fuchsite quartzite have ages up to ~3.8 Ga. Some tonalitic and granitic gneisses with ages of 3.3–3.0 Ga are locally exposed in East Hebei and near Anshan, probably representing parts of ancient continental nuclei (Deng et al., 1999). These old gneisses were strongly migmatized, reworked and intruded by younger granite sills. Most metabasites formed between ~2900 and 2700 Ma, although some did not form until the end of the Neoarchean (Wan et al., 1998). Therefore, the main period of crustal growth was early Neoarchean (Zhang et al., 1998; Wan et al., 1998). The 2900–2700 Ma granitoid rocks are trondhjemitic or granitic in composition, and their formation was related to volcano-magmatic events. Granites and charnockites formed between 2600 and 2450 Ma and are commonly the products of crustal melting related to late Neoarchean metamorphic events (Geng, 1998a).

Recently, many geochemical, geochronological, structural and metamorphic studies have been carried out and great advances have been made, including: discovery of high-temperature and high-pressure metamorphic rocks; determination of two textural types of mafic granulite facies

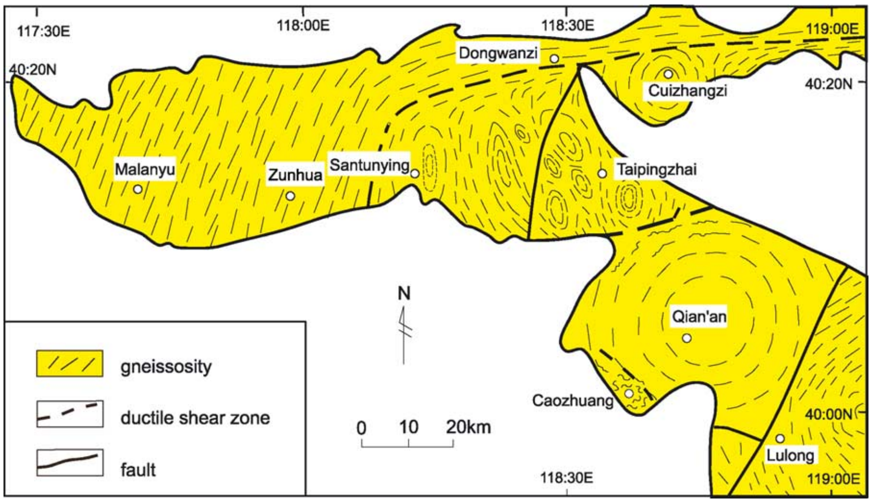

Fig. 2. Simplified sketch map of the Archean geology of Eastern Hebei.

rocks with different *PT* paths; subdivision of the NCC into geological terrains (for example, old island arc and ophiolite complexes); leading to establishment of Archean continental evolution and reconstruction of Precambrian plate tectonic settings. Some of these advances have been reflected in recent publications by Zhao et al. (1998, 1999a, 1999b, 2000a, 2000b, 2001a) and other authors. However, many more papers published in Chinese remain unknown to the wider geological community. This paper provides an overview of these and other studies on Neoarchean continental evolution and the tectonic history of the NCC, based on both published literature and our own studies.

2. Geological rock units and terrains

2.1. Rock units

Three major types of basement rocks occur in the NCC:

Supracrustal rocks: commonly consist of intercalated volcano-sedimentary sequences at amphibolite to granulite facies and include mafic two-pyroxene granulites or amphibolites, intermediate to felsic granulites, fine- to medium-grained gneisses, banded iron formations (BIFs), metapelites, and minor marbles, mica quartzites and mica schists. BIFs are common in the supracrustal sequences, with Sm–Nd whole rock isochron ages ranging from 3.5 Ga to 2.5 Ga, and they are closely associated with amphibolites or mafic granulites (Zhai and Windley, 1990). The Hongtoushan Group in northern Liaoning Province, NE China (Fig. 1), is at amphibolite facies and does not contain BIF, but comprises cyclical basic–intermediate–acidic volcanics and sediments with Cu–Zn massive sulfide ores. The Lushan Group in central Henan Province (Fig. 1) is composed predominantly of metasediments, including garnet–sillimanite gneisses, graphite-bearing gneisses, marbles and quartz–mica schists.

Orthogneisses: quartzo-feldspathic gneisses at amphibolite to granulite facies are the dominant rock unit and constitute between 70 and 85% of the exposed Archean rocks in the NCC. The most common type contains plagioclase, K-feldspar, quartz, biotite and/or hornblende, with or without hypersthene and garnet. Based on petrology and geochemistry, orthogneisses can be divided into two series: the trondhjemitic–tonalitic–granodioritic (TTG) series and the granitic–monzonitic series. The TTG gneisses commonly lack sharp contacts with the supracrustal rocks and some gneisses are banded or intercalated with amphibolites. These are the result of deformation involving only a minor component of supracrustal rocks (Zhang et al., 1985). The TTG gneisses have generally experienced strong migmatization, a characteristic of lower crustal reworking (Ernst et al., 1988; Zhao et al., 1993; Shen et al., 1992). The granitic–monzonitic gneisses include anatectic granites and granite sills. Some of them display clear intrusive contacts with other rocks and commonly have a weak to strong gneissic structure.

Metamorphosed ultramafic to mafic bodies: occur as thin layers of pyroxene amphibolite or mafic granulite within orthogneisses. These have been recognized as tectonic lenses of deformed and metamorphosed layered mafic igneous bodies (Zhang, 1986; Zhai and Yang, 1988). Most metamorphosed layered igneous bodies are part of gabbroic–ultramafic complexes, similar to those on the Scourian mainland in northwestern Scotland (Sills et al., 1982). Archean layered anorthosite–gabbro complexes that are commonly seen in other cratons are absent in the NCC. Mafic dykes are locally present in the NCC and show different deformation and metamorphic histories and three discrete age populations: >2650 Ma, 2550–2450 Ma, and 1800–1700 Ma (Zhao et al., 1993), corresponding with the main tectonic episodes identified in the evolution of the NCC.

2.2. High-grade terrains and greenstone belts

Archean cratons around the world contain two types of terrains: high-grade gneiss terrains and greenstone belts dominated by low-grade metamorphosed volcanics. The NCC also contains these two types, although nearly all rocks underwent metamorphism at amphibolite or granulite facies.

High-grade terrains: high-grade granulites and gneisses are extensively developed in the NCC. The high-grade terrains include the Baishanzhen and Anshan terrains in NE China, the Qian'an terrain in East Hebei, the Taishan terrain in Shandong, the Huai'an terrain at the junction of Hebei–Shanxi–Inner Mongolia and the Lushan terrain in central Henan (Fig. 1). The relationship between greenstone belts and high-grade terrains is not clear and both were intruded by later granitic bodies, now gneisses and charnockites. The high-grade terrains are composed of orthogneisses (80–90%), meta-gabbros (5–10%) and slabs of supracrustal rocks (10–15%), accompanied by strong and complex deformation. The supracrustal rocks comprise mafic granulites/amphibolites, BIFs and medium-grained biotite gneisses, their chemistry consistent with derivation from slate-greywacke and intermediate to acid volcanics (Sills et al., 1987). The Qian'an terrain is at granulite facies and the Anshan terrain is at amphibolite facies. Both are characterized by abundant BIFs, although BIFs are generally uncommon in other high-grade regions of the NCC. Field relations and geochemistry show that these BIF-bearing supracrustal terrains and associated intrusions have been produced by subduction-related processes, with early arcs and back-arc basins engulfed by later plutonic rocks developed at active continental margins (Zhai and Windley, 1990; Windley, 1995).

