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Research paper

Multi-stage crustal growth and cratonization of the North China Craton

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ABSTRACT

The North China Craton (NCC) has a complicated evolutionary history with multi-stage crustal growth, recording nearly all important geological events in the early geotectonic history of the Earth. Our studies propose that the NCC can be divided into six micro-blocks with $>\sim 3.0$–3.8 Ga old continental nuclei that are surrounded by Neoarchean greenstone belts (GRB). The micro-blocks are also termed as high-grade regions (HGR) and are mainly composed of orthogneisses with minor gabbros and BIF-bearing supracrustal beds or lenses, all of which underwent strong deformation and metamorphism of granulite- to high-grade amphibolite-facies. The micro-blocks are, in turn, from east to west, the Jiaoliao (JL), Qianhuai (QH), Ordos (ODS), Ji'ning (JN) and Alashan (ALS) blocks, and Xuchang (XCH) in the south. Recent studies led to a consensus that the basement of the NCC was composed of different blocks/terranes that were finally amalgamated to form a coherent craton at the end of Neoarchean.

Zircon U-Pb data show that TTG gneisses in the HGRs have two prominent age peaks at ca. 2.9–2.7 and 2.6–2.5 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 3.0–2.6 Ga with a peak at 2.82 Ga. Recent studies revealed a much larger volume of TTG gneisses in the NCC than previously considered, with a dominant ca. 2.7 Ga magmatic zircon ages. Most of the ca. 2.7 Ga TTG gneisses underwent metamorphism in 2.6–2.5 Ga as indicated by ubiquitous metamorphic rims around the cores of magmatic zircon in these rocks. Abundant ca. 2.6–2.5 Ga orthogneisses have Hf-in-zircon and Nd whole-rock model ages mostly around 2.9–2.7 Ga and some around 2.6–2.5 Ga, indicating the timing of protolith formation or extraction of the protolith magma was from the mantle. Therefore, it is suggested that the 2.6–2.5 Ga TTGs probably represent a coherent event of continental accretion and major reworking (crustal melting).

As a distinct characteristic, nearly all GRBs in the NCC underwent amphibolite-facies metamorphism. Zircon U-Pb ages of metamorphosed GRB mafic rocks mainly show two peak ranges at ∼2.6–2.5 and 2.8–2.7 Ga. The mafic rocks are commonly believed to be derived from metabasalts, it is therefore possible that the ages represent the time of metamorphism. The tectonic settings of the GRBs are still a problem. Their geochemical characteristics are, respectively, similar to back-arc basins, rifts, island arcs or suggest imprints of mantle plumes. BIFs occur in all GRBs but also in the HGRs. This metallogenic specificity is quite different from all Phanerozoic geotectonic settings.

The ∼2.5 Ga metamorphic-magmatic event is stronger than in most other cratons in the world. How to understand the geological significance of the 2.5 Ga event? The following points are emphasized: (1) nearly all old rocks >2.5 Ga underwent metamorphism at ∼2.52–2.5 Ga; (2) Archean basement rocks in the NCC experienced strong partial melting and migmatization; (3) granitoid rocks derived from partial

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melting include potassium granites, TTG granites and monzonites. These granitoids rocks intruded both the Archean greenstone belts and micro-blocks; (4) ~2.5 Ga mafic dikes (amphibolites), granitic dikes (veins) and syenitic-ultramafic dykes are also developed. Therefore, we suggest an assembly model that all micro-blocks in the NCC were welded together by late Archean greenstone belts at the end of the late Neoarchean. We also propose that the various micro-blocks were surrounded by small ocean basins, and the old continental crust and the oceanic crust were hotter than today. Subduction and collision were on much smaller scales as compared to the Phanerozoic plate tectonic regime, although the tectonic style and mechanisms were more or less similar. The formation of crustal melt granites is one of the processes of cratonization, inducing generation of stable upper and lower crustal layers. This process also generated an upper crust of more felsic composition and a lower crust of more mafic composition, due to molten residual materials and some underplated gabbros.

1. Introduction

It is generally believed that the generation and growth of continental crust largely achieved in the early Precambrian time, and ~75–80% or more continental crust had formed before 2.5 Ga (e.g., Brown, 1979; Armstrong, 1981; Dewey and Windley, 1981; McLennan and Taylor, 1982; Windley, 1995; Condie, 2000; Rogers and Santosh, 2003). The recent studies show that the oldest continental rocks in the Earth are tonalitic gneiss and the oldest zircons are detrital zircons in sedimentary rocks which were sourced from TTG protoliths (e.g., Wilde et al., 2001; Iizuka et al., 2006; Nemchin et al., 2006; Harrison, 2009; Herzberg et al., 2010; Condie and Kröner, 2013; Nance et al., 2013). Many of the Archean terranes with ages ranging up to 4.0–3.8 Ga over the globe dominantly comprise TTG (tonalite-trondhjemite-granodiorite gneisses) with or without minor volumes of meta-supracrustal rocks and meta-gabbros (e.g., Nutman et al., 1993, 2000). The continental nuclei, in general, are surrounded by younger supracrustal rocks and intrusives. The general consensus is that the major part of continental crust on the globe was generated during 2.8–2.7 Ga, marked by the formation of voluminous TTGs and volcanic rocks (Zhao et al., 1993; Windley, 1995; Goodwin, 1996). However, growth of continental crust seemly is episodic (Condie, 2000, 2001, 2004; Condie and Kröner, 2008), the most significant growth episodes probably are ~3.8, ~3.3, ~2.9–2.7 and 2.6–2.5 Ga (Zhai, 2011, 2013a). The formation of TTGs is contributed to the generation of large volumes of juvenile crust, and the TTG rocks were probably derived from mafic rocks by partial melting with varying degrees of interaction with mantle peridotite (e.g., Martin et al., 2005; Smithies et al., 2007).

The craton is described in geological literatures as a part of the Earth's crust which has attained stability, and which has been subjected to little deformation for a prolonged period. Most cratons in the world are considered to have been formed in late Neoarchean, with only minor amounts formed in Paleoproterozoic (ca. 2.0–1.9 Ga). Nearly all of the older cratons are thought to have been incorporated within a supercraton at ca. 2.5 Ga (Rogers and Santosh, 2003, 2004; Kusky et al., 2007; Zhai et al., 2007; Zhai, 2008). However, the mechanism and pattern of aggregation of the early Precambrian continental blocks to form a supercraton is controversial, for example, rifting, density-inversion, back arc basin formation, arc-arc accretion, subduction of oceanic lithosphere, and arc-continent or continent-continent collision (Windley, 1973, 1993, 1995; Jordan, 1978; Arndt, 1983; Nisbet, 1987; Hoffman, 1988; Kusky, 1990; Mitchell, 1991; Kröner and Layer, 1992; Goodwin, 1996; Condie, 2000; Eriksson and Catuneanu, 2004; Kusky et al., 2004). The driving mechanism of the above processes is also debated with models varying from intra-continent tectonics, plume tectonics to plate tectonics.

Zhai et al. (2010) estimated that the volumetric crustal growth of the NCC was about 90% by 2.5–2.45 Ga based on new geological map, geophysical data and geochronological data. 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, 1998; Wan et al., 2005, 2011a; Wu et al., 2005; Geng et al., 2006, 2012; Zhai et al., 2007; Jahn et al., 2008; Liu et al., 2009). The samples before 2.9 Ga account for ~15% of the total, whereas samples after 2.5 Ga account for only ~7%. Samples with T_{DM} ages between 2.9 and 2.5 Ga account for 78% of the total (Jahn and Zhang, 1984; Jahn, 1990; Zhang, 1998). Two discernible peaks are at ~2.7 and 2.9 Ga. The relationship of $\varepsilon_{Nd}(t)$ and t/Ga shows two characteristics: all values of $\varepsilon_{Nd}(t)$ are positive, and there is an obvious change of $\varepsilon_{Nd}(t)$ with the change of t. The values of $\varepsilon_{Nd}(t)$ deviate from the depleted mantle evolution curve at about 3.0 Ga, which is attributed to contamination of crustal materials and indicates that a thick continental crust existed in the NCC during the Neoarchean. Rare earth elements (REE) also demonstrate the same tendency, for example the higher La/Nb ratios of pre 3.0 Ga mafic rocks indicate the presence of a considerable continent crust by this time (Jahn, 1990). The most mafic granulites and amphibolites from the NCC display REE patterns similar to those of basalts from island arc, continental margin and within continent settings, indicating that these rocks formed in different tectonic settings. However, few samples have mid-ocean ridge basalt (MORB) characteristics. The Hf isotopic model ages range from ~1.95 to 3.8 Ga, the main scope is 2.6–3.0 Ga with a peak of 2.82 Ga. Zircon U-Pb ages from magmatic rocks, mainly orthogneiss, demonstrate several scopes of 3.6–3.8, 3.0–3.3, 2.7–2.9 Ga with a peak value of 2.5–2.6 Ga, the latest one of which indicates an extensively crust partial melting event in the NCC.

