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LATE NEOARCHEAN MAGMATIC – METAMORPHIC EVENT AND CRUSTAL STABILIZATION IN THE NORTH CHINA CRATON

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ABSTRACT. The *ca.* 2.5 Ga as the time boundary between the Archean and the Proterozoic eons is a landmark, indicating the most important continental crust evolving stage of the Earth, that is, the global cratonization or the formation of supercraton(s) that was unseen before and is unrepeated in the following history of the Earth's formation and evolution. The North China Craton (NCC) is one of the best recorders of the *ca.* 2.5 Ga event, and therefore studies in the thorough understanding of early Precambrian continental evolution are continuous.

The period from 2.8 to 2.6 Ga is the major crustal growth period of the NCC and formed seven micro-blocks. All the micro-blocks in the NCC were surrounded by 2.6 to 2.54 Ga greenstone belts. The clear geological presentations are as follows: (1) Archaic basement rocks in North China (various micro-blocks) experienced strong partial melting and migmatization. The granitoid rocks derived from crustal partial melting include potassium, TTG and monzonitic granitoids, which come, respectively, from continental crust (sedimentary rocks with TTG gneisses), juvenile crust (mafic rocks with TTG gneisses) or mixed crust; (2) the BIF-bearing supracrustal rocks are mainly distribute in greenstone belts. The lithologic associations in the greenstone belts within the NCC are broadly similar, belonging to volcano-sedimentary sequences, with common bimodal volcanic rocks (basalt and dacite) interlayered with minor amounts of komatiites in the lower part, and calc-alkalic volcanic rocks (basalt, andesite and felsic rocks) in the upper part; (3) nearly all old rocks of >2.5 Ga underwent ~2.52 to 2.5 Ga metamorphism of amphibolite–granulite facies. Most metamorphosed rocks show high-temperature-ultra-high-temperature (HT–UHT) characteristics and record anticlockwise *P–T* paths, albeit a small number of granulites seemingly underwent high-pressure granulite facies metamorphism and record clockwise *P–T* paths; (4) ~2.5 Ga mafic dikes (amphibolites), granitic dikes (veins) and syenitic–ultramafic dikes developed across these archaic basements and were strongly deformed or un-deformed; (5) the extensive 2.52 to 2.48 Ga low-grade metamorphic supracrustal covers has been recognized in eastern, northern and central parts of the NCC, which are commonly composed of bi-modal volcanic rocks and sedimentary rocks.

The above mentioned ~2.5 Ga geological rocks and their characters imply that the seven micro-blocks have been united through amalgamation to form the NCC. The metamorphosed late Neoarchean greenstone belts, as syn-formed mobile belts, welded the micro-blocks at the end of the Neoarchean. However, the metamorphic thermal grades of the greenstone belts are lower than those of the high-grade terranes within the micro-blocks, suggesting that the latter might have developed under a higher geothermal gradient than the former. Besides, the greenstone belts surround the various micro-blocks in the late Neoarchean when both the old continental crust and the oceanic crust were hotter. The subduction during the amalgamation, if it happened, must have been much smaller in scale as compared to those in the Phanerozoic plate tectonic regime, and all stages occurred at crust-scale instead of lithosphere-scale

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or mantle-scale. This is why most rocks record HT-UHT and anti-clockwise metamorphism, while only a few samples record high-pressure granulite facies metamorphism with clockwise *P–T* paths.

The micro-block amalgamation was accompanied by extensive crust partial melting and granitization, which finally gave rise to the stabilization of the NCC. Except for the vast granitoid intrusions, mafic-syenitic dike swarms and sedimentary covers are also landmarks of cratonization. The *ca.* 2.5 Ga cratonization is a global epoch-making geological event, although the accomplishment of cratonization in various cratons is somewhat different in time. Cratonization declared the formation and stabilization of global-scale supercratons or cratonic groups coupling with lithosphere, which was followed by a "silent period" with rare tectonic-thermal action lasting 150 to 200 Ma (from 2.5 Ga – 2.3 or 2.35 Ga), and then followed by the Great Oxidation Event (GOE).

Key words: Late Neoarchean, North China Craton (NCC), magmatic-metamorphic event, cratonization

INTRODUCTION

The International Union of Geological Sciences approved the terms "Archean and Proterozoic" and set 2.5 Ga as the time boundary between the Archean and Proterozoic eons (James, 1978). Nevertheless, their mutual time boundary varies slightly from continent to continent (Windley, 1984). This is because the final cratonization in various continent is slightly asynchronous. The principle for this time boundary between the Archean and the Proterozoic followed with the completion of cartonization represented by magmatic-metamorphic events, rather than the Phanerozoic stratigraphic classification. Zhao (1993) emphasized that the age of Shanhaiguan granite is 2.45 Ga, representing final stabilization of the NCC, and therefore, the time boundary between the Archean and the Proterozoic in the NCC should be 2.45 Ga.

Zhai and others (2010) showed that the NCC reached ~90 percent of its present crust volume during 2.9 to 2.45 Ga based on geological map, geophysical data and geochronological data. The zircon U-Pb ages from the volcanic and granitoid rocks are concentrated on the *ca.* 2.5 Ga peak with a secondary peak of 2.9 to 2.7 Ga (fig. 1). They have been explained as magmatic-metamorphic events representing dominant crustal growth in the NCC. The Proterozoic peak of 2.0 to 1.6 Ga is also strong and is considered to record a crustal reworking event corresponding to the Nuna or Columbia supercontinent. The characteristics of Nd isotope, Hf isotope and trace elements for early Precambrian rocks in the NCC and their implication for the crustal growth were discussed (Jahn, 1990; Zhang and others, 1998; Wan and others, 2005, 2011a, 2011b; Wu and others, 2005; Geng and others, 2006a, 2006b, 2012; Zhai and others, 2007; Jahn and others, 2008; Liu and others, 2009). Two discernible peaks are at ~2.7 Ga and 2.9 Ga (fig. 2B). The Nd T_{DM} ages can roughly indicate the formation ages of the crustal components. The ε_{Nd} (t) versus t (Ga) (fig. 2A) diagram of early Precambrian rocks in the NCC shows two characteristics: all values of ε_{Nd}(t) are positive, and there is an obvious change of ε_{Nd}(t) with the change of t. The values of ε_{Nd}(t) deviate from the depleted mantle evolution curve at about 3.0 Ga, which is attributable to contamination of crustal materials and indicates that a thick continental crust existed in the NCC during the Neoarchean. Rare earth elements (REEs) of rocks in the NCC also demonstrate the same tendency. For example, the high La/Nb ratios of pre-3.0 Ga mafic rocks indicate the presence of a considerable amount of continent crust by this time (Jahn, 1990). Most mafic granulites and amphibolites from the NCC display REE patterns similar to those of basalts generated an island arc, continental margin and within continent settings, indicating different tectonic background. However, a few samples have mid-ocean ridge basalt (MORB) characteristics. The Hf isotopic model ages range from ~3800 to 1950 Ma, with the main concentration 3000 to 2600 Ma, with

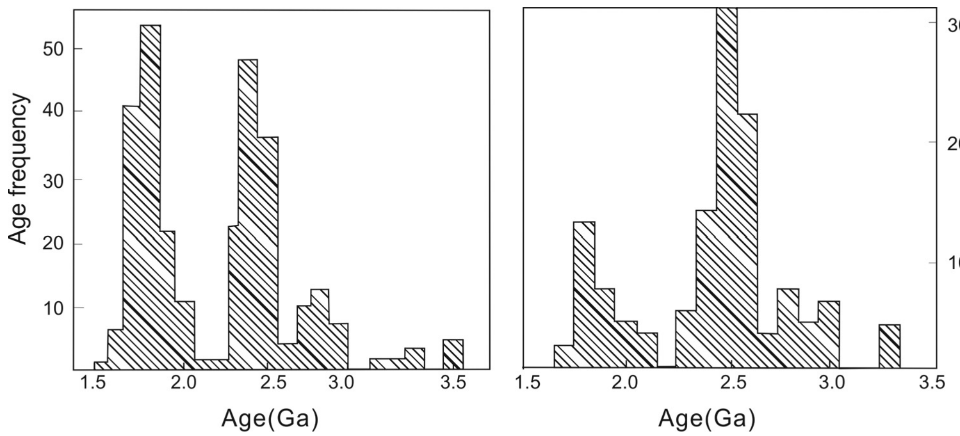

Fig. 1. Histogram of zircon U-Pb ages from granitoids and volcanic rocks of the NCC (after Zhai and others, 2010).

a peak of 2820 Ma (fig. 2C). However, zircon U-Pb ages from magmatic rocks, mainly orthogneisses, demonstrate several peaks of 3800 to 3600 Ma, 3200 to 3000 Ma, 2900 to 2700 Ma, 2600 to 2500 Ma and ~2450 Ma, with the youngest one indicating an extensive crust partial melting event in the NCC.

~2.6 to 2.5 Ga granites and metamorphic events commonly occur in nearly all cratons in the world (Windley, 1995), but ~2.5 Ga geological records remain weak relatively to the ~2.7 Ga crustal growth event in some cratons. In the northern hemisphere, the Superior Craton (Percival and others, 2006), the western Canadian Shield (Sandeman and others, 2006), the Wyoming Greenstone Belt (Rino and others, 2008), the Baltic Shield (Samsonov and others, 2005) and western Greenland Craton (Friend and Nutman, 2005), and in the southern hemisphere, the South Africa and Zimbabwe Cratons (Hofmann and others, 2004) and the Pilbara and Yilgarn Cratons in western Australia (Rasmussen and others, 2005), all record a significant influence of the *ca* 2.7 to 2.8 Ga event responsible for the rapid formation of the continent crust in the Archean. The ~2.5 Ga metamorphic–magmatic event in the NCC is stronger than that in most other cratons worldwide. This provides an ideal example to discuss the process and mechanism of the stabilization of the NCC, and to compare with other cratons for the purpose of further understanding global cratonization and continental evolution.

