Formation and Evolution of Archean Continental Crust of the North China Craton

Yu-Sheng Wan, Dun-Yi Liu, Chun-Yan Dong, Hang-Qian Xie, Alfred Kröner, Ming-Zhu Ma, Shou-Jie Liu, Shi-Wen Xie and Peng Ren

Abstract The North China Craton (NCC) has had a long geological history back to ca. 3.8 Ga ago. In the Anshan area, northeastern part of the craton, three distinct complexes with ages of 3.8–3.1 Ga (Baijiafen, Dongshan, and Shengousi) have been identified, along with widespread 3.1–2.5 Ga rocks of different origins and ages. In eastern Hebei Province, abundant 3.88–3.4 Ga detrital zircons were obtained from metasedimentary rocks of the Caozhuang Complex, and the oldest rock identified is a 3.4 Ga gneissic quartz diorite. The oldest zircons that may originally have been derived from the NCC are 4.1–3.9 Ga grains in Paleozoic volcano-sedimentary rocks in the northern Qinling Orogenic Belt bordering the NCC in the south. 3.0–2.8 Ga rocks occur in Anshan, eastern Hebei, eastern Shandong, and Lushan. ca. 2.7 Ga rocks of igneous origin are exposed in eight areas of the NCC, but ~2.7 Ga supracrustal rocks have so far only been identified in western Shandong. ca. 2.5 Ga intrusive and supracrustal rocks and associated regional metamorphism occur in almost all Archean areas of the NCC. Banded iron formations contain the most important ore deposit of the Archean in the NCC and mainly formed during the late Neoarchean. Ancient crustal records obtained from deep crust beneath the NCC are similar to those in the exposed areas, with the oldest ca. 3.6 Ga rock enclaves occurring in Xinyang near the southern margin of the NCC. This synthesis is based on the compilation of a large database of zircon ages as well as whole-rock Nd isotopic and Hf-in-zircon isotopic data in order to understand the formation and evolution of the early Precambrian basement of the NCC. Considering the craton as an entity, there is a continuous age record from 3.8 to 1.8 Ga, and two tectono-thermal events are most significant in the late Neoarchean to the earliest Paleoproterozoic and late Paleoproterozoic history, with age peaks at ~2.52 and ~1.85 Ga, respectively. Whole-rock Nd and Hf-in-zircon isotopic data show similar features, documenting the addition of juvenile material to the continental crust at 3.8–3.55, 3.45, 3.35–3.3, 2.9, and 2.85–2.5 Ga with the late

Y.-S. Wan (✉) · D.-Y. Liu · C.-Y. Dong · H.-Q. Xie · A. Kröner · M.-Z. Ma · S.-J. Liu
S.-W. Xie · P. Ren
Beijing SHRIMP Center, Institute of Geology, Chinese Academy of Geological Sciences,
26 Baiwanzhuang Road, Beijing 100037, China
e-mail: wanyusheng@bjshrimp.cn

M. Zhai (ed.), *Precambrian Geology of China*,
Springer Geology, DOI 10.1007/978-3-662-47885-1_2

Mesoarchean to early Neoarchean being the most important period. Crustal recycling began as early as 3.8 Ga and continued until 3.25 Ga and appears to have played a more important role than juvenile additions between 3.25 and 2.90 Ga. After outlining the general geological history of the NNC basement, we discuss several issues relating to Archean crust formation and evolution and arrive at the following major conclusions: (1) Similar to several other cratons, the late Mesoarchean to early Neoarchean was the most important period for rapid production of continental crust, and the most intensive and widespread tectono-thermal event occurred at the end of the Neoarchean. (2) In our new tectonic model, we define and outline three ancient terranes containing abundant 3.8–2.6 Ga rocks, namely the Eastern Ancient Terrane, Southern Ancient Terrane, and Central Ancient Terrane. (3) Vertical magmatic growth is seen as the main mechanism of crust formation prior to the Mesoarchean. We favor a multi-island arc model related to subduction/collision and amalgamation of different ancient terranes in the late Neoarchean. (4) The NCC may already have been a large crustal unit as a result of cratonic stabilization at the end of the late Neoarchean, probably due to magmatic underplating.

Keywords North China Craton · Archean · Magmatism · Metamorphism · Zircon dating · Nd–Hf isotopes

1 Introduction

The North China Craton (NCC) is one of the largest cratons in the eastern Eurasian continent with a total area of 300,000 km^2. It has a triangular shape and is surrounded by young orogenic belts in the north and south, and faces the Pacific Ocean in the east. The major tectonic structures are cut off by the craton boundary, and this suggests that the NCC is a fragment of a once larger craton (Li et al. 2000). It is one of a few areas on the Earth where >3.8 Ga rocks have been identified (Liu et al. 1992; Song et al. 1996; Wan et al. 2005a, 2012a). Rocks older than ca. 2.6 Ga occur widely in the craton (Fig. 1). The NCC is characterized by strong late Neoarchean tectono-thermal events (Shen et al. 2005; Wan et al. 2011a; Zhai and Santosh 2011), and this makes it different from several other cratons worldwide, providing a chance for better understanding the tectonic property of the Archean/Proterozoic boundary. Similar to other cratons, 80–90 % of the continental crust of the NCC may have formed in the Archean.

The Archean rocks are covered in many areas by Paleo- to Neoproterozoic sedimentary sequences deposited into major basins such as the Songliao basin, North China basin, and Ordos basin. Furthermore, several events since the Paleoproterozoic modified the original features of the Archean basement, including (1) Paleoproterozoic tectono-thermal events that resulted in strong reworking of Archean crust and overprinted the original geological relationships; (2) long-term

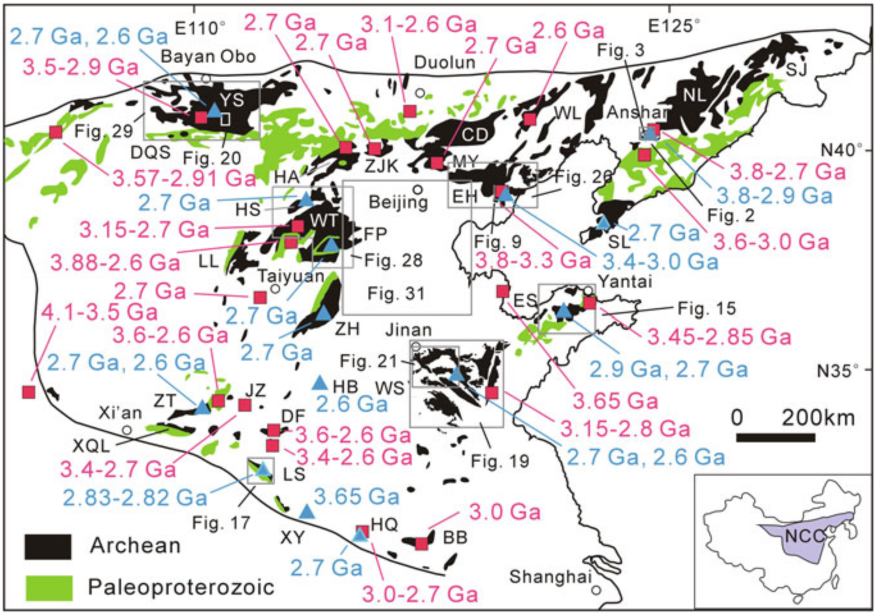


Fig. 1 Simplified sketch map showing distribution and zircon ages for the early Precambrian rocks in the North China Craton. Also shown are the locations of rocks and zircons of >2.6 Ga and Figs. 2, 3, 9, 15, 17, 19, 20, 21, 26, 28, 29, and 31. *YS* Yinshan; *HA* Huai'an; *ZJK* Zhangjiakou; *HS* Hengshan; *WT* Wutai; *FP* Fuping; *LL* Lüliang; *ZH* Zanhuang; *ZT* Zhongtiao; *JZ* Jiaozuo; *DF* Dengfeng; *XQL* Xiaoqinling; *LS* Lushan; *CD* Chengde; *MY* Miyun; *EH* eastern Hebei; *WL* western Liaoning; *SL* southern Liaoning; *NL* northern Liaoning; *SJ* southern Jilin; *WS* western Shandong; *ES* eastern Shandong; *HQ* Huoqiu; *BB* Bengbu. *Blue triangle* rock age; *red square* detrital or xenocrystic zircon age

erosion destroyed part of the Archean basement; and (3) craton destruction since the Mesozoic was mainly related to deep crustal processes but also influenced the shallow crust. All these modifications make it difficult to comprehensively understand the Archean geology of the NCC. Nevertheless, geoscientists carried out geological, petrological, geochronological, and geochemical studies in almost every Archean area of the craton. Research was also undertaken on rock samples recovered from drill cores that penetrate into basement beneath some sedimentary basins and on Archean enclaves brought up from the deep crust by young igneous rocks. In view of all these new data, the main features of the Archean basement of the NCC have become better understood although significant debates still occur as indicated by different tectonic models (e.g., Kusky and Li 2003; Wu et al. 1998; Zhai and Santosh 2011; Zhao et al. 2002, 2005; Zhao 2014).

The NCC has a long history of geological studies, and some specific case studies carried out in the last century laid important foundations for later work (e.g., Bai et al. 1986, 1996; Cao et al. 1996; Cheng et al. 1982; Li et al. 1986; Lu et al. 1996; Qian et al. 1985, 1994; Shen et al. 1990, 1992, 1994a, b, 2000; Sun et al. 1984;

Sun and Hu 1993; Wu et al. 1989, 1998; Zhang et al. 1988; Zhao et al. 1993). Since the beginning of this century, numerous papers were published on Archean rocks and their evolution, and in this chapter, we try to synthesize present knowledge by first outlining the general geological records of the Archean basement and then discussing several important issues relating to Archean crust formation and evolution.

2 Archean Geological Record

2.1 Eoarchean (>3.6 Ga)

Rocks older than 3.8 Ga have been discovered in only a few areas worldwide such as northern Canada (Bowring and Williams 1999; O'Neil et al. 2007), eastern Antarctica (Black et al. 1986), West Greenland (Kinny 1986; Nutman et al. 1996), and around Anshan city in the NNC (Liu et al. 1992; Song et al. 1996; Wan et al. 2005a, 2012a). Anshan is located southwest of the Anben (Anshan-Benxi) area where 2.5 Ga BIF-bearing supracrustal rocks (the Anshan "Group," we use the word group with quotation marks to indicate that it does not conform to modern stratigraphic terminology but constitutes a tectono-stratigraphic term) and granitoids (mainly syenogranites) occur widely (Fig. 2).

In Anshan, 3.8 Ga rocks occur within three complexes, namely the Baijiafen, Dongshan, and Shengousi complexes (Fig. 3). Baijiafen quarry was the site where 3.8 Ga rocks were first discovered (Liu et al. 1992). The complex is ~700 m long and ~50 m wide in exposure and extends in a NW–SE direction, in tectonic contact with the 3.3–3.1 Ga Chentaigou granite in the southwest and 3.36 Ga Chentaigou supracrustal rocks in the northeast (Wan et al. 2005a; Wan unpublished data). It is mainly composed of strongly mylonitized trondhjemitic gneiss of different ages with some biotite schist, gneissic monzogranite, and quartz diorite (Fig. 4). In an early study, all granitoids of the complex were considered to have formed at 3.8 Ga (Liu et al. 1992), but later studies indicated that these rocks formed at different times ranging from 3.8 to 3.1 Ga (Liu et al. 2008). The 3.8 Ga mylonitized trondhjemitic gneiss occurs in narrow layers such as sample A0518 (Fig. 5a) that is distinguished from the surrounding rocks (also trondhjemitic gneisses) by containing less biotite. The biotite schist (Fig. 5b) varies in thickness between a few centimeters and half a meter and alternates with igneous units, including trondhjemitic gneiss. There are two opinions on the origin of the schist, namely an altered mafic dike (Song et al. 1996) or a metasedimentary rock (Liu et al. 2008). The latter is based on the observation that the schist is interlayered with chert that is composed of recrystallized quartz with some banded biotite + epidote aggregates. However, at some localities, quartz veins occur together with biotite schist; therefore, the "chert" may, in fact, be a deformed quartz vein. Although it is uncertain whether the biotite schist is derived from a mafic dike or a supracrustal

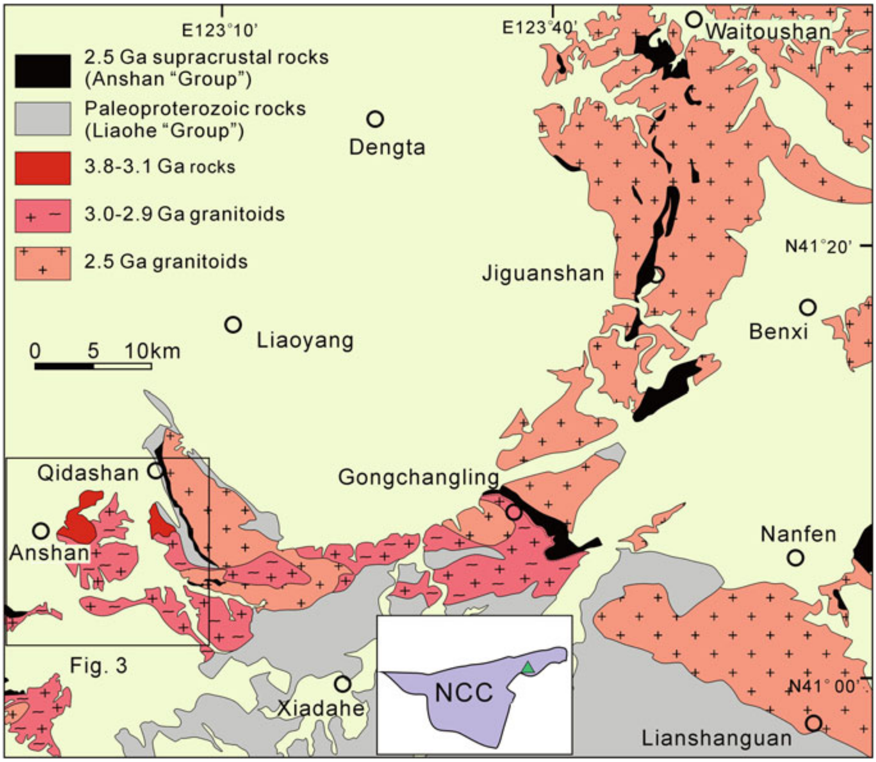


Fig. 2 Geological map of the Anben (Anshan-Benxi) area, North China Craton. Modified after LBGMRE (1975a, b, 1976); Wan (1993), and Wan et al. (2015a). *Triangle* in *inset* map shows location of Fig. 2 in the NCC

rock, it is considered to be older than 3.6 Ga because it is cut by 3.62 Ga trondhjemitic gneiss (Fig. 5b). Some younger magmatic rocks (samples A0405, A0517, A0521) contain xenocrystic zircons with ages of 3.8–3.6 Ga.

Rocks of the Dongshan Complex trend approximately WNW–ESE (Fig. 3), and the exposure is more than 10 m wide and up to 1000 m long. It occurs as a large enclave within the 3.14 Ga Lishan trondhjemite and is cut by veins derived from the Lishan trondhjemite intrusion. Different types of 3.8–3.1 Ga rocks have been identified in the complex, including banded trondhjemitic gneiss, gneissic trondhjemite, gneissic monzogranite, pegmatite, meta-ultramafic rock (komatiite?), amphibolite (metabasalts or gabbro), and meta-quartz diorite. These units are mostly structurally concordant to each other because of strong ductile deformation, and their original contact relationships are often difficult or impossible to recognize. Rocks older than 3.6 Ga were identified in three locations, including 3.81–3.68 Ga banded trondhjemitic gneisses and 3.79 Ga meta-quartz diorite. The 3.81 Ga banded trondhjemitic gneiss (sample Ch28, Fig. 5c) near a pavilion was first identified in the complex (Song et al. 1996). 3.79 Ga meta-quartz diorite (sample

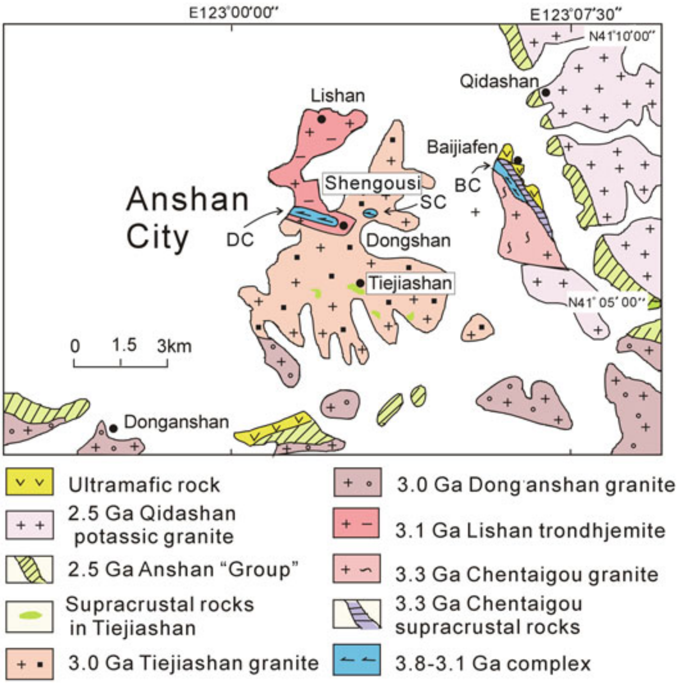


Fig. 3 Geological map of the Anshan area (Wan et al. 2012a). *BC* Baijiafen Complex; *DC* Dongshan Complex; *SC* Shengousi Complex

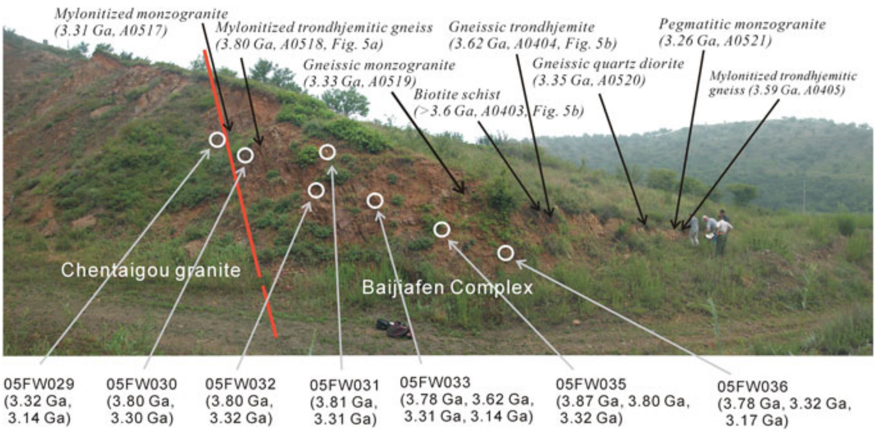


Fig. 4 Photographic mosaic showing studied section of the Baijiafen Complex with sampling sites marked (Liu et al. 2008). Samples with prefix 05FW are from Wu et al. (2008)

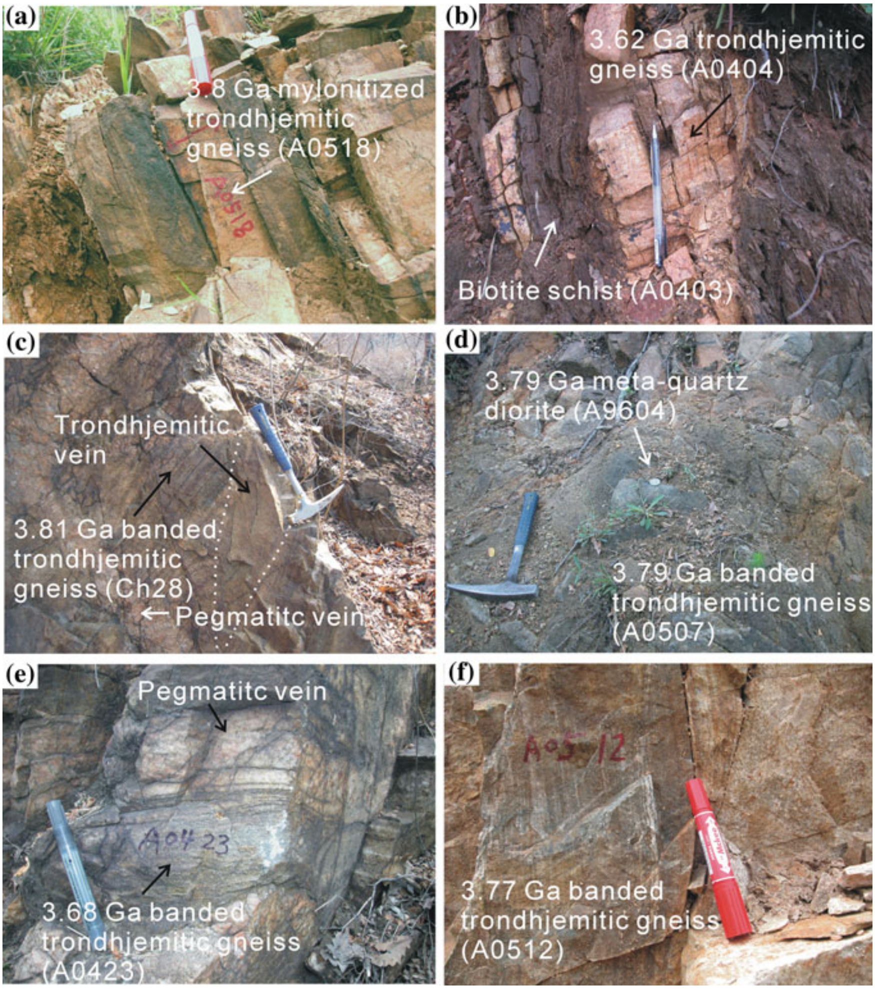


Fig. 5 Field photographs of Eoarchean rocks in the Anshan area. **a** 3.80 Ga mylonitized trondhjemitic gneiss (A0518), Baijiafen Complex; **b** biotite schist (A0403) intruded by 3.62 Ga trondhjemitic gneiss (A0404), Baijiafen Complex; **c** 3.81 Ga banded trondhjemitic gneiss (Ch28) intruded by trondhjemitic and pegmatitic veins, Dongshan Complex; **d** 3.79 Ga meta-quartz diorite (A9604) occurring in 3.79 Ga banded trondhjemitic gneiss (A0507), Dongshan Complex; **e** 3.68 Ga banded trondhjemitic gneiss (A0423) intruded by pegmatitic vein, Dongshan Complex; **f** 3.77 Ga banded trondhjemitic gneiss (A0512), Shengousi Complex

A9604) occurs as a small enclave within the 3.79 Ga banded trondhjemite (sample A0507) in an outcrop near the southeastern end of the Dongshan Complex (Fig. 5d). The identification of 3.68 Ga banded trondhjemitic gneiss (sample A0423, Fig. 5e) indicates that there are Eoarchean banded trondhjemitic gneisses of different ages in the complex although they are similar in field appearance and composition (Liu et al. 2008).

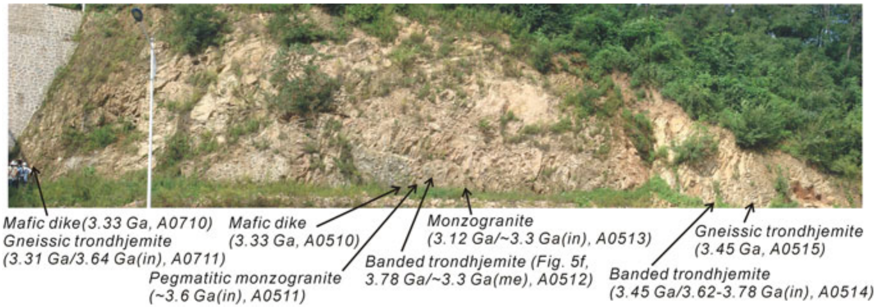


Fig. 6 Photographic mosaic showing the section of the Shengousi Complex in the Anshan area (Wan et al. 2012a)

The Shengousi Complex is located between the Dongshan and Baijiafen complexes, and its full extent is unknown due to poor exposure and is only readily apparent in a deep road cut (Wan et al. 2012a). The key locality is a ~50 m-long and up to ~10 m-high section on an elevated bench in this road cut (Fig. 6). The complex comprises polyphase migmatites, and despite a strong structural overprint through ductile deformation, there are small areas of lower strain where the relative chronologies between the different migmatite components are preserved. The youngest component on the basis of field relationships is a pegmatitic monzogranite dike. Eight samples were collected for zircon dating in this section, and these samples revealed a protracted tectono-magmatic history from 3.77 to 3.13 Ga with the oldest rocks being 3.77 Ga banded trondhjemitic gneisses (sample A0512, Fig. 5f). The complex mainly contains monzogranite and mafic metamorphic rocks besides trondhjemitic rocks of different ages (Fig. 6).