At least six micro-blocks have been identified including the Jiaoliao Block (JL), the Qianhuai Block (QH), the Ordos Block (OR), the Ji'ning Block (JN), the Xuchang Block (XCH), and the Alashan Block (ALS) (Zhai, 2011; Zhai and Santosh, 2011, see Figs. 1 and 8A). The cratonization of the NCC at the end of Neoarchean (Archean–Proterozoic boundary) through the amalgamation of micro-blocks was accompanied by granulite facies metamorphism and voluminous intrusion of crustally-derived granitic melts leading to the construction of the basic tectonic framework of the NCC. Several Neoarchean greenstone belts surround the micro-blocks and represent the vestiges of older arc-continent collision.

The above-mentioned demonstrates that the NCC had a complicated evolutionary history with multi-stage crustal growth, recording nearly all important geological events in the early geotectonic history of the Earth. The ~2.5 Ga metamorphic-magmatic event in the NCC is stronger than in most other cratons in the world. The formation of crustal melt granites is one of the processes of cratonization, inducing generation of stable upper and lower crustal layers. This process also generated an upper crust of more felsic composition and a lower crust of more mafic composition, due to molten residual material and some underplated

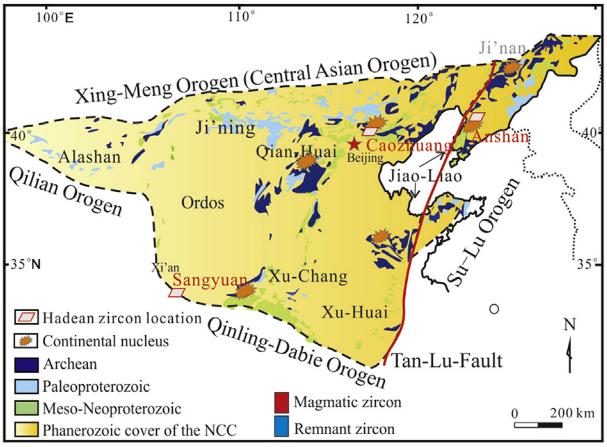

Figure 1. Simplified map of the NCC showing Precambrian rocks.

gabbros. ∼2.5 Ga cratonization of the NCC probably is corresponding to a global supercraton event (Rogers and Santosh, 2009) and indicates geological implication for boundary between Archean and Proterozoic.

2. Original generation of terrestrial continental crust and continental nucleus

2.1. *The oldest terrestrial mineral record*

The oldest known rock on Earth, the Acasta gneiss, is just over 4 Ga old and occurs as a relatively small expanse of outcrops of 20 km^2 in the northwestern part of the Slave Craton, Canada (Harrison et al., 2006; Harrison, 2009). These 4.03–3.96 Ga gneisses are heterogeneous assemblage of highly deformed TTG (tonalite-trondhjemite-granodiorite) complexes, tectonically interleaved on a centimeter scale with amphibolite, ultramafic rocks and pink granites (Bowring and Williams, 1999). The oldest minerals are detrital zircons from the ca. 3.0 Ga Jack Hill and Mt. Narryer quartzites in western Australia. These detrital zircons have U-Pb SHRIMP ages ranging from about 4.4 to 3.5 Ga, although only a small fraction of the zircons are >4.0 Ga (Wilde et al., 2001). The REE distributions coupled with oxygen isotope resulting from this sample suggest that the oldest zircons came from TTGs (Mojzsis et al., 2001; Wilde et al., 2001). This would seemly mean that continental crust formed earlier than oceanic crust. The magma ocean model proposes that continental nuclei form by the process of magmatic differentiation or re-melting of magmatic rocks (Wood et al., 1970; Hostetler and Drake, 1980; Kamber, 2007; Zhang and Guo, 2009). The zircons older than 4.0 Ga have also been reported as xenocrysts in younger Archean granitoids from different cratons (Cavosie et al., 2007). The continental nuclei, in general, are surrounded by younger supracrustal rocks and intrusives. Windley and Bridgwater (1971) first pointed out that there are two fundamentally different types of Archean terranes, granulite-gneiss and greenstone-granite belts, which have different protoliths and represent different erosional levels of the crust. The history of research on early Earth rocks revealed a secular change in ideas applied to the origin of tectonic belts, from pre-mobilist (plate tectonic) geosynclinal theory to initial, simplistic plate tectonic ideas, to increasingly sophisticated plate tectonic models. Generation and growth of juvenile continental crust (TTGs) suggested subduction-accretion model or plume (e.g., Condie, 2004; Windley, 2007). The next oldest expanse of terrestrial rocks is ∼3.8 Ga (3.9–3.6 Ga), some outcrops in different cratons have been studied, for example the Itsaq gneiss complex of SW Greenland (Nutman et al., 2007) and the Nuvvuagittuq (Porpoise Cove) Greenstone Belt, northeastern Superior Province, Canada (O'Neil et al., 2007). The study on Sm-Nd isotopic geochemistry for ∼3.8 or >3.8 Ga TTGs and mafic-ultramafic rocks shows that the mantle in Archean–Hadean boundary period had an obvious depletion, ε_{Nd} rapidly changed to +5 from chondritic at ∼4.0–4.2 Ga. The above mentioned indicates that the terrestrial continental crust possibly formed in >4.0–4.4 Ga, ∼3.8 Ga is an important generation period (Bennett et al., 1993; O'Neil et al., 2007).

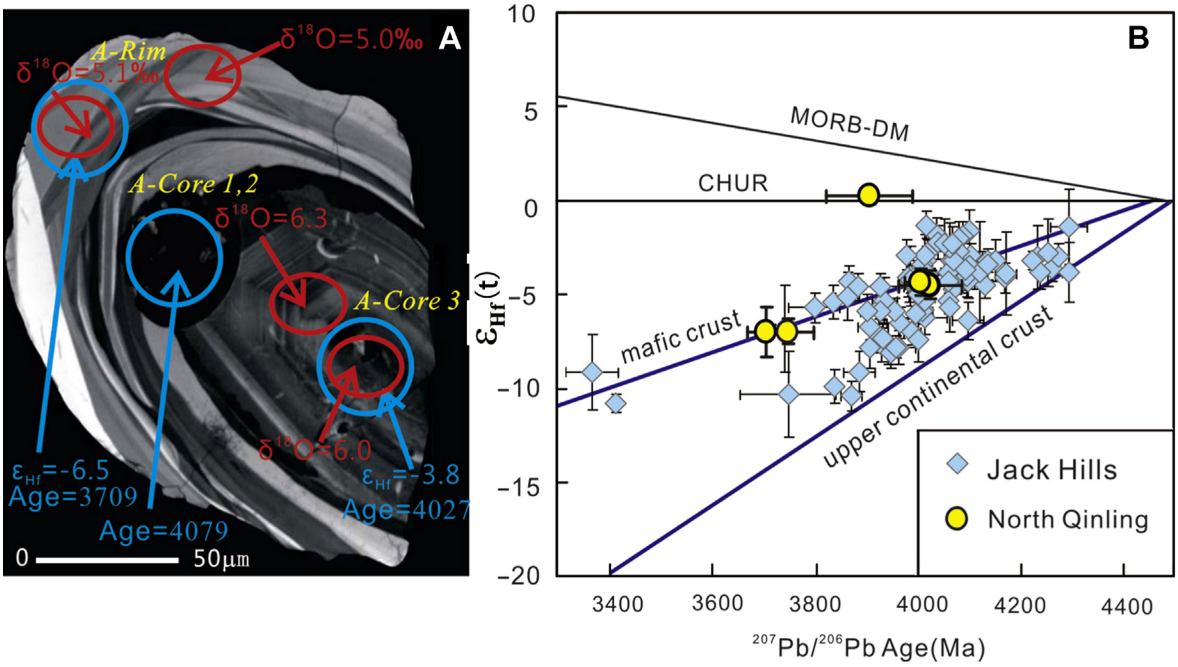

Figure 2. Zircon cathodoluminescence images (A) and plot of $\varepsilon_{Hf}(t)$ vs. age (B) (from Diwu et al., 2013).