NEOARCHEAN MICRO-BLOCKS AND ROCK UNITS

Neoarchean Micro-blocks

The major crustal growth in the NCC occurred at *ca.* 2.7 Ga surrounding older nuclei and formed several micro-blocks (Shen and Qian, 1995; Bai and others, 1996; Wu and others, 1998). The seven identified micro-blocks include the Jiaoliao Block (JL), the Qianhuai Block (QH), the Ordos Block (OR), the Jining Block (JN), the Xuchang Block (XCH), the Xuhuai Block (XH) and the Alashan Block (ALS) (fig. 3A, Zhai and others, 2001a; Zhai and others, 2010). The proposal for these blocks is based on the identification of ancient tectonic boundaries represented by granite-greenstone belts. Examples include the Zunhua greenstone belt located between the JN and QH Blocks, the Wutaishan greenstone belt between the OR and QH Blocks, the Yanling-guan greenstone belt between the JL and QH Blocks, the Dongwufenzi greenstone belt between the JN and OR Blocks, the Xuchang greenstone belt between the XCH and

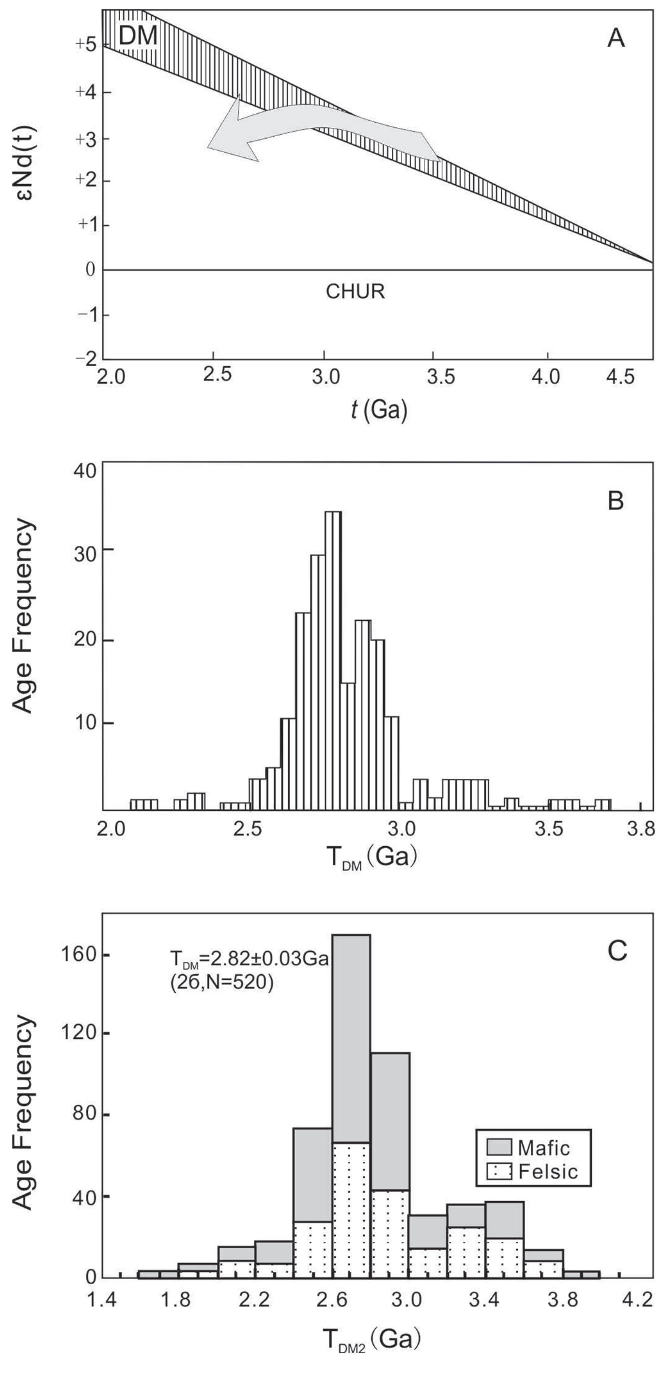

Fig. 2. ε_{Nd} (t) – t diagram (A), Nd T_{DM} age histogram (B) (after Zhai and others, 2010) and Hf isotopic model ages (C) of mafic igneous rocks from the NCC (after Wu and others, 2005).

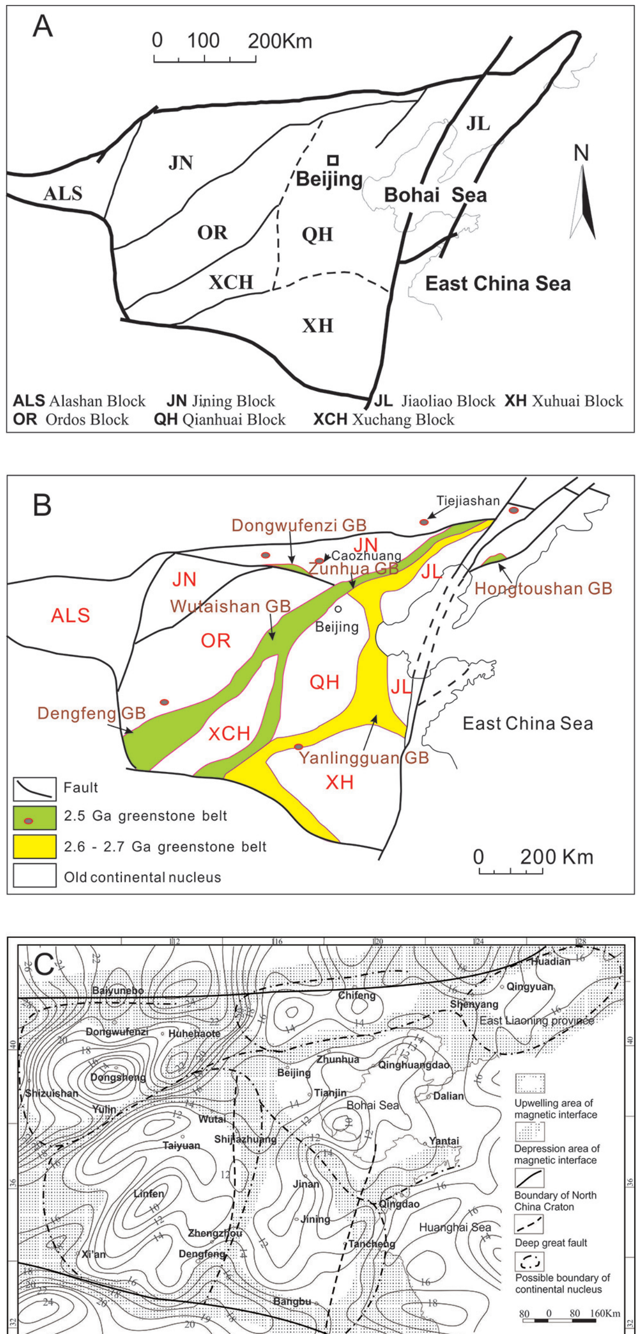

Fig. 3. Outline of micro-blocks (A), greenstone belts (B) and distribution of magnetic boundary isopleths and micro blocks of the NCC (C) (after Guan and others, 1987).

QH blocks, among others (fig. 3B, Zhai and others, 2010; Zhai and Santosh, 2011). Some of the boundaries are obscured as they are covered by younger rocks or Quaternary sediments, and have therefore been inferred using multiparametric approaches (Qian and Wang, 1994; Bai and others, 1996; Wu and others, 1998). The above division scheme is also supported by geochemical boundaries (Liu and others, 1998) as well as geophysical boundaries imaged from the deep crust (fig. 3C, Guan and others, 1987).

These seven micro-blocks exhibit some differences in rock associations and crustal evolutionary histories. The QH and JL Blocks contain remnants of *ca.* 3.8 Ga orthogneisses and supracrustal rocks with banded iron formations (BIFs), although these rocks record different metamorphic evolutionary patterns. ~3.6 Ga xenolith of old metamorphic rock enclosed in Phanerozoic volcanic rock in the XH Block (Zheng and others, 2004). 2.9 to 2.7 Ga orthogneisses occur in all blocks, which are outcropping to different degrees. Two episodes of metamorphism have been distinguished from the Archean rocks of the JL Block: granulite to upper amphibolite facies metamorphism at *ca.* 2.52 to 2.51 Ga and *ca.* 1.9 to 1.82 Ga. On the other hand, the Archean rocks of the QH Block underwent three episodes of high grade metamorphism: a granulite facies event at *ca.* 2.6 to 2.56 Ga, a granulite to upper amphibolite facies event at *ca.* 2.52 to 2.51 Ga and a granulite to lower amphibolite facies event at *ca.* 1.9 to 1.82 Ga (Liu and others, 1996; Geng, 1998; Li, ms, 1999; Wan and others, 2000; Li and others, 2000; Geng and others, 2002; Shen and others, 2004). The JN Block has Neoarchean metamorphic basement and is covered by a carbonate-evaporite sequence and Al-rich sedimentary rocks. The XCH Block mainly has two complexes with ages of *ca.* 2.7 Ga and *ca.* 2.6 to 2.5 Ga, respectively (Geng and others, 2006a; Diwu and others, 2007; Liu and others, 2009; Zhou and others, 2009). The *ca.* 2.7 Ga group dominantly comprises TTG gneisses of granulite to upper amphibolite facies and the *ca.* 2.6 to 2.5 Ga group is composed of BIF-bearing supracrustal rocks and orthogneisses of amphibolite facies. The ALS Block contains orthogneisses and metasedimentary rocks. The supracrustal sequence is composed of metabasic rocks and metamorphosed intermediate to acid volcanic rocks. BIFs are not common in the ALS Block (Yang and others, 1988; Geng and others, 2006b). Most areas of the OR and XH Blocks are covered by younger sedimentary rocks and Quaternary sediments, although Neoarchean orthogneisses and granulites have been found in some drill cores or Mesozoic granites (as xenoliths) (Wang and others, 2012; Zhang and others, 2015).

Rock Units

There are mainly three types of rocks with Neoarchean ages in the NCC, including the supracrustal rocks, the orthogneisses and metamorphosed ultramafic to mafic bodies.

Supracrustal rocks commonly consist of intercalated volcanic-sedimentary rocks of granulite–amphibolite facies, which include mafic two-pyroxene granulites or amphibolites, felsic granulites or fine- to medium-grained gneisses, BIFs, metapelites, and minor amounts of marbles, mica quartzites and mica schists. The BIFs are a common rock type among supracrustal sequences with different Sm-Nd whole rock isochron ages from 3.5 Ga to 2.5 Ga, and amphibolites or mafic granulites are closely associated with the BIFs (Zhai and Windley, 1990).

The quartzo-feldspathic gneisses of amphibolite to granulite facies are the dominant orthogneisses, and usually constitute as much as ~70 to 85 volume percent of the Archean exposures in the NCC. Based on geochemistry and petrology, orthogneisses can be divided into two series: trondhjemitic-tonalitic-granodioritic (TTG) series and granitic-monzonitic series. The TTG gneisses commonly have no sharp contact boundaries with supracrustal rocks. Some of them are banded or intercalated within amphibolites. The TTG gneisses in the NCC commonly experienced strong potassic migmatization, showing a characteristic of lower crustal reworking. The granitic gneisses include anatectic granites and granite sills.

Pyroxene amphibolites and mafic granulites within orthogneisses have been recognized as tectonic lenses of deformed and metamorphosed layered ultramafic to mafic igneous bodies (Zhai and others, 1985; Zhang, 1986). Most metamorphosed layered igneous bodies are of gabbroic-ultramafic complexes, like those on the Scourian mainland in northwestern Scotland. The common Archean layered anorthosite-gabbro complexes in other cratons are absent in the NCC. Mafic dikes have been categorized into, at least, three groups according to their isotopic ages and deformation - metamorphism histories: >2600 Ma, 2550 to 2450 Ma, and 1800 to 1700 Ma, representing the main geological events in the evolving history of the NCC.