The above three complexes are similar in their geochronological record. Apart from >3.6 Ga gneisses, 3.45–3.0 Ga rocks have been identified. Many >3.6 Ga rocks notably contain younger (mainly 3.3 Ga) zircons. Some authors considered this as evidence that the trondhjemitic gneisses formed at 3.3 Ga and contained numerous 3.8 Ga zircon xenocrysts (Wu et al. 2008). However, based on field observations, zircon morphology, and cathodoluminescence (CL) images, a better explanation may be that these granitoid gneisses predominantly constitute strongly deformed igneous injection migmatites containing igneous components of several ages and/or are related to anatexis of 3.8 Ga rocks at 3.3 Ga (Liu et al. 2008; Nutman et al. 2009; Song et al. 1996; Wan et al. 2012a). There is no doubt that the 3.79 Ga quartz diorite identified in the Dongshan Complex is magmatic in origin, as indicated by its geological, petrological, and compositional features, although it also contains younger zircons (Wan et al. 2005a). Some of the <3.6 Ga rocks in the three complexes that do not show banded structures or strong deformation also contain old zircon xenocrysts (Fig. 7). All ~3.8 Ga gneisses are trondhjemitic in composition with high SiO_2 and Na_2O, and low ΣFeO ($FeO + 0.9 \times Fe_2O_3$), MgO, CaO, and K_2O. They have very low total rare earth element (REE) contents, positive or negligible Eu anomalies, and weakly fractionated REE patterns (Fig. 8a).

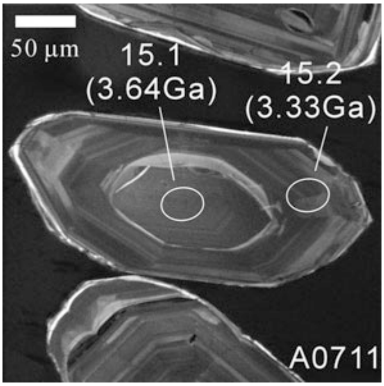


Fig. 7 3.64 Ga xenocrystic zircon core occurring in 3.33 Ga magmatic zircon from gneissic trondhjemite (A0711) in the Shengousi Complex, Anshan

Many >3.6 Ga detrital and xenocrystic zircons were also discovered in the Gongchangling and Waitoushan areas (Fig. 2) (Wan 1993; Wan et al. 2015a). This suggests that Eoarchean rocks may occur in a wider area of Anben than currently identified. The single zircon age of 4.17 Ga reported by Cui et al. (2013) from an amphibolite (metabasalt) of the 2.5 Ga Anshan "Group" in Waitoushan is questionable after rechecking the original LA-ICP-MS data (Diwu personal communication).

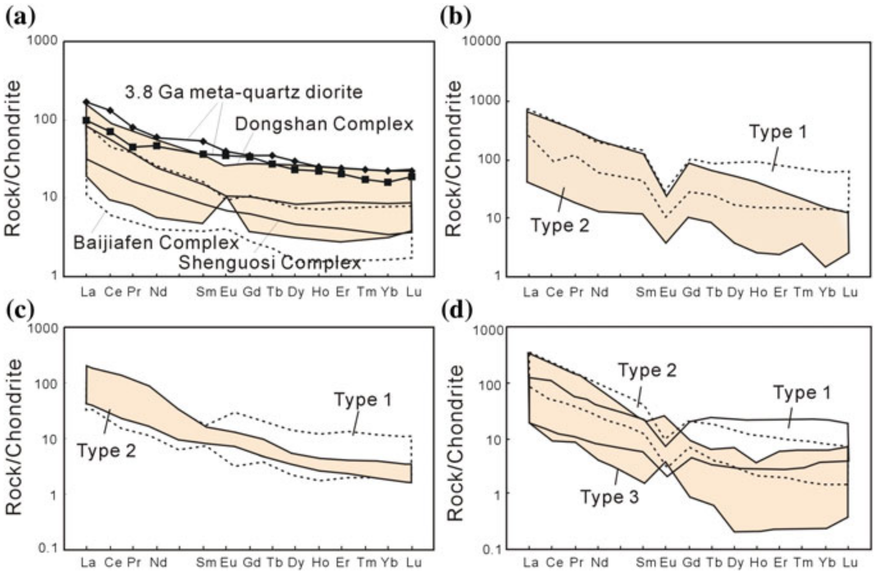


Fig. 8 Chondrite-normalized REE patterns for Archean rocks from the North China Craton. **a** 3.8 Ga trondhjemitic rocks in Anshan; **b** 3.0–2.9 Ga Tiejiashan K-rich granite in Anshan; **c** 2.75–2.7 Ga TTG rocks in the North China Craton; **d** 2.53–2.50 Ga syenogranite in the North China Craton. Data are from Jahn et al. (2008), Wan et al. (2005a, 2007, 2011b, 2012a, b, 2014a), Yang et al. (2013), and Zhu et al. (2013)

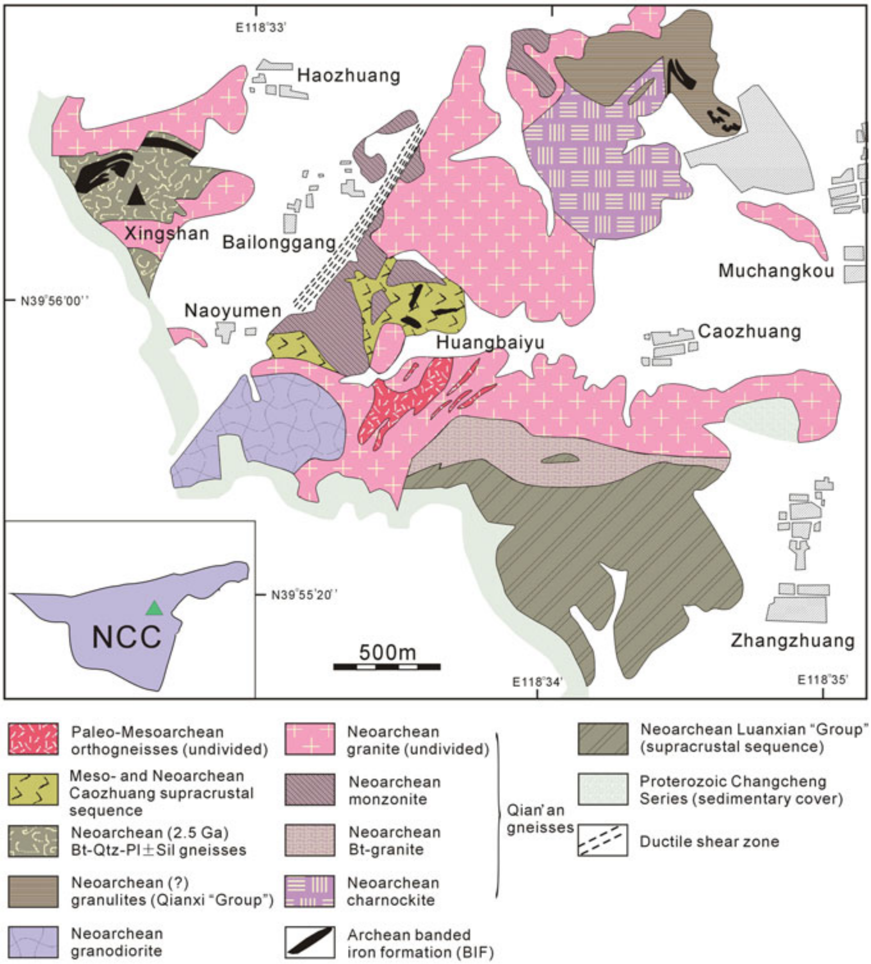


Fig. 9 Simplified geological map of the Caozhuang area, eastern Hebei. Modified after Chen (1988), Liu et al. (2013a), and Nutman et al.(2011). *Triangle* in *inset* map shows location of Fig. 9 in the NCC

Eoarchean rocks within relatively large areas in the NCC have so far only been identified in the Anben area. However, abundant Eoarchean zircons were discovered in rocks of the Caozhuang Complex, eastern Hebei Province. This complex is composed of amphibolite- to granulite-facies granitoids and a supracrustal sequence (Fig. 9). The supracrustal sequence is composed of Bt-Pl-Qtz ± Sil and Bt ± Grt gneisses, amphibolite, marble, calc-silicate, fuchsite quartzite, and banded iron formation (BIF) and was considered to have an age of 3.5 Ga on the basis of a Sm–Nd isochron age for amphibolites (Jahn et al. 1987). However, the Sm–Nd isochron was later interpreted as a mixing line (Nutman et al. 2011). The oldest rocks

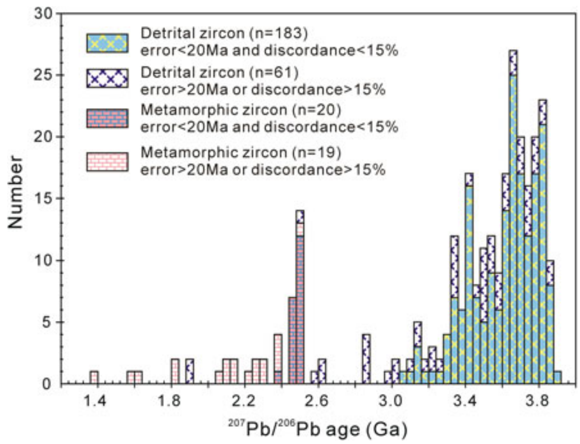


Fig. 10 Age histogram for zircons from metasedimentary rocks (including fuchsite quartzite, para-amphibolite, and metapelitic rock) in the Caozhuang area, eastern Hebei. Metamorphic zircon ages of 2.5 Ga have been identified only in para-amphibolite and metapelitic rock. Data are from Liu et al. (1992, 2013a), Nutman et al. (2011), Wilde et al. (2008), and Wu et al. (2005a)

identified in the area are 3.4–3.3 Ga granitoid gneisses (Nutman et al. 2011; Liu unpublished data). Detrital zircons with ages of 3.88–3.55 Ga were reported from the Caozhuang (fuchsite) quartzite (Liu et al. 1992; Nutman et al. 2011; Wilde et al. 2008; Wu et al. 2005a). Recently, Liu et al. (2013b) carried out SHRIMP dating on detrital zircons from para-amphibolite and Grt-Bt gneiss and obtained detrital core ages ranging from 3.8 to 3.4 Ga and metamorphic rim ages of ∼2.5 Ga. Combining the detrital zircon data of the three rock types, age peaks at ∼3.83, ∼3.67, 3.55, and ∼3.41 Ga can be recognized (Fig. 10), suggesting that detrital material was derived from crustal sources of different ages. Based on zircon morphology and inclusion studies, Nutman et al. (2014) suggested that the Caozhuang quartzite is most likely a <3.5 Ga immature sedimentary rock of local provenance. This interpretation strengthens the case for Eoarchean rocks with a substantial 3.88–3.80 Ga component occurring in eastern Hebei Province and indicates that the paragneiss protoliths of the Caozhuang Complex were deposited between 3.4 and 2.5 Ga ago (Liu et al. 2013b; Nutman et al. 2014).

Rocks and zircons older than 3.6 Ga have also been identified elsewhere in the NCC (Fig. 1), including 3.65 Ga felsic granulite enclaves in Mesozoic volcanic rocks of the Xinyang area (Zheng et al. 2004a) and ≥3.6 Ga detrital zircons in the Zhongtiao and Dengfeng areas (Liu et al. 2012a; Zhang et al. 2014a). Interesting is the discovery of three 4.1–3.9 Ga xenocrystic or detrital zircons, together with younger Archean and Paleoproterozoic grains, in Paleozoic volcano-sedimentary rocks of the northern Qinling Orogenic Belt (Diwu et al. 2010a, 2013, personal communication; Wang et al. 2007). One zircon has a 3.71 Ga overgrowth rim (Fig. 11), suggesting a tectono-thermal event at that time in the zircon source

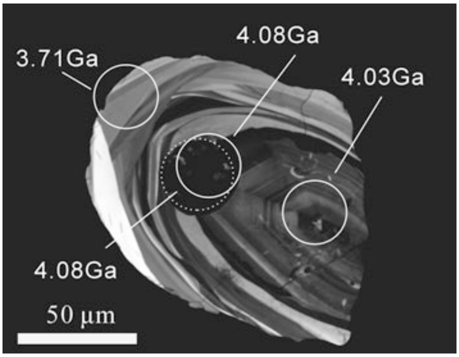


Fig. 11 Cathodoluminenscence image showing 3.71 Ga overgrowth rim on 4.08 Ga xenocrystic or detrital zircon from pyroclastic rock in the Paleozoic Caotangou Group in northern Qinling, near the North China Craton (from Diwu et al. 2010a, b). *Circle* and *dashed circles* refer to SHRIMP and LA-ICPMS dating locations, respectively

region. The volcanic rock is located near the southern margin of the NCC, and the old zircons are considered to be derived from the NCC basement (Diwu et al. 2013; Wan et al. 2009a).

2.2 Paleoarchean (3.6–3.2 Ga)

Paleoarchean rocks and components have been identified in many areas of the NCC and reflect the most important tectono-magmatic events in Anshan as indicated by their distribution and zircon age histogram (Fig. 12). The 3.36 Ga Chentaigou supracrustal rocks near Baijiafen (Fig. 3) are the oldest supracrustal rocks identified

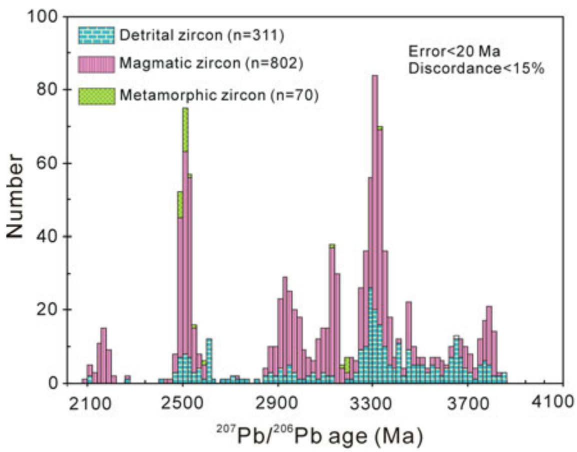
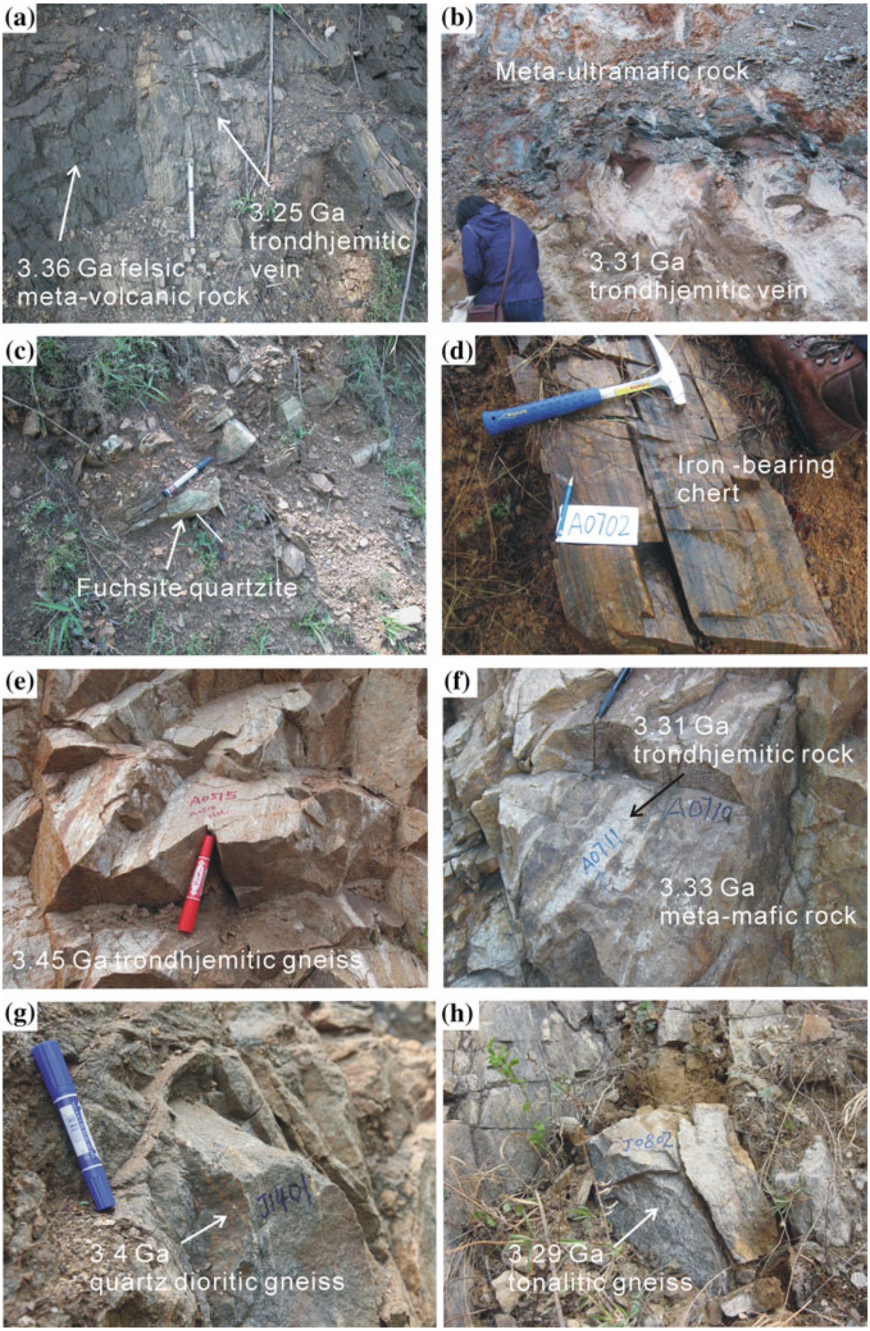


Fig. 12 Age histogram of zircons from Archean rocks in the Anben area. Data are from Liu et al. (1992, 2008), Song et al. (1996), Wan et al. (2005a, 2007, 2012a, b, d, 2015a, unpublished data), Wu et al. (2008), Yin et al. (2006), and Zhou et al. (2007, 2009)

in the NCC. Their formation age is limited by 3.36 Ga felsic metavolcanic rocks in the sequence and 3.34–3.31 Ga trondhjemitic veins intruding the sequence (Fig. 13a, b) (Song et al. 1996; Wan unpublished data). The main rock types include amphibolite, meta-ultramafic rocks, felsic metavolcanic rock, meta-calc-silicate, fuchsite quartzite, and iron-bearing chert (Fig. 13c, d). The meta-ultramafic rocks occur over a relatively large area in the northeastern exposure of the sequence, and their protolith was uncertain (volcanic or intrusive) in early studies. They are intruded by 3.31 Ga trondhjemitic veins (Fig. 13b) and are considered to belong to the sequence. They are similar to komatiites in chemical compositions with MgO contents up to 38 %, but no spinifex textures have been identified because of strong modification. The amphibolite is tholeiitic in composition, showing a flat REE pattern with no large ion lithophile element (LILE) enrichment. This is the main reason for the speculative interpretation that these supracrustal rocks formed in an arc environment (Wan et al. 1997a).

The oldest Paleoarchean rock is a 3.45 Ga trondhjemitic gneiss in the Shengousi Complex (Fig. 13e). It is considered to have interacted with Eoarchean trondhjemitic rocks nearby to form an injection migmatite that subsequently underwent strong deformation to produce a rock with layers of different ages (Wan et al. 2012a). Igneous rocks of 3.35–3.2 Ga widely occur in the Anshan area, including the Baijiafen, Dongshan, and Shengousi complexes. The rock types are metagabbro, metadiorite, meta-quartz diorite, granite, as well as trondhjemitic gneiss (Dong et al. 2013; Liu et al. 2008; Wan et al. 2001, 2012a; Zhou et al. 2007, 2009). It is common that different rocks with similar or different ages occur within a single outcrop (Fig. 13f). The Chentaigou granite was considered to be the largest pluton formed at ~3.3 Ga (Song et al. 1996). However, Wu et al. (2008) obtained ~3.3 and ~3.1 Ga zircon ages for three Chentaigou granite samples near the Baijiafen Complex and thought the latter to represent the emplacement time of the pluton. Based on geological mapping and zircon dating, Li et al. (2013) suggested that the Chentaigou granite is composed of 3.3 and 3.1 Ga granitoid rocks. Trondhjemitic rocks in the Anshan area, between 3.45 and 3.3 Ga in age, show a significant variation in REE composition from very low ΣREE contents and weakly fractionated REE patterns to high ΣREE contents and strongly fractionated REE patterns (Wan unpublished data).

In Caozhuang, eastern Hebei Province, 3.4 Ga quartz dioritic gneiss and 3.3–3.2 Ga tonalitic gneiss (Fig. 13f, g) occur as enclaves within 2.5 Ga granite (Nutman et al. 2011; Liu unpublished data). This is the second area where Paleoarchean igneous rocks were identified in the NCC. Based on the youngest detrital zircons at 3.55 Ga from a fuchsite quartzite and the oldest TTG rock at ~3.3 Ga in the area, Wan et al. (2009a) suggested that deposition of the Caozhuang Complex supracrustal rocks occurred between 3.55 and 3.3 Ga. However, the relationship between the supracrustal rocks and the ~3.3 Ga TTGs is uncertain. Based on the metamorphic zircon age of 2.5 Ga and the believable youngest detrital zircon age of 3.4 Ga of the metasedimentary rocks (Fig. 10), we can now only limit deposition to between 3.4 and 2.5 Ga. Mainly based on zircon dating, Han et al. (2014a) concluded that the supracrustal rocks in Xingshan, ~1.5 km northwest of


(a)
3.25 Ga
trondhjemitic
vein
3.36 Ga felsic
meta-volcanic rock
(b)
Meta-ultramafic rock
3.31 Ga
trondhjemitic vein
(c)
Fuchsite quartzite
(d)
Iron -bearing
chert
A0702
(e)
A0515
3.45 Ga trondhjemitic gneiss
(f)
3.31 Ga
trondhjemitic rock
A0710
A0711
3.33 Ga
meta-mafic rock
(g)
J1401
3.4 Ga
quartz dioritic gneiss
(h)
J0802
3.29 Ga
tonalitic gneiss

◀ **Fig. 13** Field photographs of Paleoarchean rocks in the North China Craton. **a** 3.36 Ga felsic meta-volcanic rock (the Chentaigou supracrustal rocks) intruded by 3.25 Ga trondhjemitic vein, Anshan; **b** meta-ultramafic rock (the Chentaigou supracrustal rocks) intruded by 3.31 Ga trondhjemite vein, Anshan; **c** fuchsite quartzite in the Chentaigou supracrustal rocks, Anshan; **d** iron-bearing chert in the Chentaigou supracrustal rocks, Anshan; **e** 3.45 Ga trondhjemitic gneiss in the Shengousi Complex, Anshan; **f** 3.31 Ga gneissic trondhjemite and 3.33 Ga meta-mafic rock in the Shengousi Complex, Anshan; **g** 3.4 Ga gneissic quartz diorite, Huangbaiyu, eastern Hebei; **h** 3.29 Ga gneissic trondhjemite, Huangbaiyu, eastern Hebei

Huangbaiyu, that belong to the Caozhuang Complex, were deposited at 3.39 Ga. However, the dated rock contains garnet and many 3.76–3.43 Ga zircons, similar in features to the metasedimentary rocks in Huangbaiyu. Therefore, it is possible that the 3.39 Ga zircon is detrital in origin, and this age therefore only constrains the upper depositional age of the Caozhuang supracrustal rocks.