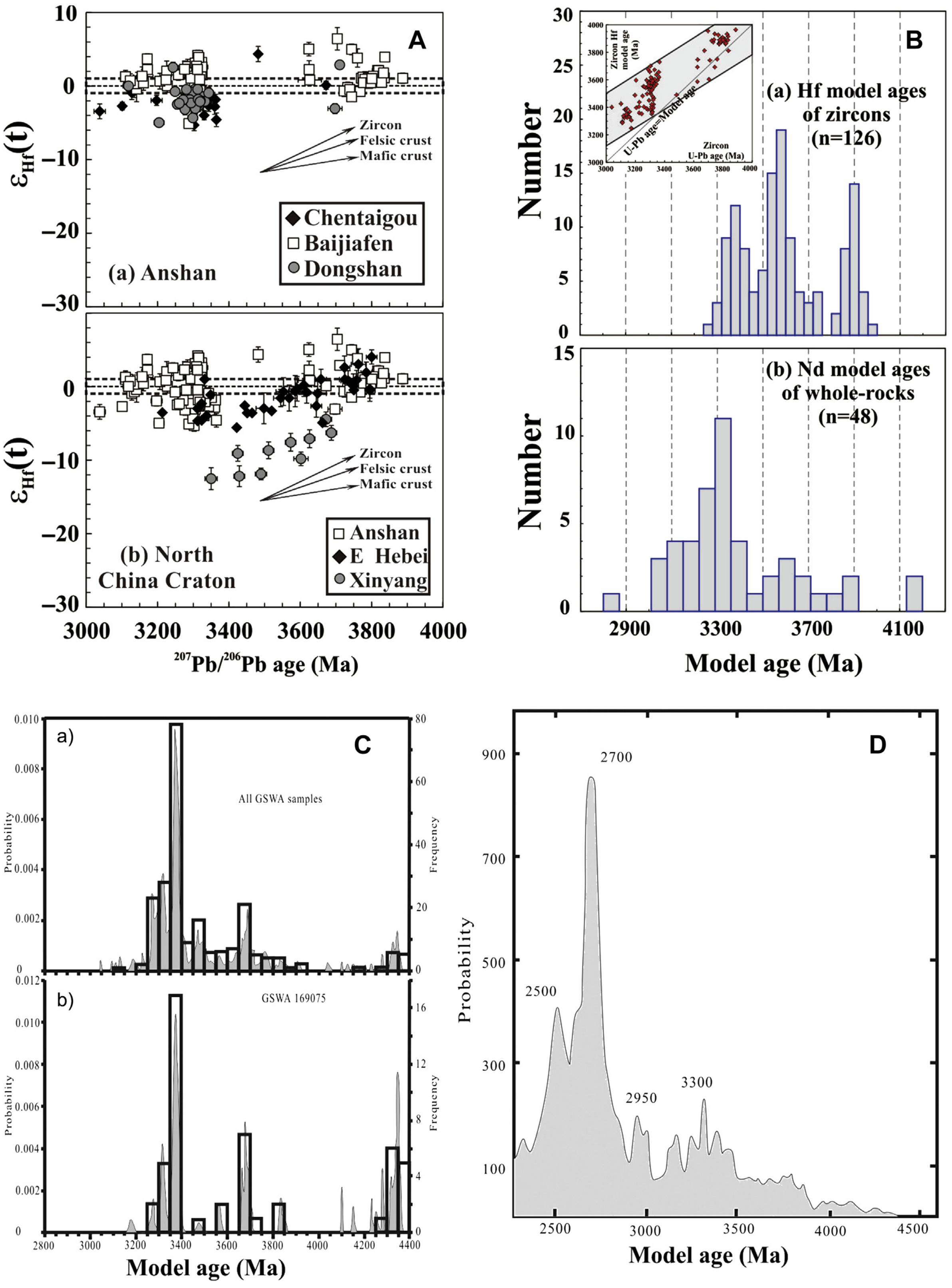

Figure 3. (A) $\varepsilon_{\mathrm{Hf}}(t)$ versus age for the ancient zircons in (a) Anshan and (b) the North China Craton as a whole. Data sources for (a) Wu et al., 2008; (b) eastern Hebei (Wu et al., 2005; Liu et al., 2013) and Xinyang (Zheng et al., 2003); (B) comparisons of zircon Hf model ages (a) with the Nd model ages of whole rocks (b) from the Anshan area. Nd model age data of whole-rocks are from Wan et al. (2005) and Wu et al. (2005, 2008); (C) probability density diagrams for U-Pb ages of detrital zircons in the Maynard Hills and Illaara greenstone belts, Youanmi Terrane (after Wyche, 2007). In each case, the dark grey area and frequency histograms (bin width 50 Ma) include only concordant data, defined here as analyses with f204 (i.e., fraction of common ^{206}Pb in total ^{206}Pb) <1% and discordance <10%; the light grey area includes all data: (a) all Geological Survey of Western Australia samples from the Maynard Hills and Illaara greenstone belts = 226 concordant analyses of 209 zircons (293 of 265 total); (b) Geological Survey of Western Australia sample 169,075 from the Maynard Hills greenstone belt = 49 concordant analyses of 35 zircons (61 of 39 total); (D) synthesizing zircon U-Pb ages from early Precambrian orthogneisses in the world (after Condie and Kröner, 2008).

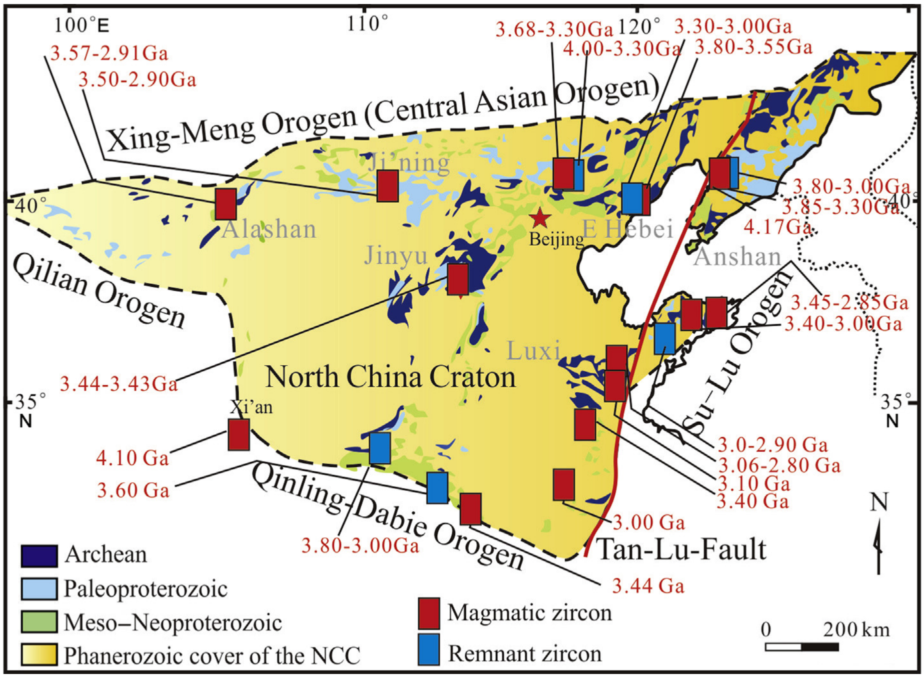

Figure 4. Localities of >3.0 Ga old rocks in the NCC (modified from Wan et al. (2009) with new data see text references).