Greenstone belts: can be either at greenschist or amphibolite facies in the NCC (Zhai and Windley, 1990; Windley, 1995). The main greenstone belts are located at

Yanlingguan in western Shandong, Dengfeng in central Henan, Dongwufenzi in Inner Mongolia, Wutaishan in Shanxi, Qinglong in Eastern Hebei, and Qingyuan (Hongtoushan) in NE China. The first three of the aforementioned belts formed between 2900 and 2700 Ma and are composed of bimodal volcanic and sedimentary rocks metamorphosed to amphibolite facies. Mafic rocks are mainly amphibolites, hornblendites and pyroxenites, which are tholeiitic in composition. Most rocks exhibit slight LREE enrichment and others have flat or LREE depleted patterns (Zhai, 1991; Wan et al., 1998). Some hornblendites and pyroxenites are similar to basaltic komatiites in chemistry, but typical spinifex texture is lacking, possibly because of metamorphic recrystallization. The sedimentary rocks include BIFs, metapelites and/or marbles. The latter three greenstone belts mentioned above formed in the late Neoarchean at ~2550 Ma (Zhai, 1997; Zhao et al., 1999a; Geng, 1998a). The volcanic rocks range in composition from basalt, through andesite, to rhyolite and show geochemical characteristics of island arc association. The BIFs in the Wutaishan greenstone belt constitute an industrial deposit, whilst the Qingyuan greenstone belt contains a Cu–Zn massive sulfide deposit with only a few BIFs.

2.3. Remnants of ancient oceanic crust and island arcs

Oceanic crust: the recognition of Archean ophiolites would be highly significant because it would indicate that Phanerozoic-style plate tectonic processes can be extrapolated back to the Archean. Li (1982) first reported possible Paleoarchean oceanic crust (now at granulite facies) at Taipingzhai in Eastern Hebei (Fig. 2), which includes ultramafic–mafic volcanic rocks, BIFs, mafic dykes, metagabbros and serpentinites. However, detailed investigations in the area appear to disprove this view. The ultramafic–mafic rocks with high REE abundance show different geochemical characteristics, ranging from MORB to komatiite. Furthermore, supracrustal rocks, gabbros and mafic dykes yield different Sm–Nd whole rock isochron ages; at ~2.7 Ga (Li, 1999), ~2.5 Ga (Jahn and Zhang, 1984) and ~1.8 Ga (Li, 1999), respectively. Other mafic–ultramafic associations in the NCC have been studied in detail to test if ophiolites may be represented, including the metamorphosed mafic rocks in the Yanlingguan greenstone belt, amphibolites with apparent pillow-lava texture in the Qinglong greenstone belt and ultramafic–mafic rock associations in the Jiangouhe complex of northwest Hebei. Most researchers concluded that these rock associations do not represent remnants of ancient oceanic crust and mantle. Kusky et al. (2001) have recently suggested that metamorphic rocks exposed in southern Kuanping, Eastern Hebei, are an Archean ophiolite, and that an ultramafic–mafic body at Dongwanzi (Fig. 2) represents 2505 Ma old oceanic mantle. Zhai et al. (2002) argued that the so-called Archean ophiolite is a composite body of lithologies ranging from late Archean to Proterozoic, or even Mesozoic, in age. The rocks with different ages are separated by Mesoproterozoic cover or juxtaposed by faults. The Dongwanzi ultramafic body was earlier regarded as an early Mesozoic ultramafic intrusive, with zircon U–Pb ages ranging from 320 to 280 Ma, and components of the Mesoproterozoic Changcheng–Jixian System (pers. com., Brian Windley). Hornblendite dykes in the Dongwanzi body do not have sheeted dyke characteristics, as reported by Kusky et al. (2001). Recently, Li et al. (2002) reported that serpentinite lenses in the Neoarchean Zunhua complex in Eastern Hebei (Fig. 2) contain podiform chromites, and suggested that these lenses represent an Archean ophiolite mèlange belt extending from Eastern Hebei to western Liaoning, with a total length of >2000 km. Alternatively, Zhang et al. (2003) argued that these chromites in serpentinite lenses are enriched in Fe and Cr, and are not related to an oceanic mantle/ophiolite sequence. The attempt to identify Archean ophiolite in the North China Craton is nonetheless significant, but will not be resolved until considerably more detailed work is undertaken.

Island arcs: the Archean high-grade orthogneiss-dominant regions and some greenstone belts in the NCC are petrologically and geochemically comparable to modern island arcs or roots of Andean-type arcs (Windley, 1984, 1995; Wan et al., 1998; Zhao et al., 1999a; Wang et al., 1997). The Hongtoushan and Wutaishan greenstone belts have been considered as island arc terrains (Zhai and Windley, 1990; Windley, 1995; Zhao et al., 1999a; Kröner et al., 2004). However, the remainder of the NCC is not well constrained in terms of its early Precambrian tectonic evolution. Further study on the geological relationships between ancient island arc systems is therefore a key to understanding the Archean tectonics of the craton.

As an example of high-grade metamorphic complexes, the Archean rocks of Eastern Hebei have been extensively studied in recent years (Geng, 1998a, 1998b; Wu et al., 1998; Li, 1999; Zhai and Liu, 2001). The region comprises three litho-tectonic units: the Paleoarchean Caozhuang complex, the Mesoarchean Qian'an complex and the Neoarchean Zunhua complex (Fig. 2). The Caozhuang complex is the oldest terrain and contains the earliest sialic crust in the NCC. It only occupies ~4 km^2 and is covered by Quaternary sediments in the east and by the Mesoproterozoic Changcheng System and Paleoproterozoic Lulong Group to the west and south, respectively. To the north, the Caozhuang complex is in contact with the Qian'an complex along a ductile shear zone that shows evidence of multiple deformation, with the Caozhuang complex considered to be thrust over the Qian'an complex (Li et al., 1980; Zhao et al., 1993). The Caozhuang complex includes supracrustal rocks at upper amphibolite facies (the Caozhuang Group) and tonalitic gneisses (Huangboyü gneiss). The Caozhuang Group is composed of thin layers of metavolcanic (30–53%) and sedimentary (65–70%) rocks, which were metamorphosed to amphibolites, BIFs, serpentine marbles, fuchsite quartzites and some tremolites and diopsidites. Geochemically, the protoliths of amphibolites and tremolites are tholeiitic or komatiitic. The amphibolites do not show high REE abundance but do have slightly enriched LREE patterns, and their contents of Cr (~226 ppm), Ni (~144 ppm) and MgO (up to 9.44%) are also high. These basalts were possibly derived from large-scale mantle melting (Sun and Nesbitt, 1977). The Huangboyü tonalitic gniesses underwent complex deformation and have zircon U–Pb ages of 3.4–3.2 Ga (Zhao et al., 1993). The Caozhuang complex is similar in its rock association and chemistry to Meso-Neoarchean high-grade complexes in Eastern Hebei (Li et al., 1980; Wang et al., 1985; Zhao et al., 1993). Zhai and Liu (2001) suggested that this early sialic crust was possibly an old arc related to subduction of intra-oceanic crust. The Qian'an complex occurs as a dome with an area of ~700 km^2 (Fig. 2) and has traditionally been termed the Qian'an migmatite–gneiss uplift terrain (Qian et al., 1985). It is unconformably overlain by the Mesoproterozoic Changcheng System and Mesozoic rocks along its western and north-eastern margins, respectively. Its northern boundary is a fault that separates the complex from the Neoarchean Zunhua terrain. Tonalitic–granodioritic orthogneisses and migmatites occupy the center of the complex and meta-supracrustal rocks commonly occur as complicated folded slabs along the margins, especially the western and northern margins. The main supracrustal rocks are mafic granulites, pyroxene amphibolites, pyroxene-bearing biotite plagioclase gneisses, and minor garnet–sillimanite gneisses and garnet-bearing fayalite peridotites. Abundant BIFs constitute some of the most important iron deposits in China. The supracrustal rocks underwent metamorphism at moderate pressure granulite facies. The supracrustal rocks and intrusive granitic sills have Sm–Nd and U–Pb zircon ages of 3280–3049 Ma (Geng, 1998b). The Qian'an complex is considered to be a typical example of an old island arc complex based on its rock association, deformation and geochemistry (Sills et al., 1987; Wang et al., 1985; Windley, 1995). However, granitic and charnockitic bodies occurring along the northern margin yield much younger U–Pb zircon ages of 2647–2495 Ma (Liu et al., 1990; Zhao et al., 1993).