High-grade Terrains and Greenstone Belts

The Archean cratons worldwide contain two types of terrain: high-grade gneiss-dominant terrains, and well-preserved greenstone belts dominated by low-grade metamorphic volcanics (Condie, 1981; Windley, 1984). The NCC, in general, also contains these two types, although nearly all rocks underwent metamorphism of granulite to amphibolite facies.

Greenstone belts.—According to rock associations, greenstone belts of amphibolite facies were recognized in the NCC (Zhai and Windley, 1990; Windley, 1995). Main greenstone belts in the NCC are the Yanlingguan Greenstone Belt in western Shandong, Dengfeng Greenstone Belt in central Henan, Dongwufenzi Greenstone Belt in Inner Mongolia, Wutaishan Greenstone Belt in Shanxi, Zunhua Greenstone Belt in East Hebei, and Qingyuan (Hongtoushan) Greenstone Belt in NE China. Most greenstone belts formed at 2600 to 2540 Ma and metamorphosed up to amphibolite or upper amphibolite facies, whereas the Yanlingguan Greenstone Belt formed at 2800 to 2700 Ma and underwent greestone-amphibolit facies metamorphism at ~2.7 Ga and deformed at ~2.5 Ga (Cheng and Kusky, 2007). The lithologic associations in the greenstone belts within the NCC are broadly similar, belonging to volcano-sedimentary sequences, with common bimodal volcanic rocks (basalt and dacite) interlayered with minor amounts of komatiites in the lower part, and calc-alkalic volcanic rocks (basalt, andesite and felsic rocks) in the upper part. The Yanlingguan Greenstone Belt is particularly characterized by metamorphosed komatiites, pillow basalts, BIFs, conglomerates and graywacke sandstones. The belt was intruded by high-Al TTG plutons (Zhang R and others, 1998; Polat and others, 2006), and komatiites partly preserve remnant igneous spinifex textures. Some metamorphosed basalts preserve pillow structures in the Wutaishan, Yanlingguan and Zunhua greenstone belts. The sedimentary sequences are commonly metamorphosed sandstone-pelite-BIF with or without a few carbonate (marble) horizons. As mentioned above, mafic granulites and amphibolites in the greenstone belts from the NCC show geochemical characteristics comparable with basalts from different tectonic settings, for example island arc and back arc basin settings (fig. 4A). Figure 4B shows that based on REE compositions, these rocks can be further subdivided into two groups, corresponding to TH1 and TH2 types of basaltic rocks respectively, belonging to the Archean greenstone belts as reported by Condie (1981, 1984). The REE pattern of TH2 and TH1 groups are comparable to those of basalts from island arc–continental margin and back-arc basin-ocean basin settings, respectively (Wang and others, 1985; Zhai, 1991, 2004; Wilde and others, 2004; Zhao and Kröner, 2007; Zhao and others, 2007; Wang, 2009). Notably, only a few samples show mid-ocean ridge basalt (MORB) affinities (Zhai, 1991; Kusky and others, 2001, 2004a; Li and others, 2002, 2006; Kusky, 2004; Li and Kusky, 2007a; Wang, 2009).

High-grade terrains.—High-grade granulites and gneisses are extensively developed in the NCC. Main high-grade terrains include the Baishanzhen terrain in NE China, Qian'an terrain in East Hebei, Yishui terrain in Shandong, Huai'an terrain in the

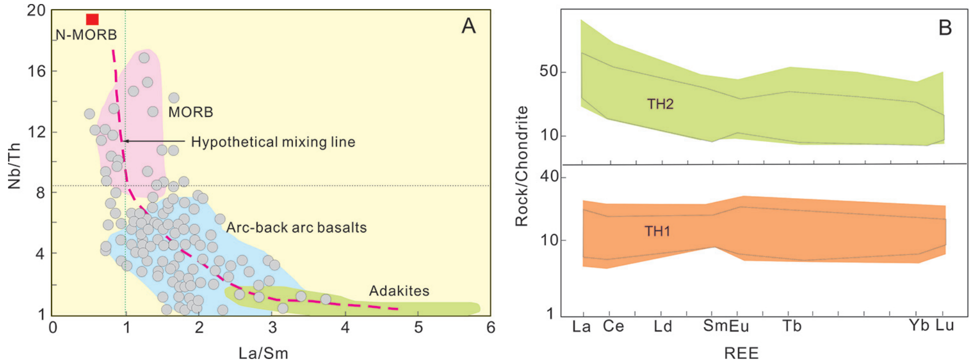

Fig. 4. (A) Nb/Th versus La/Sm diagram of mafic granulites and amphibolites in the NCC and (B) REE plot normalized by chondrite for meta-basalts from Archean greenstone belts in the NCC (after Sun and McDonough, 1989; Zhai, 1991, 2004; Polat and Kerrich, 2000; Wang, 2009). The fields bound by black lines are TH1 and TH2 type basalts from Archean greenstone belts worldwide as compiled by Condie (1981, 1984).

juncture area of Hebei-Shanxi-Inner Mongolia, and Taihua terrain in central Henan. The relationship between greenstone belts and high-grade terrains is not clear, whereas both were intruded by granitic gneisses and charnockites. The high-grade terrains are composed of orthogneisses (80–90%), rootless meta-gabbros (5–10%) and slabs of supracrustal rocks (10–15%), associated with strong and complicated deformation. The supracrustal rocks comprise mafic granulites or amphibolites, BIFs, and medium-grained biotite gneisses with geochemical compositions similar to slate-graywacke and intermediate-acid volcanics. Orthogneisses are mostly felsic with high sodium contents, showing tonalitic-trondhjemitic evolving trends (fig. 5A). Potassium granitic and monzonitic gneisses formed usually a little later than the TTG gneisses. The crustal accretion events of high grade terrains have been correlated to a mantle plume, or superplume event (for example, Condie and others, 2001; Condie and Kröner, 2008; Condie and others, 2009).

Most of ~2.7 Ga TTG gneisses in the NCC underwent 2.6 to 2.5 Ga metamorphism or reworking, as revealed by the ubiquitous metamorphic rim around the core of the

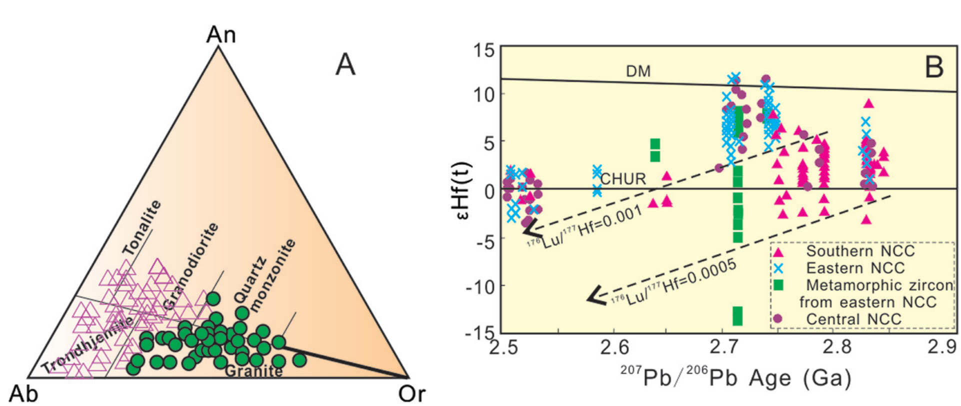

Fig. 5. An–Ab–Or diagram of Neoarchean felsic orthorgneisses (A) and εHf(t) versus $^{207}Pb/^{206}Pb$ age plot of TTGs (B) in the NCC (modified from Zhai, 2014).

magmatic zircons in these rocks. Their Hf model ages range from 2.9 to 2.7 Ga (fig. 5B), indicating that ~2.7 Ga TTGs came from ~2.9 to 2.7 Ga juvenile crustal rocks. Abundant ~2.5 Ga orthogneisses distribute among the NCC, including dominant granitic gneisses and some TTG gneiss. The orthogneisses have Hf model ages mainly around 2.9 to 2.7 Ga, albeit some TTG gneisses show almost contemporary zircon Hf model ages (fig. 5B, after Zhai and Santosh, 2011, 2013; Zhai, 2014), indicating the formation time of the protoliths or extraction time of the protolith magma from the mantle. Such an important crust growth event occurring during 2.9 to 2.7 Ga, is in accordance with global crust growth (Zhai and others, 2001a; Zhai and Liu, 2003; Zhai and Santosh, 2011; Wan and others, 2014). Coincidentally, the 2.6 to 2.5 Ga metamorphic zircon grains from the widespread mafic rocks also have Hf model ages ranging from 2.9 to 2.7 Ga. Therefore, the NCC has a distinct characteristic of multi-stage crust growth, with the most important period of 2.9 to 2.7 Ga and followed by the 2.6 to 2.5 Ga crust growth- reworking event during Neoarchean (Wan and others, 2011a; Jia and others, 2017; Zhou and others, 2018).

~2.5 GRANITES AND METAMORPHISM

~2.5 Ga Granites

Many detailed studies on ~2.5 Ga granitoids have been reported in recent years all over the NCC (for example, Zhai and Santosh, 2011, 2013; Diwu and others, 2011; Ma and others, 2012; Wang and others, 2012; Zhang and others, 2012; Peng and others, 2013; Deng and others, 2016; Chen and others, 2016; Jia and others, 2017; Liu and others, 2018; Zhou and others, 2018; Shan and others, 2019). The studies show that ~2.5 Ga granitoids can be sub-classified into two groups according to formation ages, namely the ~2.57 to 2.53 Ga and the 2.52 to 2.45 Ga. Some researchers referred ~2.52 to 2.45 Ga granites to late Neoarchean-early Paleoproterozoic granites, and all of which are termed as late Neoarchean granites (see Introduction) in this paper. The ~2.57 to 2.53 Ga granitoids are mainly biotite monzonitic granites with minor TTGs and dioritic rocks, and occasionally sanukitic granites. They share similar geochemical characteristics of granites from arc or arc-basin settings, and underwent metamorphism from greenshcist to amphibolites facies, same as those rocks in adjoining greenstone belts. Most studies suggested that this group experienced a geological process similar to subduction-collision (for example, Chen and others, 2016; Jia and others, 2017; Liu and others, 2018). The 2.52 to 2.45 Ga granites are mainly high-K granites and syenitic granites together with some migmatites. Geochemically, they formed in extensional tectonic settings, likely recording a post-orogeny event (for example, Jia and others, 2017; Zhou and others, 2018). Usually they do not exhibit any sign of metamorphism or deformation. In the field, these granites intruded into all older rocks including the 2.57 to 2.53 Ga granites. Extensive migmatization is the last magmatic activity during the Archean, occurring in old rocks, also in the 2.57 to 2.53 Ga granites. The leucosomes and melanosomes give ~2.5 to 2.45 Ga zircon ages similar to, or a little younger than, the coeval granite bodies. After that, nearly all Archean geological activities stopped in the NCC.