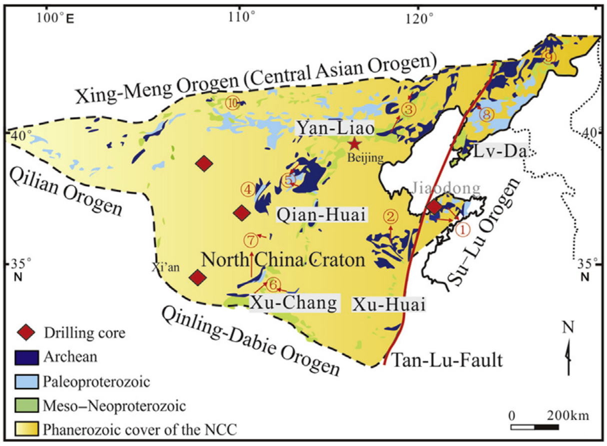

Figure 5. Main study areas for TTGs in the NCC.

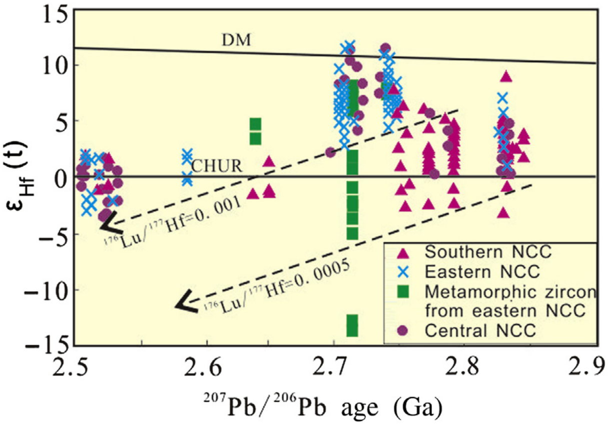

Figure 6. $\varepsilon_{\rm Hf}(t)$ vs. ^{207}Pb/^{206}Pb age plot of TTGs in the NCC (modified from Zhai and Santosh, 2011).

Fig. 1 is a simplified map of the NCC showing Precambrian rocks. Six >3.3 Ga old continental nuclei have been proposed (Zhai and Liu, 2003; Zhai and Santosh, 2011). Recently, more Archean rocks have been acquired from drilling cores and small outcrops in the Ordos that is covered by Phanerozoic sedimentary rocks (e.g., Wang, 2013). $\sim$4.1 Ga Hadean zircon grain was reported from the Ordovician ignimbrite, which is in a low grade greenschist-facies terrigenous clastic-volcanic association in Sangyuan, the North Qinling Orogenic Belt (Wang et al., 2007; Fig. 1), and it is believed that are trapped zircons from basement rocks in the southern margin of the NCC (Wang et al., 2007; Diwu et al., 2013; Zhai, 2013b). Cathodoluminescence (CL) imaging of zircon grains reveal oscillatory zoning and a core-rim structure (Fig. 2A; Diwu et al., 2013). A concordant LA-ICPMS ^{207}Pb/^{206}Pb age of 4079 ± 5 Ma from the grain A was reported by Wang et al. (2007). Two new sites were selected for SHRIMP analyses in the Beijing SHRIMP Center. One site was selected in oscillatory zoned zircon near the center of the grain and revealed an age of 4027 ± 12 Ma. The other was placed in the rim domain and recorded an age of 3709 ± 15 Ma. Following SHRIMP analysis, the mount was lightly re-polished and oxygen isotope analyses were determined by Cameca IMS 1280 at the Institute of Geology and Geophysics, Chinese Academy of Sciences, in Beijing. The site that gave a U-Pb age of 4027 ± 12 Ma recorded a δ^{18}O value of 6.0‰, whereas an adjacent site in the core δ^{18}O value of 5.1‰, with an adjacent site (Fig. 2A) giving a value of 5.0‰, both close to the mean mantle value. The ^{176}Hf/^{177}Hf value obtained from the 4027 ± 12 Ma core site was 0.280108 and for the rim 0.280258. The calculated initial $\varepsilon_{\rm Hf}(t)$ value and two-stage model age ($T_{\rm DM}^{2}$) for the core are −4.6 and 4449 Ma, respectively, and for the rim they are −7.1 and 4357 Ma, respectively. Trace element analyses of the core and rim yield similar patterns, both showing prominent positive Ce anomalies, negative Eu anomalies, and heavy rare earth element (HREE) enrichment, typical of magmatic zircon. $\sim$4.0 Ga ages have been interpreted magmatic age and $\sim$3.7–3.8 Ga ages represents reworking age (Diwu et al., 2013). These zircons were from orthogneiss with perhaps the intermediate generation of

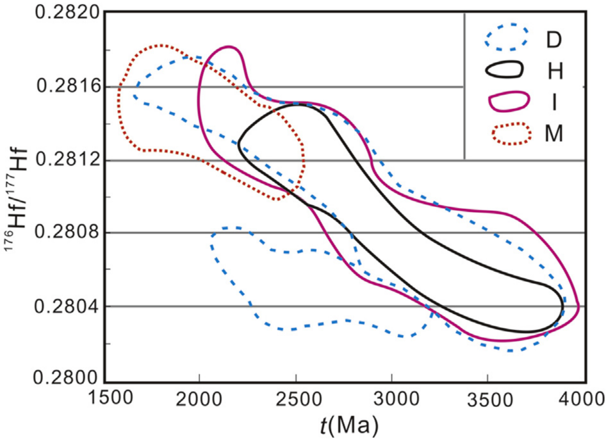

Figure 7. Zircon formation age vs zircon ^{176}Hf/^{177}Hf ration diagrams. D—detrital zircons, H—inherited zircons, I—magmatic zircons, M—metamorphic zircons (modified from Geng et al. (2012) with new data see text references).

TTGs (Blichert-Toft and Albarede, 2008). Fig. 2B is plot of $\varepsilon_{\mathrm{Hf}}(t)$ versus age. The yellow circles show the Hf isotope composition of xenocrystic zircons from the western North Qinling Orogenic Belt, China; the shaded diamonds are the Hf isotopic data from the Jack Hills detrital zircon suite (after Kemp et al., 2010). The isotope trajectories of putative upper continental crust (^{176}Lu/^{177}Hf = 0.008; Rudnick and Gao, 2003), mafic crust (^{176}Lu/^{177}Hf = 0.022) and TTG reservoirs (formed at 4.3 Ga with ^{176}Lu/^{177}Hf = 0.005; Blichert-Toft and Albarede, 2008) are shown for reference. These zircons provide important evidence regarding the nature of the basement to the North China Craton. The $\varepsilon_{\mathrm{Hf}}(t)$ values of the North Qinling zircons range from chondritic to −4.6, with T^{2}_{DM} model ages ranging from 4076 to 4449 Ma. The latter are the oldest Hf model ages recorded from the NCC (Wang et al., 2007; Diwu et al., 2013), and fall within the range of values reported for the ancient detrital zircon suite from Jack Hills, western Australia. The 4076 Ma probably recorded a reworking event, and 3709–3751 Ma in the rim of the zircon recorded another reworking or metamorphic event. Importantly, the North Qinling data fall on the ^{176}Lu/^{177}Hf = 0.020 trend as defined by the most pristine oscillatory zoned zircons from Jack Hills and zircons from the Apollo 14 breccias (Taylor et al., 2009; Kemp et al., 2010). This lends credence to the idea that the earliest crust on Earth may have evolved from a KREEP-like reservoir, similar to that on the Moon (Diwu et al., 2013). Another example, an oldest zircon xenocryst (4.17 Ga) from the Anshan-Benxi supracrustal belt, northeastern NCC is reported by Cui et al. (2013). In the sample area, the exposed Archean rocks belong to the Cigou Formation and consist of banded iron formation and amphibolites wrapped in the hybrid granitegneiss, located at Waitoushan iron deposit. The zircons were separated from massive fine-grained amphibolite. The 4.17 Ga zircon xenocryst is hosted within ~2523 ± 12 Ma massive fine-grained amphibolite which was subsequently metamorphosed at ~2481 ± 19 Ma.