The Zunhua terrain can be divided into two parts: the Zunhua unit at upper amphibolite facies (locally granulite facies) and the Taipingzhai unit at granulite facies (Li, 1999) (Fig. 2). The Zunhua unit occurs as NE–E trending strata and mainly comprises supracrustal sequences with some granitoid sills. The Taipingzhai unit occurs as domes with complicated fold patterns and mainly comprises magmatic rocks and some lenses of supracrustal rocks. The supracrustal rocks in both units are almost identical in terms of geochemistry, rock association and metamorphic history. The main rock types include amphibolites, two pyroxene granulites, biotite felsic gneisses/intermediate-acid granulites and BIFs (He et al., 1991). Meta-volcanic rocks demonstrate an evolving trend from basaltic, through andesitic, to rhyolitic types, and have geochemical features similar to modern island arc volcanic rocks (Zhai, 1991; Wan et al., 1998; Li, 1999). Sm–Nd isochron ages for mafic rocks from Zunhua and Taipingzhai are 2591 ± 142 Ma and 2644 ± 112 Ma, respectively (Li, 1999). The metamorphic texture of the mafic granulites is characterized by clinopyroxene surrounded by small garnets, defining an anticlockwise *PT* path (Fig. 3, after Li, 1999). The Taipingzhai unit comprises tonalitic granulites and some meta-gabbros (mafic granulites) and their Rb–Sr and Sm–Nd isochron ages are 2470 ± 70 Ma and 2480 ± 125 Ma, respectively (Jahn and Zhang, 1984; Jahn, 1990). Therefore, Li (1999) and Zhai and Liu (2001) suggested that the Zunhua and Taipingzhai units jointly constitute a Neoarchean island arc terrain, representing the upper part and root part, respectively. The Eastern Hebei high-grade region is mainly composed of three ancient island arc terrains that formed during the Paleoarchean, Mesoarchean and Neoarchean. This seems to indicate a tectonic process of island arc accretion achieved by arc–arc or arc–micro-continent collision (Zhai and Liu, 2001).

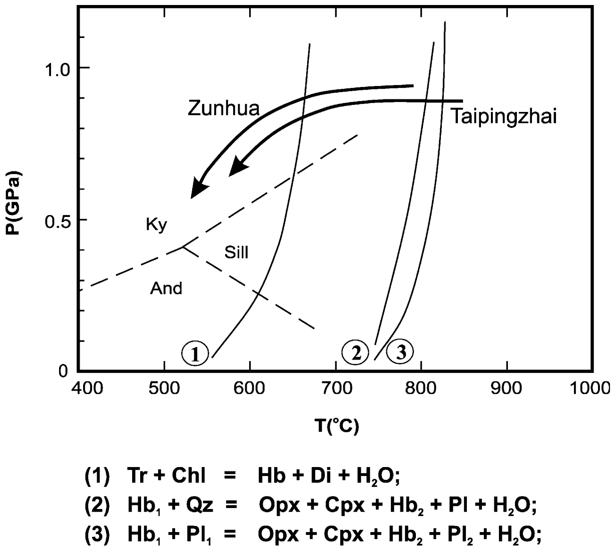

Fig. 3. *P–T* path for mafic rocks in the Zunhua complex (after Li, 1999).

3. Metamorphism, including high-pressure and high-temperature rocks

3.1. Metamorphism

Cheng and Zhang (1982) divided Archean metamorphism of the NCC into two metamorphic events: an older granulite facies event and a younger amphibolite facies event, with the former occurring in the Paleo-Mesoarchean and the latter at the end of the Neoarchean. The metamorphic history of Archean rocks in the NCC is, in fact, more complicated than this. Detailed studies show that some Archean rocks underwent two high-grade metamorphic events (granulite and upper amphibolite to granulite facies) at >2.7 Ga and ~2.5 Ga, respectively. All early Precambrian rocks underwent a later metamorphic overprint of low- to mid-amphibolite facies (Zhao et al., 1993). Granulite facies rocks are well exposed along the eastern and southern margin of the NCC, but are especially well-developed along the northern margin. The *P–T* conditions of most granulite facies rocks are moderate or moderate-low pressure and high temperature (Shen et al., 1992; Zhao et al., 1993; Lu et al., 1995). Typical mineral assemblages are: (1) mafic granulite: hypersthene (Hy) + diopside (Di) + plagioclase (Plg) ± hornblende (Hb) + quartz (Qtz); Hy + Hb + Plg; Hy + Di + Plg; (2) intermediate-acid granulite: biotite (Bi) + Hy + Qtz + Plg ± microcline (Mc); Bi + Hy + Grt + Plg ± Mc + Qtz; Hb + Bi + Plg + Qtz ± Mc; (3) BIF: magnetite (Mt) + Qtz + Hy ± Di ± Plg; Mt + Qtz + olivine (Ol) + Hy; Mt + Qtz + Hy + Hb; (4) meta-sedimentary rock: sillimanite (Sill) + Grt + K-feldspar (Kf) + Bi + Qtz; Sill + Grt + Plg + graphite (Grph) + Bi; Grt + Grph + Bi + Kf + Qtz; Sill + Grt + Kf + Plg + Bi ± Qtz; Grt + Hb + Bi + Plg; cordierite (Cord) + Sill + Grt + Bi + Plg ± Qtz; Qtz + Grt ± Sill. Shen et al. (1992) summarized numerous *P–T* estimates and indicated that the peak metamorphic *P–T* ranges for typical granulite complexes in the NCC are similar. The estimated metamorphic pressures and temperatures of granulites are 6.5–8 kbar and 750–850 °C in Eastern Hebei, 7–8 kbar and 740–840 °C in the area near the junction of Hebei–Shanxi Inner Mongolia, 5–7 kbar and 700–750 °C in Huadian, NE China, and 4–7 kbar and 650–810 °C in central-western Inner Mongolia. Shen et al. (1992) reported that their metamorphic ages are 2.6–2.5 Ga.