Geng and others (2012) synthesized more than 2600 Hf isotope data on the late Neoarchean zircons from the NCC, mainly from the eastern and central parts, with some from the western part. Recalculated single stage and two-stage Hf model ages of these zircons show age peaks of 3902 $\pm$ 13 Ma and 3978 $\pm$ 18 Ma, respectively, and also small peaks between 4.0 Ga and 3.5 Ga. The majority of zircon $\varepsilon Hf(t)$ values are positive, suggesting the possibility of crust and mantle differentiation at 4.0 to 3.9 Ga. Most magmatic zircons from the whole NCC have a Hf model-age range of 2.9 to 2.4 Ga, and the single stage model ages cluster at 2698 $\pm$ 4 Ma, whereas the two-stage model ages concentrate at 2714 $\pm$ 5 Ma, implying the protoliths were juvenile crustal

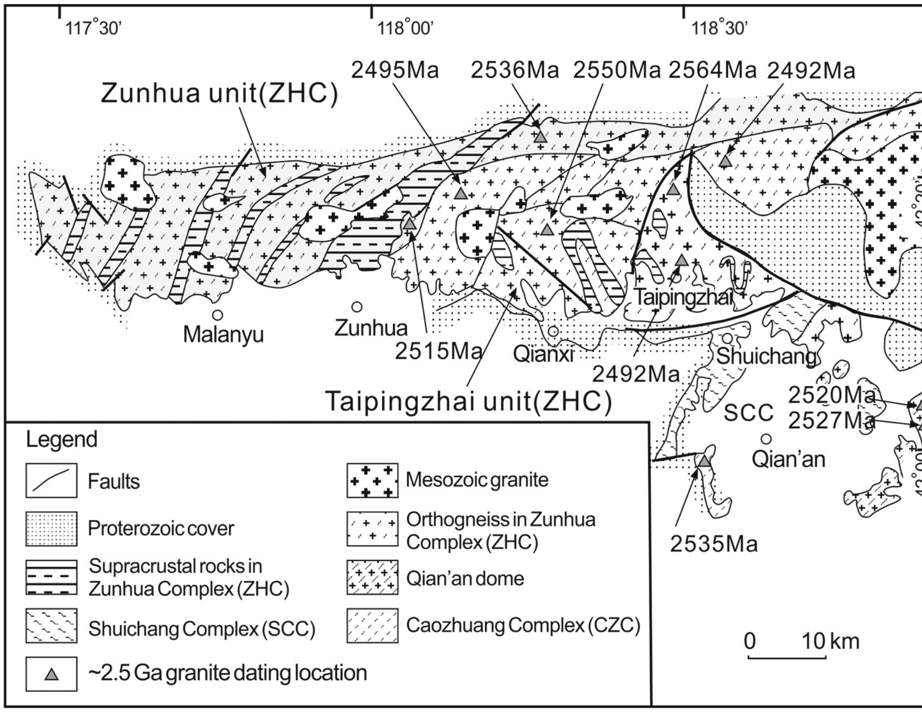

Fig. 6. ~2.5 Ga granites in eastern Hebei (modified from Geng and others, 2012).

rocks. The most prominent peak at 2.7 Ga indicates that this period marks the most important stage of the crust-mantle differentiation and crust formation of the NCC. The widespread ~2.5 Ga rocks in the NCC and the absence of the ~2.5 Ga peak in Hf model ages are consistent with the conclusion that many juvenile rocks were partially melted and reworked at 2.5 Ga.

Two phases of syenogranitic magmatism at ~2.5 Ga are recognized based on geological relationships, various degrees of metamorphism and deformation, as well as magmatic zircon ages. Syenogranitic granites commonly occur as intrusive bodies in basement rocks (fig. 6). Rocks produced during the first phase show gneissic textures, with zircon ages of 2.53 and 2.52 Ga, and locally comprise abundant TTG (Wan and others, 2012). Rocks of the second phase cut late Neoarchean TTG and supracrustal rocks, displaying a massive structure, and mainly formed between 2.52 and 2.50 Ga. All syenogranites share the same features in major element compositions. However, they are different in trace element, REE and Sm-Nd isotopic compositions, and can be subdivided into three types. Whole-rock Sm–Nd isotopic compositions show large variations in $\varepsilon_{Nd}(t)$ values and $T_{DM}(Nd)$ model ages. Those with $\varepsilon_{Nd}(t)$ values and $T_{DM}(Nd)$ modal ages within ranges of −9.49 to −4.72 and 3.70 to 3.25 Ga are Type 1. These with $\varepsilon_{Nd}(t)$ values and $T_{DM}(Nd)$ model ages within ranges of 0.55 to 1.03 and 2.77 to 2.71 Ga are Type 2 and those with $\varepsilon_{Nd}(t)$ values and $T_{DM}(Nd)$ model ages within ranges of −2.35 to 1.23 and 2.93 to 2.66 Ga are Type 3. Zircon Hf isotopic compositions of the three sample types show $\varepsilon_{Hf}(t)$ values and $T_{DM1}(Hf)$ ages of 0.7 to 7.2 and 2.84 to 2.56 Ga (Type 1), 2.6 to 7.4 and 2.74 to 2.56 Ga (Type 2) and 2.1 to 6.3 and 2.76 to 2.60 Ga (Type 3). It is suggested that syenogranites were mainly generated by melting of continental crust with different mean crustal residence ages, and most of them were emplaced during the second phase (2.52–2.50 Ga) in an extensional tectonic regime.

~2.5 Ga Metamorphism

Archean rocks in the NCC underwent multi-stage metamorphism (Zhao, 1993; Cheng, 1994; Zhai, 2004). Studies on ~2.7 Ga, ~2.6 Ga and ~2.5 Ga metamorphism have all been reported (for example, Chen and Li, 1996; Liu and others, 2008; Bai and others, 2016). Usually, metamorphic grades of the rocks from greenstone belts are relatively lower than those from high-grade regions, with the former being greenschist to amphibolite facies and rare granulite facies, while the latter being mainly granulite facies and partly high-grade amphibolites facies (Zhai, 2004). Recently, ~2.5 Ga granulite facies metamorphism got more attention and discussions (Santosh and others, 2012; Kwan and others, 2016; Yang and others, 2016, 2019; Duan and others, 2017; Wei, 2018).

Most Neoarchean amphibolites in the Qingyuan, Anshan, Jiapigou, Dengfeng, Yanmenguan and Wutai greenstone belts underwent metamorphism with temperatures of 500 to 650 °C and pressures of 5 to 8 kbar. The typical metamorphic mineral assemblage is amphibole (Amp) + plagioclase (Pl) +/− clinopyroxene (Cpx) +/− epidote (Ep) +/− quartz (Qz). Garnet rarely occurs in amphibolites in the Anshan (Gongchangling) and Wutai greenstone belts. Chlorite commonly replaced amphiboles, indicating retrograde metamorphism at greenschist facies. Meta-sedimentary rocks in Gongchangling and Benxi in the Anshan greenstone belt have paragenetic minerals of garnet (Grt) and staurolite (St), estimated metamorphic temperatures and pressures are ~500 to 550 °C and 5 to 7 kbar, respectively (Zhai and others, 1990). The Hongtoushan Group in the Qingyuan greenstone belt consists of fine grained biotite (Bt) gneiss, garnet-sillimanite gneiss and amphibolite. Their metamorphic temperature is up to 700 °C (Zhai and others, 1985; Gu and others, 2001). The meta-volcanic-sedimentary rocks in the Wutai Group commonly underwent greenschist-amphibolite facies metamorphism. Some rocks locally, for example in Zhijiafang Village, have paragenic minerals of staurolite and kyanite (Ky), estimated temperatures and pressures are 550 to 600 °C and 5 to 7 kbar, respectively (Tian, 1991; Zhao and others, 1999a). Taken together, a clockwise *P-T* path was constructed for the Wutai amphibolites (fig. 7). Recent studies (Qian and others, 2013; Qian and Wei, 2016) reported that garnet–mica schist in the lower part of the Wutai Group from Erkou may have experienced four metamorphic stages. The first-stage (S-I), which is revealed only from the infrequent garnet core zoning, is characterized by a flat *P-T* vector dominated by heating, closing to the low-pressure facies series. The second-stage (S-II) exhibits a steep *P-T* vector with increasing pressure and temperature to the pressure peak at >9.0 kbar/615 to 645 °C, being the medium-pressure facies series (kyanite type). The third stage (S-III) is the decompression with heating to the temperature peak at ~7.5 kbar/660 °C. The fourth stage (S-IV) is the further decompression after the temperature peak, accompanied with considerable cooling. This estimated pressure of peak metamorphism is the highest among the amphibolites of greenstone belts in the NCC. However, Qian and Wei (2016) further emphasized that the peak metamorphic age (S-II) is ~1.95 Ga, indicating this superimposed metamorphism occurred in the Paleoproterozoic rather than Archean.

Metamorphism of the rocks in the high-grade regions in the NCC are represented by high-temperature and medium pressure granulites, whose metamorphic temperatures and pressures are mostly of 750 to 850 °C and 6 to 8 kbar, respectively (Shen and others, 1990; Zhao, 1993; Cheng, 1994). Zhao (1993) emphasized that HT-MP metamorphism of the Neoarchean granulites was mainly controlled by early Precambrian hot thermal gradients, and garnet is commonly absent in mafic two pyroxene granulites. Zhai and others (1992, 2001b) and Zhao and others (1999b, 2000) pointed out

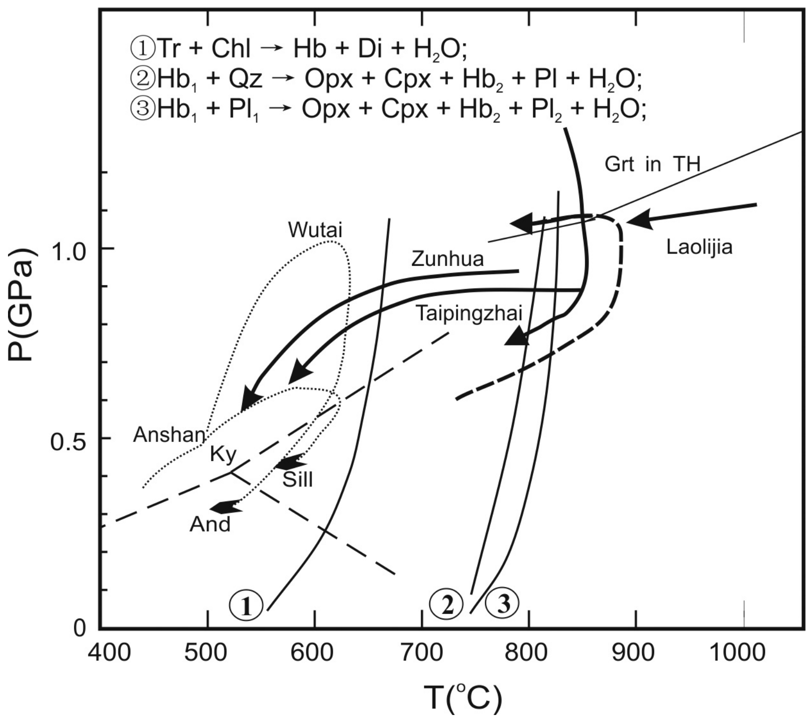

Fig. 7. Metamorphic *P–T* paths of the ~2.5 Ga metamorphic rocks (modified from Zhai and others, 1985; Tian, 1991; Zhao, 1993; Zhao and others, 1999a; Zhai and Santosh, 2013; Lu and others, 2017; Yang and Wei, 2017; Wei, 2018).