2.2. ~3.8 Ga nuclei

Zircon U-Pb isotopic ages of ≥3.8 Ga have been reported near Anshan, northeast China and near Caozhuang, eastern Hebei in the NCC, indicating the presence of old continental crust at least from two localities (Fig. 1). The Tiejiashan complex in Anshan area is composed of trondhjemitic-quartz diorite gneisses and granitic gneiss with subordinate meta-sedimentary rocks. The trondhjemitic and granitic gneisses show two zircon populations with ages of 3805 ± 5 and 3300 Ma (Liu et al., 1992; Song et al., 1996; Wan et al., 2001; Wu et al., 2008). The Hf model ages of these zircons show three peaks at 3.3, 3.6 and 3.9 Ga, and zircon isotopic constraints suggest that the crust beneath Tiejiashan formed not earlier than 4.0 Ga (Wu et al., 2008). Wan et al. (2001) reported that the oldest quartz diorite gneiss in Tiejiashan occurs as a large lens in the trondhjemitic country gneiss, the former yielding an age of 3792 ± 12 Ma, and the latter showing 3.1 Ga, both from SHRIMP zircon U-Pb technique. These data show that the Tiejiashan complex preserves a complex geological history. The 3792 ± 12 Ma SHRIMP zircon U-Pb age of quartz diorite probably represents the formation age of the juvenile crust derived from the partial melting of mafic volcanic rock. However, Wu et al. (2008) suggested that most samples from Anshan area contain younger zircons with ages of 3.1–3.3 Ga, although they contain a few zircon grains with age of ~3.6–3.8 Ga. The 3.1–3.3 Ga zircons show typical igneous oscillatory zoning and do not show any evidence that were produced by metamorphism, indicating that these samples were emplaced at 3.3 and 3.1 Ga, respectively and the zircons with older ages are interpreted as inherited in origin. The exposure of 3.8 Ga rock is therefore much smaller than previously thought.

The Caozhuang complex in eastern Hebei is composed of a suite of volcano-sedimentary rocks metamorphosed to upper amphibolite to granulite facies. Tonalitic magmas (ca. 3.3 Ga; U-Pb zircon age) intruded into the Caozhuang supracrustal rocks (Zhao et al., 1993). The Caozhuang supracrustal rocks contain the various rock types including marble, diopsidite, amphibolite, biotite felsic gneiss, fuchsite quartzite, pyroxene-horblendite and BIF. The zircon dating of the amphibolite yielded concordant ^{207}Pb/^{206}Pb ages ranging from 3684 to 3354 Ma. However, an older date of 3782 Ma with 18% discordancy was also obtained (Liu et al., 2013). Detrital zircons from the fuchsite quartzite show two prominent U-Pb age peaks of 3794 ± 15 and 3733 ± 17 Ma, and single-stage Hf model ages between 3965 and 3633 Ma with a mean age of 3799 Ma (Wu et al., 2005). The fuchsite quartzite represents the oldest sedimentary unit in this suite, with a depositional age of probably between 3.7 and 3.3 Ga. Detrital zircon grains from the garnet-biotite gneiss gave a similar ^{207}Pb/^{206}Pb age range, from 3838 to 3342 Ma (Liu et al., 2013). The metamorphic domains of the zircon grains from both samples, including the strongly recrystallized cores and rims, recorded an overprinting metamorphism at ca. 2.5 Ga, which correlates with the most widespread tectono-thermal event in the NCC. In situ zircon Hf-isotope analyses on the dated zircon grains yielded a wide range of model ages (T^{1}_{DM}) from 4.0 to 3.3 Ga with corresponding $\varepsilon_{\mathrm{Hf}}(t)$ from −36.0 to +4.8. This suggests that the evolution of the crustal segment in this area involved multiple phases of juvenile crustal addition as well as recycling of older crustal rocks.

2.3. ~3.3 Ga crustal growth event

Above two old rock examples show an important age record that is ~3.3 Ga, which implies a strong magmatic event in Anshan area (Fig. 3), probably indicating a significant continental growth in the NCC. Recently, Wan et al. (2013) reported a newly discovered area of ancient rocks, which is the full geological context for more ancient rocks from a third Anshan locality – the polyphase migmatite Shengousi complex. SHRIMP U-Pb zircon dating indicates a protracted tectono-magmatic history for the Shengousi complex: the oldest recognized component is banded trondhjemitic gneiss (3773 ± 6 Ma), which is veined by strongly deformed granitic pegmatite. These occur with a second generation of trondhjemitic rocks (3454 ± 8 and 3448 ± 9 Ma). The next generation of plutonic rocks is a composite suite of iron-enriched mafic dykes (3332 ± 6 and 3331 ± 8 Ma) with broadly coeval felsic veins (3311 ± 4 Ma). Finally there was intrusion of monzogranite (3129 ± 6 Ma).

Previous literatures did not pay enough attention to ∼3.3 Ga magmatic-metamorphic event in the other cratons, although this record has been reported in some places. For example, the Jimperding greenstone belt in the Southwest Terrane of the Yilgarn Craton that consists of thin units of quartzite, pelitic schist, amphibolite, metamorphosed ultramafic rocks, and metamorphosed BIFs, interleaved with a variety of gneisses, including garnetiferous gneiss. There are no direct ages for rocks within the greenstone belt, but the granites to the west were probably emplaced between ca. 2650 and ca. 2630 Ma (Wilde, 2001). Following evidence of old zircons in meta-sedimentary rocks in the Jimperding metamorphic belt in the Southwest Terrane, Kinny (1990) analyzed 50 zircon grains from quartzite from the Windmill Hill locality, and Bosch et al. (1996) analyzed a further 12 grains from a sample of nearby pelitic schist. Fig. 3C is probability density diagrams for U-Pb ages of detrital zircons in the Maynard Hills and Illaara greenstone belts, Youanmi Terrane (after Wyche, 2007). Zircons ranged in age mainly up to ca. 3500 Ma, with Kinny (1990) finding one zircon with an age of ca. 3735 Ma. The youngest concordant zircon obtained has a $^{207}Pb/^{206}Pb$ age of 3055 ± 6 Ma, which represents the maximum age of deposition of the precursor sedimentary rock. Obviously, the most important age peak is ∼3.3–3.4 Ga, which should represent a crustal growth event. Fig. 3D is a diagram showing the crustal evolution and growth synthesizing zircon U-Pb ages from old orthogneisses in the world (after Condie and Kröner, 2008). Significantly, there are 4 most important peaks, ∼3.3, ∼2.95, ∼2.7 and 2.5 Ga, which should represent major continental crustal growth episodes after Hadaen crust nuclei generation.

In southern NCC, granulite xenoliths within Mesozoic volcanic rocks in Xinyang show ca. 3.6 Ga, with Hf isotopic ratios lower than those for the rocks in Tiejiashan and Caozhuang. The Hf modal age of ca. 4.0 Ga indicate extraction of protoliths from the mantle at ca. 4 Ga or earlier, or by remelting at 3.6–3.7 Ga (Zheng et al., 2003). Fig. 4 shows locations of the >3.0 Ga old rock samples (Wan et al., 2009), these samples extensively distribute in the northern, eastern, southern margins as well as within the NCC. Therefore, we can infer that there were ancient continental rocks in the NCC in Paleoarchean, only we poorly understood ancient continental crust generation.

3. Neoarchean continental crust macro-growth

3.1. Neoarchean continental crust

Although a variety of authors have produced a host of different crustal growth models depending on their discipline and standpoint, Neoarchean is commonly considered to be the most major stage of continental growth. Some popular models propose that 80–90% of the global crust formation occurred during early Precambrian and mostly in Neoarchean (2.7–2.5 Ga) (Brown, 1979; Dewey and Windley, 1981; Mclennan and Taylor, 1982, 1983; Condie and Kröner, 2008; Zhao and Zhai, 2013). Windley (1995, 2007) compared differences between greenstone belt and Phanerozoic orogenic belt, heat production and secular trends in metamorphic belts between Archean and younger times. Some geologists spare no effort to look for Archean ophiolite suite or relict, although this work is difficult (Kusky, 2004; Kusky et al., 2004; Shchipansky et al., 2004; Stern, 2007). Komatiites were developed during early Precambrian (>2.7 Ga) that are indicative mark of hotter mantle and crust, and the quantity of komatiite was less since late Neoarchean. A vast amount of komatiites has been suggested to link to large igneous province and mantle plume (e.g., Condie, 2001, 2004). ∼2.7 Ga is the most important crustal growth and main mechanism is related to mantle plume and partial melting of komatiites and basalts. Recently, Condie and Kröner (2013) published a new paper to discuss a major change in the tectonic setting of continental growth at the end of the Archean. They proposed that widespread propagation of plate tectonics in the late Archean may have led not only to rapid production of continental crust, but to a change in the primary site of production of continental crust, from accreted oceanic arcs and oceanic plateaus in the Archean to primarily continental arcs thereafter.