3.2. High-pressure and high-temperature rocks

High-pressure mafic granulites and retrograded eclogites were discovered in 1992 and 1995, respectively (Zhai et al., 1992, 1995). They occur within granitoid gneisses that commonly underwent strong deformation and mylonitization. The high-pressure rocks occur in two ways: (1) as long, flat tectonic slabs at the northern boundary of the Sanggan–Chengde structural belt (S–CS Belt in Fig. 1) (Guo et al., 1993; Li et al., 1994). Here, the high-pressure granulite layers are interdeveloped with two-pyroxene mafic granulites and intermediate to acid (tonalitic) granulites; for example, at Manjinggou, NW Hebei. They are locally sheared and mylonitized; (2) as enclosures or lenses within tonalitic gneisses, migmatites and granites, distributed throughout the S–CS Belt. The enclosures are normally several meters to more than ten meters long, and commonly occur in groups. Locally, tens of different size enclosures occur in narrow belts, for example, at Baimashi in northern Shanxi. The typical mineral assemblages of the high-pressure mafic rocks are clinopyroxene (Cpx) + Grt ± Plg + Qtz + rutile, Cpx + Grt + Hb + Plg ± Qtz and Cpx + orthopyroxene (Opx) + Grt + Plg ± Qtz. The garnets are surrounded by a symplectite of fine-grained Opx + Cpx + Plg, indicating decompression. The high-pressure rocks also underwent a strong metamorphic overprint in the amphibolite facies and, as a result, some mafic granulites have been completely or partially retrogressed to amphibolites. Liu et al. (1996) suggested two metamorphic epochs of high-pressure granulite facies in the NCC and several geochronological methods have been used to determine the age of these events. The data concentrate in two ranges: from 2640 to 2510 Ma and 1850–1770 Ma. Therefore, the timing of high-pressure metamorphism is still controversial, with one interpretation that the age of high-pressure metamorphism is ~2.5 Ga and the age of moderate-pressure granulite facies is ~1.8 Ga, as indicated by symplectite minerals (Guo et al., 2005; Zhang et al., 1996; Hu et al., 1999; Mao et al., 1999; Li et al., 2000). The other interpretation is that the age of high-pressure metamorphism is ~1.8 Ga and that the protolith age is ~2.5 Ga (Zhao et al., 2000a, 2000b, 2001b; Guo et al., 2001, 2002; Kröner et al., 2001). Zhai and Liu (2003) suggested that there are two kinds of HP rocks in the NCC, with the Neoarchean one representing lower crust (Zhai et al., 2001) and the Paleoproterozoic one representing the products of a collisional event (Zhao, 2001; Zhao et al., 2001b; Guo et al., 2002).

3.3. Two textural types of mafic granulite

Garnet-bearing mafic granulites from the NCC can be divided into two textural types, referred to as near-isobaric cooling (IBC) type and near-isothermal decompression (ITD) (Jin and Li, 1996; Zhao et al., 1999b).

The IBC-type mafic granulites characteristically display garnet + quartz symplectic coronas surrounding clinopyroxene or hornblende and have been called red-eye texture by Chinese geologists (see also O'Brien et al., 2004). Four distinct metamorphic stages can be recognized in the IBC-type mafic granulites. The prograde metamorphic stage (M_1) is represented by mineral inclusion assemblages of Plg + Hb (yellowish green) + Qtz ± Cpx ± Mt ± Bi inside large Opx (Hy) or Cpx and Grt grains. This M_1 mineral assemblage formed under amphibolite facies conditions. The peak metamorphic stage (M_2) represents the growth of garnet porphyroblasts and matrix Opx, Cpx, Plg and some coarse brown Hb and Bi. The presence of Hb inclusions in granulites suggests that the peak assemblage was produced from the prograde metamorphic assemblage through various dehydration reactions (Zhao et al., 1999b). Following the peak metamorphic stage, Grt + Qtz symplectic coronas formed around the large Opx, Cpx and Plg grains (M_3). The IBC-type mafic granulites commonly exhibit the retrograde mineral assemblage of blue-green amphibole + Qtz (M_4). The mineral assemblages of the four stages constitute an anticlockwise *P–T* path (Fig. 4a) that is characterized by initial amphibolite facies prograde metamorphism (M_1), followed by peak granulite facies

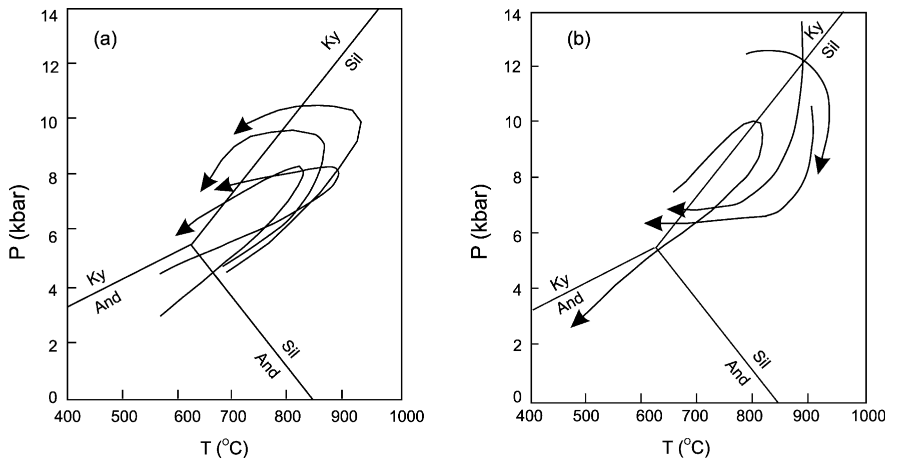

Fig. 4. $P-T$ paths of (a) IBC-type and (b) ITD-type mafic granulites (after Jin and Li, 1996; Zhao et al., 1999b).

metamorphism (M_2) and near-isobaric cooling post-peak metamorphism (M_3).

The ITD-type mafic granulites characteristically display Opx + Cpx + Plg ± Hb symplectic coronas surrounding garnet and have been called white-eye texture by local geologists (see also O'Brien et al., 2004). Petrographically, at least four metamorphic stages can be distinguished in the ITD-type mafic granulites. The main mineral assemblage is composed of medium-coarse grained Grt + Cpx + Plg ± Qtz, representing the high-pressure and high-temperature metamorphic stage (M_2). Mineral inclusions in garnet are fine-grained Qtz, Cpx, rutile and ilmenite, which possibly represent an earlier high-pressure metamorphic stage (M_1) (Liu et al., 1996; Guo et al., 1999). The third mineral assemblage is represented by coronas around Grt, composed of Hy + Plg + Cpx + minor Qtz and Mt (M_3). The fourth stage (M_4) is characterized by amphiboles replacing pyroxenes and plagioclase replacing garnet, representing retrograde metamorphism. The estimated temperatures and pressures of stages M_2 to M_4 are 760–820 °C and 11–14 kb, 800–840 °C and 7–9 kb, and 600–700 °C and 6–7 kb, respectively (Zhai et al., 1992, 1995; Guo et al., 1993; Jin and Li, 1996; Zhao et al., 1999b). The ITD-type granulites display clockwise $P-T$ paths (Fig. 4b) that are characterized by high-pressure granulite facies (M_2), followed by near-isothermal decompression (M_3), and cooling and retrogression (M_4).