that the *P-T* paths of the Neoarchean mafic granulites are mostly anticlockwise (fig. 7), indicated by red-eye-sockets of fine-grained garnet coronas surrounding pyroxenes, which usually suggest decreasing temperatures with isobaric or weak decreasing pressures. The metamorphic *P-T* paths of Neoarchean rocks are different from the Paleoproterozoic (1.92–1.85 Ga) granulite metamorphism and the latter extensively overprinted the former one. The Paleoproterozoic metamorphism is HP granulite facies or granulite- eclogite transitional facies. The typical metamorphic textures of the Paleoproterozoic mafic granulites are white-eye-sockets of fine grained Cpx + Opx + Pl coronas surrounding Grts, indicating isothermal or weakly increasing temperature decompression in clockwise *P-T* paths (Zhai and others, 1992, 1995; Zhai, 2009; Zhou and others, 2017). Some recent studies discussed Neoarchean metamorphic temperature-pressure conditions and metamorphic paths and suggested a few new tectonic interpretations. The mafic granulites in the Taipingzhai–Laolijia domain in eastern Hebei contain two-pyroxene granulite facies assemblages which are commonly overprinted by a late phase of granulite facies marked by tiny-grained vermicular orthopyroxene-bearing assemblages. They only record the Neoarchean metamorphic ages at 2.53 to 2.52 Ga (M1) and 2.51 to 2.48 Ga (M2) as indicated by zircon U-Pb data, para-simultaneously with the emplacement of TTG rocks (Yang and Wei, 2017; Wei, 2018). The Archean two-pyroxene granulite assemblages are locally preserved, showing "red-eye socket" textures consisting of garnet coronas or fine-grained garnet and clinopyroxene bearing assemblages surrounding the early-stage pyroxenes. The peak metamorphic *P-T* conditions are 10 to 12 kbar and >900 °C, or even up to 1000 °C, and the retrograde metamorphic *P-T* conditions are 7 kbar and 870 to 890 °C. Therefore, Wei (2018) argues that the Neoarchean granulite facies metamorphism in eastern Hebei is ultra-high temperature metamorphism. Lu and others (2017) reported new studies of the Neoarchean granulites at Louzishan village in eastern Hebei. Four metamorphic mineral assemblages, formed at different metamorphic stages, are identified in pelitic granulites. Prograde mineral assemblage (M1) is represented by biotite, plagioclase, quartz, and ilmenite, preserved as mineral inclusions within garnet porphyroblasts. Peak mineral assemblage (M2), represented by the garnet cores, rutile, pseudomorphs of sillimanite after kyanite, and some matrix minerals, indicating *P-T* conditions of 12 to 13 kbar/820 to 850 °C. Post-peak mineral assemblage (M3), what consists of the inner rims of garnets and some matrix minerals, formed at *P-T* conditions of 11 kbar/850 °C. The final retrograde mineral assemblage (M4) is mainly represented by matrix biotite without rutile exsolution, and minor matrix plagioclase with relatively high anorthite contents. High-resolution secondary ion mass spectrometry (SIMS) U-Pb dating of metamorphic zircons demonstrates that the pelitic granulites possibly reached peak metamorphic stage at 2.5 Ga. Younger metamorphic ages (2.45–2.41 Ga) possibly represent the cooling ages of the granulites or the strong influence of a later event. Accordingly, it is to be emphasized that the pelitic granulites record clockwise *P-T-t* paths with sequential isothermal decompression and isobaric cooling segments, similar to Paleoproterozoic granulite facies metamorphism, although the latter commonly overprinted on the Neoarchean metamorphism with anticlockwise *P-T* paths. Two other localities of Neoarchean HP granulites with clockwise *P-T* paths have been reported by Wang and Guo (2017) and Liu and others (2015), although Zhou and others (2017) argued that they are probably Paleoproterozoic granulites.

In summary, ~2.5 Ga metamorphism in the NCC has the following characteristics; (1) Rocks in greenstone belts underwent greenschist-amphibolite facies metamorphism and have clockwise *P-T* paths; (2) rocks in high-grade regions mostly underwent HT-MP granulite facies metamorphism and have anticlockwise *P-T* paths; (3) recent studies show that metamorphic grade of some granulites in high-grade regions could reach ultra-high temperature granulite facies; (4) a small number of granulite samples in high-grade regions have higher metamorphic pressures (>10–12 kbar) and record clockwise *P-T* paths. Two *P-T* paths (clockwise and anticlockwise) probably coexist in Neoarchean high-grade regions; (5) Paleoproterozoic HT-HP granulite facies metamorphism was extensively superposed on the Neoarchean metamorphic rocks.

MICRO-BLOCK AMALGAMATION AND CRATONIZATION

Combining the lithologic associations and geochemical characteristics of the greenstone belts and related granitoids in the NCC, we suggest that most of the greenstone belts in the NCC were formed in island arc or back-arc basin settings, although Kusky and others (2001, 2004b) and Li and others (2002) reported dismembered ophiolitic remnants in the Zunhua (Dongwanzi) orogenic belt. As a typical example for our above proposal, the Zunhua greenstone belt (Zunhua unit) and a related granulite complex (Taipingzhai unit) occurring in the east of the Zunhua unit are considered to jointly constitute a Neoarchean island arc terrane, with the greenstones representing the upper domain and the granulite complex representing the root zone (Zhai and others, 2001a). Zhai (2004) postulated that the Zunhua greenstone belt and late Archean granites in eastern Hebei (Geng and others, 2006a; Yang and others, 2008) mark the boundary between the QH Block and the JN Block and represent an arc-continent collision zone. Wu and others (1998), Chen and others (2006), Liu and others (2006) and Wang (2009) considered the Mengyin greenstone belt and Wutaishan greenstone belt and related granitoids to represent the boundary between the JL Block and QH Block and between the OR and QH Blocks, respectively, each formed via limited subduction and collision.

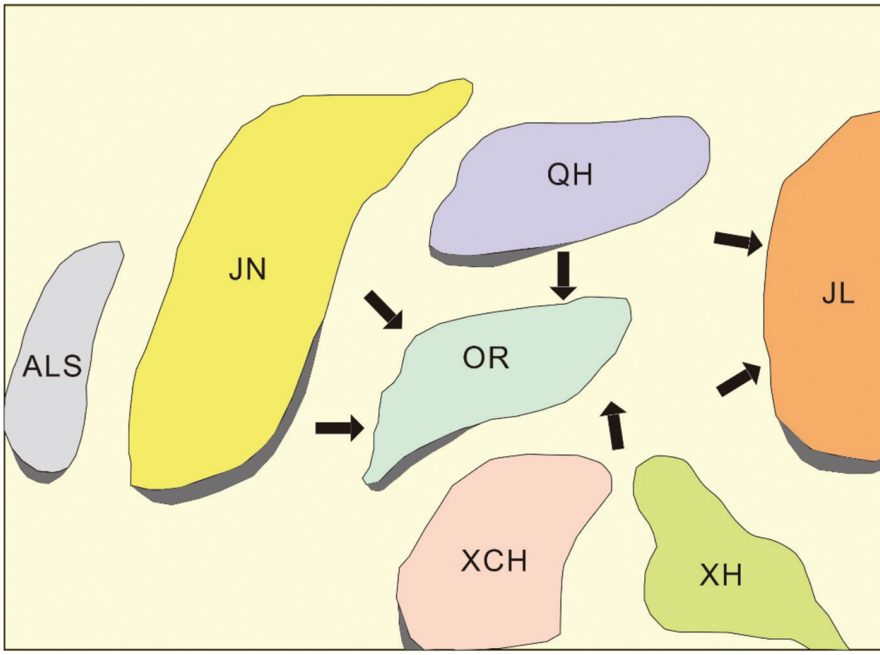

Fig. 8. Schematic diagram showing amalgamation of micro-blocks.

All the micro-blocks in the NCC were probably welded by late Archean greenstone belts at the end of the late Neoarchean (figs. 3B and 8, Zhai and others, 2001a; Zhai, 2004, 2011, 2014; Zhai and Santosh, 2011, 2013). The following evidence supports this argument: (1) Comprehensive U-Pb zircon data from the various blocks show that all the rocks underwent *ca.* 2.55 to 2.5 Ga metamorphism; (2) voluminous granitic sills of *ca.* 2.5 Ga intruded into the neighboring rock units; (3) deformed mafic dikes are extensively preserved as lenses within the various blocks, and 2.5 Ga coeval ultramafic-mafic and syenitic dikes have been reported from eastern Hebei (Li and others, 2010), indicating that the NCC probably had a large and rigid continental crust of considerable thickness over this time; (4) the 2.52 to 2.48 Ga volcano-sedimentary rocks occurring within the NCC cover the different blocks, such as the Qinglong, Upper Dantazi and some part of the Hongqiyingzi groups that occur in the JL and QH Blocks, the upper Zanhuang Group in the XCH and QH Blocks. Several studies reveal that the granite sills and pegmatites with magmatic zircon ages of 2570 to 2457 Ma and metamorphic ages of 2515 to 2500 Ma are extensively developed in all the micro-blocks (Guan and others, 2002; Shen and others, 2004; Wang and others, 2004; Luo and others, 2004; Jian and others, 2005; Wilde and others, 2005; Kröner and others, 2005; Wan and others, 2005; Lu and others, 2006; Zhang and others, 2012).

Recently, a group of papers discussed and demonstrated the processes of micro-block amalgamation in various areas of the NCC, such as south Jilin, Liaoning–northeastern Hebei, western Shandong, Yinshan in the northwestern NCC, southern Henan, northern Hebei–northern Shanxi, western East Hebei–northestern Shandong, Fuping–Wutai and other areas (for example, Nutman and others, 2011; Zhang and others, 2012; Wang and Liu, 2012; Santosh and others, 2016; Yang and others, 2016, 2019; Tang and others, 2016; Wang and others, 2017; Jia and others, 2017; Zhou and others, 2018; Tang and Santosh, 2018; Deng and others, 2018; Shan and others, 2019).

The characteristics of the boundaries between the micro-blocks, metamorphism of the greenstone belts, igneous and sedimentary rock associations, distribution and geochemistry of the ~2.5 Ga granites, 2.48 to 2.45 Ga migmatization, Neoarchean–Paleoproterozoic geochronological framework and tectonic models for the amalgamation are major issues to be discussed.