The age distribution of >3.3 Ga detrital zircons from the Caozhuang Complex is similar to that of magmatic zircons in the Anshan area (Figs. 10 and 12). However, it appears that the detrital material was derived from the surrounding area, rather than Anshan, which is too far from Caozhuang.

Paleoarchean detrital and xenocrystic zircons were identified in many areas of the NCC such as Alax, Guyang, Wutai, Jiaozue, Dengfeng, Zhongtiao, eastern Shandong, and Bengbu (Fig. 1) (Diwu et al. 2008; Gao et al. 2006; Ji 1993; Jian et al. 2012; Jin et al. 2003; Liu et al. 2012a; Shen et al. 2005; Wan et al. 2006, 2009a, c, 2010a; Wang et al. 1998; Xie et al. 2014a; Zhang et al. 2014a, b).

2.3 Mesoarchean (3.2–2.8 Ga)

Mesoarchean rocks are more widespread in the NCC than Paleoarchean rocks. In Anshan, large Mesoarchean intrusive bodies include the 3.14 Ga Lishan trondhjemite, the 3.0 Ga Dong'anshan granite, the 3.0–2.9 Ga Tiejiashan granite, and part of the 3.3–3.1 Ga Chentaigou granite (Fig. 3). The Tiejiashan granite (Fig. 14a) is the oldest and largest K-rich granite pluton in the NCC (Wan et al. 2007; Wu et al. 1998) and occupies a total area of >150 km^2 (Fig. 2). The rocks vary in their REE fractionation patterns but have high ΣREE contents and strong negative Eu anomalies (Fig. 8b). The Tiejiashan granite contains supracrustal xenoliths such as BIF and quartzite (Fig. 14b, c). There are also some mica–quartz schists (Fig. 14d) that were considered to be supracrustal enclaves (Yin et al. 2006). However, they show similar geochemical features as the Tiejiashan granite, and the so-called detrital zircons in the rocks are mainly ~3.0 Ga in age. In some thin sections, K-feldspar grains occur at different sizes in the fine-grained sericite + quartz groundmass. These features suggest that sericite resulted from strong deformation and alteration of K-feldspar during shearing. Therefore, we suggest that at least some schists are due to strong deformation and alteration of granite. Besides the large Mesoarchean granitoid bodies, many small Mesoarchean granitoid bodies or


(a)
2.91 Ga K-rich granite
(b)
BIF
(c)
(d)
K-rich
granite
Mica-quartz
schist
(e)
3.13 Ga augen-like granite
(f)
3.14 Ga monzogranite
3.14 Ga
trondhjemite
(g)
~3.2 Ga
gneissic tonalite
(h)
2.94 Ga
anatectic granitoid

◀ **Fig. 14** Field photographs of Mesoarchean rocks in the North China Craton. **a** Mesoarchean Tiejiashan K-rich granite, Anshan; **b** BIF in Mesoarchean Tiejiashan K-rich granite, Anshan; **c** quartzite in Mesoarchean Tiejiashan K-rich granite, Anshan; **d** mica–quartz schist in Mesoarchean Tiejiashan K-rich granite, Anshan; **e** 3.13 Ga augen-like granitic gneiss in the Baijiafen Complex, Anshan; **f** 3.14 Ga trondhjemite and 3.14 Ga monzogranite, Dongshan Complex, Anshan; **g** ca. 3.2 Ga gneissic tonalite, Huangbaiyu, eastern Hebei; **h** 2.94 Ga anatectic granitoid, Huangbaiyu, eastern Hebei

veins also occur in the Baijiafen, Dongshan, and Shengousi complexes (Figs. 4, 6 and 14e, f).

In Caozhuang, eastern Hebei Province, Mesoarchean igneous rocks have also been discovered (Fig. 14g, h) (Nutman et al. 2011), but they only occur on a very small scale. However, Mesoarchean xenocrystic zircons are more widespread.

In eastern Shandong, 2.9 Ga rocks are widely distributed, extending from Mazhuanghe in the west to Hexikuang in the east, with some occurring in the southern portion of the area (Fig. 15). Most of the so-called Mesoarchean Tangjiazhuang "Group" consists of intrusive rather than supracrustal rocks. Only a few 2.9 Ga supracrustal rocks, named Huangyadi supracrustal rocks, occur on a small scale within 2.9 Ga igneous rocks (Jahn et al. 2008). Mesoarchean supracrustal rocks in eastern Shandong are much smaller in scale than thought before (BGMRSP 1991). At least three types of 2.9 Ga igneous rocks, namely quartz diorite, tonalite, and high-Si trondhjemite, have been identified (Jahn et al. 2008; Liu et al. 2011, 2013a; Wang et al. 2014a; Wu et al. 2014; Xie et al. 2014b). Of these, tonalite seems to be the most common, with a total area up to several tens of square km. 2.9 Ga gneissic tonalite occurs in the lower part along a ~200 m-long road cut northeast of Zhoujiagou. It is in contact with 2.9 Ga gneissic high-Si trondhjemite in the upper part; both show strong deformation with their foliations parallel to each other (Fig. 16a–c). At the Hexikuang reservoir dam, 2.9 Ga gneissic quartz diorite occurs as enclaves within 2.9 Ga gneissic tonalite, and these show a differently oriented foliation (Fig. 16d). Felsic veins in the quartz diorite are parallel to the foliation and are considered to be anatectic products. Both the gneissic quartz diorite and tonalite contain ca. 2.5 Ga metamorphic or anatectic zircon, and the gneissic tonalite around the enclave shows strong deformation and anatexis. It seems likely that the quartz diorite enclaves were rotated after leucosome formation during the ca. 2.5 Ga tectono-thermal event (Xie et al. 2014b). 2.9 Ga gneissic tonalites exhibit strong anatexis with trondhjemitic leucosomes and biotite-rich melanosomes in local outcrops (Fig. 16e). Some leucosome forms layers and lenses at different scales and is strongly or weakly deformed. Anatexis occurred syntectonically in a regime locally changing from compression to extension at the end of the Neoarchean because 2.5 Ga metamorphic or anatectic zircons have been identified.

2.8 Ga supracrustal rocks and TTGs have been identified in the Lushan area on the southern margin of the NCC (Fig. 17). These rocks are mainly composed of (garnet-bearing) amphibolite, hornblende–plagioclase gneiss, and biotite–plagioclase gneiss. Some amphibolites show a layered structure (Fig. 16f), mainly due to

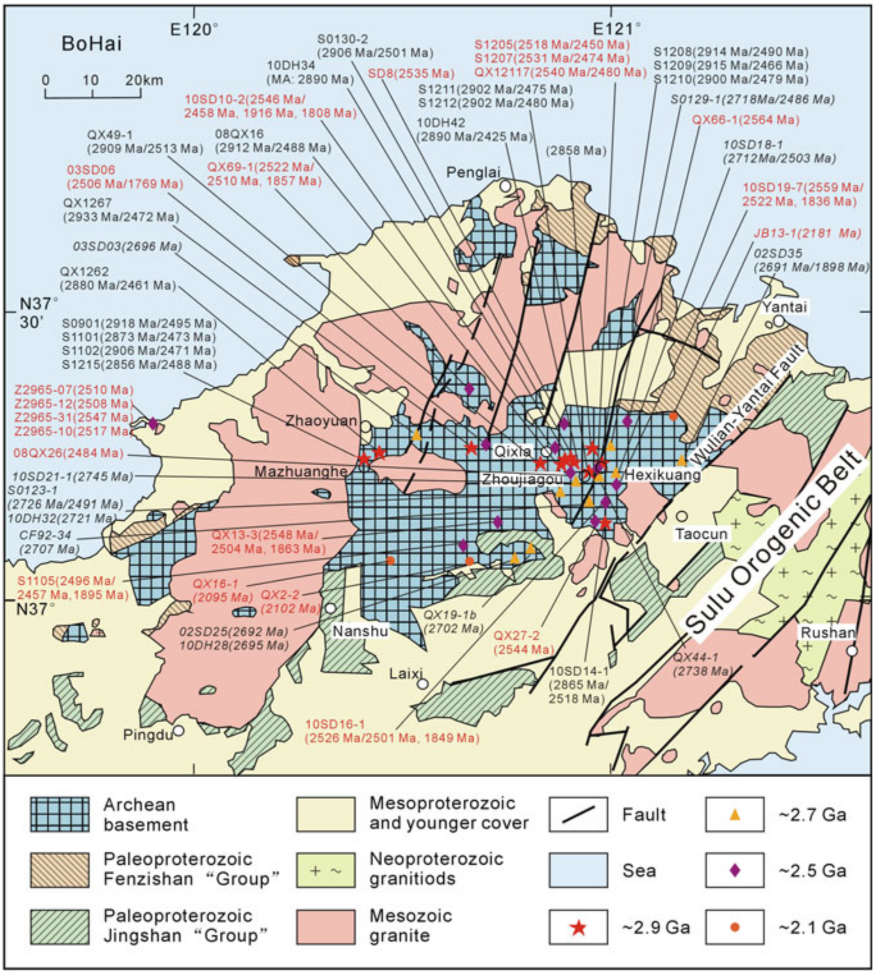
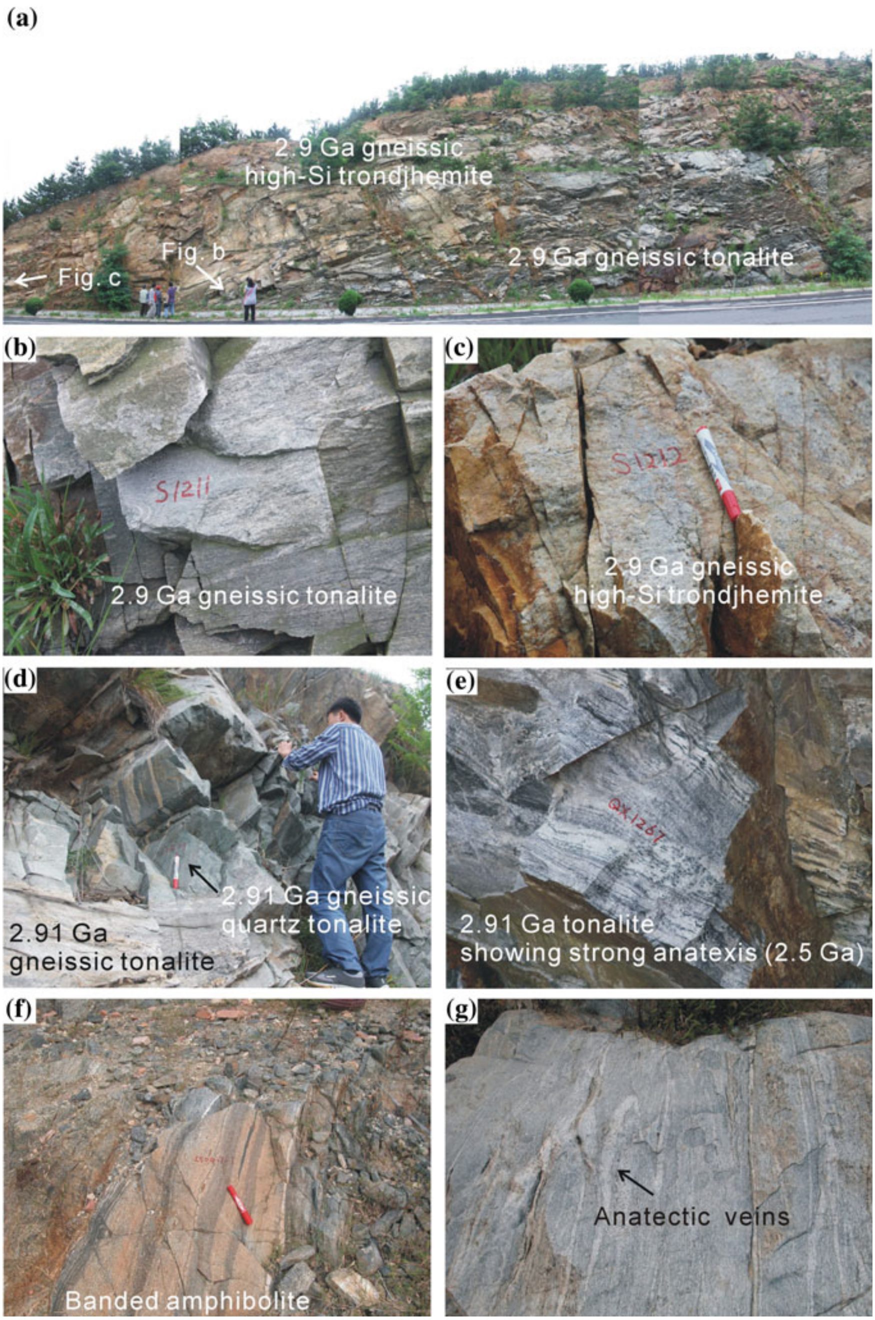


Fig. 15 Geological map of eastern Shandong. Shown also are locations of zircon dating samples, and ages in parenthesis are magmatic zircon age or magmatic zircon age/metamorphic zircon age. Data are from Jahn et al. (2008), Liu et al. (2011), Liu et al. (2011, 2013a, 2014), Liu et al. (2013b), Liu et al. (2014), Shan et al. (2015), Tang et al. (2007), Wang and Yan (1992), Wang et al. (2014a), Wu et al. (2014), Xie (2012), Xie et al. (2013, 2014b), and Zhou et al. (2008). See Fig. 1 for location of the figure in the NCC

variations in plagioclase and hornblende contents. They occur as enclaves within TTG rocks with strong deformation and local anatexis (Fig. 16g). Zircon dating of the supracrustal rocks and TTGs yielded 2.83 Ga magmatic ages and two sets of metamorphic ages at 2.79–2.77 and 2.67–2.64 Ga (Liu et al. 2009a). Huang et al. (2010) performed zircon dating on TTG-like and TTG rocks in the same area and interpreted the ages of 2.77 and 2.72 Ga as the time of crystallization of the host igneous rocks. Similar conclusions were arrived at by Diwu et al. (2010b).


(a)
2.9 Ga gneissic
high-Si trondjhemite
Fig. b
Fig. c
2.9 Ga gneissic tonalite
(b)
S1211
2.9 Ga gneissic tonalite
(c)
S1212
2.9 Ga gneissic
high-Si trondjhemite
(d)
2.91 Ga gneissic
quartz tonalite
2.91 Ga
gneissic tonalite
(e)
QX1267
2.91 Ga tonalite
showing strong anatexis (2.5 Ga)
(f)
Banded amphibolite
(g)
Anatectic veins

◀ **Fig. 16** Field photographs of Mesoarchean rocks in the North China Craton. **a** 2.9 Ga gneissic high-Si trondhjemite (*top*) in contact with gneissic tonalite (*bottom*), Qixia, eastern Shandong; **b** 2.9 Ga gneissic tonalite, local enlargement in figure a; **c** 2.9 Ga gneissic high-Si trondhjemite, local enlargement in figure a; **d** relationship between 2.91 Ga gneissic quartz diorite and 2.91 Ga gneissic tonalite, Qixia, eastern Shandong; **e** 2.91 Ga gneissic trondhjemite, Qixia, eastern Shandong; **f** 2.84 Ga amphibolites showing banded structures, Lushan, Henan; **g** anatectic veins in 2.83 Ga gneissic tonalite, Lushan, Henan

However, the dated zircons exhibit strong recrystallization and overgrowth, and it is therefore likely that these are ~2.8 Ga TTG rocks that underwent strong metamorphism in the early Neoarchean. More work is required to identify whether or not there are ~2.7 Ga rocks in the area.

Mesoarchean detrital and xenocrystic zircons were discovered all over the NCC such as Alax, Guyang, Wutai, Fuping, Dengfeng, eastern Hebei, Huoqiu, western Shandong, and eastern Shandong (Fig. 1) (Jian et al. 2012; Kröner et al. 1988; Shen et al. 2004, 2005; Wan et al. 2006, 2010a, b; Wang et al. 1998, 2014a, b, c, d, e; Zhang et al. 2014a, b).

2.4 Neoarchean (2.8–2.5 Ga)

2.4.1 Early Neoarchean (2.8–2.6 Ga)

Two magmatic events can be recognized in the Neoarchean crust formation and evolution, namely an early Neoarchean event (2.8–2.6 Ga) and a late Neoarchean event (2.6–2.5 Ga). 2.80–2.76 Ga rocks are rare, and the most important tectono-thermal event is 2.79–2.77 Ga metamorphism recorded in the Lushan area near the southern margin of the craton (Liu et al. 2009a). The identification of widespread ~2.7 Ga rocks is one of the most important discoveries made in recent years. These rocks are widespread, including western Shandong, eastern Shandong, Guyang, Fuping, Hengshan, Zanhuang, Zhongtiao, and Huoqiu (Fig. 1) (Cao et al. 1996; Dong et al. 2012a; Du et al. 2003, 2005, 2010; Guan et al. 2002; Han et al. 2012; Jahn et al. 2008; Jiang et al. 2010; Kröner et al. 2005a; Lu et al. 2008; Wan et al. 2010b, 2011b; Wang et al. 2014a, b, c, d, e; Wang et al. 2009a, b; Yang et al. 2013a, b; Zhu et al. 2013).

In eastern Shandong, the spatial distribution of 2.7 and 2.9 Ga rocks is uncertain. However, they show close spatial relationships with 2.7 Ga rocks occurring extensively in a southwest to northeast direction with a total area of >100 km^2 (Fig. 15). These Archean rocks underwent strong upper amphibolite- to granulite-facies metamorphism at the end of the Neoarchean (Jahn et al. 2008; Liu et al. 2011; Wu et al. 2014; Xie et al. 2014b). Similar to 2.9 Ga rocks, the 2.7 Ga assemblages exhibit strong deformation and anatexis with neosome material occurring in local outcrops (Fig. 18a). This makes it difficult to distinguish between

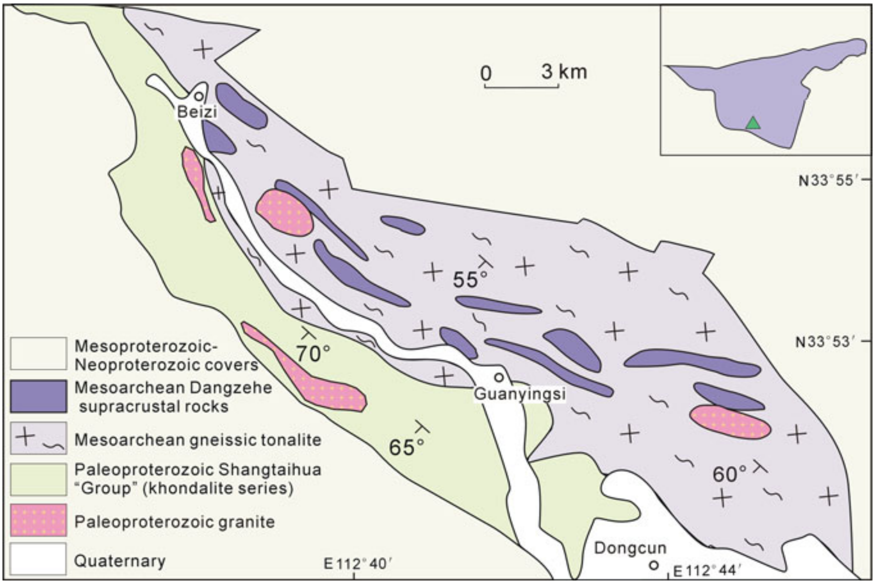
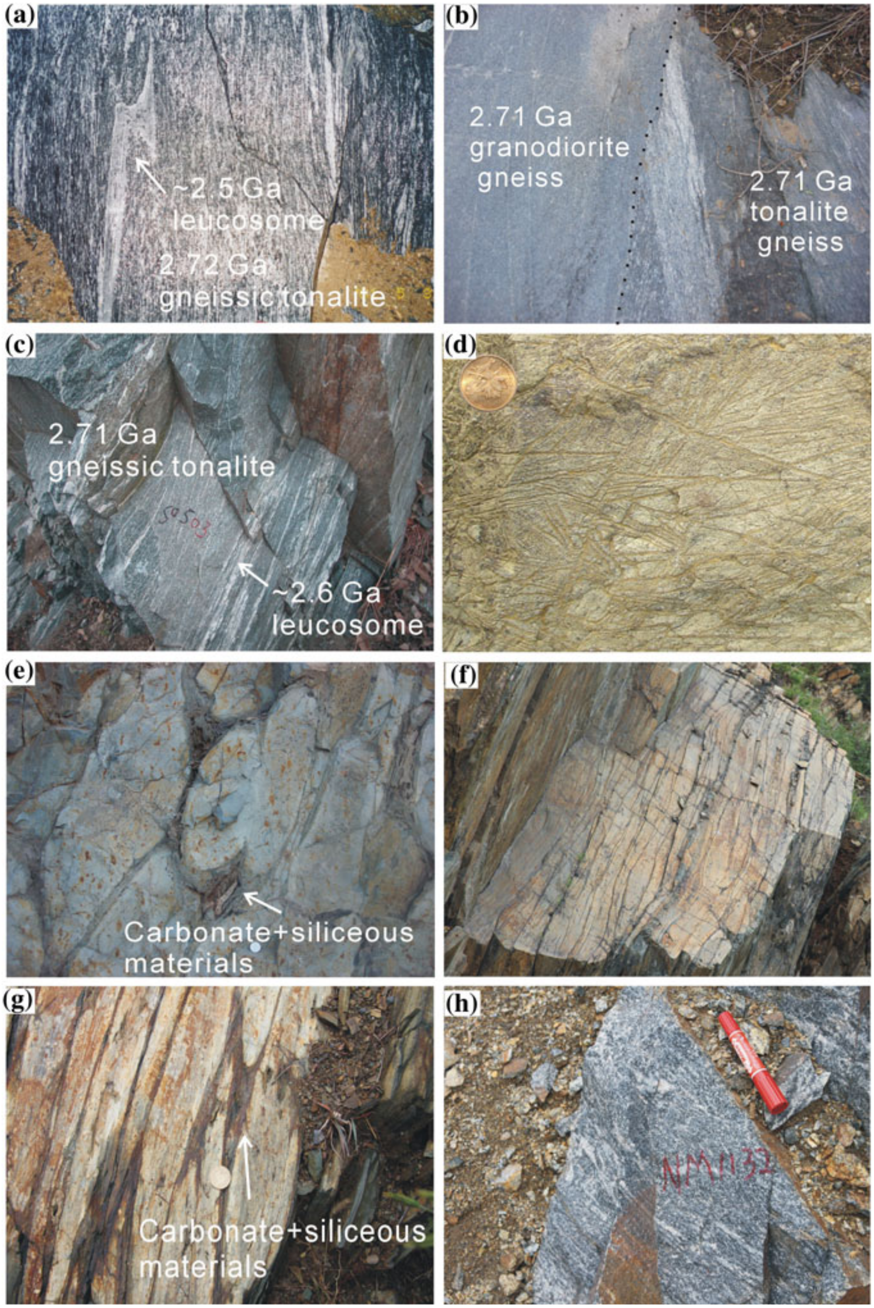


Fig. 17 Simplified geological sketch map of the Lushan area, southern margin of the North China Craton. Modified after Liu et al. (2009c). Triangle in inset map shows location of Fig. 17 in the NCC

2.9 and 2.7 Ga assemblages. At present, the only way to identify these different rocks is by zircon dating.