The early continental crust comprises mainly greenstone belts and high-grade regions, the later occupies >60–70%. TTGs are dominant in high-grade regions and commonly termed as juvenile crust. Therefore, how to produce TTGs is a key issue to discuss continental generation and growth. In the NCC, the greenstone belts occupy <30%, and the high-grade regions occupy >70%. The two prominent age peaks at ca. 2.9–2.7 and 2.6–2.5 Ga might correspond to the earlier events of major crustal accretion in the NCC (Zhai, 2004). The Hf isotopic model ages range from ca. 1950 to 3800 Ma, and mostly in the range of 2600–3000 Ma with a peak of 2820 Ma (Wu et al., 2005; Yang et al., 2008).

3.2. Greenstone belts

The greenstone belts in the NCC usually underwent strong metamorphism of amphibolite facies, some granulite facies or low grade amphibolite facies. The main greenstone belts include the Yanlingguan in the central-eastern NCC, the Dengfeng in the southwestern NCC, the Dongwufenzi in the northwestern NCC, the Wutaishan in the central-western NCC, the Qingyuan (Hongtoushan) in northeastern NCC and the Zunhua in the eastern NCC. The most greenstone belts have ∼2.6–2.5 Ga U-Pb zircon ages from amphibolites. These ages are mainly interpreted as metamorphic age, a minor amount of zircons probably are magmatic zircons. The Zunhua greenstone belt is composed of interlayered BIF, amphibolite and fine-grained biotite felsic gneiss. The SIMS U-Pb dating and oxygen isotopic analysis of zircon cores and rims from amphibolites obtain 2541–2553 Ma with $\delta^{18}O$ values of 5.9–7.6‰ and 2510–2512 Ma, $\delta^{18}O$ values of 6.8–9.9‰, respectively, providing the forming time of the Neoarchean protolith and metamorphic time (Zhang et al., 2012). The Mengyin komatiites are located at the base of the ca. 2.8–2.7 Ga Taishan Complex of the Yanlingguan greenstone belt in western Shandong (Cheng et al., 2007). Wan et al. (2011a) reported the SHRIMP U-Pb dating and LA-ICPMS Hf isotope composition of zircons from 2.75 to 2.70 Ga supracrustal rock from the Yanlingguan greenstone belt. Although the komatiites underwent metamorphism of greenschist-amphibolite facies at 2.7 Ga (Zhang et al., 1998; Polat et al., 2006), they partly preserve remnant igneous spinifex textures, and even rare fresh olivine. The lithologic association here is characterized by metamorphosed komatiites, pillow basalts, BIFs, conglomerates and greywacke sandstones. The belt was intruded by high-Al TTG plutons. The spinifex-textured komatiites occurring at stratigraphically lower levels have slight depleted or concave-upward LREE patterns and negative Nb anomalies ($Nb/Nb^* = 0.19–0.96$). Based on mass equilibrium between olivine and melt, the potential eruption temperature of the Mengyin komatiites is estimated to be around 1270 °C at 1 atm pressure (Polat et al., 2006), therefore the temperature of komatiite magma chamber is much higher, suggesting a plume tectonic setting.

3.3. TTGs and crust growth-reworking

Synthesizing zircon U-Pb data of the TTGs in the NCC, Wan et al. (2003, 2011b) proposed that the major continental growth in the

NCC operated at the end of Neoarchean (~2.5–2.55 Ga), which is different from other cratons in the world (~2.7 Ga). Zhai (2004, 2011) emphasized that major crustal growth time in the NCC is ~2.7 Ga based on the geological distribution of early Precambrian litho-structural units and Nd or Hf isotopic model ages of zircons from the TTGs. The most zircons from TTGs suffered strong affection by metamorphism at ~2.5 Ga. Recent studies reveal much more volume of TTG gneisses with ~2.7 Ga magmatic zircon U-Pb age. Fig. 5 shows the main 10 TTGs study areas, which include western Shandong, eastern Shandong, Hengshan, Fuping, eastern Hebei, Henan, Taihangshan and other areas within the NCC, covering eastern, western and southern NCC and also samples from drill holes in the Ordos (Guan et al., 2002; Liu et al., 2002; Zhao et al., 2007; Jahn et al., 2008; Liu et al., 2009; Wan et al., 2011a; Zhou, 2011; Geng et al., 2012; Wang et al., 2013a, b; Wang, 2013; Yang et al., 2013; Zhai, 2013b; Zhu et al., 2013).

Most of ~2.7 Ga TTG gneisses underwent 2.6–2.5 Ga metamorphism, as indicated by the ubiquitous metamorphic rim around the core of the magmatic zircons in these rocks. Abundant ~2.5 Ga orthogneisses in the NCC have Hf and Nd model ages mostly around 2.9–2.7 Ga, indicating the timing of formation of the protoliths or extraction of the protolith magma was from the mantle. Jiang et al. (2010) reported granulite xenoliths (lower crust rocks) occurring within the Tertiary alkali basalt from Hanuoba in northern Hebei, amphibolite from Hebei and tonalitic gneiss from Taishan, western Shandong. The granulite xenoliths carry zircons with U-Pb age ranges of 2.50–2.55 Ga. The amphibolite and tonalitic gneiss carry zircons with U-Pb ages of ~2.6–2.5 Ga. All the samples show Hf model ages of ca. 2.8–2.7 Ga, suggesting that they were probably derived from a ~2.7 Ga crust. The diagram of $\varepsilon_{\mathrm{Hf}}$ age (^{207}Pb/^{206}Pb) for zircons from the orthogneisses in the NCC shows that the most important crust growth occurred during 2.9–2.7 Ga (Fig. 6, modified from Zhai and Santosh, 2011), in accord with global crust growth (Zhai and Bian, 2001; Zhai and Liu, 2003). Moreover, the metamorphic zircon grains from the widespread mafic rocks with Nd and Hf model ages ranging from 2.9 to 2.7 Ga yield the zircon U-Pb ages of 2.6–2.5 Ga. Therefore, the 2.6–2.5 Ga TTGs are mostly attributed to partial melting of 2.9–2.7 Ga mafic rocks. The NCC has a distinct characteristic of multi-stage crust growth, most important of which are 2.9–2.7 Ga major growth event and 2.6–2.5 Ga crust growth-reworking event during Neoarchean.

4. Cratonization at the end of Neoarchean and assembly of the NCC

4.1. What happened at the end of Neoarchean

The ~2.5 Ga is the time boundary between the Archean and Proterozoic. Although the ~2.5 Ga geological records are weak in some cratons, the record of Earth's environment change is abrupt and enormous in all cratons in the world, which was followed by a "silent period" without tectonic-thermal action lasting 150 to 200 Ma (from 2.5 to 2.3 or 2.35 Ga), and then followed by the Great Oxidation Event (GOE) (Condie and Kröner, 2008). It is worth pointing out that the ~2.5 Ga geological event in the NCC is much stronger than in some cratons in the world, which brings a good research example. Main geological phenomena of ~2.5 Ga geological event are as follows: (1) 2.5 to 2.6 Ga orthogneisses are extensively distributed in the NCC and usually contain layers or lenses of amphibolites and mafic granulites; (2) ca. 2.5 Ga greenstone belts are located in the northeastern, northwestern, eastern, central, and southern NCC, such as Hongtoushan, Anshan, Xuchang, Zunhua, and Wutaishan. The ca. 2.7 Ga greenstone belts in the NCC, such as the Yanlingguan, have been metamorphosed and deformed at ca. 2.5 Ga. All greenstone belts surround old micro-blocks (high-grade regions) and constitute a tectonic pattern marked by the coexisting of greenstone belt and high-grade region; (3) a large number of granites derived from crustal partial melting at 2.52–2.49 Ga, and intruded into both greenstone belts and high-grade regions; and (4) all the Archean rocks in the NCC underwent a strong ca. 2.5 Ga metamorphism from granulite facies to amphibolite facies (Zhai, 2004, 2011). From new studies, the author take note that magmatic rocks from supracrustal sequences and orthogneisses of ~2.7 and ~2.5 Ga show different rock associations and magmatic characters. The ~2.7 Ga magmatic rock associations are komatiite-basalt-dacite with a minor amount of calc-alkaline volcanic rocks in supracrustal sequences and dominant TTGs with some granitic-granodioritic gneisses. The ~2.5 Ga magmatic rock associations are basalt-calc-alkaline volcanic rocks with a minor amount of komatiite and dominant granites with some TTGs. These differences probably indicate an evolving trend of crust to higher maturity from ~2.7 to ~2.5 Ga. Fig. 7 is a diagram of Archean–Paleoproterozoic zircon formation age vs. zircon ^{176}Hf/^{177}Hf ration from the NCC. Four kinds of zircon have been classified, which are detrital zircons (D), inherited zircons (core, H), magmatic zircons (I) and metamorphic zircons (rim, M). The fields of I and H zircons in the Fig. 7 demonstrate a regular change trend of increasing ^{176}Hf/^{177}Hf ration along with decreasing age from <4000 to ~1600 Ma (Geng et al., 2012), indicating more material from continental source. Paleoproterozoic magmatic zircons mainly were selected from ~2.35 to 2.0 Ga granites. Metamorphic zircons yield ~2.5–1.8 Ga age peak, and their high ^{176}Hf/^{177}Hf rations are attributed to affection of metamorphic fluid. Detrital zircons mainly collected from Proterozoic sedimentary rocks, they fall into two fields, one of which is similar to H and M zircons, another of which has low ^{176}Hf/^{177}Hf ration, probably were affected in supergene process.