The Neoarchean greenstone belts probably represent arc–continent collision zones resulting in the amalgamation of the various micro-blocks. However, the metamorphic grades of the greenstone belts are lower than those of the complexes within the micro-blocks, suggesting that the latter might have developed under higher geothermal gradients. Therefore, we propose that the various micro-blocks were surrounded by small ocean basins in the late Neoarchean, whereas the old continental crust and the oceanic crust were hotter. Although the crustal subduction and micro-block collision were much smaller in scale than present, the main tectonic mechanism of the NCC has switched to lateral movements from vertical-movement dominated mechanism during ~2.7 Ga (Zhai, 2004; Zhao and Zhai, 2013). The amalgamation of the various micro-blocks and the formation of the NCC at *ca.* 2.5 Ga constitutes one part of the *ca.* 2.5 Ga supercraton event (Rogers and Santosh, 2003, 2004; Condie, 2004; Santosh and others, 2010). The formation of a large volume of granites by crustal melting is an important process of cratonization, generating the stable upper and lower crust layers. This process would lead to an upper crust of more granitic composition, and a lower crust with molten residual materials together with underplated materials of gabbroic components. The underlying mantle drives the cratonization process, through thermal and material input. A part of the asthenosphere mantle was transformed into the lithosphere mantle through magma extraction, resulting in crust-mantle coupling. The evolution of the lithospheric is closely linked to the cratonization process in the early history of the planet. The available lines of evidence show that the NCC behaved mostly as a stable continental block during *ca.* 2500 to 2350 Ma, and therefore, the 2.5 Ga boundary of Archean/Proterozoic is the most critical period in this craton, similar to the cases of many other ancient cratons globally (for example, Condie and others, 2001; Condie and Kröner, 2008).

Condie and Kröner (2013) propose that during the Archean, oceanic arcs may have been thicker due to higher degrees of melting in the mantle, and oceanic lithosphere would be more buoyant. These arcs may have accreted to each other and to oceanic plateaus; a process that eventually led to the production of Archean continental crust. After the Archean, oceanic crust became thinner due to cooling of the mantle and less melt production at ocean ridges, and hence, oceanic lithosphere became more subductable. This suggestion is similar to that of Zhai and others (2001a), besides, this author's other papers (Zhai, 2009, 2011, 2014; Zhai and Santosh, 2013) have discussed major difference of metamorphic *P-T* conditions between the Archean and Paleoproterozoic metamorphic rocks in the NCC. It is further suggested that there were some geological records in the NCC involving ocean closure, accretion and collision during 2.3 to 1.85 Ga, represented by three main collisional sutures (also termed as mobile belts): the Jiaoliao mobile belt in the northeastern NCC, the Jinyü mobile belt in the central and the Fengzhen mobile belt in the northwestern NCC. These collisional orogens formed through subduction and collision, whereas accompanying high pressure and ultrahigh-temperature metamorphic granulite facies rocks were developed (for example, Santosh and others, 2012; Tam and others, 2012), representing the operation of early plate tectonics in the NCC at least since ~2.0 Ga. As mentioned above, the metamorphic grades of the Neoarchean greenstone belts are lower compared to Paleoproterozoic metamorphism within the mobile belts, only reaching greenschist – amphibolite facies with medium-pressure conditions and clockwise *P–T* paths. However, the metamorphic grades of the high-grade regions are

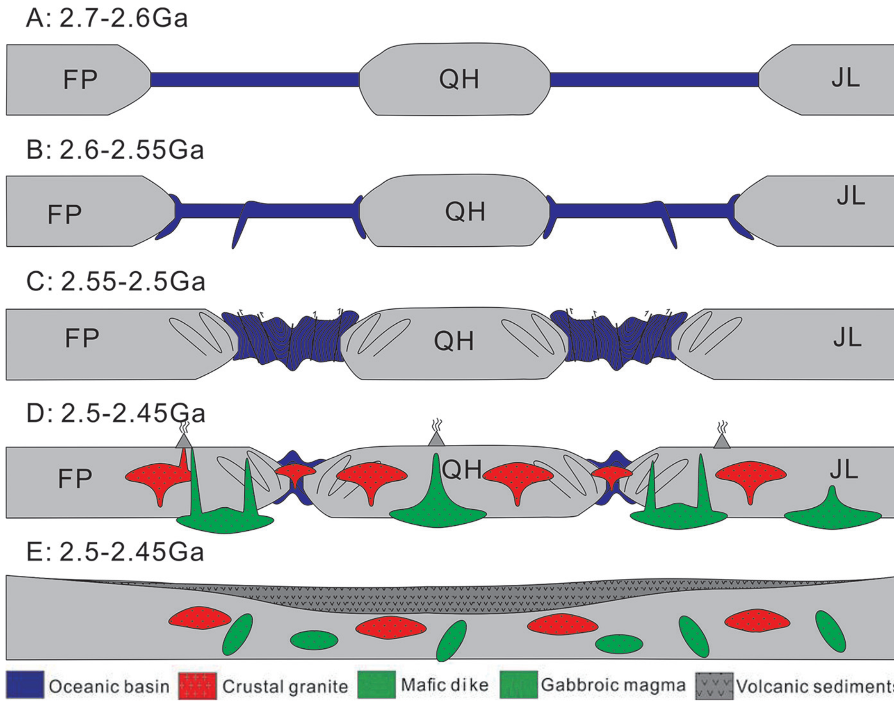

Fig. 9. Model of micro-block amalgamation (FP-Fuping terrain, QH-Qianhuai Block, JL-Jiaoliao Block).

high, up to high temperature, even ultrahigh temperature granulite facies, with typical anticlockwise *P–T* paths and rare clockwise *P–T* paths. Figure 9 shows the amalgamation processes of micro-blocks in the NCC. During 2.7 to 2.6 Ga, the micro-blocks of certain rigidity formed and were separated by small oceanic basins (fig. 9A). The compressional stresses forced the micro-blocks to move together and relative to one another during 2.6 to 2.55 Ga (fig. 9B). As result, the oceanic crusts subducted or obducted within crust-scale to micro-scale blocks. In addition, intra-oceanic subduction might have also taken place, and rock associations with arc/back-arc basin geochemical features formed. Because of high thermal gradients and great buoyancy, the oceanic crust cannot subduct beneath the micro- blocks, and therefore, the segments of ocean crust welded to the adjacent micro-blocks as boundary zones (fig. 9C). The continental stabilization or crust-mantle coupling of the NCC operated throughout the intrusion of vast crustal granites and gabbros (fig. 9D). During the latest stage of the Neoarchean, the formation of the cover sediments declared the termination of the Archean eon and meanwhile the final accomplishment of cratonization (fig. 9E). This model also gives an interpretation of Neoarchean metamorphism. The greenstone belts did not deeply subduct, thus they underwent low-medium grade metamorphism and recorded clockwise *P-T* evolution. The intrusion of gabbros and large-scale lower crust partial melting caused HT-UHT and anticlockwise metamorphic processes within the micro-blocks. Occasionally, crustal-scale subduction–collision resulted in formation of HP granulites with clockwise *P-T* paths.

CRITERION OF CRATONIZATION

Except for the vast granitoid intrusions derived from the lower crust, other criteria of cratonization, like mafic–syenitic dike swarms and sedimentary covers, were also developed during the cratonization of the NCC.

Magmatic Dikes

~2.5 to 2.45 Ga mafic dikes were extensively distributed in basement rocks in the NCC. They were metamorphosed to amphibolites or granulites, and the strong deformation gave them the appearances of lenses or boudins. They are mostly tholeiitic in composition and derive from continental mantle as indicated by their geochemical features.

Extremely rare Archean ultramafic–mafic and syenitic dikes have been found in the Xingshan, eastern Hebei. Figure 10A is a sketch geological map of the Xingshan area. The Caozhuang complex (CZC) and Shuichang complex (SCC) are metamorphosed Paleoarchean and Meso-Neoarchean complexes, respectively. The CZC contains remnants of 3.8 to 2.5 Ga old sial crust in the NCC, occupying an outcropping area of ~4 km^2. The >3.0 to 3.3 Ga rocks form approximately half of the outcropping rocks and include BIF-bearing supracrustal rocks and TTG–granitic gneisses. Although Wan and others (2016) reported Neoarchean ages for these BIFs, we still consider these are metamorphic ages. The remaining 50 percent are Neoarchean granitic rocks (Zhao, 1993). The SCC is a granulite facies metamorphic unit consisting of charnockites, granitic gneisses and BIF-bearing meta-supracrustal rocks.

The direct country rocks of the ultramafic–mafic and syenitic dikes are gneissic monzodiorite and BIF-bearing supracrustal rocks in the CZC. The intrusive boundaries are clear and the dikes cut the gneissosities of the country rocks and show spherical weathering in the field. They occur as subvertical intrusions with a NW310° striking direction, and are up to 300 m long and about 10 m wide. The ultramafic–mafic dikes are dark gray in color and consist mainly of clinopyroxene (40–70%), olivine (5–20%), orthopyroxene (5–20%), with minor hornblende (<5%), biotite (<2%), Fe–Ti oxides (<2%), spinel (<5%), with or without plagioclase (0–40%). The dikes can be subdivided into olivine pyroxenite and olivine gabbro, which exhibit medium-grained granular and gabbroic textures, respectively. The syenitic dikes consist predominantly of orthoclase (>75%) and biotite (5–15%), and minor plagioclase (<7%), quartz (<5%) and Fe–Ti oxides, but without pyroxene. The rocks display hypidiomorphic-granular texture. Their SHRIMP zircon U-Pb ages are 2504 and 2516 Ma, respectively (fig. 10B). Zircons from the olivine gabbro give single-stage Hf model ages between 2668 Ma and 2740 Ma, with a mean age of 2705 Ma, and εHf(t) values between +1.9 and +4.2. Zircons from the syenite show εHf(t) values between +2.7 and +4.4, with corresponding single-stage Hf model ages between 2705 to 2646 Ma and a mean value of 2677 Ma. Their geochemical features indicate that these dikes were derived from a deep subcontinental lithospheric mantle source, which implies that the NCC probably had a large and rigid continental crust with a considerable thickness through amalgamation of micro-blocks and cratonization of basement at *ca.* 2.5 Ga.