In western Shandong, Wan et al. (2010c, 2011b) divided the Archean basement into three belts (Fig. 19), namely a late Neoarchean belt of crustally derived granitoids in the northeast that predominantly consists of 2.53–2.49 Ga monzogranite and syenogranite (Belt A), an early Neoarchean belt in the center that is mainly composed of 2.75–2.60 Ga TTGs and supracrustal rocks (Belt B), and a late Neoarchean belt of juvenile rocks in the southwest that is dominated by granodiorite, gabbro, quartz diorite, and tonalite, with minor monzogranite and syenogranite (Belt C). Western Shandong is an area where 2.75–2.7 Ga rocks are most widely distributed in the NCC. Different types of ~2.7 Ga TTGs can be observed in contact with each other in Belt B, showing similar or different styles of deformation (Fig. 18b, c). Furthermore, western Shandong is the only area where early Neoarchean supracrustal rocks have so far been identified in the NCC. In an earlier study, the Taishan "Group," including the Yanlingguan, Liuhang, and Shancaoyu "Formations," were considered to be early Neoarchean in age (Cao et al. 1996). However, more recent studies established that only the Yanlingguan "Formation" and the lower part of the Liuhang "Formation" formed during the early Neoarchean (named the Yanlingguan-Liuhang succession). They are mainly composed of amphibolite and metamorphosed ultramafic rocks. Some of these rocks contain fine spinifex textures (Fig. 18d). Amphibolites with abundant pillow structures are abundant (Fig. 18e), and some show strong deformation (Fig. 18f, g).


(a)
~2.5 Ga
leucosome
2.72 Ga
gneissic tonalite
(b)
2.71 Ga
granodiorite
gneiss
2.71 Ga
tonalite
gneiss
(c)
2.71 Ga
gneissic tonalite
S0503
~2.6 Ga
leucosome
(d)
(e)
Carbonate+siliceous
materials
(f)
(g)
Carbonate+siliceous
materials
(h)
NM1132

◀ **Fig. 18** Field photographs of early Neoarchean rocks in the North China Craton. **a** 2.7 Ga gneissic tonalite showing anatexis, Qixia, eastern Shandong; **b** cutting relationship between 2.71 Ga gneissic tonalite and 2.71 Ga gneissic granodiorite, Taishan, western Shandong; **c** 2.71 Ga gneissic tonalite showing anatexis and deformation, Taishan, western Shandong; **d** meta-komatiite with fine spinifex structures, Sujiagou, western Shandong; **e** amphibolite with pillow lava structures, Qixingtai, western Shandong; **f** deformed pillow lava in amphibolite, Qixingtai, western Shandong; **g** carbonate + siliceous material occurring at the end of deformed pillow lava in amphibolite, Qixingtai, western Shandong; **h** 2.69 Ga gneissic tonalite showing anatexis, Xi Ulanbulang, Yinshan

Xi Wulanbulan is the only area where 2.7 Ga tonalite was identified in the Western Block of the NCC. It extends in a north–south direction over an area of >10 km^2 (Fig. 20) and shows strong metamorphism, deformation, and anatexis (Fig. 18h) with metamorphic zircons recording an age of ~2.5 Ga. These tonalities occur together with the late Neoarchean Xinghe "Group" and other TTG rocks (Dong et al. 2012a; Ma et al. 2013a, b, c).

Wan et al. (2014a) summarized the spatial distribution, rock types, geochemistry, and Nd–Hf isotopic compositions of ~2.7 Ga granitoids in the NCC. They are mainly tonalitic in composition and show large variations in SiO_2, ΣFeO, MgO, and CaO. They can be subdivided into two types in terms of REE contents (Fig. 8c). Whole-rock Nd and Hf-in-zircon isotopic compositions indicate that the strong 2.7 Ga tectono-thermal event mainly involved juvenile additions to the continental crust with recycling of older crust only in local areas.

Ca. 2.6 Ga rocks were also reported in several areas of the NCC, including western Shandong, Hebi, Zhongtiao, Guyang, and Bayan Obe (Fan et al. 2010; Jian et al. 2012; Wan et al. 2015b; Zhang et al. 2012a, b, c, d, e, f; Zheng et al. 2012; Ma unpublished data). In most of these areas, ~2.7 Ga rocks also occur. Western Shandong is the area where both 2.7 and 2.6 Ga rocks are widely distributed (Wan et al. 2015b). They mainly occur together in Belt B (Fig. 21) and include hornblendite (meta-pyroxenite), gneissic tonalite, gneissic trondhjemite, and gneissic granite (Fig. 22a–d). Geological records are almost continuous from 2.75 to 2.59 Ga (Fig. 23). Ca. 2.6 Ga metamorphism and anatexis have also been identified (Du et al. 2003, 2005; Lu et al. 2008; Ren unpublished data). This strong tectono-thermal event resulted in the formation of migmatites in Belt B (Fig. 22e–f). These are important for considering 2.6 Ga as the boundary between the middle to early Neoarchean and late Neoarchean (2.6–2.5 Ga) in western Shandong. No ~2.7 Ga metamorphism and ~2.6 Ga supracrustal rocks have been identified there, and it appears that there was a "quiet period" between 2.60 and 2.56 Ga. We speculate that this time subdivision is applicable to the entire NCC.

2.4.2 Late Neoarchean (2.6–2.5 Ga)

2.59–2.57 Ga rocks and metamorphism are rare. However, a 2.56–2.5 Ga tectono-thermal event is very strong, resulting in extensive distribution of supracrustal and intrusive rocks and metamorphism of this age all over the NCC

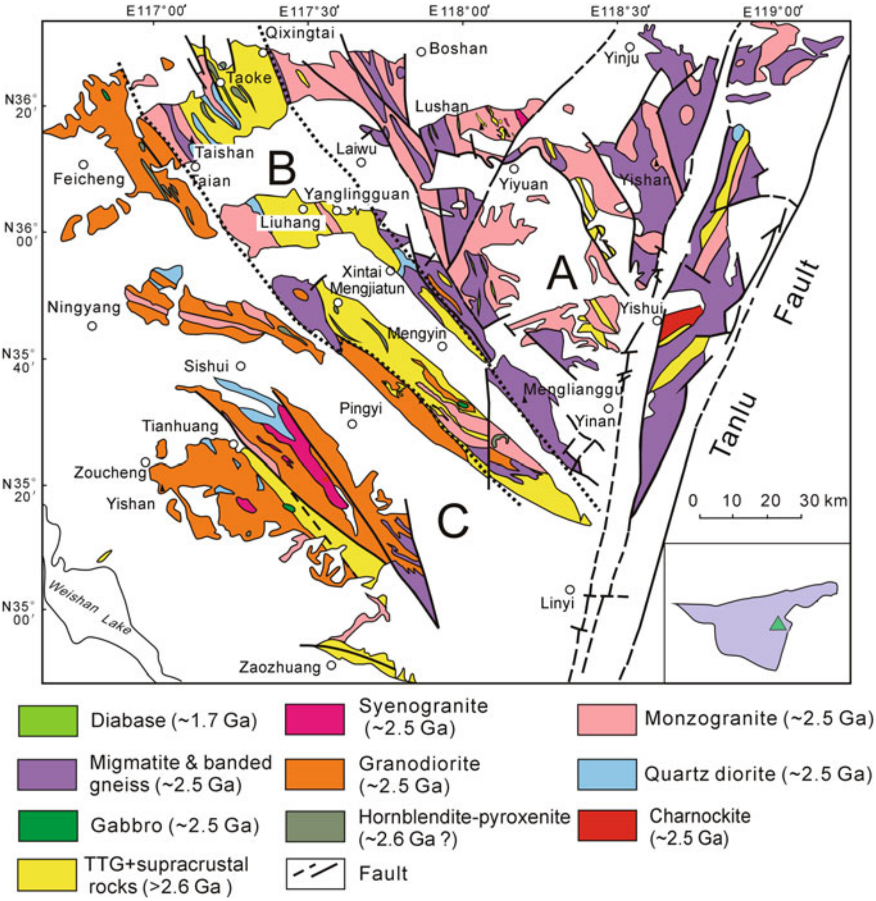


Fig. 19 Geological map of western Shandong. Modified after Wan et al. (2010c). *Belt A* A late Neoarchean crustally derived granite belt in the northeast that consists predominantly of 2.525–2.49 Ga monzogranite and syenogranite; *Belt B* An early Neoarchean belt in the center which is mainly composed of 2.75–2.60 Ga TTG and supracrustal rocks; *Belt C* A late Neoarchean belt of juvenile rocks in the southwest that is dominated by granodiorite, gabbro, quartz diorite, and tonalite, with some monzogranite and syenogranite. *Triangle* in *inset* map shows location of Fig. 19 in the NCC

(Chen 2007; Cheng et al. 2004; Cui et al. 2013, 2014; Dai et al. 2012, 2013; Dong et al. 2012b; Geng et al. 2002, 2006, 2010; Grant et al. 2009; Guo et al. 2005, 2008; Han et al. 2014a, b; He et al. 2005; Jahn et al. 1988; Jian et al. 2012; Kröner et al. 1998, 2005a, b; Li et al. 2010a, b, 2012; Liu et al. 2002, 2004a, 2007, 2009b, 2011, 2012a, 2012b; 2012c, 2014, 2011a; Lu et al. 2008; Lü et al. 2012; Ma et al. 2012, 2013a, b, c; Ma et al. 2013a, b, 2014a, b; Peng et al. 2012; Peng 2013; Peng et al. 2013; Ren et al. 2011; Shen et al. 2004, 2005, 2007; Shi et al. 2012; Song et al. 2009; Sun et al. 1991, 2010, 2014; Sun and Guan 2001; Tian et al. 2005; Wan et al.

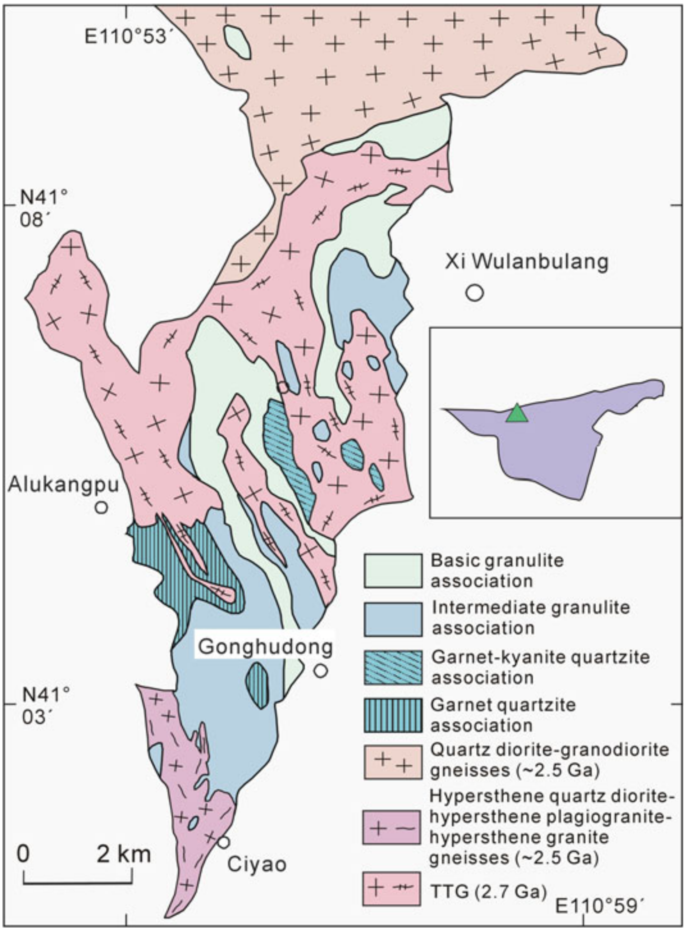


Fig. 20 Geological map of the Xi Ulanbulang area, Yinshan. Modified after Dong et al. (2012a) and Ma et al. (2013). *Triangle* in *inset* map shows location of Fig. 20 in the NCC

2005b, 2009b, c, 2010b, c, 2011a, c, 2012b, c, d, 2015a; Wang et al. 2004, 2011; Wang et al. 2014; Wang et al. 2014; Wang et al. 2010; Wang et al. 2009; Wilde et al. 2004a, 2005; Wu et al. 1998; Xiang et al. 2012; Yang et al. 2008, 2009, 2011; Yang 2013; Zhai et al. 2000, 2005; Zhang et al. 2013; Zhang et al. 2012a; Zhang et al. 2011; Zhang et al. 2014; Zhao et al. 2002, 2009; Zhao et al. 2008; Zhao et al. 2008; Zhou et al. 2009, 2011, 2014).

There are abundant Neoarchean (mainly 2.55–2.5 Ga) detrital and xenocrystic zircons in younger rocks and river sands (e.g., Diwu et al. 2012; Wan et al. 2011a). Late Neoarchean supracrustal rocks are mainly composed of mafic to felsic granulite, amphibolite, fine-grained biotite gneiss (leptinite), banded iron formation (BIF), and (fuchsite) quartzite, with the metamorphic grade ranging from

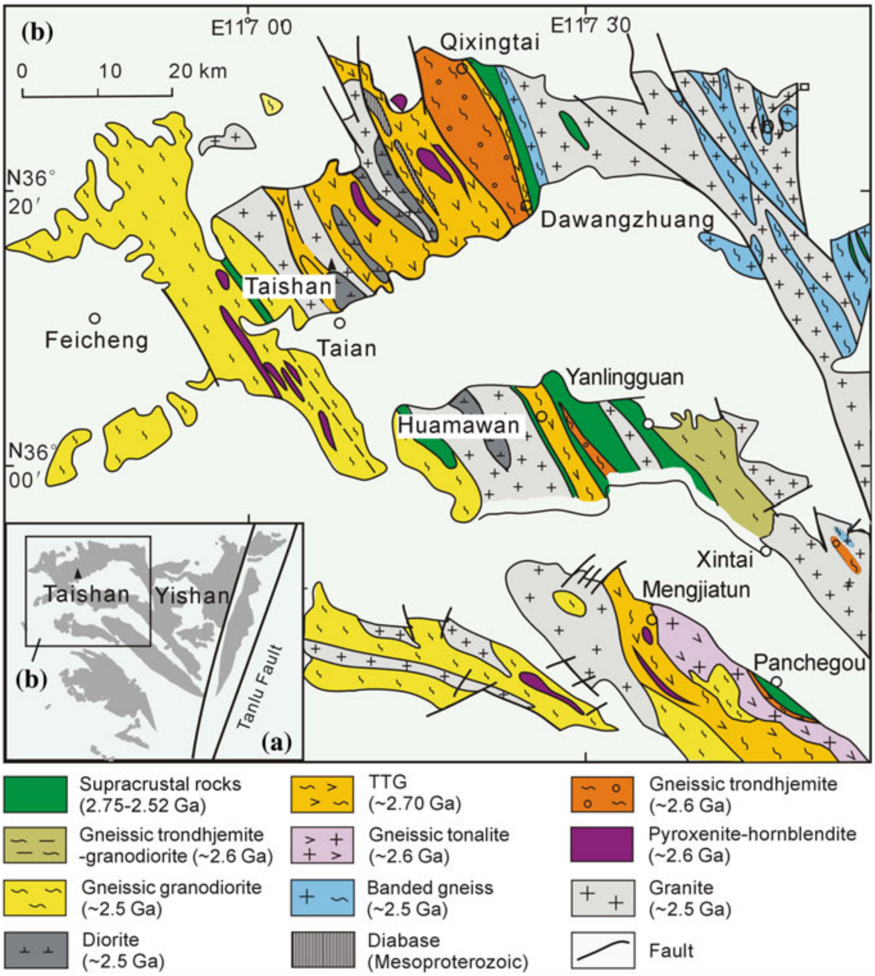


Fig. 21 Geological map of the Taishan-Mengjiatun area, western Shandong (Wan et al. 2015b)

predominantly amphibolite to granulite facies. Mafic granulite and amphibolite show light REE enrichment or flat REE patterns and are commonly rich in LILE and depleted in Nb and Ta (Wan et al. 1997b). Fine-grained biotite gneisses generally show compositional features of dacitic rocks. Late Neoarchean intrusive rocks are variable in composition, ranging from ultramafic to felsic, but TTGs and crustally derived granites constitute the main components. It is not until the late Neoarchean that granodiorites are widely distributed in the NCC. Syenogranites predominantly formed between 2.53 and 2.49 Ga and can be further subdivided into two phases with most showing massive structures and emplacement during the second phase (2.52–2.48 Ga), whereas the first phase (2.53–2.52 Ga) syenogranites show metamorphism and deformation (Wan et al. 2012b). All syenogranites share

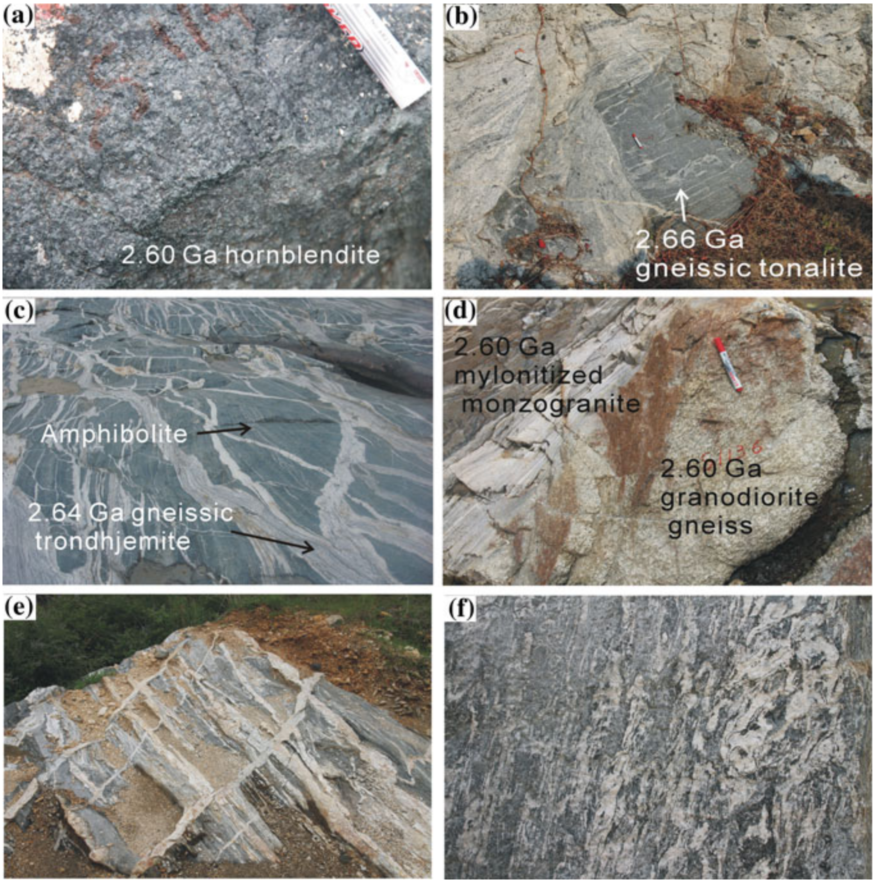


Fig. 22 Field photographs of early Neoarchean rocks in western Shandong. **a** 2.60 Ga hornblendite, southwest of Qixingtai; **b** 2.66 Ga gneissic tonalite, Yishan; **c** gneissic trondhjemite cutting amphibolite, Taishan; **d** relationship between 2.60 Ga gneissic granodiorite and 2.60 Ga mylonitized monzogranite, Xintai; **e** 2.7 Ga gneissic tonalite showing anatexis at ∼2.6 Ga, Taishan; **f** 2.7 Ga gneissic tonalite showing anatexis at ∼2.6 Ga, Taishan

the same major element compositions, being high in SiO_2 and low in CaO, ΣFeO, MgO, TiO_2, and P_2O_5. However, they have variable REE compositions and can be subdivided into three types (Fig. 8d). In order to better understand the late Neoarchean geological features in various parts of the NCC, several areas are described below.

(1) Western Shandong

Late Neoarchean magmatism is widespread with peak ages of 2.53–2.52 Ga (Fig. 24). A recent study indicated that the Shancaoyu "Formation" and the upper part of the Liuhang "Formation" formed during the late Neoarchean rather than in the early Neoarchean (Wan et al. 2012c). Western Shandong is the only area where

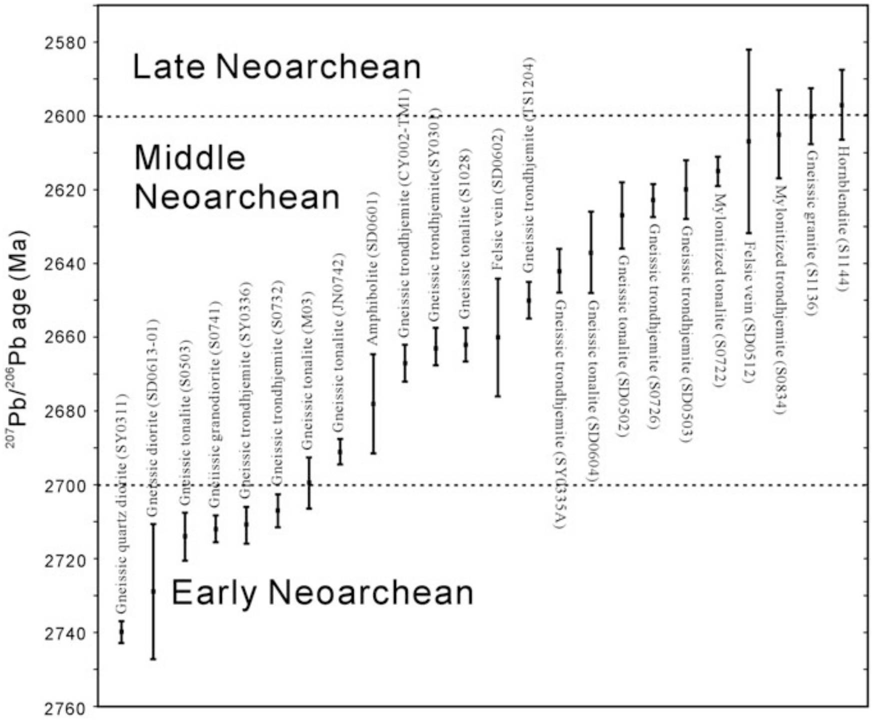


Fig. 23 Zircon age variation diagram (with *error bars*) for early to *middle Neoarchean* magmatic rocks in western Shandong. Data are from Du et al. (2003), Jiang et al. (2010), Lu et al. (2008), and Wan et al. (2011b, 2015b)

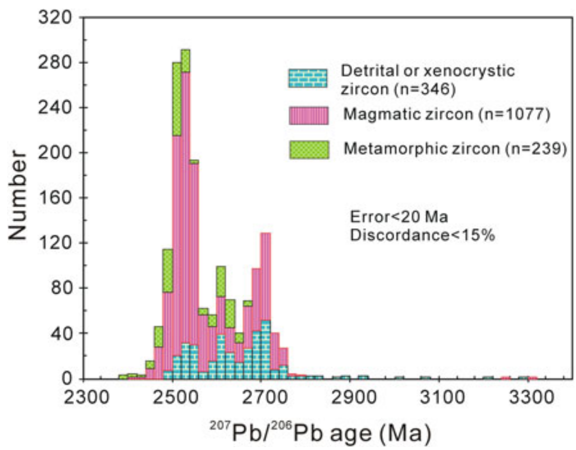


Fig. 24 Age histogram of zircons from Neoarchean rocks in western Shandong. Data are from Du et al. (2003), Jiang et al. (2010), Lu et al. (2008), Wan et al. (2010c, 2011b, 2015b), and Wan (unpublished data)

both early and late Neoarchean supracrustal rocks were identified. The late Neoarchean supracrustal rocks occur in different belts and mainly consist of meta-conglomerate, fine-grained biotite gneiss, fine-grained two-mica gneiss, mica schist, BIF, and felsic metavolcanic rocks. The metaconglomerates are interlayered with fine-grained biotite gneiss (Fig. 25a), and the conglomerate pebbles vary in size and mainly consist of TTG, monzogranite, and fine-grained felsic volcanic rocks. Some fine-grained biotite gneisses show sedimentary structures such as bedding (Fig. 25b), suggesting a clastic origin. However, in many cases, their protoliths are difficult to determine (volcanic or sedimentary) because of strong metamorphism and deformation (Fig. 25c). Mantle-derived igneous rocks in Belt C predominantly consist of gabbro, diorite, tonalite, and granodiorite. Magma mixing can be observed between different rock types (Fig. 25d, e). Different migmatite types are associated with crustally derived granites in Belt A as a result of anatexis of early supracrustal and granitoid rocks. TTGs of early and late Neoarchean ages were identified as protoliths of the anatectic rocks (Figs. 22b and 25f).