4.2. Late Neoarchean magmatism and granites

Based on geological relationships, degree of metamorphism, deformation and magmatic zircon ages, two phases of syenogranitic magmatism at ~ 2.5 Ga are recognized (Wan et al., 2012). Rocks produced during the first phase show a gneissic texture and were formed between 2.53 and 2.52 Ga and locally comprise abundant TTG. Rocks of the second phase cut late Neoarchean TTG and supracrustal rocks, display 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 and REE compositions and Sm-Nd isotopic, and can be subdivided into three types. Whole-rock Sm-Nd isotopic compositions show large variations in $\varepsilon_{\mathrm{Nd}}(t)$ values and T_{DM}(Nd) modal ages, ranging from −9.49 to −4.72 and 3.70 to 3.25 Ga (Type 1), 0.55–1.03 and 2.77–2.71 Ga (Type 2) and −2.35 to 1.23 and 2.93–2.66 Ga (Type 3), respectively. Hf isotopic compositions of zircons from three samples have $\varepsilon_{\mathrm{Hf}}(t)$ values and T_{DM1}(Hf) ages of 0.7–7.2 and 2.84–2.56 Ga (Type 1), 2.6–7.4 and 2.74–2.56 Ga (Type 2) and 2.1–6.3 and 2.76–2.60 Ga (Type 3). It is concluded that syenogranites were 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.

Geng et al. (2012) synthesized more than 2600 Hf isotope data on the Archean–Paleoproterozoic zircons from the NCC, mainly from the eastern and central parts. Recalculation of the data based on single stage and two-stage Hf model ages of the NCC shows peak ages of 3902 ± 13 and 3978 ± 18 Ma, respectively, and also small peaks at 4.0–3.5 Ga. The majority of zircon $\varepsilon_{\mathrm{Hf}}(t)$ values are positive, suggesting the possibility of the crust and mantle differentiation at ca. 4.0–3.9 Ga. Most magmatic zircons from the whole of NCC have their Hf model age range of 2.9–2.4 Ga, and the single stage model ages is cluster at 2698 ± 4 Ma, whereas the two-stage model ages concentrate at 2714 ± 5 Ma, implying that the protoliths were juvenile crustal 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 peaks in Hf model ages are consistent with the partial melting and reworking of the juvenile rocks at 2.5 Ga. Furthermore, the 2.5–1.7 Ga zircon Hf isotope features are also related to the reworking of the crustal rocks.

The study results of detrital zircons from modern rivers in the NCC have been reported (Yang et al., 2009; Diwu et al., 2012). The 4 rivers are the Luan and Yongding in the eastern NCC and Wei and Jing rivers in the western NCC. All detrital zircons dating from 4 rivers are similar. The Paleoproterozoic and Archean U-Pb ages show 2 peaks, one of which is ∼2.5 Ga and another one is about 1.8–2.0 (18.5) Ga. >2.6–3.3 Ga zircons are more in quantity in the eastern NCC than in the western NCC. However Hf model ages of zircons from the western NCC also show a strongest peak of ∼2.6–3.5 (2.7 Ga) that is similar to the eastern NCC.

∼2.5–2.45 Ga maifc dykes in the NCC were metamorphosed to amphibolites or granulites, and usually strongly deformed. Li et al. (2010) reported coeval olivine-gabbroic and syenitic dykes in eastern Hebei, SHRIMP zircon U-Pb ages of which are 2.504 and 2.516 Ga, respectively. Their geochemical features indicate that these dykes 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. Low-grade metamorphosed volcanic-sedimentary rocks in the northern NCC, traditionally termed as the Hongqiying Group (unpublished data), the Dantazi Group and the Qinglong Group (Lv et al., 2012), are obviously inconsistent with high-grade metamorphosed basement rocks in metamorphic grade and occurrence. The high-grade metamorphic rocks commonly have metamorphic ages of ∼2.60 Ga and ∼2.56–2.50 Ga. The low-grade metamorphic rocks, recently, yield 2.52–2.49 Ga forming ages. Therefore, the lower grade supracrustal rocks are probably were deposited within craton at the end of Neoarchean, representing a sedimentary cover after cratonization of the NCC.

4.3. Assembly of micro-blocks and cratonization

The results seemly support the conclusion that the essential cratonization of the NCC took place at the end of Neoarchean (Zhai and Bian, 2001; Zhai, 2004, 2011; Zhai et al., 2010; Geng et al., 2012; Wan et al., 2012; Wang et al., 2013a; Zhu et al., 2013). Partial melting of crust is important one of cratonization processes, inducing formation of the stable upper and lower crust sphere-layers. This process also induced that upper crust contain more felsic materials and the lower crust contain more mafic materials due to that some molten residual materials and some underplating gabbros joint into lower crust sphere-layer. The metamorphic grades of upper crust and lower crust are obviously different. The upper crust is of un-metamorphosed – low grade metamorphic facies, and the lower crust moderate-high grade metamorphic facies. The lower crust sphere-layer can be usually subdivided into four metamorphic facies layers from bottom to upper, which are granulite facies, migmatized granulite facies, migmatized amphibolite facies and amphibolite facies (Weaver and Tarney, 1983). These layers of composition and metamorphic facies cause to coupling between upper crust and lower crust on physical and chemical situation. In this cratonization process, the mantle provides necessary energy and some materials. A part of asthenosphere mantle was changed to lithosphere mantle throughout magma extraction, as a result, crust and mantle reached equilibrium. It is proposed that formation of global lithosphere is coupling with global cratonization (Zhai et al., 2010). The evolution of the lithosphere is closely linked to the cratonization process in the early history of the planet. The NCC behaved as a stabilization continent without tectonic-thermal action during ∼2.50–2.35 Ga, as other cratons in the world (Condie et al., 2001), therefore, the 2.5 Ga as boundary of Archean–Proterozoic have epoch making significance in Earth's origin and evolving history.