$P-T$ paths estimated from the two types of mafic granulites are important in constraining the tectonic evolution of the NCC. The IBC-type mafic granulites are exposed in eastern, northern and northwestern Hebei, Inner Mongolia and northern Shanxi. Zhao et al. (1998, 1999b) and Jin and Li (1994) suggested that the IBC-type granulites were formed and metamorphosed at ca. 2600–2500 Ma. Zhao et al. (1999b, 2000a) showed that the ITD-type mafic granulites are mainly exposed in the central zone of the NCC, which comprises the Fuping, Wutai, Hengshan, Lüliang, Zhongtiao, Huaian and northern Hebei complexes, separating the west and east blocks of the NCC. Zhao et al. (2001a) also proposed that formation of IBC-type mafic granulites was related to a late Archean mantle plume whereas the ITD-type granulites were the result of Paleoproterozoic collisional tectonics. In their models, the anticlockwise $P-T$ paths of the IBC-type granulites in the west and east parts of the NCC reflect an origin related to the underplating and intrusion of large amounts of mantle-derived magmas that not only provide heat for the metamorphism but also add a large volume of mostly mafic material to the base of the crust (e.g. Zhao et al., 1998). In combination with lithological, structural and geochronological data, the west and east blocks of the NCC are considered to represent two continental blocks that developed through the interaction of mantle with lithosphere from the Paleoarchean to the Neoarchean (Zhao et al., 2001a). The ITD-type mafic granulites and associated rocks in the Central Zone represent a magmatic arc that underwent metamorphism and deformation during amalgamation of the western and eastern continental blocks in the late Paleoproterozoic (Zhao et al., 2000a, 2001a). The mineral relations and clockwise $P-T$ paths of the ITD-type mafic granulites from the Central Zone record the tectonothermal history of the collision that resulted in the final assembly of the NCC at ca. 1.8 Ga (Zhao, et al., 2000a). However, recent studies show that the distribution and metamorphic history of the two mafic granulite types are more complicated than this. For example, some IBC-type mafic granulites are also exposed in the central zone, and ITD-type mafic granulites are developed in the east and west block, such as in eastern Shandong, southern Henan and western-central Inner Mongolia. The protoliths of the IBC-type and ITD-type mafic granulites are diverse, including metamorphosed basalts, mafic dykes and gabbros. The metamorphic *PT* conditions and $P-T$ paths of the ITD-type mafic granulites in different outcrops also display obvious differences (Liu et al., 1996; Guo et al., 1999). The timing of metamorphism resulting in the two types of granulites requires further study.

3.4. Lowermost crust

Granulite facies rocks are commonly interpreted to represent lower crustal rocks and high-pressure mafic granulites to represent the lowermost crustal portion. An exhumed cross section through the lower continental crust has been recognized in the northern NCC (Zhai et al., 1996, 2001). There is a continuous transition from amphibolite to granulite facies observed near the junction of the provinces of Hebei–Shanxi–Inner Mongolia. A typical geological section (A–A′ in Fig. 1) of this area is from Manjinggou–Wayaokou–Mashikou–Xiabaiyao to Shangyi (Fig. 5a). This exposed cross-section of the lower crust in the North China Craton is similar to the Ivrea cross-section in Italy (Percival et al., 1992) and comparable to Archean lower crustal sections in Kapuskasing, Canada (Percival et al., 1992) and in Dharwar, India (Newton, 1988) (Fig. 5b).

The A–A′ cross-section of the lower crust can be divided into five layers from south (lowermost crust) to north (uppermost lower crust). Along the section, the metamorphic grade gradually decreases from high-pressure granulite facies, through medium-pressure granulite facies, to moderate- to low-pressure granulite facies and finally to amphibolite facies (Fig. 5a). The metamorphic pressures of these five layers are: 12–14 kbar, 9 kbar, 7–8 kbar, 6 kbar and 5 kbar, respectively. The petrological compositions of the layers changes from south to north from gabbroic granulites, intermediate-felsic orthogneisses to metamorphosed supracrustal rocks. Geochemically, the lowermost crust (gabbro) and lower crust (intermediate to acid orthogneiss) are relatively poorer in Si and Al compared to the middle-lower crust and uppermost lower crust. The cross-section shows a depletion trend of heat-productive elements, such as decreasing abundance of Th, U, K and Rb from the uppermost lower crust to the lowermost crust. The rocks in the lowermost crust and lower crust contain only CO_2 fluid inclusions, whereas the rocks in the middle-lower crust and uppermost lower crust commonly contain H_2O fluid inclusions. Data for compressional wave velocities from the oblique cross-section study area were reported by Zhang and Sun (1998) and are consistent with seismic data (P-wave velocities of 7.0 to 7.2 km s^{-1}) from geophysical refraction profiles of the lowermost crust in the North China Craton (Gao et al., 1998a, 1998b).

4. Archean tectonic evolution

4.1. Continental nuclei

It is evident that the oldest rocks on the earth formed at least 4.4 Ga ago (Wilde et al., 2001). Windley (1995) observed that Archean rocks tend to occur as cratons surrounded by Proterozoic mobile belts, and it was formerly thought that these were Archean nuclei around which the Proterozoic belts accreted. In the NCC, possible Paleo-Mesoarchean nuclei are enclosed within Neoarchean and Paleoproterozoic rocks. For example, Wu et al. (1998) and Deng et al. (1999) suggested there were six or ten nuclei, respectively. The two oldest nuclei, the Tiejiashan and Caozhuang complexes, occur in NE China and eastern Hebei Province (Fig. 1). Two samples of sheared granitic

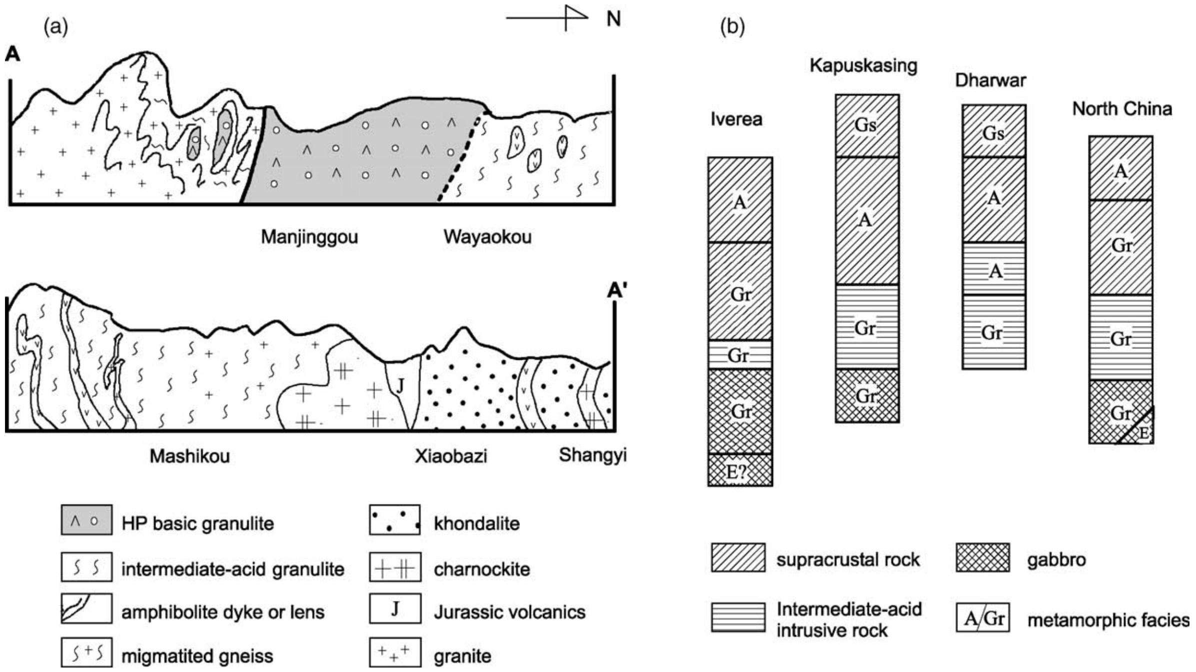

Fig. 5. Geological sketch profile of (a) the lower crust from Manjinggou, through Wayaokou, Mashikou and Xiabaiyao to Shangyi in the NCC, showing vertical lithological section (after Zhai et al., 2001); (b) comparative sections at Iverea, Italy, Kapuskasing, Canada (Percival et al., 1992) and Dharwar, India (Newton, 1988). Symbols for metamorphic facies are: Gs—greenschist; A—amphibolite; Gr—granulite; E—eclogite.