(2) Eastern Hebei

Late Neoarchean supracrustal and intrusive rocks are widespread (Fig. 26), apart from ancient crustal components documented by 3.88–3.40 Ga detrital zircons and 3.40–2.95 Ga orthogneisses in Huangbaiyu, as mentioned before. 2.55–2.53 Ga tonalites and quartz diorites are most important in the west, and 2.53–2.51 Ga granites are most important in the east, where magma mingling between granite and diorite has been also identified (Fig. 27a) (Nutman et al. 2011; Yang et al. 2008).

The Qian'an "Group" was considered to be Mesoarchean in age, but recent zircon dating indicates that most of the supracrustal rocks formed at the end of the Neoarchean (Han et al. 2014a; Zhang et al. 2011; Wan, unpublished data). Late Neoarchean supracrustal rocks commonly occur as enclaves of variable sizes in granitoids and show spatial variations in rock association, metamorphism, and deformation, with metamorphic grades varying from granulite facies in the west to lower amphibolite facies (epidote amphibolite facies) in the east and greenschist facies in local areas. These rocks have different names in different areas (Fig. 26). The Zunhua and Qian'an "Groups" and associated TTG rocks in the Zunhua-Santunying area underwent granulite-facies metamorphism and were commonly affected by amphibolite-facies retrogression. The supracrustal rocks extend in a north–south direction and are mainly composed of biotite–plagioclase gneiss, hornblende–plagioclase gneiss, two-pyroxene granulite, amphibolite, meta-ultramafic rock, and BIF. Strong metamorphism resulted in anatexis of the supracrustal rocks (Fig. 27b).

The Luanxian "Group" occurs in the Luanxian-Lulong area and is composed of fine-grained biotite gneiss, amphibolite, and BIF, whereas at Huangbaiyu, the Qian'an "Group" and Luanxian "Group" are separated by a $\sim$2.5 Ga granite. The Dantazi and Zhuzhangzi "Groups" at Qinlong exhibit lower amphibolite-facies metamorphism. The Dantazi "Group" (or Shuangshanzi "Group") is dominated by fine-grained two-mica gneiss, garnet–mica schist, two-mica quartz schist, mafic and felsic metavolcanic rocks, and BIF. It is covered unconformably by the Zhuzhangzi "Group" (or Qinglong "Group"), commonly with >100 m of conglomerate at the

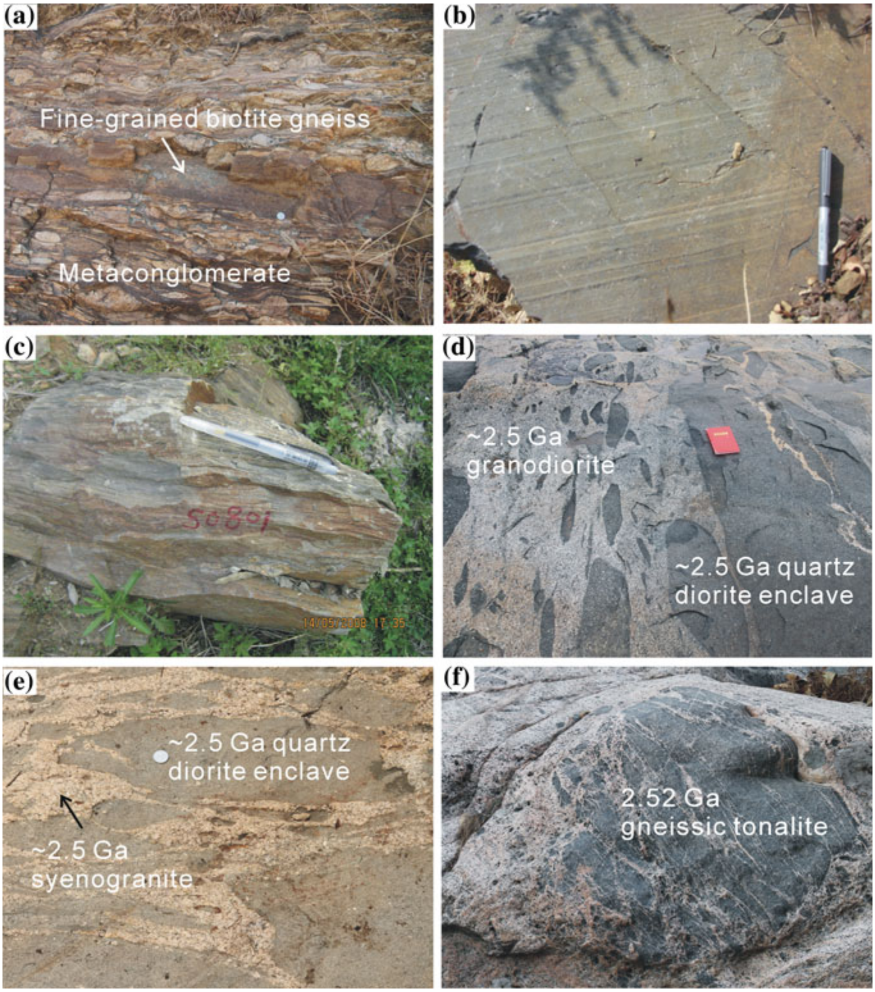


Fig. 25 Field photographs of late Neoarchean rocks in western Shandong. **a** Metaconglomerates interlayered with metasediments; pebbles are mainly TTG and felsic volcanic rocks, upper part of Liuhang "Formation," Huamawan; **b** metasedimentary rock showing bedding, Shancaoyu "Formation," Qixingtai; **c** mylonitized fine-grained biotite gneiss (S0801) of Shancaoyu "Formation," Panchegou; **d** magma mingling between ∼2.5 Ga granodiorite and quartz diorite, showing large variations in proportion, southeast of Tianhuang; **e** magma mingling between ∼2.5 Ga syenogranite and quartz diorite, southeast of Tianhuang; **f** 2.52 Ga gneissic tonalite showing anatexis, Yinshan

base (Fig. 27c). Furthermore, the Zhuzhangzi "Group" contains fine-grained two-mica gneiss, fine-grained biotite gneiss, mica schist, quartz schist, biotite–hornblende schist, and BIF. Ca. 2.5 Ga BIFs are well developed in eastern Hebei and contain important iron deposits. The supracrustal rocks in the Qinlong area

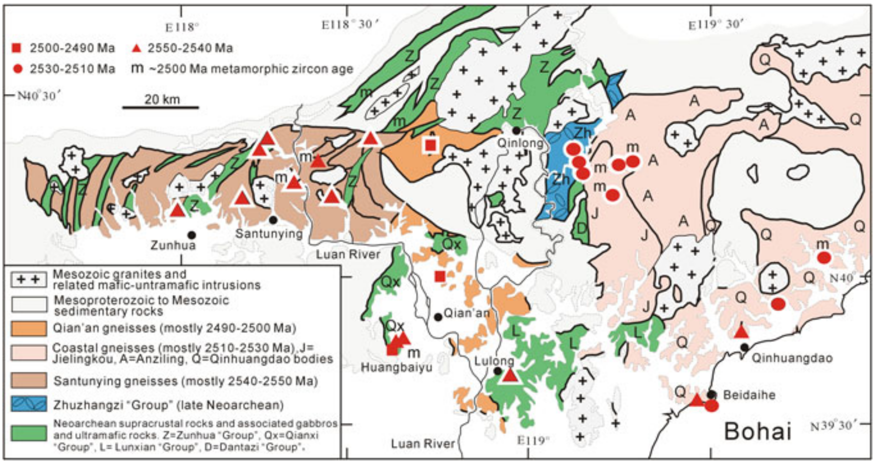


Fig. 26 Geological map of eastern Hebei, modified after Nutman et al. (2011). For location in the NCC, see Fig. 1

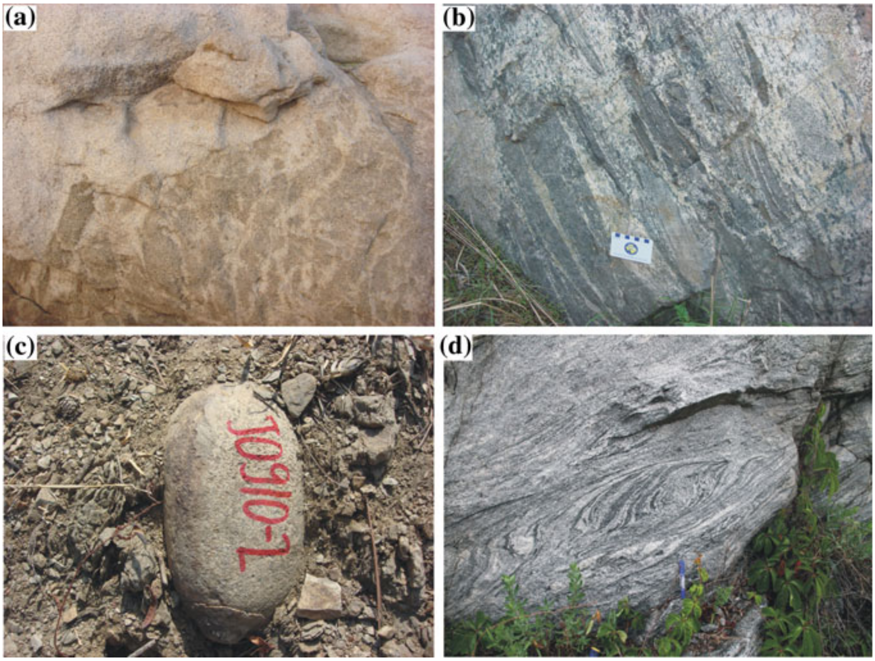


Fig. 27 Field photographs of late Neoarchean rocks in eastern Hebei. **a** Magma mingling between ~2.5 Ga granite and diorite, Beidaihe; **b** anatexis of granulite-facies gneiss (the Zunhua "Group"), north of Santunying; **c** metaconglomerate at the bottom of the Zhuzhangzi "Group," southeast of Qinlong; **d** anatexis of TTG rock, west of Anziling

commonly underwent lower amphibolite-facies metamorphism, but the TTG rocks east of Qinlong show strong anatexis and deformation (Fig. 27d). In the eastern coastal area of Hebei Province, weakly deformed 2.53–2.51 Ga granites occur together with subordinate granodiorites, diorites, and magnesian gabbros and contain slightly older Neoarchean granitoid inclusions.

Nutman et al. (2011) suggested that Neoarchean magmatism in eastern Hebei was not a single protracted event but was marked by temporally, geographically, and geochemically distinct pulses of igneous activity at 2.55–2.535, 2.53–2.52 Ga, and 2.50–2.49 Ga, respectively, with the latter accompanied by granulite-facies metamorphism.

(3) Fuping-Wutai-Hengshan

This is an important and famous exposure of Neoarchean rocks in the NCC with a long history of research. Based mainly on the work of Cheng et al. (2004), Guan et al. (2002), Han et al. (2012), Kröner et al. (2005a, 2005b, 2006), Li et al. (2010a), Liu et al. (2002), Liu et al. (2004a), Miao (2003), Qian et al. (2013), Trap et al. (2007, 2008), Wan et al. (2010a), Wang et al. (2010), Wei et al. (2014), Wilde et al. (2004a, 2004b, 2005), Wu et al. (1989, 1998), Zhang et al. (2006); Zhang et al. (2006); Zhang et al. (2007, 2009), and Zhao et al. (2011), some common features of the basement are summarized as follows (Fig. 28).

(1) The early Precambrian basement is composed of the Fuping Complex in a southeastern belt, the Wutai Complex in a central belt, and the Hengshan Complex in a northwestern belt. All of these are composed of intrusive and supracrustal rocks of different ages.
(2) Early Precambrian intrusive rocks mainly formed during the late Neoarchean (2.55–2.5 Ga), including TTGs (mainly tonalite and granodiorite) with some monzogranite and K-rich granite. 2.2–2.0 Ga intrusive rocks occur on a relatively small scale and are predominantly crustally derived granites with a few mantle-derived mafic–ultramafic rocks. Early Neoarchean (~2.7 Ga) TTGs and early Neoarchean and older detrital and xenocrystic zircons were also identified in the Fuping and Hengshan areas.
(3) No early Neoarchean or older supracrustal rocks have so far been found, but this does not mean that they do not occur in these areas. Late Neoarchean supracrustal rocks in the Wutai area are composed of mafic to felsic metavolcanic and clastic metasedimentary rocks, BIF, and minor limestone (the Wutai "Group"). In Fuping, late Neoarchean supracrustal rocks, named the Fuping "Group," are mainly composed of mafic to intermediate metavolcanic and clastic metasedimentary rocks and minor BIF and marble. Some or many biotite–plagioclase gneisses and hornblende–plagioclase gneisses of the Suojiazhuang-Yuanfang unit I of the Fuping "Group" may be strongly metamorphosed and deformed intrusive rocks (Yang, unpublished data). Late Neoarchean supracrustal rocks rarely occur as enclaves in the Hengshan Complex, including garnet-bearing biotite–plagioclase gneiss, BIF, and amphibolite. High-pressure garnet two-pyroxene granulites are derived from gabbroic dikes.

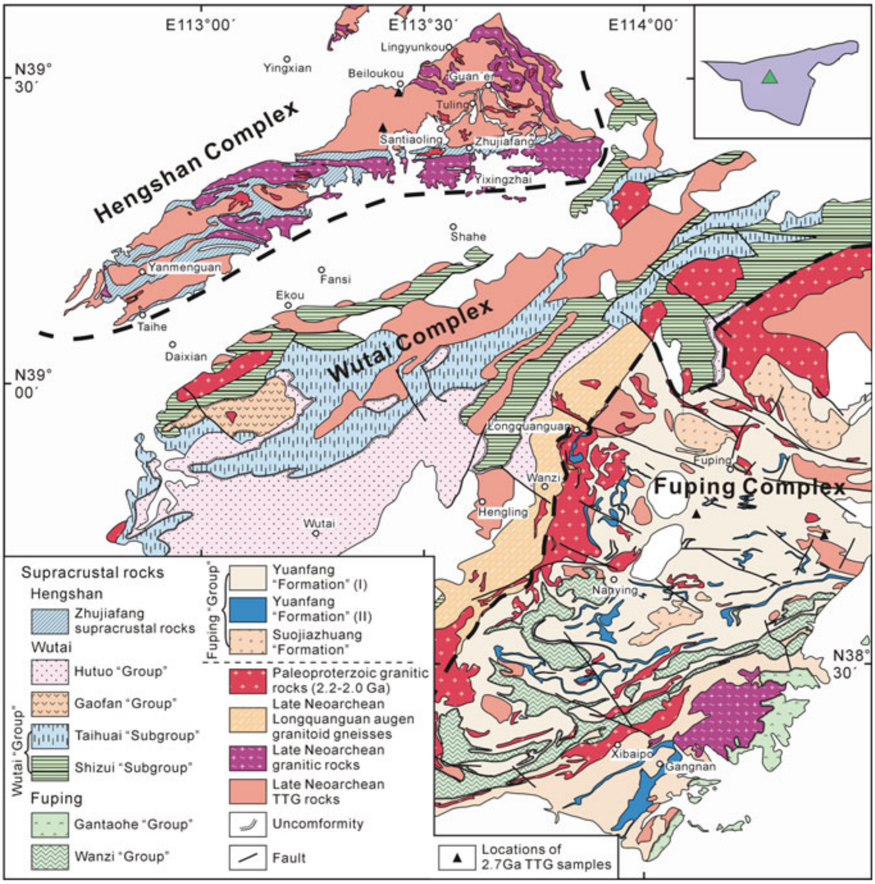


Fig. 28 Geological map of Hengshan-Wutai-Fuping, modified after Miao (2003), Cheng et al. (2004), Liu et al. (2004b), Li et al. (2010a, b), Zhao et al. (2011), and Qian et al. (2013). *Triangle* in *inset* map shows location of Fig. 28 in the NCC. The Yuanfang "Formation"(I) of the Fuping "Group" is mainly composed of anatectic biotite–plagioclase gneiss, hornblende–biotite plagioclase gneiss, and fine-grained biotite–plagioclase (two feldspar) gneiss (leptinite), and some of them may be metamorphic igneous rocks; Yuanfang "Formation"(II) of the Fuping "Group" is composed mainly of amphibolite, fine-grained garnet–biotite gneiss, fine-grained feldspar gneiss, fine-grained hornblende gneiss, banded iron formation, calc-silicate rock, and marble

(4) In Wutai, the Gaofan "Group," originally named as the Gaofan "Subgroup" of the Wutai "Group," unconformably overlies the Wutai "Group" and was deposited between 2.47 and 2.14 Ga. It should therefore be excluded from the Wutai "Group." The Hutou "Group" unconformably overlies the Gaofan "Group" and is considered to be $\sim$2.14 Ga or younger in age. The Wanzi "Group" in the Fuping Complex was originally considered to be late Neoarchean in age, but some authors considered it to be early Paleoproterozoic (Guan et al. 2002; Li et al. 2005). It is composed of

metasedimentary rocks including marble and is similar to the khondalite sequences of the northwestern NCC in rock association and metamorphism.

(5) Whole-rock Nd and Hf-in-zircon isotopic studies indicate that the formation of all early and most late Neoarchean TTGs involved juvenile magmatic additions to the continental crust; most late Neoarchean and early Paleoproterozoic (2.2–2.0 Ga) granitoids formed by recycling of early Neoarchean or older crustal material.

(6) The Fuping Complex and the northern portion of the Hengshan Complex underwent upper amphibolite- to granulite-facies metamorphism, whereas the Shizui "Subgroup" of the Wutai "Group" and the southern portion of the Hengshan Complex underwent lower amphibolite-facies metamorphism, and the Taihuai "Subgroup" of the Wutai "Group" underwent greenschist-facies metamorphism. Metamorphic grades vary from granulite facies to greenschist facies from both sides to the center. Consequently, the late Neoarchean granitoid bodies in Wutai commonly show weaker metamorphism and deformation than their equivalents in the Fuping and Hengshan complexes.

(7) Fold axes, foliations, and lineations mainly extend in a west–east or southwest–northeast direction. Three episodes of folding and two phases of ductile thrusting and shearing have been identified (Li et al. 2010a). There are two major shear zones: One is the west–east-striking Zhujiafang shear zone separating the granulite-facies Hengshan Complex in the north from the amphibolite-facies Hengshan Complex in the south. Another is the southwest–northeast-striking Longquanguan shear zone separating the Wutai "Group" in the northeast from the Fuping Complex in the southwest.

(8) A strong late Paleoproterozoic tectono-thermal event is recorded by well-developed 1.95–1.83 Ga metamorphic zircons. This event resulted in strong metamorphism and deformation in the Fuping and Hengshan complexes and the lower part of the Wutai Complex and formation of the above two shear zones. ~2.5 Ga metamorphic zircons have also been identified in Fuping (Yang, unpublished data), but their significance is uncertain.

(4) Yinshan

Little was known about the early Precambrian basement of the Yinshan Block, but new data were acquired in recent years (Chen 2007; Dong et al. 2012a, b; Fan et al. 2010; Jian et al. 2012; Li et al. 1987; Liu et al. 2012d, 2014; Ma et al. 2013; Ma 2013a, b, 2014a, b; Mei 1991; Zhang et al. 2003; Zhang and Liu 2004; Zhang et al. 2014). The main features of the basement are summarized as follows (Figs. 29 and 30).

(1) There are 2.7 Ga tonalites and 2.6 Ga granites and older xenocrystic zircons in ~2.5 Ga granitoid rocks. The 2.7 Ga tonalite exposure is >10 km^2 in size. Zhang et al. (2014) obtained a zircon age of 2.51 Ga for a charnockite exposed near a 2.7 Ga tonalite dated by Ma et al. (2013) and interpreted this to reflect emplacement of the charnockite precursor. However, considering strong recrystallization of the zircon cores, the significance of the 2.51 Ga age is

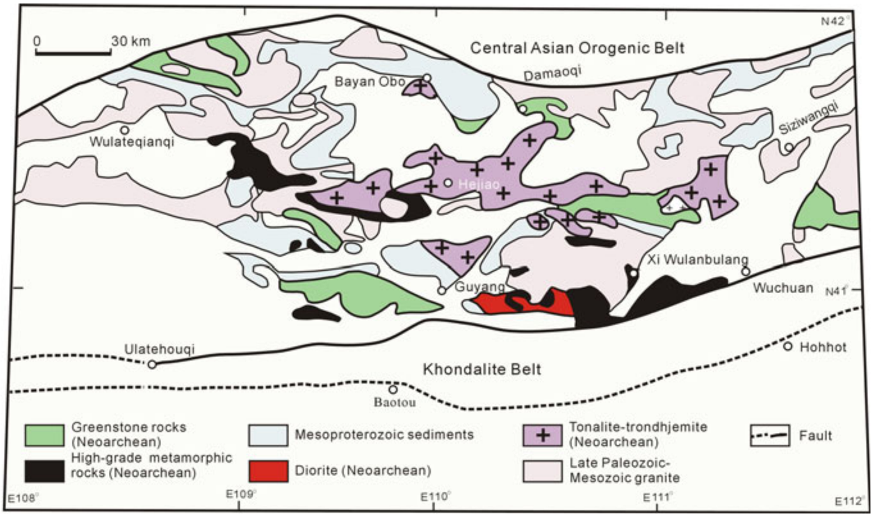


Fig. 29 Geological map of Yinshan, modified after Jian et al. (2012). For location in the NCC, see Fig. 1

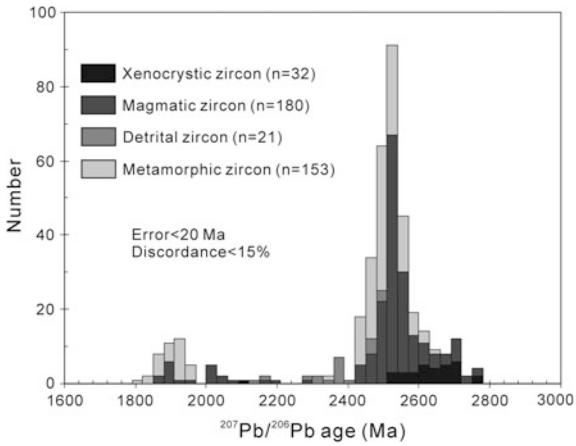


Fig. 30 Age histogram of zircons from early Precambrian rocks in Yinshan Block. Data are from Dong et al. (2012a, b), Fan et al. (2010), Jian et al. (2012), Liu et al. (2012d, 2014), Ma et al. (2013); Ma et al. (2013a, b, 2014a, b), and Zhang et al. (2014)

uncertain. We suggest that more >2.6 Ga rocks and zircons will be discovered in Yinshan as more work is carried out.

(2) 2.55–2.5 Ga magmatism was widespread and resulted in the formation of intrusive rocks composed of tonalite–trondhjemite and subordinate gabbro, diorite, granite, and syenogranite, whereas granodiorite is rare. It appears that

most tonalite–trondhjemite formed during an early phase in this event. It also seems likely that, for some rocks, strong recrystallization and Pb loss caused the magmatic zircon apparent ages to become younger than their original ages. Middle to late Paleoproterozoic (2.2–1.9 Ga) granitoid rocks were identified in local areas.