Cratonic Sedimentary Cover

Low-grade metamorphic volcanic-sedimentary rocks in the northern NCC, traditionally termed as the Hongqiyingzi Group (un-published data), the Dantazi Group, the Qinglong Group and the upper Zanhuang Group (Lü and others, 2012; Zhai, 2014), are obviously different from the high-grade metamorphosed basement rocks, either in metamorphic grades or in field occurrences. The high-grade metamorphic rocks commonly have metamorphic ages of ~2.60 Ga and ~2.56 to 2.50 Ga. The low-grade metamorphic rocks commonly have ages of 2.52 to 2.49 Ga. Therefore, the

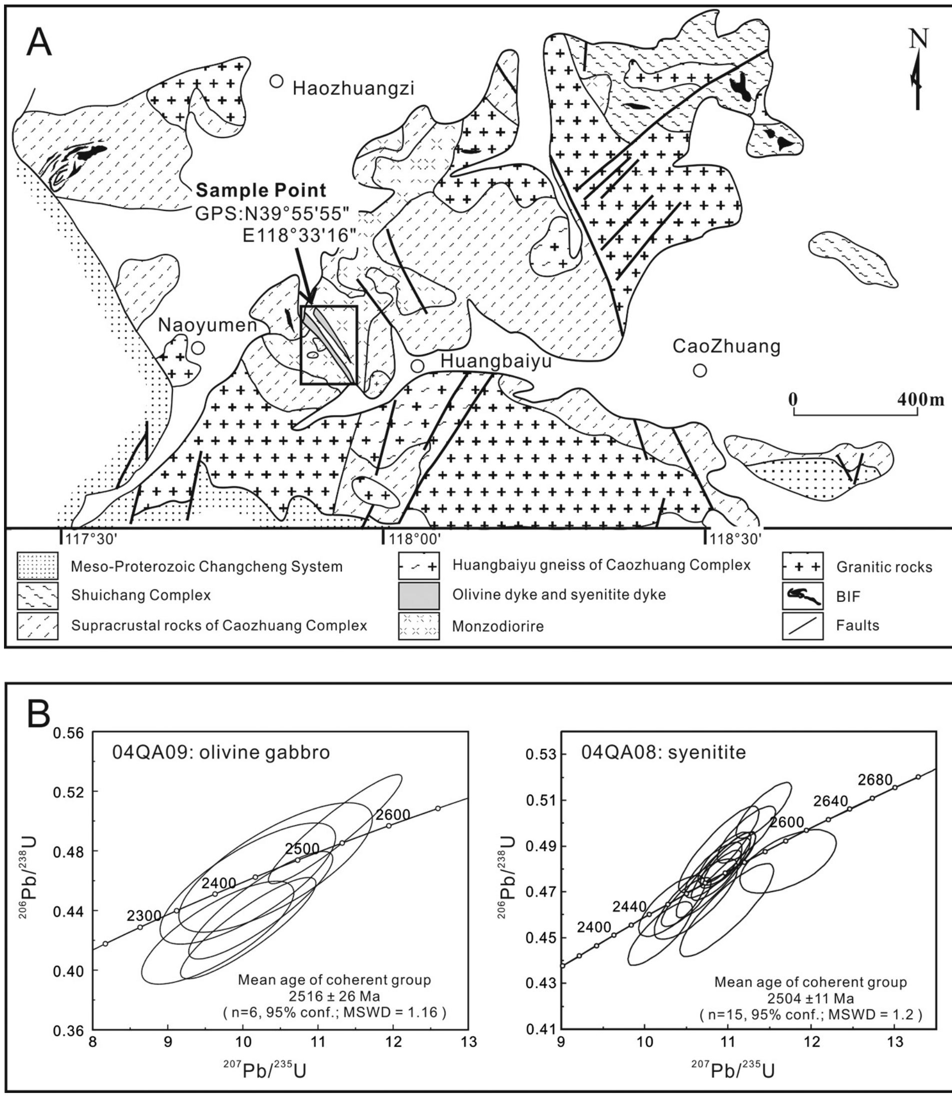

Fig. 10. Sketch map of the Xingshan area (A) and Zircon U-Pb ages of olivine gabbroic and syenititic dikes (B) (after Li and others, 2010).

lower grade supracrustal rocks were probably deposited within the craton at the end of the Neoarchean, representing a sedimentary cover after cratonization of the NCC.

The Qinglong volcano-sedimentary rock sequence (QVRS) is located in the eastern part of eastern Hebei, mainly along the Mutoudengzi-Shuangshanzi-Jiashijiao belt-like area. It is unconformably covered by the Mesoproterozoic Changcheng System, and overlies the neighboring Qianxi Complex, which experienced relatively high-grade metamorphism to the west, and is in fault contact with the dome-shaped Anziling pluton and Jielingkou metadiorite to the east. The QVRS is composed of greenschist to lower amphibolite facies metamorphic rocks, which are amphibolite, meta-felsic rocks, meta-basic to meta-felsic volcanic rocks, schists, metaconglomerates,

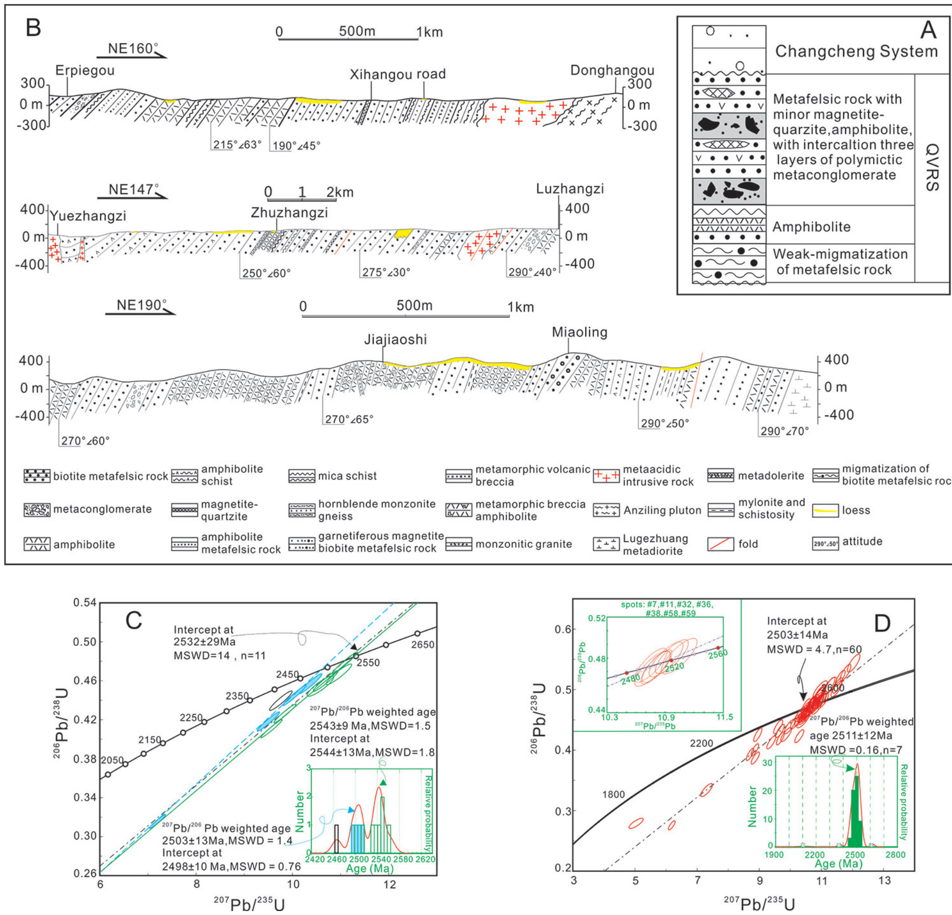

Fig. 11. Comprehensive columnar section of the QVRS (A), three geological profiles in the Qinglong area (B), and SIMS U-Pb zircon concordia diagrams for metafelsic rock (C) and meta-basalt (D) (after Lü and others, 2012).

as well as a small amount of meta-sandstones, magnetite-bearing quartzites, and BIF (fig. 11A). The QVRS is generally northeast-oriented, dipping west with dipping angles between 30° and 70°. The lowest part shows the low-migmatization of biotite meta-felsic rocks, which are intercalated with hornblende-biotite meta-felsic rocks, and magnetite quartzite. This part is distributes in a south-north trending area, neighboring the Anziling pluton. Relic sedimentary structures, such as cyclothem structure have been preserved. The middle part varies from chlorite-quartz schist to amphibolite and schist. In the Xihangou cross-section (fig. 11B), several pillow lava layers are preserved. This cross-section is composed of about 30 percent metasedimentary rocks, 29 percent meta-basic volcanic rocks, 39 percent meta-felstic volcanic rocks, and 2 percent meta-intermediate volcanic rocks. The upper part consists of biotite meta-felsic rocks and hornblende meta-felsic rocks, with minor magnetite quartzite, amphibolite, and three intercalation layers of polymictic meta-conglomerate. The Luzhangzi cross-section consists of approximately 78 percent meta-sedimentary rocks, 9 percent meta-basic volcanic rocks, 8 percent meta-felsic volcanic rocks, and 5 percent meta-conglomerates. The volcanic rocks in this sequence show bimodal compositions. The

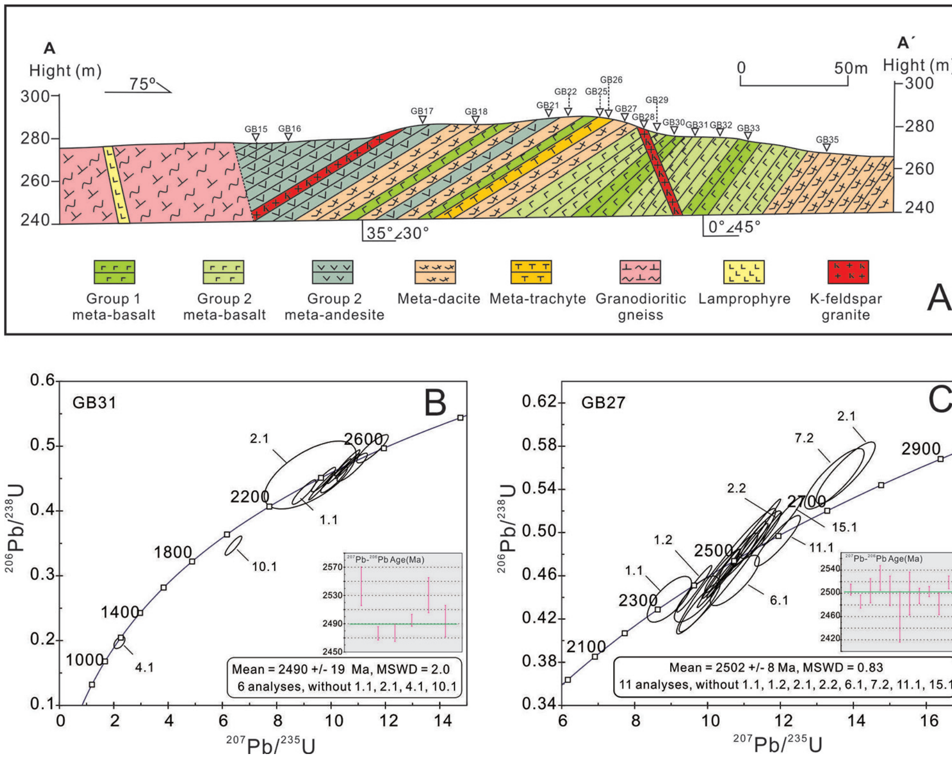

Fig. 12. Geological profile of the upper Dantazi Group in the Dayinshan area (A) and SHRIMP zircon U-Pb ages of basalt (B) and dacite (C) (after Ge and others, 2015).