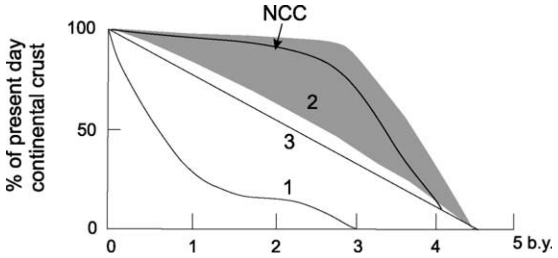

Fig. 6. Basic models of the volumetric growth of the continental crust during geological history. Lines 1, 2 and 3 after Hurley and Rand (1969), Nelson (1991) and Windley (1995), respectively. Shaded area is for the NCC.

gneiss from the northwestern margin of the Tiejiashan complex contain two generations of zircons, which yield U–Pb zircon ages of ca. 3810 Ma and ca. 3300 Ma, respectively (Liu et al., 1992). Zircons in an associated layered siliceous supracrustal rock yield a SHRIMP U–Pb zircon age of 3362 ± 5 Ma (Song et al., 1996). In the Caozhuang complex, zircons from tonalitic gneiss yield U–Pb ages of 3300–3000 Ma (Zhao et al., 1993), amphibolites yield Sm–Nd whole rock isochron ages of ~3500 Ma (Huang et al., 1983; Jahn and Zhang, 1984) and fuchsitic quartzites have U–Pb zircon ages of ~3830–3600 Ma (Liu et al., 1992). Besides these two oldest crustal remnants, other Mesoarchean continental nuclei are the Huai'an complex in the western-central NCC, the Yishui complex near Taishan in the eastern NCC and the Baishanzhen complex in the northeastern NCC. These have zircon U–Pb ages of 3.5–3.3 Ga (Guo et al., 1991; Kröner et al., 1987), 3.1–2.97 Ga (Wu et al., 1998), and 3.1–3.0 Ga (Zhai and Windley, 1990), respectively. The precise relationship of these older rocks to the enclosing Neoarchean and Paleoproterozoic rocks has yet to be defined.

4.2. 2.9–2.7 Ga crustal growth

Three basic models (Fig. 6) can be considered to explain the volumetric growth rate of continental crust (Veizer, 1976). These are: crustal growth increasing exponentially to the present, linear crustal growth from the earliest stage to the present and rapid growth at an early stage followed by a more gradual increase (Hurley and Rand, 1969; Nelson, 1991; Windley, 1995). Windley (1984, 1995) summarized the main conclusions that 60–85% of continental crust was created by the end of the Archean. The shaded area in Fig. 6 shows estimated volumetric crustal growth of the NCC by synthesizing data from new geological maps and geophysical and geochronological studies.

The characteristics of Nd isotopes and trace elements from early Precambrian rocks of the NCC and their implications for crustal growth have been discussed by Jahn (1990a) and Zhang (1998). Fig. 7a is a diagram of $\varepsilon Nd_{(t)}-t$/Ga (model age) for metamorphic mafic rocks from the NCC. All values of $\varepsilon Nd_{(t)}$ are positive, however, they do not show a consistent relationship with the evolution of depleted mantle. In general, the values of $\varepsilon Nd_{(t)}$ increase with the evolution of depleted mantle in the time range from 3.5 to 3.0 Ga, but deviate from about 3.0 to 1.5 Ga. Zhang (1998) suggested that this deviation is attributable to contamination by crustal materials, indicating a thick crust existed in the NCC during the Mesoarchean. The rare earth elements also demonstrate the same change. For example, higher La/Nb ratios show the early Precambrian mafic rocks contain a high proportion of crustal material (Jahn, 1990a, 1990b). Most Archean mafic granulites from the NCC display REE patterns similar to those of basalts from island arc, continental margin and within-continent sources, with some evidence of crustal contamination. Fig. 7b is a histogram of t_{DM} ages for early Precambrian mafic rocks from the NCC. Most t_{DM} ages concentrate in the range from 3000 to 2500 Ma with two peaks; at ~2900 Ma and 2700 Ma. From these data, a tentative conclusion is that the main crust of the NCC formed during the Neoarchean from 2900 Ma to 2700 Ma (Lu et al., 1995; Zhang, 1998; Wan et al., 1998; Geng, 1998a; Zhai and Liu, 2001).

4.3. 2.5 Ga and younger geological events

Cheng and Zhang (1982) suggested that two important metamorphic episodes took place in the NCC; a 2600–2450 Ma granulite facies metamorphic event and a 1900–1750 Ma amphibolite–granulite facies metamorphism (here after referred to as the 2.5 Ga event

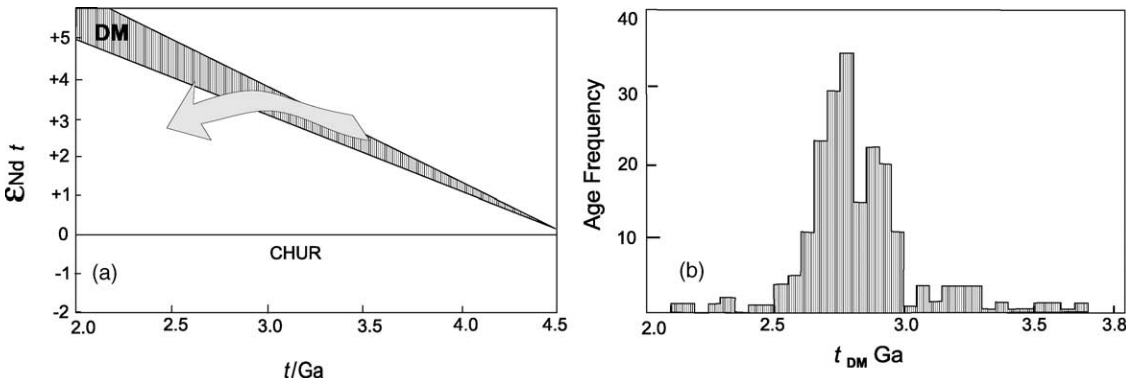

Fig. 7. Diagram of (a) $\varepsilon Nd_{(t)}-t$/Ga and (b) histogram of t_{DM} ages for early Precambrian mafic rocks from the NCC.

and 1.8 Ga event, respectively). Many protoliths of granulite facies rocks were formed in the Paleo-Mesoarchean, and their 2600–2450 Ma isotopic dates represent metamorphic ages (Shen et al., 1992). Most early Precambrian rocks have metamorphic and isotopic records of these two events (Zhao et al., 1993). There were fewer volcanic rocks formed during the 2.5 Ga event than in the 2.9–2.7 Ga event (Wu et al., 1998; Geng, 1998a, 1998b). Metamorphosed volcano-sedimentary rocks are only developed in the Wutaishan area of Shanxi Province, the Qinglongshan area of Eastern Hebei Province and the Hongtoushan area in Liaoning Province (Fig. 1). Basic volcanic rocks in these areas coexist with intercalated intermediate to acid volcanic rocks, and are distinct from 2.9 to 2.7 Ga volcanic associations, with the latter lacking andesitic components (Wan et al., 1998). The main features of the 2.5 Ga event is that all Archean rocks older than 2600 Ma in the NCC underwent the 2.5 Ga high-grade metamorphic event. The metamorphism was commonly followed by emplacement of charnockites and granitoids into the metamorphic rocks. The contact relationships between intrusive and country rocks are complex or transitional, showing characteristics of anatexis and migmatization. For example, in Eastern Hebei some sodic intermediate to acid granulites, with tonalitic geochemistry and high $-\varepsilon Nd_{(t)}$, were derived from the melting of mafic rocks (Jahn and Zhang, 1984; Jahn, 1990a).