(3) Late Neoarchean supracrustal rocks include metavolcanic and volcano-sedimentary sequences including BIFs. Two types of supracrustal sequence can be recognized in terms of metamorphic grade. The high-grade metamorphic supracrustal rocks (the Xinghe "Group") consist of mafic to felsic granulite with some containing garnet, and the low-grade metamorphic supracrustal rocks (the Sheerteng "Group" or greenstone belt) consist of greenschist- to lower amphibolite-facies mafic to felsic metavolcanic rocks and minor metamorphosed ultramafic rocks, clastic metasediments, and BIF, with some mafic lavas showing relict pillows. The supracrustal and associated intrusive rocks broadly extend in an east–west direction. Some metasedimentary rocks of the high- and low-grade supracrustal sequences are Paleoproterozoic in age (Z.Y. Xu, unpublished data).

(4) Whole-rock Nd and Hf-in-zircon isotopic analyses of 2.7, 2.6, and 2.55–2.50 Ga intrusive as well as 2.55–2.50 Ga supracrustal rocks indicate that addition of significant juvenile material from the mantle occurred at 2.8–2.7 Ga, and both juvenile magmatism and crustal recycling played significant roles during magmatic events at the end of the Neoarchean.

(5) A late Neoarchean tectono-thermal event was widespread in the Yinshan Block as indicated by abundant ~2.5 Ga metamorphic zircons. Late Paleoproterozoic (1.94–1.86 Ga) metamorphic zircons were also found at several localities. These metamorphic zircons are rare in the high-grade metamorphic rocks, and this was interpreted to be due to late Paleoproterozoic metamorphism having occurred in a dominantly "dry" system caused by previous late Neoarchean high-grade metamorphism (Ma et al. 2012; Wan et al. 2011a, b, c)

3 Distribution of Zircon Ages and Isotope Geochemistry

3.1 Zircon Age Distribution

Wan et al. (2011a) compiled a total of 7586 early Precambrian zircon age data for the entire NCC and arrived at the conclusion that the most significant zircon-forming tectono-thermal events occurred in the late Neoarchean to the earliest Paleoproterozoic (2.55–2.48 Ga) and in the late Paleoproterozoic (1.95–1.80 Ga), with age peaks at ~2.52 and ~1.85 Ga, respectively. In the present study, we compiled additional zircon age data bringing the total to 15060. The geographic distribution of these data is similar to those compiled by Wan et al. (2011a).

The main differences include the following: (1) More data were obtained from the Western Block, including the basement of the Ordos basin. (2) Only data are considered where the 1σ error and discordance are less than 20 Ma and 15 %, thus excluding many results obtained by LA-ICP-MS. (3) In areas where rocks underwent strong metamorphism during the late Neoarchean and late Paleoproterozoic, such as eastern Shandong and Daqingshan, some published ages of 2.45–2.0 Ga are not included in our compilation. Although these data satisfy the above analytical conditions, they may still be geologically meaningless because of likely partial resetting of the U–Pb isotopic systems in the zircons and/or partial Pb loss during high-grade metamorphism.

Our new compilation of zircon data supports the earlier conclusions of Wan et al. (2011a) that, considering the NCC as an entity, there is a continuous age record from 3.8 to 1.8 Ga. Two tectono-thermal events are very significant in the late Neoarchean to the earliest Paleoproterozoic and late Paleoproterozoic history of the craton, reflected by age peaks at ~2.52 and ~1.85 Ga, respectively (Fig. 31a). However, the age valleys are slightly different in our new compilation at ~3.6, ~3.2, ~2.85, ~2.65, ~2.25, and 2.0 Ga. Although there is an age valley at ~2.3 Ga worldwide for zircon ages (Condie et al. 2009), rocks of this age were widely identified along the southern margin of the NCC (Diwu et al. 2007, 2014; Huang et al. 2012a b, 2013; Jiang et al. 2011; Wang et al. 2012).

As indicated by Wan et al. (2011a), the Eastern Block shows an important difference to the Western Block and the Trans-North China Orogen (TNCO) in showing abundant ages >3.0 Ga (Fig. 31b–d) because of the well-studied ancient rocks in Anshan and eastern Hebei. The discovery of many >3.3 Ga detrital zircons in the Zhongtiao, Dengfeng, and Jiaozuo areas (Diwu et al. 2008; Gao et al. 2006; Liu et al. 2012a; Yin et al. 2015) reduces the previous age difference between the TNCO and Eastern Block. Significant progress was recently made in dating of early Precambrian basement rocks in the Western Block, including the discovery of 2.7 Ga TTGs and identification of strong magmatism and metamorphism at ~2.5 Ga in the Yinshan Block (Dong et al. 2012a, b; Jian et al. 2012; Liu et al. 2014; Ma et al. 2012, 2013a, b, 2014a, b; Zhang et al. 2014). More data were also obtained from the TNCO and Eastern Block. However, these new results do not change the earlier conclusion that the Eastern Block, Western Block, and TNCO have almost identical late Neoarchean age distribution patterns with zircon ages varying from 2.55 to 2.48 Ga and a prominent age peak at ~2.52 Ga. The prominent age peak in the Western Block seems slightly shifted toward younger ages (Fig. 31d), probably due to the significant early and late Paleoproterozoic metamorphic events.

3.2 Whole-Rock Nd Isotopic Composition

Wu et al. (2005b) compiled Nd isotopic data from NCC rocks and constructed depleted mantle Nd model age histograms that indicated an important period of

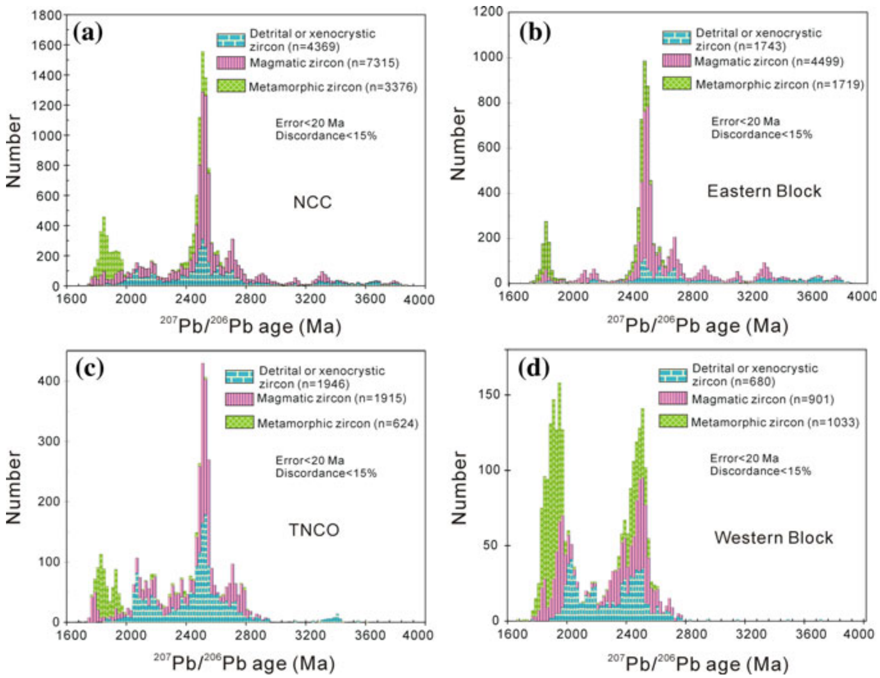


Fig. 31 Age histogram for zircons from the early Precambrian basement of the North China Craton. **a** All data for the North China Craton; **b** data for the Eastern Block; **c** data for the Trans-North China Orogen (TNCO); **d** data for the Western Block. See text for interpretation and references

crustal growth during 3.0–2.6 Ga and minor events at 3.6–3.2 and ~2.2 Ga. Many samples in their compilation were Paleoproterozoic or even younger in age. In order to better understand the Archean geological evolution, we only used data of Archean rocks in our compilation, including some 2.5–2.45 Ga samples. The total number of samples for our $\varepsilon_{Nd}(t)$ versus formation age diagram and the Nd model age histogram are 1103 and 871, respectively. The data are mainly from references published within the last twenty years (more than 70 papers, most are listed in the "References") together with our unpublished data. Similar to the zircon ages, the whole-rock Nd isotopic data show an uneven geographic distribution. Most results come from the eastern Block, and rock samples older than 2.9 Ga are mainly from Anshan, eastern Hebei, and eastern Shandong. We divided the samples into four types, namely ultramafic to intermediate rocks (including gabbro, diorite, quartz diorite, metamorphic ultramafic rocks, mafic granulite, amphibolite, greenschist, fine-grained hornblende gneiss), TTG and related rocks (e.g., metadacite, fine-grained biotite gneiss), crustally derived granites, and metasedimentary rocks. All parameters and equations used for calculation of depleted mantle Nd model ages are those of Jahn et al. (1990) and Wu et al. (2005b). The crystallization ages of most geological bodies in the NCC were determined from zircon dating.

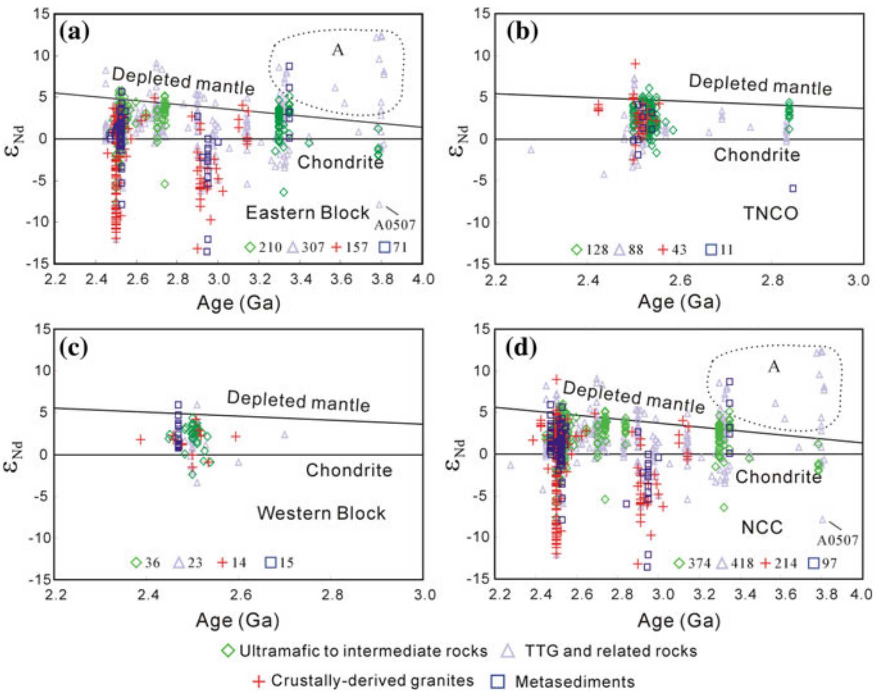


Fig. 32 $\varepsilon_{Nd}(t)$ versus formation age diagram for Archean rocks of the North China Craton. **a** Data for the Eastern Block; **b** data for the Trans-North China Orogen (TNCO); **c** data for the Western Block; **d** all data for the North China Craton. See text for interpretation and references

This made it possible to construct $\varepsilon_{Nd}(t)$ versus crystallization age diagrams for the Archean rocks (Fig. 32a–d). Some important features are as follows.

(1) Juvenile, mantle-derived material was added to the crust during several major periods, namely at 3.8, 3.35–3.3, 3.1, 2.9, 2.8, and 2.75–2.5 Ga. Crustal recycling occurred during almost every period of juvenile crustal additions. Some 3.8 Ga rocks from Anshan have negative $\varepsilon_{Nd}(t)$ values, probably suggesting that crustal recycling was already an important process in the Eoarchean. This is similar to the most ancient rocks in Canada (Acasta gneiss, Iizuka et al. 2009) and the Ancient Gneiss Complex of Swaziland, southern Africa (Kröner et al. 2014). Crustal recycling became more dominant with the evolution of continental crust as indicated by $\varepsilon_{Nd}(t)$ values becoming more negative with time.

(2) Neoarchean (2.75–2.5 Ga) rocks from the Eastern and Western blocks and TNCO show similar Nd isotopic features. However, the Eastern Block shows higher maturity in crustal evolution than the Western Block and TNCO at the end of Archean.

(3) Young, crustally derived rocks inherited the Nd isotopic features from their source material in different areas to variable degrees. In Anshan, for example, some 2.5 Ga crustally derived granites have very negative $\varepsilon_{Nd}(t)$ values due to long geological history up to 3.8 Ga. In contrast, in western Shandong, where the majority of the oldest rocks formed during 2.75–2.7 Ga as addition of juvenile material from depleted mantle source, the 2.5 Ga crustally derived granites commonly have depleted mantle Nd model ages of 2.8 2.7 Ga.

(4) Some rocks older than 3.3 Ga show very high $\varepsilon_{Nd}(t)$ values (Fig. 32a, d). Many of these are from the Anshan area and have very low Sm and Nd contents and are strongly deformed and metamorphosed. Therefore, the above positive anomalies are not considered to be original features of the rocks but are likely due to analytical uncertainty and/or more probably to post-crystallization Nd mobility during metamorphism and other late, fluid-induced geological processes. Some rock samples reported in the earlier literature from the Baijiafen Complex may not be ~3.8 Ga in age, and thus, their $\varepsilon_{Nd}(t)$ values were incorrectly calculated.

The $f_{Sm/Nd}$ values for Archean rock samples selected for the Nd model age histogram are limited to between –0.2 and –0.6 in order to reduce the uncertainties in the model age calculations caused by strong Sm/Nd fractionation during geological processes (Jahn et al. 1990; Wu et al. 2005b). In the single-stage Nd model age (depleted mantle Nd model age) histogram, the data are concentrated between 2.8 and 2.6 Ga with a model age peak at ~2.75 Ga (Fig. 33a). Different rock types show similar single-stage Nd model ages between 3.1 and 2.5 Ga. Compared with TTGs, however, ultramafic to intermediate rocks commonly have young Nd model ages. A model age valley is seen at ~3.1 Ga, and the model ages show a plateau distribution between 3.9 and 3.1 Ga. Two-stage model ages (crustal model ages) show a similar distribution but are commonly shifted toward older ages by 100–50 Ma (Fig. 33a, b).

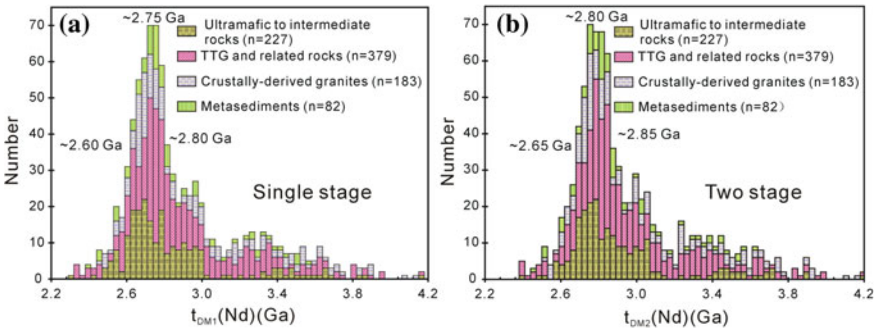


Fig. 33 Nd model age histograms for Archean rocks of the North China Craton. **a** *Single-stage* model age (depleted mantle model age); **b** *two-stage* model age (crustal model age). See text for further interpretation and references

3.3 Hf-in-Zircon Isotopic Composition

Geng et al. (2012) and Wang and Liu (2012) summarized the Hf isotopic features of zircons from early Precambrian basement rocks of the NCC and arrived at the conclusion that crust formation and growth of the craton mainly occurred during the early Neoarchean (2.8–2.7 Ga). In this paper, we used 8564 and 8736 data to compile $\varepsilon_{Hf}(t)$ versus formation age diagrams and Hf model age histograms, respectively. These data are mainly from Archean rocks of the NCC (some are 2.49–2.45 Ga in age, and some detrital zircon data are from Paleoproterozoic metasedimentary rocks). The data sources are mainly from references published within the last ten years (more than 80 papers, many listed in the "References"), together with our unpublished data, and the geographic distribution of the data is similar to those of zircon U–Pb ages with most data for >2.9 Ga rocks being from Anshan, eastern Hebei, and eastern Shandong. Zircon subdivisions are the same in Sect. 3.1. All parameters and equations used for calculation and diagram are those used by Bouvier et al. (2008), Griffin et al. (2000), and Söderlund et al. (2004).

In $\varepsilon_{Hf}(t)$ versus formation age diagrams, data points far below the depleted mantle evolution line have two possible interpretations: (1) the rock formed by melting of older crustal material; (2) zircons with apparently depleted mantle Hf isotopic compositions underwent lead loss, and therefore, their age assessment is wrong. In order to avoid such possibly erroneous data, we only used weighted mean $^{207}Pb/^{206}Pb$ ages and upper concordia intercept ages for magmatic and metamorphic zircons. We also excluded data where zircon analyses have a discordance of >40 %. For detrital zircons, individual data were only used when the 1σ error is less than 20 Ma and the discordance is less than 15 %. Considering the entire NCC, the Hf-in-zircon isotopic data show a similar distribution as the whole-rock Nd isotopic compositions, namely addition of juvenile material to the crust at 3.8–3.55, 3.45, 3.35–3.3, 2.9, and 2.8–2.5 Ga (Fig. 34a–d). Crustal recycling began as early as 3.8 Ga, lasted from 3.8 to 3.25 Ga and, between 3.25 and 2.90 Ga, played a more important role than addition of juvenile material. Ca. 2.90 Ga granitoids in Anben and eastern Shandong show different zircon Hf isotopic features, reflecting differences in their early geological histories. It seems that the original features of Hf-in-zircon isotopic compositions are better preserved than those of whole-rock Nd isotopic compositions. Compared to the whole-rock Nd isotopic data, Hf-in-zircon data reveal significant additions of juvenile material and stronger crustal recycling. This is probably due to a much larger data set and may thus more objectively reflect the Archean geological evolution of the NCC. For the Eastern Block and TNCO, whole-rock Nd isotopic data show obvious differences in the $\varepsilon_{Nd}(t)$ versus formation age diagram (Fig. 32a–b), whereas the Hf-in-zircon isotopic data are similar in the $\varepsilon_{Hf}(t)$ versus formation age diagram (Fig. 34a–b). For example, many detrital zircons from the Zhongtiao area of the TNCO have distinctly negative $\varepsilon_{Hf}(t)$ values, suggesting that >2.9 Ga rocks may occur in this area, and therefore, the TNCO shows similar isotopic features in early crustal evolution as the Eastern Block. In many cases, metamorphic zircons inherited the Hf isotopic

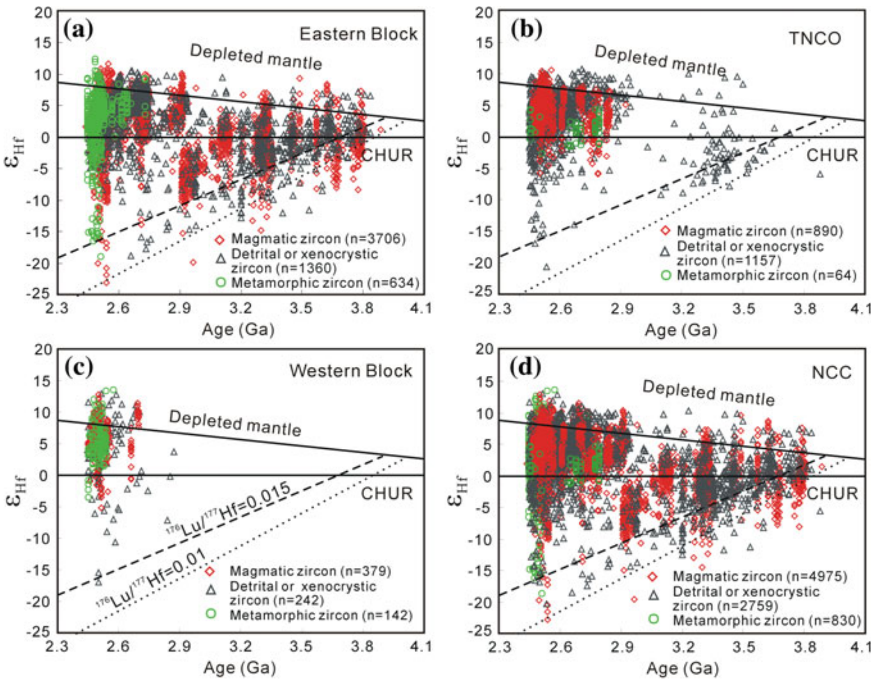


Fig. 34 $\varepsilon_{Hf}(t)$ versus formation age diagrams for zircons of Archean rocks from the North China Craton. **a** Data for the Eastern Block; **b** data for the Trans-North China Orogen (TNCO); **c** data for the Western Block; **d** all data for the North China Craton. *Dotted* and *dashed lines* represent felsic crust with $^{176}Lu/^{177}Hf$ being 0.01 and 0.015, respectively. See text for interpretation and references

features of their magmatic zircons in the same rocks unless metamorphic garnet occurs in the metamorphic rocks. It may therefore be incorrect to assign a metamorphic age to the $^{176}Hf/^{177}Hf$ ratio, but it should be the igneous age of the host rock. However, if using the igneous ages, metamorphic zircon analyses will occur in the same area as the magmatic zircons, making it more difficult to distinguish them. Considering this and presence of garnet in only a few metamorphic rocks, we still use metamorphic zircon ages in this paper. It is easily observed that metamorphic zircons are similar in their Hf isotopic features to magmatic zircons.

Zircons do not generally crystallize from magmas derived directly from mantle sources. Therefore, their single-stage Hf model ages (depleted mantle Hf model ages) are geologically meaningless, and corresponding histograms are not shown here. Two-stage Hf model ages (crustal Hf model ages) are commonly shifted by about 100–50 Ma toward old ages compared with depleted mantle Hf model ages. In the two-stage Hf model age histogram, the data are concentrated between 2.85 and 2.6 Ga with an age peak at ~2.8 Ga (Fig. 35). The age valley occurs at ~3.3 Ga. Compared with the whole-rock Nd model ages, the zircon Hf model ages show an obvious plateau distribution but with a larger age variation between 4.1 and 3.2 Ga. We point out that the continuous whole-rock Nd and zircon Hf model

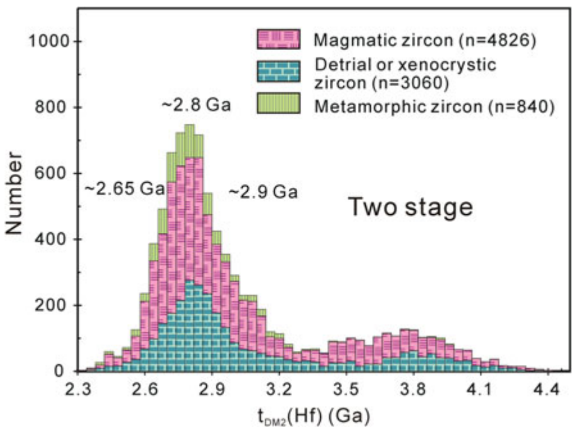


Fig. 35 *Two-stage* Hf model age (crustal Hf model age) histogram for zircons of Archean rocks from the North China Craton. Some are 2.49–2.45 Ga in age, and some detrital zircons are from Paleoproterozoic metasedimentary rocks. See text for interpretation and references

age distributions do not mean that juvenile material was continuously added to the continental crust. We rather suggest that the patterns in whole-rock $\varepsilon_{Nd}(t)$ and zircon $\varepsilon_{Hf}(t)$ versus formation age diagrams are partly a result of mixing of juvenile and recycled material.

4 Formation and Evolution of the Archean Basement of the NCC

4.1 Temporal Evolution

Rocks older than 2.8 Ga only occur in local areas such as Anshan, eastern Hebei, eastern Shandong, Lushan, and Xinyang, amounting to less than 5 % of the area of the NCC Archean basement. However, detrital and xenocrystic zircons older than 2.8 Ga occur over a wider area. Rocks >3.4 Ga consist mainly of granitoids, but ultramafic to mafic rocks of these ages are also present, but most were not dated due to lack of magmatic zircon. Almost all rocks and zircons were involved in a late Neoarchean tectono-thermal event. Rocks >2.8 Ga do not show an increasing trend in distribution with time, but this may be due to uneven reworking of old rocks during later geological processes. 2.75–2.6 Ga magmatic rocks have recently been identified in many areas, and 2.55–2.5 Ga rocks occur more widely than thought before.