distribution of these rocks is controlled by the Qinglong Fault zone. Zircons give a weighted mean $^{207}Pb/^{206}Pb$ age of 2511 ± 12 Ma for the meta-felsic volcanic rocks and 2503 ± 13 Ma for the meta-basic volcanic rocks (figs. 11C and 11D). These ages indicate that the QVRS formed during the period of 2511 to 2503 Ma. The meta-felsic volcanic rocks display low MgO (0.96 wt. %–2.67 wt.%), Cr (50.9 ppm–87.1 ppm), and Ni (2.78 ppm–6.18 ppm) contents. Low Nb/Ta ratios (13.56–14.54) and high light rare earth elements (LREEs) ($(La/Yb)_N$= 14.75–22.04) indicate they should been produced by the partial melting of the lower crust. The meta-basic volcanic rocks (low-grade amphibolites) have MgO of 3.86 wt.% to 7.74 wt.% , and SiO_2 of 46.11 wt.% to 51.99 wt.% . They are enriched in LREEs and depleted in high field strength elements (HFSEs) with positive $\varepsilon_{Nd}(t)$ values (+2.6–+2.9). The zircon $\varepsilon_{Hf}(t)$ (t = 2511 Ma) values of amphibolite range from −4.7 to +5.7, with corresponding single-stage Hf model ages from 2622 Ma to 3030 Ma (peak at 2835 Ma). For the meta-felsic volcanic rocks, the zircon ε_{Hf} (t) values range from −3.2 to +5 with two-stage model ages ranging from 2683 Ma to 3180 Ma (peak at 2872 Ma). As a part of the late Neoarchean cover of the NCC, the QVRS is proposed to have formed during an intra-continent rift at 2500 Ma, followed by the regional high-grade metamorphism of 2.52 to 2.54 Ga (Lü and others, 2012).

Another well studied low-grade volcano-sedimentary rock series is the upper Dantazi Group distributed in Dayinshan–Hushihan area, northern Hebei. In the Dayinshan cross-section (fig. 12A), these rocks commonly occur as thick-bedded and massive blocks and show transitional relationships among various units. In some cases, they also occur as xenoliths of various dimensions within the Xiaoguanzhuang granodioritic gneiss, suggesting that they were intruded by the protoliths of the Xiaoguanzhuang gneiss. The meta-volcanic rock sequence in the Dayinshan cross-section consists of approximately 40 percent meta-basalt, 23 percent meta-andesite, 2 percent meta-trachyte and 35 percent meta-dacite. In addition, these meta-volcanic rocks were invaded by K-feldspar granitic veins of different scales. These meta-volcanic rocks consist of bimodal basalt-andesite and trachyte-dacite with a SiO_2 gap between 54.4 wt. % and 60.7 wt. %. SHRIMP zircon U-Pb ages of the meta-mafic and meta-felsic volcanics are 2490 ± 19 Ma (MSWD = 2.0) and 2502 ± 8 Ma (MSWD = 0.83), respectively (figs. 12B and 12C), representing the timing of igneous activity. On the basis of petrography and whole-rock geochemistry, the metamorphosed mafic volcanic rocks can be divided into two groups. The Group 1 rocks might have resulted from the cumulation of Fe-Ti oxides and large amounts of trapped differentiated liquids during cumulate formation in the lower part of a magma chamber at the crust/mantle boundary. This is also consistent with the presence of a large amount of Fe-Ti oxide phenocrysts in the rocks of Group 1. The meta-basalts and meta-andesites of Group 2 represent the primary and evolved magmas, respectively. All the meta-mafic volcanic rocks display coherent trace element and REE patterns which are characterized by enriched LILE and LREE but depleted HFSE and HREE with $(La/Yb)_N$ values being 6.29–15.10). Combining these trace element features with the positive zircon εHf(t) values (+1.0 to +6.3), it was proposed that the mafic rocks were likely derived from partial melting of a previously metasomatized lithospheric mantle. In the primitive mantle-normalized diagram, the felsic rocks display uniform patterns enriched in LILE but depleted in Nb and Ta, similar to those of lower crust. Furthermore, their strongly fractionated REE ($(La/Yb)_N$ = 15.24–61.20), lower HREE concentrations (Yb = 0.47–1.65 ppm) and positive zircon εHf(t) values (+1.7 to +5.0) suggest that they were derived from partial melting of the lower crust with garnet in the residue. This coeval occurrence of metasomatized mantle-derived mafic magmas and potassic felsic magmas from different source regions reflects an intra-continental extensional setting in the NCC after the amalgamation of the micro-blocks at the end of the Neoarchean (Zhai, 2014; Ge and others, 2015).

SUMMARY AND CONCLUSION

The *ca.* 2.5 Ga time boundary between the Archean and the Proterozoic eons represents one of the most important evolving stages of the Earth, that is, the global cratonization or the formation of supercraton(s) that was unseen and is unrepeated in the following history of the Earth's formation and evolution. The NCC experienced a complex geological evolution history since the early Precambrian onwards, and carries important records of the secular changes in crustal growth and tectonic evolution.

1. Figure 13 demonstrates frequency of geological history and crustal growth in the NCC (red lines) and other cratons in the world (black lines). For continental crustal growth, the NCC experienced multi-stage growth processes with a dominate peak at ~2.9 to 2.7 Ga (Wan and others, 2011a, 2011b). By contrast, ~2.5 Ga crustal growth in the NCC is obviously stronger than that in other cratons (Zhai, 2004; Geng and others, 2012). Recent studies show that zircon U-Pb data of TTG gneisses have two prominent age peaks at *ca.* 2.9 to 2.7 Ga and 2.6 to 2.5 Ga which may correspond to the earliest events of major crustal growth in the NCC. Hafnium isotopic model ages range from *ca.* 3.8 to 2.5 Ga and mostly are in the range of 3.0 to 2.6 Ga, with a peak at 2.82 Ga. Most of the 2.9 to 2.7 Ga TTG gneisses underwent metamorphism at 2.6 to 2.5 Ga as indicated by ubiquitous metamorphic rims around the cores of magmatic zircon in these rocks. Abundant *ca.* 2.6 to 2.5 Ga orthogneisses have zircon Hf and whole-rock Nd model ages mostly around 2.9 to 2.7 Ga and some around

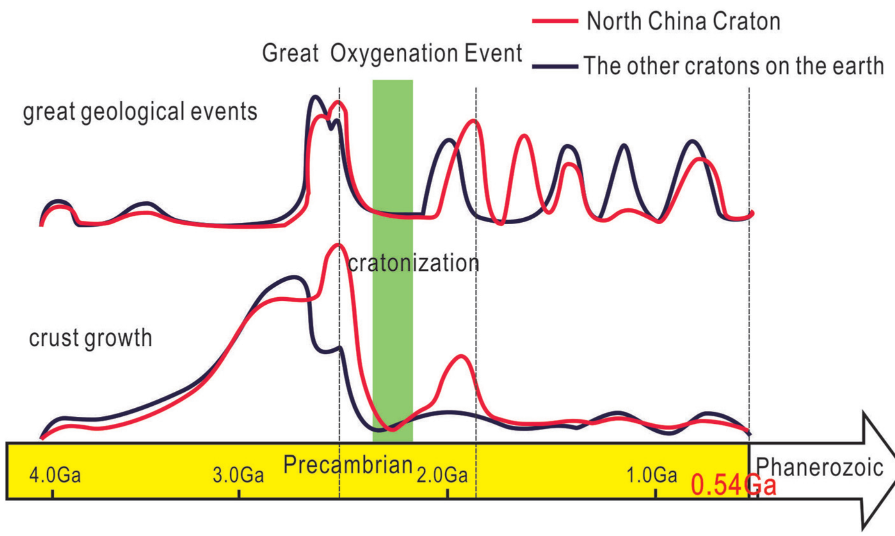

Fig. 13. Diagram showing change trends of crust growth and tectonic evolution in the NCC and other cratons in the world (after Zhai and Santosh, 2013).

2.6 to 2.5 Ga, indicating the timing of protolith formation or extraction of the protolith magma from the mantle. Therefore, it is suggested that the 2.6 to 2.5 Ga TTGs probably represent a coherent event of continental accretion and major reworking (crustal melting).

2. Zhai and others (2001a) and Zhai (2014) interpreted that the ~2.5 Ga crustal growth event represents cratonization of the NCC throughout assembly of micro-blocks and reworking of old metamorphic basement. The main evidence is as follows: (1) nearly all old rocks of >2.5 Ga underwent ~2.52 to 2.5 Ga metamorphism of amphibolite–granulite facies; (2) archaic basement rocks in the North China (various micro-blocks) experienced strong partial melting and migmatization; (3) the granitoid rocks derived from crustal partial melting include potassic granites, TTG granites and monzonites, which come, respectively, from continental crust (sedimentary rocks with TTG gneisses), juvenile crust (mafic rocks with TTG gneisses) or mixed crust. These granitoids intrude both the Archean greenstone belts and micro-blocks; (4) ~2.5 Ga mafic dikes (amphibolites), granitic dikes (veins) and syenitic–ultramafic dikes are extensively developed and experienced strong deformation; (5) Low grade sedimentary sequences as the cover of the craton extensively were deposited within the craton after the major tectono-thermal event (amalgamation).
3. The formation of crust-melting granites is one of the key processes of cratonization, inducing the generation of stable upper and lower crustal layers. This process also results in a more felsic composition of the upper crust, and more mafic composition of the lower crust. Because some molten residual materials and some underplating gabbros were the components of lower crust, the metamorphic grades of upper crust and lower crust are obviously different. The difference in compositions and metamorphic facies of these layers led to the coupling between upper and lower crust both physically and chemically.
4. The ~2.5 Ga amalgamation of the micro-blocks in the NCC implies interaction between continent and ocean with limited subduction and collision, showing an important transform from early vertical movement dominated tectonics to

limited horizontal tectonics, which, in turn, is still different in regime from modern-style plate tectonics (Zhai and others, 2010).

5. The NCC behaved as a stable continental land with rare tectonic-thermal action during ~2500 to 2350 Ma, as in other cratons in the world, and therefore, the 2.5 Ga time boundary of Archaean/Proterozoic have epoch-making significance in Earth's origin and evolving history (Condie and others, 2001). It is proposed that the global lithosphere formed with a global cratonization process. A supercraton or a cratonic supergroup with a short distance to each other possibly had formed at the end of late Neoarchchean, which was similar in volume to the Pangea supercontinent as suggested by Rogers and Santosh (2003, 2004). After the tectonic unconformity period of ~2.45 (2.5) to 2.35 (2.3) Ga, the supercraton or cratonic supergroup then experienced a global rifting event, the Huronian glaciation and the Great Oxygen Event. All above events indicate a sharp and fundamental change, adjustment and new coupling between solid spheres, atmosphere and hydrosphere of the Earth. The important significance and profound connotation of Neoarchean craton-iztion is worth continuing with in-depth studies and discussions.

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