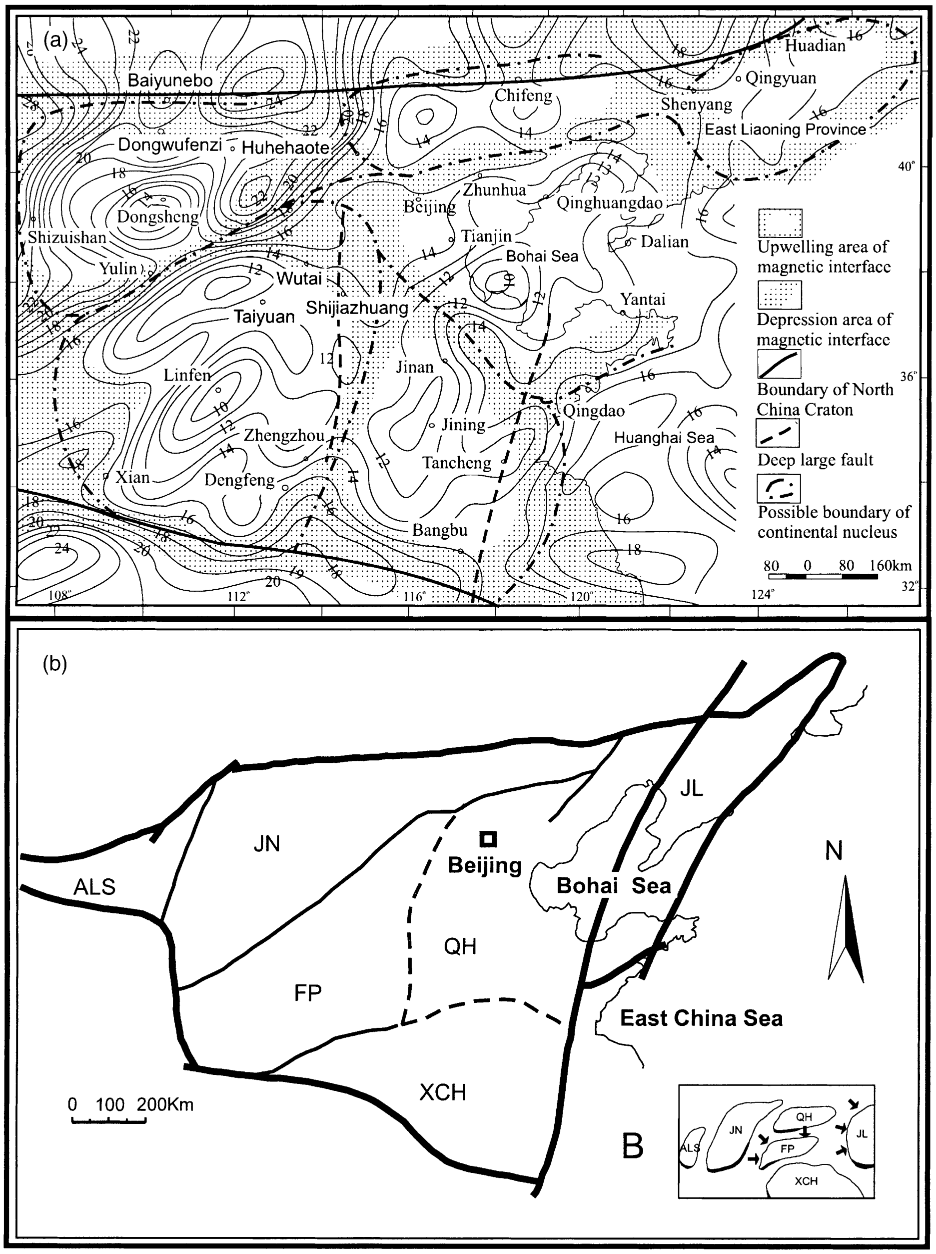

Fig. 8. (a) Airborne magnetic map of the NCC (after Bai et al. 1993) and (b) location of micro-blocks in the NCC see text for names of blocks (after Zhai et al., 2000).