Only a few >2.6 Ga supracrustal rocks have been identified, including the 3.36 Ga Chentaigou supracrustals and the 3.0–2.9 Ga Tiejiashan supracrustals in Anshan, the 2.9 Ga Huangyadi supracrustals in eastern Shandong, the 2.82 Ga

Xiataihua supracrustals in Lushan, and the 2.75–2.71 Ga Yanlingguan-Liuhang succession in western Shandong. However, 2.56–2.51 Ga supracrustal rocks occur in almost every late Neoarchean terrane, although their proportions are small (commonly <10 %). Basaltic, intermediate, and felsic volcano-sedimentary rocks are the predominant protoliths of the supracrustal sequences.

Intrusive rocks show variations in rock types with time. The 3.8–3.1 and 2.9–2.7 Ga intrusive rocks are mainly trondhjemitic and tonalitic in composition, respectively, but some gabbroic and dioritic rocks also occur. The oldest large-scale K-rich granite body is the crustally derived 3.0–2.9 Ga Tiejiashan pluton. Granodiorites only began to occur in the late Neoarchean on a large scale, together with tonalites and trondhjemites, whereas crustally derived late Neoarchean granites (mainly monzogranites and syenogranites) are widely distributed.

TTG rocks with ages between 3.45 and 3.3 Ga exhibit variable REE contents, resulting in weakly to strongly fractionated REE patterns. This is considered to be a result of cooling of the Earth (Wan et al. 2005a). However, Moyen (2011) indicated that variable REE patterns in TTGs do not have any relationships with the cooling Earth. Some late Neoarchean rock types such as syenogranite show large variations in REE and trace element compositions, suggesting that the source regions and conditions of magma formation became more complex with time.

The NCC exhibits a continuous evolution from 3.8 to 2.5 Ga, but there are age valleys at ~3.5, ~3.2, 2.85, and ~2.65 Ga. Whole-rock Nd isotopes and Hf-in-zircon isotopes indicate that both juvenile additions and crustal recycling played important roles during almost every tectono-thermal event. The Neoarchean was the most important period for the formation of continental crust in the NCC, and this will be discussed below in more detail.

Metamorphic zircons older than 2.8 Ga were rarely found, and their formation may be related to local events. The oldest (2.76 Ga) well-developed metamorphic zircons are from 2.82 Ga rocks in the Lushan area. Widespread 2.6 Ga metamorphic zircon ages were obtained from rocks in western Shandong. The most important Archean metamorphic event occurred at the end of the Neoarchean, as indicated by widespread ~2.5 Ga metamorphic zircon ages all over the craton. These may suggest that significant crustal thickening only occurred after the Mesoarchean and reached a climax at the end of the Neoarchean due to subduction/collision and/or underplating. Ca. 2.5 Ga metamorphic zircons have not been identified in some areas such as Wutai, but this may be due to the low metamorphic grade in these rocks. In Anshan, there are 3.8–2.5 Ga rocks and zircons, and in eastern Hebei, 3.88–3.4 Ga detrital zircons and 3.4–3.0 Ga and 2.5 Ga rocks have been identified. Many old zircons show overgrowth and recrystallization, suggesting that they became involved in later crustal recycling and metamorphism.

The most important Archean ore deposits in the NCC are BIFs and some massive Cu–Zn sulfide deposits. Although BIFs show large variations in formation age from the Paleoarchean to the early Paleoproterozoic, they are predominantly late Neoarchean in age (2.55–2.51 Ga) (Wan et al. 2012d; Zhang et al. 2012b). It seems that a stable depositional environment was necessary for the formation of large-scale BIF deposits. Gold deposits mainly formed in the Mesozoic, but it is generally considered that Archean mafic–ultramafic supracrustal rocks (greenstone belts) were the main sources (Zhai 2010).

4.2 Ancient Material Records Beneath the NCC

Understanding the geological, geochemical, and geochronological processes during the early Precambrian evolution of the NCC is mainly based on studying the exposed basement as shown above. However, some progress has been made to recognize ancient material in the deep crust of the NCC. There are two ways to obtain information from this cratonic region. One is from rock samples recovered from drill holes that penetrated the basement. One such study revealed late Paleoproterozoic magmatism and metamorphism in basement rocks beneath the Songliao basin in the northeastern NCC (Pei et al. 2007), whereas another study indicated that the basement beneath the Ordos basin in the western NCC was involved in a late Paleoproterozoic tectono-thermal event (Hu et al. 2012; Wan et al. 2013).

Wan et al. (2014b) recently carried out zircon dating, Hf-in-zircon isotopic analyses, and a whole-rock geochemical study of igneous and metasedimentary rocks from basement covered by Mesoproterozoic and younger sedimentary rocks in the Central Hebei Basin (CHB). The CHB extends in a NE–SW direction and covers an area of >35,000 km^2 (Fig. 36). Based on drill core data and geophysical investigations (NCOCP 2012), the basement is composed of greenschist- to upper amphibolite-facies magmatic and supracrustal rocks that locally experienced anatexis. The bottom of the basin shows irregular elevations with the greatest depth being >5000 m. This study identified late Neoarchean magmatic and Paleoproterozoic metasedimentary rocks that were subjected to late Neoarchean to early Paleoproterozoic and late Paleoproterozoic tectono-thermal events, similar to those identified in the early Precambrian basement around the basin. Wan et al. (2014b) concluded that the basement beneath the CHB is part of the NCC. On the basis of this study, the authors suggested that early Precambrian rocks are extensive beneath the Mesoproterozoic and younger sedimentary cover all over the NCC.

Another way to reveal ancient material in the deep crust is to study rock enclaves (xenoliths) and xenocrystic zircons brought to the surface by eruption of volcanoes and/or intrusion of magmas from a deep source. Zheng et al. (2012), Zhang et al. (2012a, b), and Zhang (2014) summarized progresses made in the investigation of such rocks and zircons. Young igneous rocks containing old xenoliths and xenocrystic zircons include Paleozoic kimberlite and lamproite, Mesozoic volcanic or intrusive rocks, and Cenozoic basalts (Fig. 37). The xenoliths are considered to be derived from the lower crust and upper mantle. The lower crustal xenoliths consist of high-grade metamorphic rocks generally less than 10 cm in diameter. Many igneous rocks also contain xenocrystic zircons that were derived from lower crustal sources or were captured during magma ascent. These samples provide important information on the age and composition of the deep NCC crust.

Fig. 36 Geological map of the Central Hebei Basin and surrounding areas, modified after NCOCP (2012) and Wan et al. (2014b). *Inset* shows location in the NCC

The concordia diagram with zircon age data from xenoliths shows several clusters around 2.5, 1.9–1.8, and 0.1 Ga (Fig. 38a). Some data for old zircons from xenoliths of the Xinyang volcanic rocks plot along a discordia line with an upper concordia intercept age of ~3.6 Ga. Note that there is significant lead loss in some of these zircons. Thus, a cumulative histogram compiling all data may lead to an overestimate of zircon crystallization events. Several lead loss trends can be recognized: (1) ancient lead loss in Paleoarchean zircon grains at ca. 2.5 and 1.8 Ga; (2) ancient lead loss in Neoarchean zircon grains at 1.8 Ga; and (3) lead loss in Neoarchean and Paleoproterozoic zircons during the Phanerozoic. The concordia diagram of zircon xenocrysts shows a similar age pattern, including lead loss (Fig. 38b). These features were also observed in the zircon age distribution of the exposed early Precambrian basement. However, there are no zircon grains with Paleoarchean ages, consistent with the limited occurrence of such rocks in the NCC.

All early Paleoproterozoic zircon data, including those with variable lead loss, are shown in Fig. 38c and d. The Hf-in-zircon isotopic data from the xenoliths show that the oldest age group has even more negative $\varepsilon_{Hf}(t)$ (Fig. 38c) than the Paleoarchean zircons in the Anben and Caozhuang areas, indicating that they represent recycled crust. The ~2.5 Ga zircon grains have both negative and

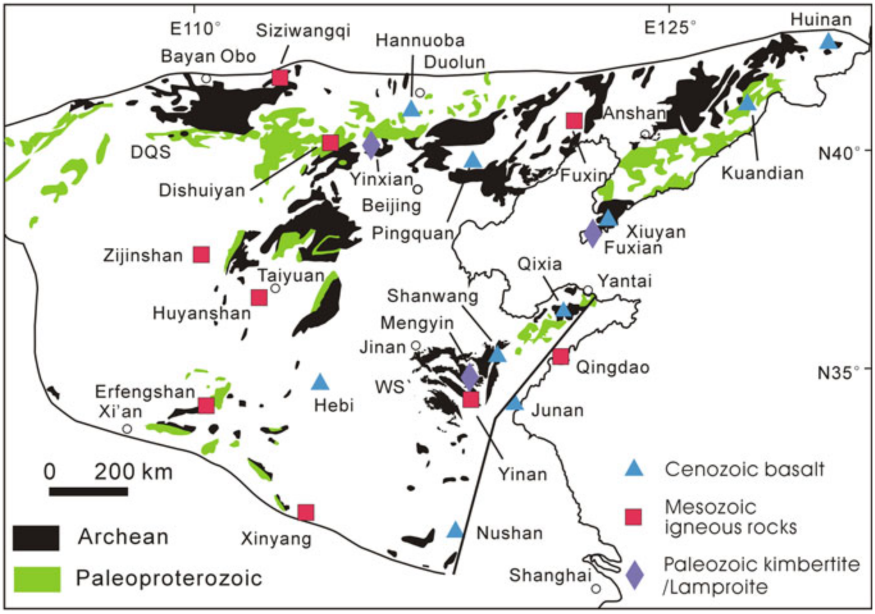


Fig. 37 Geological map showing locations of rocks containing xenoliths and xenocrystic zircons in the North China Craton and adjacent area. Paleozoic kimbertite/lamproite: Mengyin, Fuxin, and Yingxian; Mesozoic volcanic/intrusive rocks: Xinyang, Erfengshan, Yinan, Qingdao, Huyanshan, Zijinshan, Dishuiyan, Siziwangqi, and Fuxian; Cenozoic basalt: Nushan, Hebi, Junan, Shanwang, Qixia, Xiuyan, Pingquan, Hannuoba, Huinan, and Kuandian. Locations of rocks containing xenoliths and xenocrystic zircons are from HF Zhang et al. (2012a, b) and Zheng et al. (2012)

positive $\varepsilon_{Hf}(t)$, implying that juvenile material was added to the crust and recycling of older material also occurred. A similar pattern was observed in the 1.9–1.8 Ga zircons. Specifically, Phanerozoic zircon grains mainly show negative $\varepsilon_{Hf}(t)$ values, and some grains have extremely low $\varepsilon_{Hf}(t)$ of –40 and even lower. There is no doubt that some Archean material was recycled during Phanerozoic tectono-magmatic events. The Hf isotopic data of the zircon xenocryst show a similar pattern (Fig. 38d).

Both the data from xenoliths and zircon xenocrysts show similar Hf model age distributions (Fig. 38e, f) as those from basement rocks exposed on the surface. The major peak is at about 2.8 Ga, and very old model ages near the beginning of the formation of continental crust on the Earth suggest that there may be some very old material in the deep crust of the NCC.

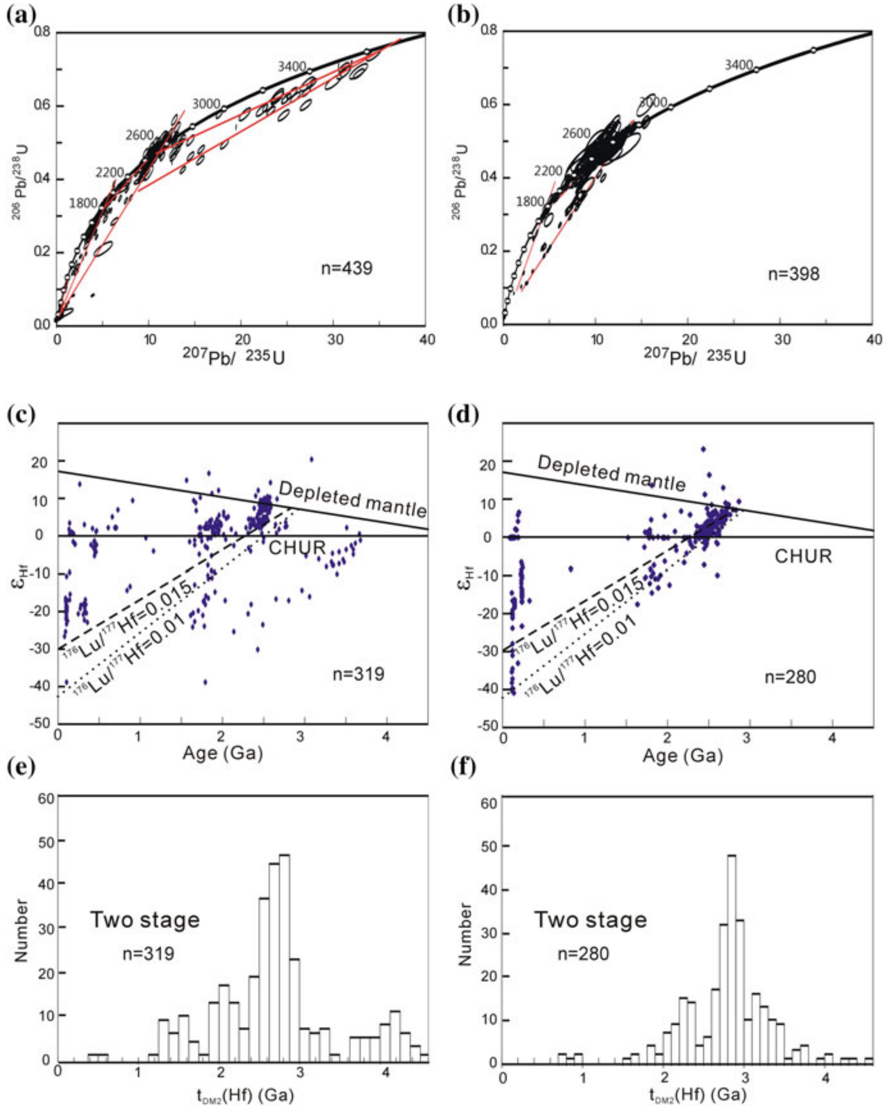


Fig. 38 Ages and Hf isotopes of zircons from deep crust in the North China Craton. **a** and **b** U–Pb concordia diagrams; **c** and **d** age versus $\varepsilon_{Hf}(t)$ diagrams; **e** and **f** Hf model age histograms. **a**, **c**, and **e** zircons from xenoliths; **b**, **d**, and **f** xenocrystic zircons. Data are from Gao et al. (2004), YS Liu et al. (2004b), Ying et al. (2011), Zhang (2012), Zhang et al. (2012a, b, c), and Zheng et al. (2004a, b, c, 2008)

4.3 Major Periods of Continent Formation

Formation of continental crust in the NCC can be traced back to the Eoarchean. Geological records earlier than Mesoarchean were most likely partly destroyed during later tectono-metamorphic processes, and it seems likely that the Neoarchean was a major period of crust formation in the NCC. This means that some crucial processes occurred in the Earth during this time, probably indicating a transformation in the global tectonic regime due to changes in the thermal state of the Earth from hot to cool. Zircon age histograms indicate that the most important tectono-thermal event occurred at ~2.5 Ga. Evidence for addition of juvenile material at ~2.5 Ga includes the following: (1) Ca. 2.5 Ga supracrustal rocks (greenstone belts), commonly with a high proportion of metabasalt, occur in almost every terrane; (2) Ca. 2.5 Ga gabbroic to dioritic rocks are widely distributed all over the NCC (Li et al. 2010b; Ma et al. 2012; Wan et al. 2010c; Wan, unpublished data); and (3) some ~2.5 Ga TTGs exhibit whole-rock Nd and Hf-in-zircon isotopic compositions similar to the depleted mantle (Diwu et al. 2012; Geng et al. 2012; Liu et al. 2009b; Wang and Liu 2012; this study). However, mafic to intermediate assemblages (including volcanic and intrusive rocks) constitute only a small portion of the granitoid–greenstone belts, and 2.5 Ga TTGs with depleted mantle model ages are relatively rare (Figs. 32d and 34d).

In western Shandong, >2.8 Ga rocks have not been identified, but voluminous ~2.5 Ga crustally derived granites show the same whole-rock Nd and Hf-in-zircon isotopic features as the 2.75–2.7 Ga rocks. Therefore, the ~2.5 Ga granitoids are considered to have been derived from 2.75–2.7 Ga sources (Wan et al. 2010c, 2011b). In areas where >2.8 Ga rocks are exposed, ~2.5 Ga granites with Nd and Hf isotopic compositions of 2.7 Ga juvenile rocks could have formed as a result of mixtures of depleted mantle-derived magmas and older crustal material. However, >2.8 Ga rocks are rare in the NCC, so this may not have been a significant process for the formation of ~2.5 Ga granitoids. On the other hand, some magmatic zircons from ~2.5 Ga gabbros, diorites, and granodiorites show Hf isotopic enrichment, similar to the Nd isotopic composition of some ~2.5 Ga amphibolites. This may be a feature of a mantle source or a result of crustal contamination of magmas derived from a depleted mantle. There are three potential sources for the ~2.5 Ga magmatic rocks with similar Nd and Hf isotopic compositions as the 2.7 Ga juvenile rocks (Wan et al. 2014a): (1) Ca. 2.7 Ga granitoids that constituted precursors for the ~2.5 Ga crustally derived granitoids; (2) Ca. 2.7 Ga mafic rocks that also constituted precursors for the ~2.5 Ga intermediate and more felsic rocks; and (3) a mantle source with ~2.7 Ga depleted mantle model ages from which some mafic rocks could have been derived. The possibility cannot be excluded that ~2.5 Ga granitoids with ~2.7 Ga depleted mantle model ages resulted from crustal recycling of ~2.5 Ga mantle-derived rocks with the same isotopic features; however, rocks formed in this way must be limited in volume. Therefore, the conclusion can be drawn that the most important period of addition of juvenile material occured in the early Neoarchean rather than in the late Neoarchean, consistent with rocks and detrital and xenocrystic zircons of these ages occurring in many areas of the NCC. Fundamentally, therefore, the NCC is similar to many other cratons elsewhere in that tectono-thermal and crust-forming events at ~2.7 Ga are globally well developed. The main difference between the NCC and many other cratons is that a superimposed ~2.5 Ga tectono-thermal event was particularly strong in the former (Wan et al. 2010c, 2011b, 2014a, 2015b; Zhai and Santosh 2011).

4.4 *Tectonic Subdivision of the NCC*

The early Precambrian subdivision of the craton is mainly based on the distribution of late Neoarchean to Paleoproterozoic rocks because of insufficient data for the earlier geological evolution. The subdivision is debated in the literature, and several schemes have been proposed as summarized by Zhai and Santosh (2011) and Zhao and Zhai (2013).

Wu et al. (1998) subdivided the NCC into five blocks, namely the Jiaoliao, Qianhuai, Jinji, Yuwan, and Mongshan blocks (Fig. 39a). The Jiaoliao and Qianhuai blocks were considered to have assembled along the Jiao-Liao-Ji Belt, resulting from an east-dipping subduction zone to form a larger block at ~2.5 Ga which then collided with other blocks to result in final amalgamation of the NCC during the late Paleoproterozoic.

Zhao et al. (2001) suggested a 3-fold subdivision of the craton, namely the Eastern Block, Western Block, and Trans-North China Orogen (TNCO). Late Archean anticlockwise P-T paths for the two blocks were interpreted to have resulted from several mantle plumes, resulting in magmatic underplating and high-grade metamorphism at ~2.5 Ga, whereas the clockwise path in the TNCO was interpreted to reflect continental collision between the Eastern and Western blocks, leading to Paleoproterozoic assembly of the NCC at ~1.85 Ga. Zhao et al. (2005) later modified this model into the currently favored 6-fold subdivision of the craton (Fig. 39b), resulting from the speculative interpretation of major collisional zones within both the Eastern and Western blocks.

Li et al. (2002), Kusky and Li (2003), and Kusky et al. (2007) suggested that collision between the Eastern and Western blocks occurred in the late Neoarchean (~2.5 Ga) along the Central Orogenic Belt (COB) to form a unified NCC. The COB is similar in spatial distribution to the TNCO of Zhao et al. (2001, 2005) with differences being that the COB extends farther northeast into southern Jilin (Fig. 39c) and that the subduction polarity was west-dipping, rather than east-dipping, as suggested by Zhao et al. (2001, 2005).

Zhai and Santosh (2011) subdivided the NCC into seven microblocks, mainly based on the spatial distribution of ancient rocks and tectonic boundaries revealed by several granite–greenstone belts. These were named the Alashan (ALS), Xuhuai (XH), Xuchang (XCH), Jining (JN), Ordos (OR), Qianhuai (QH), and Jiaoliao (JL) blocks, with very different boundaries from those of other authors. They

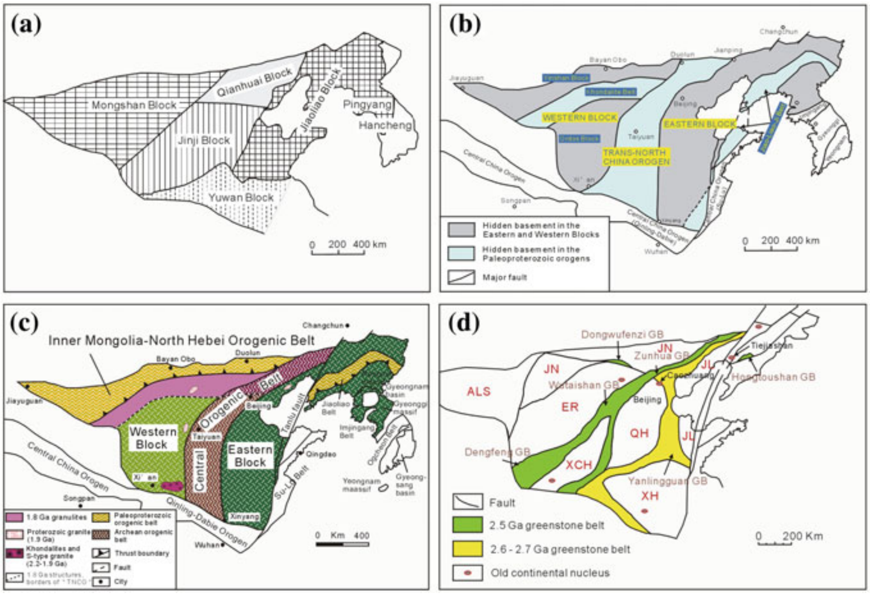


Fig. 39 Different tectonic subdivisions of the North China Craton. **a** Wu et al. (1998); **b** Zhao et al. (2005); **c** Li et al. (2002); **d** Zhai and Santosh (2011)

suggested that these microblocks were welded together along Neoarchean granite–greenstone belts at ~2.5 Ga (Fig. 39d).

In order to understand the tectonic setting of the NCC during the late Neoarchean, it is necessary to determine the spatial distribution of ancient (≥2.6 Ga) continental domains in the craton. A strong tectono-thermal event at ~2.6 Ga in western Shandong is an important reason for considering 2.6 Ga as a chronological boundary between the early and late Neoarchean. With regard to the spatial distribution of these ancient crustal domains, rocks and zircons of different origins and ages have different geodynamic interpretations. Rocks ≥2.6 Ga themselves represent ancient crust, whereas ≥2.6 Ga detrital zircons in late Neoarchean and Paleoproterozoic metasedimentary rocks suggest the existence of ancient crust in nearby areas, and ≥2.6 Ga xenocrystic zircons in young (<1.8 Ga) intrusive rocks may indicate the existence of old material in the deep crust. However, old detrital zircons in young sedimentary rocks have no significance because they may have undergone multirecycling. Figure 1 shows ≥2.6 Ga detrital and xenocrystic zircons from Paleoproterozoic or older rocks. Based on the spatial distribution of ancient rocks and zircons, three ancient terranes can be delineated, namely the Eastern Ancient Terrane, Southern Ancient Terrane, and Central Ancient Terrane (Fig. 40).