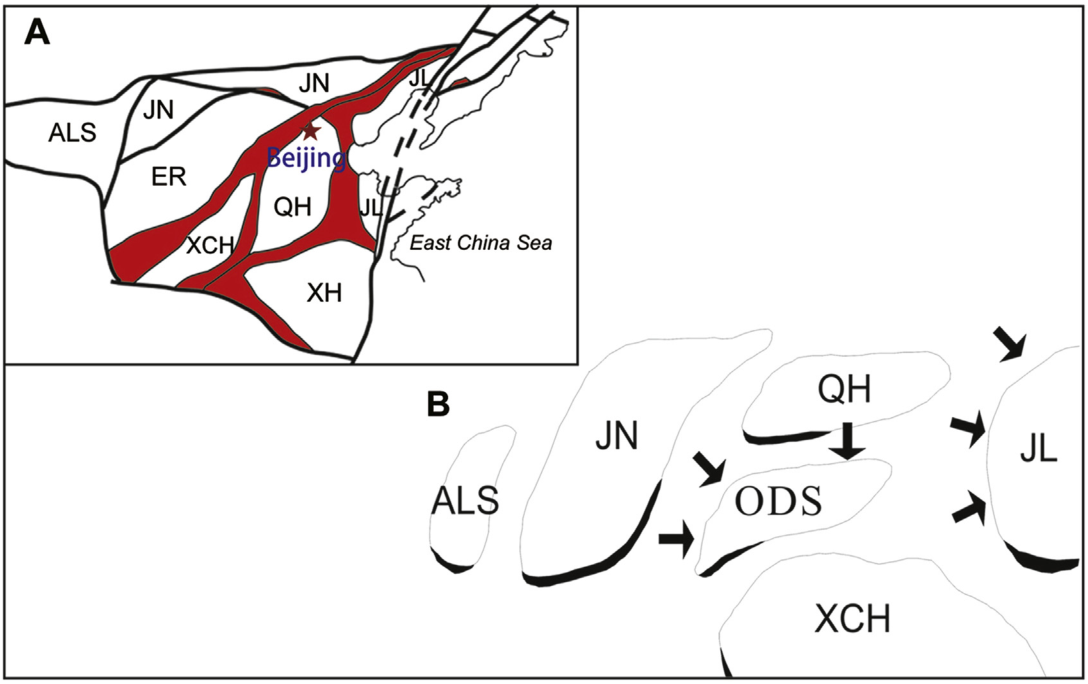

Figure 8. Assembly model of the NCC at ∼2.5 Ga.

Based on the above studies, an assembly model was suggested by Zhai and Bian (2001), in which all micro-blocks in the NCC were welded together by late Archean greenstone belts at the end of the late Neoarchean (Fig. 8A). The greenstone belts in the NCC distributed along the boundaries of the micro blocks were also subjected to the metamorphism, probably representing arc-continent collision zones (Fig. 8B). Most of the greenstone belts in the NCC show an age range of ca. 2.6–2.54 Ga, as indicated by U-Pb zircon data from metabasites (amphibolites and mafic granulites). 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 a higher geothermal gradient. Therefore, it is proposed that the various micro-blocks were surrounded by small ocean basins in late Neoarchean, whereas the old continental crust and the oceanic crust were hotter. The subduction and collision were much smaller in scale as compared to those in the Phanerozoic plate tectonic regime (Fig. 9), although the tectonic style and mechanisms are more or less similar (e.g., Santosh, 2010). The amalgamation of the various micro-blocks and the formation of the NCC at 2.5 Ga forms part of the ca. 2.5 Ga supercraton event (Rogers and Santosh, 2003, 2004; Condie, 2004). The micro-block amalgamation and followed regional extension led to the formation of a large volume of granites and final cratonization of the NCC. The available evidence shows that the NCC behaved mostly as a stable continent during ca. 2.50–2.35 Ga, and therefore, the 2.5 Ga boundary of Archean–Proterozoic is the most critical period in this craton, similar to the case with many other ancient cratons on the globe (e.g., Kröner and Layer, 1992; Windley, 1995). 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 dominant vertical tectonics to limited horizontal tectonics that is still different in regime from modern style plate tectonics (Zhai et al., 2010).

Recently, Condie and Kröner (2013) proposed 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 was thinner due to cooling of the mantle and less melt production at ocean ridges, hence, oceanic lithosphere is more subductable. This suggestion is similar to that of Zhai and Bian (2001), however author's new papers (Zhai, 2009, 2011; 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 involving ocean closure, accretion and collision until 2.3–1.85 Ga, represented by three major collisional sutures (also termed as mobile belts): the Jiaoliao mobile belt in the northeastern NCC, the Jinyv mobile belt at the central domain and the Fengzhen mobile belt in the northwestern NCC. These collisional orogens formed through subduction and accretion, and along which high pressure and ultrahigh-temperature metamorphic rocks have developed (e.g., Santosh et al., 2012; Tam et al., 2012), representing the operation of modern-style-like plate tectonics in the NCC at least from ~2.0 Ca.

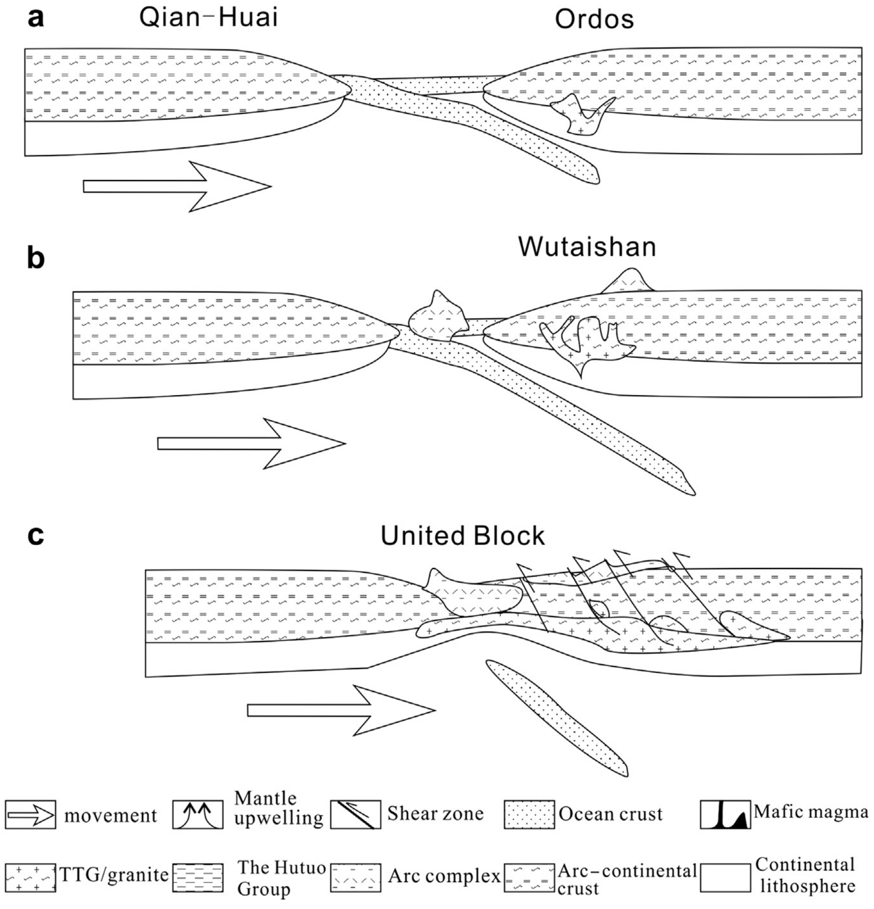

Figure 9. Small-scale subduction and collision model (example of the Qian-Huai and Ordos micro-blocks).

5. Conclusions

(1) The North China Craton (NCC) has a complicated evolutionary history with multi-stage crustal growth, recording nearly all important geological events in the early geotectonic history of the Earth.

(2) The study of trapped zircons from metamorphic and magmatic rocks reveals that the oldest continental crust rocks in the NCC are intermediate-felsic rocks (TTG). They probably generated in ∼4.4 Ga similar to those in the Jack Hill.

(3) Several ancient terrestrial continental nuclei in the NCC formed in ∼3.8–3.3 Ga. The ∼3.3 Ga is a considerable crustal growth episode that has not been paid enough attention in previous study.

(4) The major continental growth operated in 2.9–2.7 Ga. The rocks older than ∼2.7 Ga in the NCC were commonly underwent metamorphism and deformation in 2.6–2.5 Ga.

(5) Abundant ∼2.6–2.5 Ga orthogneisses have Hf-in-zircon and Nd whole-rock model ages mostly around 2.9–2.7 Ga and some around 2.6–2.5 Ga, indicating the timing of protolith formation or extraction of the protolith magma from the mantle. Therefore, the 2.6–2.5 Ga TTGs probably represent a coherent event of continental accretion and major reworking (crustal melting). The NCC established its cratonization and has formed a stable craton at ∼2.5 Ga.

(6) The ∼2.5 Ga metamorphic-magmatic event is stronger than in most other cratons of the world. Therefore, it is suggest an assembly model that all micro-blocks in the NCC were welded together by late Neoarchean greenstone belts. The various micro-blocks were surrounded by small ocean basins, and the old continental crust and the oceanic crust were hotter than today. Subduction and collision were on much smaller scales as compared to the Phanerozoic plate tectonic regime, although the tectonic style and mechanisms were more or less similar.

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