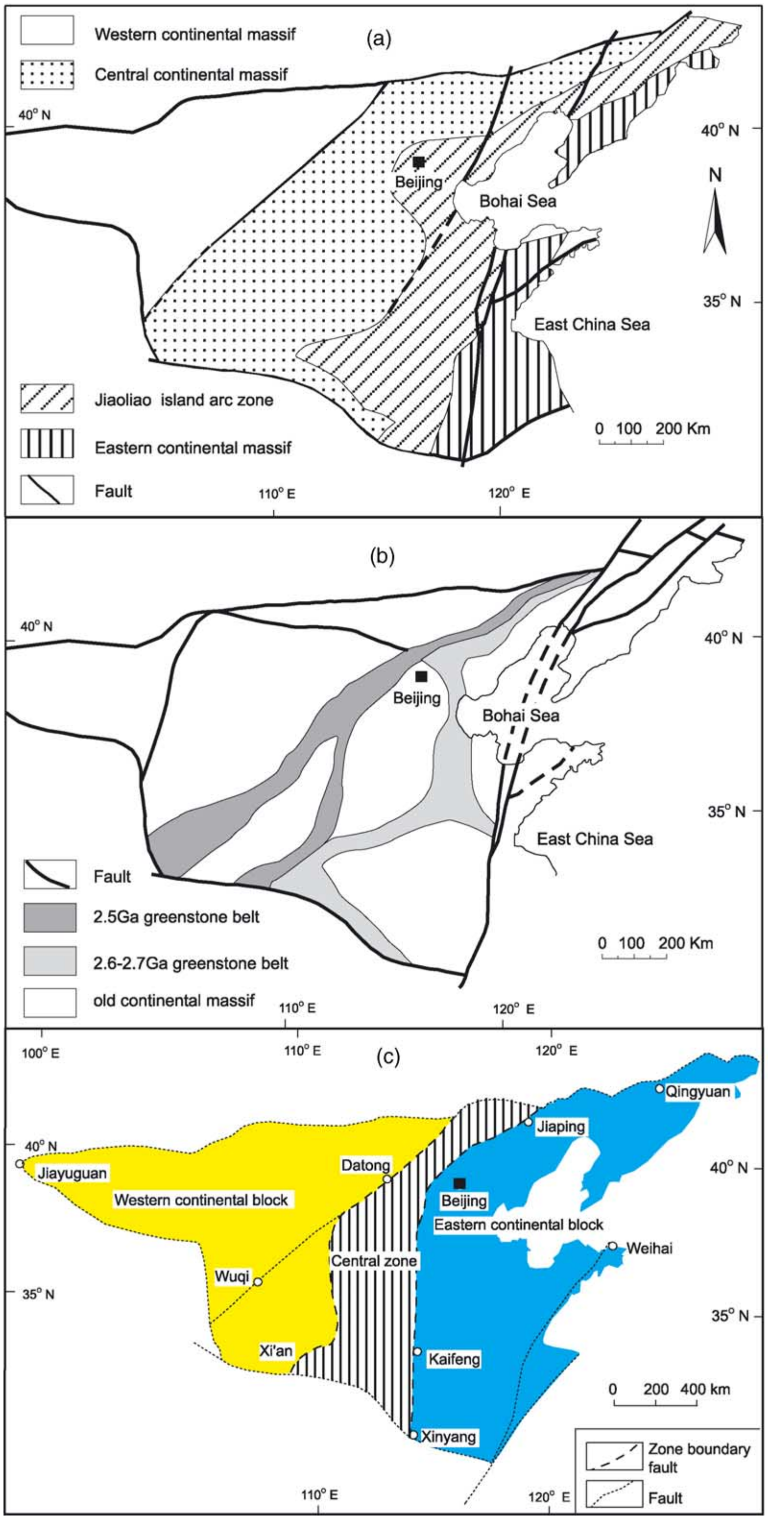

Fig. 9. Neoarchean amalgamation of North China Craton by (a) arc–continent collision (after Wu et al., 1998) and (b) continent-continent collision (after Zhang, 2000). (c) Paleoproterozoic continental–continental collision (after Zhao et al., 2001a).

Some TTG grey gneisses suffered strong in-situ or injection potassium-migmatization, forming various types of migmatite. A series of granitic sills and bodies are distributed throughout NE China, Eastern Hebei, central Henan, northern Shanxi and Inner Mongolia, with isotopic ages between 2530 and 2450 Ma. Mafic dyke swarms, now at amphibolite or granulite facies, are also widespread in the NCC and have been strongly folded and deformed by later tectonic events. These granite bodies and dykes have been taken to indicate that cratonization had already taken place and also to indicate the boundary between the Archean and Proterozoic in the NCC (Zhao et al., 1993; Shen et al., 1992; Bai et al., 1993). The 1.8 Ga event, traditionally named the Lüliang Movement, was thought to mark final stabilization of the NCC. However, various geologists have proposed that this event represents continental extension (Li et al., 1997), continental uplifting (Zhang et al., 1994), assembly (Zhao et al., 2000a) or break up (Zhai et al., 2000) of continental blocks.

4.4. Archean tectonic evolution

An examination of the distribution of early Precambrian rocks, utilizing new isotopic and geophysical data (Fig. 8a) has enabled some old nuclei to be distinguished in the NCC. Based on this, Bai et al. (1993) and Wu et al. (1998) suggested that the NCC can be divided into six micro-continental blocks: the Jiaoliao (JL), Qianhuai (QH), Fuping (FP), Ji'ning (JN), Xuchang (XCH) and Alashan (ALS) blocks (Fig. 8b). Rock types, and their distribution in these micro-blocks, display distinct differences. For example, old rocks up to 3.8 Ga and abundant Mesoarchean BIFs are only present in the Qianhuai block. Rocks older than Neoarchean are not exposed in the Ji'ning and Fuping blocks, although they may exist in the deep crust, based on geophysical data. Neoarchean volcanism and magmatism in these blocks took place at 2.9–2.7 Ga and 2.6–2.45 Ga, but their abundance in different blocks varies greatly. Volcanic activity from 2.9 to 2.7 Ga was, in general, strong in all blocks, especially in the Jiaoliao, Qianhuai and Xuchang blocks, associated with abundant BIFs. However, BIFs are not present in the Alashan block. Volcanic activity at 2.5 Ga was weak in the Ji'ning block, however, it was rather intense in the Jiaoliao, Fuping and Qianhuai blocks. Basic-intermediate-acid volcanic rocks in the Fuping and Qianhuai areas are closely associated with the BIFs. In the Jiaoliao block, however, volcanic rocks contain massive sulfide Cu–Zn ores. All these differences indicate that these micro blocks possibly developed in different tectonic settings, i.e. they had not been amalgamated into a coherent craton until at least ~2.5 Ga ago (see inset in Fig. 8b showing possible pre-collision distribution). It is noteworthy that many granitic sills with an age of 2.5–2.45 Ga intruded into neighboring blocks, suggesting amalgamation prior to intrusion. For example, a series of granite bodies are located along the contact zone between the Jiaoliao and Qianhuai blocks (Wu et al., 1998) indicating that the micro-blocks were assembled together and constituted a combined NCC by the end of Neoarchean (Li et al., 1997).

There are several different models to explain the nature of the NCC in the late Archean, e.g. classical vertical accretion models that include multi-stage cratonization (Zhao et al., 1993) and marginal accretion-reworking models (Jin and Li, 1996). Some models propose arc–continent collision or continent–continent collision similar to Phanerozoic tectonic processes. Wu et al. (1998) suggested an old volcanic–magmatic arc zone, the present location of which lies in the north, extending from Hongtoushan in NE China, via Qinglong, through Eastern Hebei to western Shandong (Fig. 1), where the arc curves westward. An old continental block is presently located east of the arc zone. The meta-volcano-sedimentary rocks with isotopic ages of 2.56–2.53 Ga in the Hongtoushan area in NE China and the Qinglongshan area in Eastern Hebei were also considered to have formed in an island arc setting (Zhai et al., 1985; Wu et al., 1998). A vast number of granitoid intrusives occur in this arc zone. TTG rocks mainly occur along the western side (outer side) and calc-alkaline granitic rocks occur on the eastern (inner side). The former evolved at 2.55–2.5 Ga and the latter formed at 2.5–2.45 Ga (Zhao et al., 1993; Li, 1999). Therefore, Wu et al. (1998) suggested that there was an ancient sea west of the continental block, and that oceanic crust was subducted eastward beneath the continent block, causing the formation of an island arc and finally arc–continent collision (Fig. 9a). Zhang (2000) suggested that greenstone belts occurring between old continental blocks represent orogenic zones. 2.5 Ga greenstone belts mainly occur between the Qianhuai, Xuchang and Fuping blocks, possibly representing continental amalgamation (Fig. 9b). 2.6–2.7 Ga greenstone belts also underwent strong reworking during the 2.5 Ga event. Zhai et al. (1992, 1995) proposed continent–continent collision between the Qianhuai and Fuping blocks and between the Qianhuai and Ji'ning blocks at 2.5–2.6 Ga, based on the distribution of high-pressure granulites. Zhai et al. (2000) also proposed that between 2.6 and 2.45 Ga, the six micro-blocks in the NCC were amalgamated together by continent–continent, continent–arc or arc–arc collision (see Fig. 9b). However, Zhao et al. (2001a) suggested an alternative model whereby the tectonic evolution of the basement of the NCC was grouped into discrete Eastern and Western Blocks that developed independently during the Archean and finally collided along the central zone to form a coherent craton during a global Paleoproterozoic collisional event at ~1.85 Ga (Fig. 9c). A great deal of knowledge has been acquired during the past decade but it is evident that further detailed work is still required to resolve these outstanding issues.

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