(1) Eastern Ancient Terrane

This is the best understood ancient terrane and occurs along the eastern margin of the NCC in a NE–SW direction, including Anben, eastern Hebei, eastern Shandong, and western Shandong. The oldest rocks and zircons mainly occur in

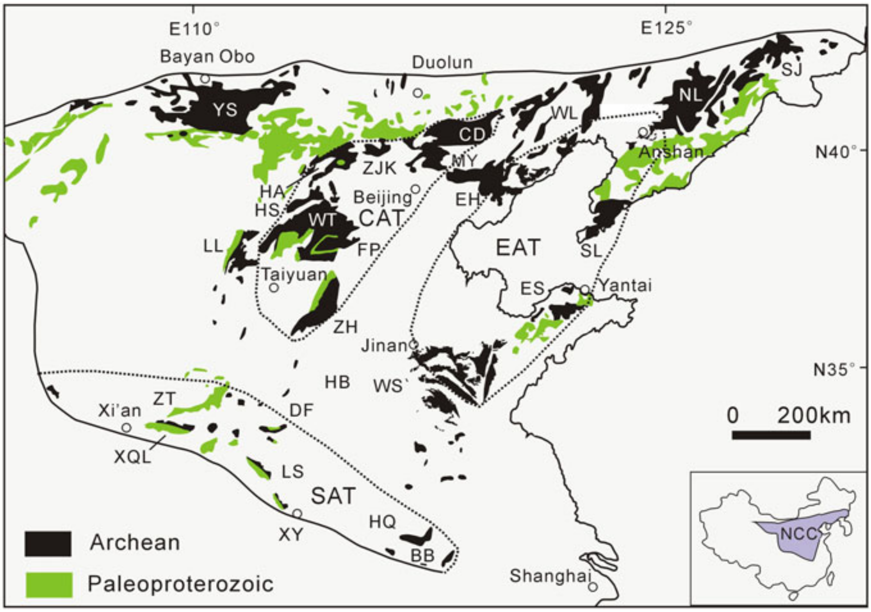


Fig. 40 Distribution of ancient (>2.6 Ga) terranes in the North China Craton. *EAT* Eastern Ancient Terrane; *SAT* Southern Ancient Terrane; *CAT* Central Ancient Terrane. Abbreviations are as in Fig. 1

this terrane. Besides the 3.8–2.9 Ga rocks in Anshan and 3.4–3.0 Ga rocks and 3.8–3.3 Ga detrital zircons in eastern Hebei, 2.9–2.6 Ga rocks were identified in eastern Shandong and western Shandong. The spatial relationships between the old rocks in the terrane may not have changed significantly since the early Neoarchean (2.6 Ga). In western Shandong, the margin of the ancient terrane is the boundary between belts B and C (Fig. 19). Although granitoids in Belt A are mainly ~2.5 Ga in age, they are derived from melting of older basement. Syenogranites and monzogranites are also widely distributed in eastern Hebei, Jinzhou, and Anben, and they constitute the largest crustally derived late Neoarchean granite belt in the NCC. It is notable that these ~2.5 Ga granitoids inherited their compositional features from older basement. As mentioned above, in Anshan, recycling of >3.0 Ga crust played a profound role in the formation of the ~2.5 Ga syenogranites, as evidenced by the presence of older xenocrystic zircons as well as whole-rock Nd and Hf-in-zircon isotopic compositions (Wan et al. 2015a). In western Shandong, on the other hand, the ~2.5 Ga crustally derived granites in Belt A have similar whole-rock Nd and Hf-in-zircon isotopic compositions as the adjacent early Neoarchean rocks (Wan et al. 2010c, 2011b).

(2) Southern Ancient Terrane

This terrane occurs along the southern margin of the NCC in a nearly E–W direction. 3.65, 2.83–2.82, 2.7, and 2.7–2.6 Ga rocks have been identified in

Xinyang, Lushan, Huoqiu, and Zhongtiao, respectively, and 3.6–2.6 Ga detrital and xenocrystic zircons were discovered in additional areas (Liu et al. 2012b). Importantly, as pointed out before, the captured or detrital 4.1–3.5 Ga zircons in Paleozoic volcano-sedimentary rocks of the northern Qinling Orogenic Belt may be derived from the southern margin of the NCC. This suggests that the Southern Ancient Terrane may have a long geological history back to 4.1 Ga ago. Widespread identification of >2.6 Ga rocks and zircons in this terrane is an important progress made in recent years.

(3) Central Ancient Terrane

This includes the Zanhuang, Fuping, Hengshan, Zhangjaikou, and Chengde areas where 2.7 Ga TTG rocks and zircons were identified, although the TTG rocks commonly occur at small scales. It is likely that more rocks and zircons older than 2.6 Ga will be discovered in this terrane, and the widespread presence of crustally derived granites in the Central Ancient Terrane is also consistent with the existence of older material in the deep crust. However, there are also many ~2.5 Ga TTG rocks in the terrane, and this makes it uncertain whether or not the Central Ancient Terrane existed prior to 2.6 Ga.

Besides the above three ancient terranes, >2.6 Ga rocks and zircons were identified in other areas of the NCC. For example, in Xi Wulanbulang, 2.7 Ga TTG rocks with a relatively wide distribution as well as older detrital and xenocrystic zircons were discovered (Jian et al. 2012; Dong et al. 2012a, 2012b; Ma et al. 2013). Ca. 2.5 Ga zircons in late Neoarchean supracrustal and intrusive rocks have the same Hf isotopic compositions as zircons from the 2.7 Ga TTG rocks, providing evidence for crustal recycling or contamination of early Neoarchean crust. Therefore, there may also be an ancient terrane in the Yinshan Block.

4.5 *Tectonic Regime*

Mantle plume activity resulting in magmatic underplating and plate tectonics are considered to have been the most important processes involving the formation and evolution of early continental crust (Van Kranendonk et al. 2014), but the timing of initiation of plate tectonics is debatable. Some authors suggested that present-type plate tectonics only began in the late Paleoproterozoic or later, whereas others considered that tectonic regimes similar to those of today occurred as early as the Eoarchean (e.g., Nutman et al. 2013). Therefore, there are different opinions on whether mantle plume activity (or underplating) and/or arc magmatism or both played key roles in the Neoarchean, an important period when much of the global continental crust formed (Bédard 2013; Condie and Kröner 2013; Dostal and Mueller 2013; Halla et al. 2009; Manikyamba and Kerrich 2012; Mohan et al. 2013; Wyman 2013a, b). Magmatic underplating is considered to be related to mantle plume activity or, more probably, to mantle overturn (Davies 1995; Rey et al. 2003) and may have been an important mechanism in continental growth and reworking (Frost et al. 2001; Warren and Ellis 1996). Mantle plumes generally last for only

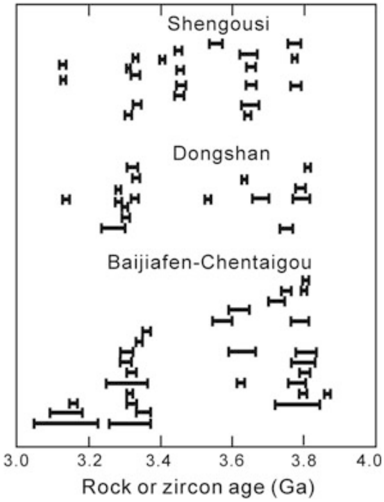


Fig. 41 Comparison of the Archean magmatic records of the Baijiafen, Dongshan, and Shengousi complexes in the Anshan area. Data are from Liu et al. (1992, 2008), Song et al. (1996), Wan et al. (2005a, b, c, 2012a), Wu et al. (2008), and Wan (unpublished data)

5–10 Ma (Abbott and Isley 2002), a much shorter time span than the late Neoarchean (2.55–2.50 Ga) igneous activity in the NCC. Mantle overturn may have led to longer magmatism.

We now have a better understanding of the early (>2.8 Ga) evolution of the NCC through detailed studies in some areas. In Anshan, magmatism almost continuously lasted for a long time from 3.8 to 2.9 Ga (Fig. 12), where multiple and complex phases of igneous activity were recorded in all three complexes (Fig. 41). The rock types include both mantle-derived and crustally derived rocks (Dong et al. 2013; Liu et al. 1992, 2008; Song et al. 1996; Wan et al. 2005a, 2007, 2012a, 2015a; Zhou et al. 2007; Zhou et al. 2009). These data suggest that long-term magmatism related to mantle activity widely occurred in Anshan and adjacent area. In eastern Hebei, detrital zircons record almost continuous ages ranging from 3.88 to 3.4 Ga, although only 3.4–3.0 Ga Paleoarchean–Mesoarchean rocks were discovered until now. We suggest that widespread magmatism due to mantle overturn activity may have been the main mechanism of continental growth and reworking before the Mesoarchean, consistent with the underplating model.

Western Shandong and eastern Shandong are areas where ~2.7 Ga rocks are most widely distributed in the NCC. Metabasalts with REE depletion and enrichment have been identified in western Shandong, and komatiites with well-preserved spinifex textures (Fig. 18d) were considered to be ~2.7 Ga in age (Polat et al. 2006a). In eastern Shandong, ~2.7 Ga TTGs formed about 200 Ma later than ~2.9 Ga TTGs, and this suggests that subduction may not have been responsible for the formation of the ~2.7 Ga rocks because a 200 Ma time span is too short for a full Wilson cycle (Jahn et al. 2008). Furthermore, the majority of TTG rocks in both western Shandong and eastern Shandong show strongly fractionated REE patterns and Nb–Ti–P depletion (Jahn et al. 2008; Wan et al. 2014a). Based on rock associations, TTG compositions, and the geological evolution, mafic magma underplating was considered as a viable process for the formation of the supracrustal and intrusive rocks (Jahn et al. 2008; Polat et al. 2006a). The tectonic setting of ∼2.7 Ga rocks in other areas is not so clear because of their small size and poor data. However, Yang et al. (2013a) favored a subduction model for the formation of ∼2.7 Ga TTG rocks in the Zanhuang area.

Underplating and arc magmatism have been proposed for crustal growth in the late Neoarchean. The former model was mainly suggested from studies of the eastern NCC (Geng et al. 2006; Yang et al. 2008; Zhao et al. 1998, 1999, 2001). Zhao and Zhai (2013) summarized the main features supporting this view as follows: (1) An exceptionally large exposure of granitoid intrusions formed over a short time period (2.55–2.50 Ga) and shows no systematic age progression across a ∼800-km-wide block; (2) generation of komatiitic magmas with eruption temperatures as high as ∼1650 °C; (3) dominant domal structures; (4) bimodal volcanic assemblages in the greenstone sequences; (5) affinities of mafic rocks to continental tholeiitic basalts; and (6) metamorphism with anticlockwise P-T paths involving isobaric cooling. Jian et al. (2012) attributed the strong late Neoarchean (2.55–2.50 Ga) magmatism and metamorphism in the Yinshan Block to episodic mantle upwelling/melting as a result of spontaneous delamination of the lower crust and periodic delamination of melt residues during granitoid production. They considered this to have occurred in a continental environment because of the presence of >2.6 Ga rocks and zircons.

Some authors suggested a scenario of arc magmatism followed by collisional orogeny, although there are different opinions on the timing and spatial distribution of collisional belts (Kröner et al. 2005a, b; Kusky and Li 2003; Kusky et al. 2007; Li et al. 2002; Nutman et al. 2011; Polat et al. 2006b; Wan et al. 2005b, c, 2010c, 2012c; Wilde et al. 2005; Wu et al. 1998; Zhang et al. 2007, 2009; Zhao et al. 2001, 2002, 2005). The main points include the following: (1) Igneous rocks of different ages and compositions occur in different zones and spatially show an asymmetrical distribution in some areas such as western Shandong and eastern Hebei; (2) compared with TTGs, syenogranites and monzogranites commonly formed during a slightly late phase; (3) older rocks (2.56–2.525 Ga) commonly underwent stronger deformation and metamorphism than younger rocks (2.525–2.48 Ga); (4) intrusive and volcanic activities occurred during almost a same period, and the intrusive rocks were uplifted quickly to the surface to form the source for sediments in the late Neoarchean basins, suggesting an active tectonic environment; (5) there are metabasaltic rocks with depletion and enrichment features in many supracrustal belts; and (6) intrusive rocks of different compositions are commonly depleted in Nb and Ta and thus display a subduction-related chemical signature. Nutman et al. (2011) indicated that the complexity of the late Neoarchean eastern Hebei arc magmatism matches that found in long-lived arc systems that involved older continental crust, such as the Andean margin of South America (Hildreth and Moorbath 1988), the Paleoproterozoic of South Greenland (Garde et al. 2002), and the Neoarchean crustal development in southern India (Chadwick et al. 2007).

In fact, some of the above features can be intercepted by both the underplating and subduction models. More data, including geophysical surveys, are required in order to better understand the tectonic regime in the NCC during the late Neoarchean. These include (1) the difference in the spatial distribution of Archean rocks at present and in the late Neoarchean and (2) the compositions and ages of the unexposed basement. It is difficult to explain that the above two different tectonic settings worked at the same time with underplating having occurred beneath the Eastern and Western blocks when both these blocks moved toward each other resulting in subduction/collision. On the basis of similarities in rock association, ages of formation, and geological evolution in different areas, we suggest that only one tectonic setting played an important role in the NCC during the late Neoarchean.

It is notable that globally, apart from the NCC, ~2.5 Ga rocks only occur in a few areas such as southern India (Chadwick et al. 2007; Clark et al. 2009; Dey et al. 2012; Jayananda et al. 2000; Moyen et al. 2003), Antarctica (Corvino and Henjes-Kunst 2007; Clark et al. 2012; Duclaux et al. 2008; Tsunogae et al. 2014), and northern Australia (Drüppel et al. 2009; McCready et al. 2004). The NCC underwent a much stronger tectono-thermal event at ~2.5 Ga than many other cratons characterized by ~2.7 Ga events (Condie 2000; Condie et al. 2009). It may be possible that all these continental terranes once belonged to a single block (Clark et al. 2012; Wan et al. 2011a; Zhao et al. 2003), but more work is required to identify this. If underplating was active at ~2.5 Ga, it may have modified an early Neoarchean supracontinent previously formed by a widespread and strong ~2.7 Ga tectono-thermal event. On the other hand, if arc magmatism was active at this time, the areas where ~2.5 Ga TTG rocks are well developed may represent an ancient subduction/collision belt between two large blocks of the early Neoarchean. In both cases, the different cratons may be dispersed remnants of what was once a single continent at the end of the Neoarchean, consistent with many cratons showing fragmented features (Bleeker 2003).

All late Neoarchean tectono-magmatic belts so far proposed in the NCC, such as the Liao-Ji-Lu magmatic belt (Wu et al. 1998), the Central Orogenic Belt (Li et al. 2002), and the greenstone belts (Zhai and Santosh 2011), only contain a relatively small portion of the late Neoarchean areas. Therefore, these are not consistent with the arc magmatism model. In order to overcome this problem, we propose a multi-island arc model in which the three ancient terranes, and possibly other old terranes, occurred in an oceanic domain, and amalgamation of these terranes due to subduction/collision resulted in the formation of supracrustal and intrusive rocks as well as juvenile additions and crustal recycling and finally assembled the NCC at the end of the Neoarchean. This is consistent with rocks of continental and oceanic affinities in many areas of the NCC. In the western Liaoning, Dengfeng and Huai'an areas, for example, there are supracrustal and intrusive rocks apparently derived from depleted mantle sources, but crustally derived granites and sediments have also been identified (Diwu et al. 2011; Liu et al. 2009b; Wang et al. 2011). The late Neoarchean may have been a period when plate tectonics began to play an important role in crust formation, although subduction/collision would have been different in pattern and scale from present-day processes because the Earth was hotter than now and the oceanic lithosphere was thicker, softer, and more buoyant, and continent blocks were smaller.

4.6 Craton Stabilization

Although there are different opinions on the late Neoarchean tectono-thermal event in the NCC, it is accepted by many authors, including those who favored the arc magmatism model (Nutman et al. 2011; Wan et al. 2010c, 2011b), that the latest Neoarchean event was related to an extensional tectonic setting, probably due to magmatic underplating. Most latest Neoarchean crustally derived granites have formation ages of 2.52–2.49 Ga and either are undeformed and massive or show weak deformation. They intruded into earlier, deformed rocks and are associated with undeformed, mantle-derived gabbroic and dioritic rocks of the same age. In western Shandong, for example, intrusive rocks older than 2.525 Ga commonly show strong deformation, whereas intrusive rocks younger than 2.525 Ga commonly are undeformed or only weakly deformed (Fig. 42). This suggests that the tectonic regime probably changed from compressional to extensional between 2.53 and 2.52 Ga (Wan et al. 2010c). Similar scenarios were proposed for other areas of the NCC such as Wutai and Zanhuang (Wilde et al. 2005; Yang et al. 2013a).

It is also evident that migmatites occur on large scales and are associated with crustally derived granites in many areas such as western Shandong (Fig. 19). Migmatization occurred at the same time or slightly earlier than the formation of granites. Metamorphism and associated crustally derived granites were identified all

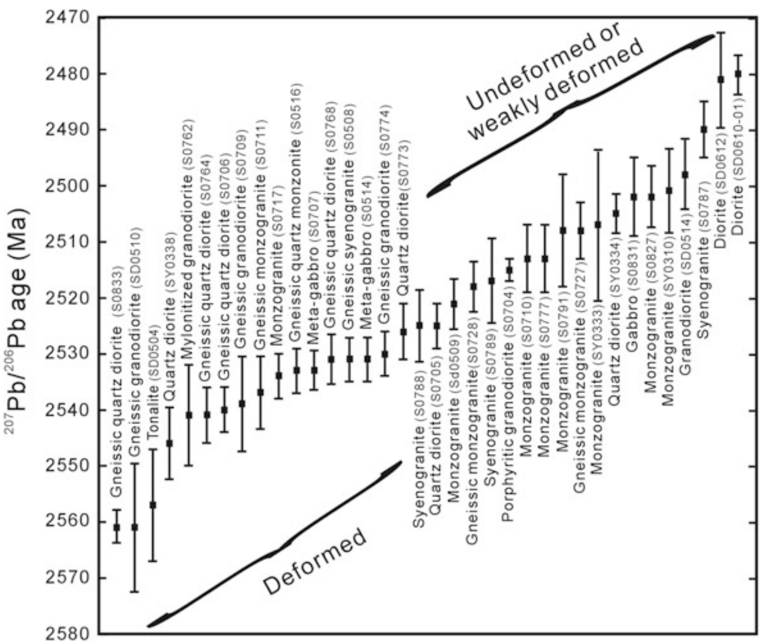


Fig. 42 Zircon age variation diagram (with *error bars*) for different types of intrusive rocks in western Shandong. Data are from Lu et al. (2008) and Wan et al. (2010c)

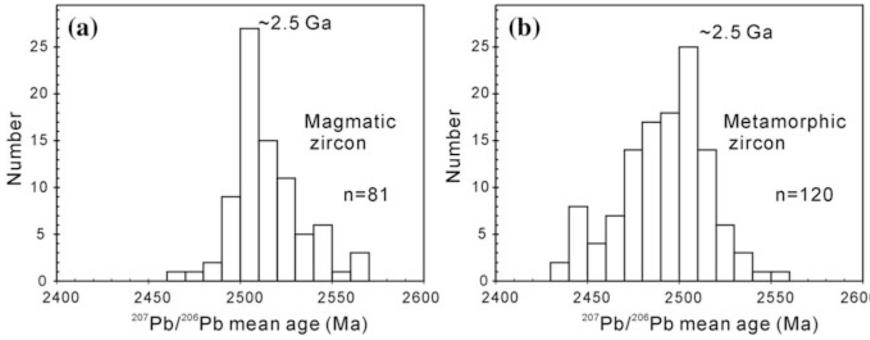


Fig. 43 Weighted mean ^{207}Pb/^{206}Pb age histograms for magmatic zircons from crustally derived granites (**a**) and metamorphic zircons from high-grade metamorphic rocks (**b**) in the North China Craton. See text for interpretation and references

over the NCC, including eastern Shandong, western Shandong, northern Liaoning, western Liaoning, eastern Hebei, Dengfeng, Yinshan, and Daqingshan, with metamorphic ages identical to crystallization ages of many crustally derived granites, mainly ranging from 2.53 to 2.49 Ga and 2.53 to 2.45 Ga, respectively (Fig. 43) (Bai et al. 2014; Chen et al. 2006; Cui et al. 2013; Dai et al. 2013; Deng et al. 2014; Dong et al. 2012a, b; Geng et al. 2006; Grant et al. 2009; Guan et al. 2002; Guo et al. 2013; Han et al. 2014a; Jahn et al. 2008; Jian et al. 2012; Kröner et al. 1998, 2005a; Li et al. 2009, 2010b, 2011a, b 2013a, b; Lu et al. 2008; Lü et al. 2012; Ma et al. 2013, 2013a; Nutman et al. 2011; Peng et al. 2012, 2013a, b; Ren 2010; Ren et al. 2013; Shen et al. 2004; Shi et al. 2012; Sun et al. 2010; Wan et al. 2005b, 2009c, 2010c, 2012b, d, 2015a, unpublished data; Wang et al. 2000, 2011, 2012, 2013, 2014a, b; Wilde et al. 1997, 2005; Wu et al. 2013, 2014; Xie et al. 2013, 2014b; Yang et al. 2008, 2011; Zhang et al. 2011, 2012a, 2014; Zhao et al. 2002, 2008b2009, 2011; Zhu et al. 2015). The association of undeformed, mantle-derived rocks (gabbro, diorite) of the same age (mainly 2.52–2.49 Ga) suggests that underplating may have played an important role in causing metamorphism and anatexis in the lower crust to produce crustally derived granites during extension in the NCC basement at the end of the Neoarchean. These magmas moved to higher crustal levels to form intrusive bodies at different scales, including syenogranites. The formation of large-scale granite batholiths and widespread high-grade metamorphism and anatexis are considered to have been important processes to cause cratonic stabilization of the NCC at the end of the Neoarchean, a convenient time to set 2.5 Ga as the Archean–Proterozoic boundary (Wan et al. 2012b, 2015a; Yang et al. 2011).

Metamorphic zircon ages are younger than magmatic zircon ages of crustally derived granites in some areas, down to 2.45 Ga or even later, although some may be the result of partial resetting of the U–Pb isotopic system in the zircons due to the strong late Paleoproterozoic tectono-thermal event. It is uncertain whether the metamorphism lasted from the late Neoarchean to the earliest Paleoproterozoic (~2.45 Ga) or whether the earliest Paleoproterozoic metamorphism was a different event. In western Liaoning, metamorphism was considered to be one event and lasted from the latest Archean to early Paleoproterozoic (Kröner et al. 1998; Liu et al. 2011a). In Daqingshan, however, the earliest Paleoproterozoic Daqingshan supracrustal sequence (mainly metasediments) contains 2.45 2.40 Ga metamorphic zircons, suggesting that here the earliest Paleoproterozoic metamorphism was a separate tectono-thermal event.

Cratonic stabilization implies that the NCC was already a single tectonic unit at the end of the Neoarchean as suggested by Wan et al. (2011a), Zhai and Peng (2007), and Zhai and Santosh (2011). The Eastern and Western blocks and the TNCO share many common features, and some have been discussed before: (1) These tectonic units display almost identical late Neoarchean zircon age spectra with age peaks at ~2.52 Ga; (2) there is evidence for >2.8 Ga material, although this is more evident in the Eastern Block; (3) there are ~2.7 Ga TTGs in all three blocks; (4) there are ~2.5 Ga supracrustal rocks with similar rock associations with BIFs being typical components; (5) there was strong juvenile magma addition from mantle sources to the crust between 2.8 and 2.7 Ga; (6) there are abundant ~2.5 Ga TTGs, associated with minor gabbroic and dioritic rocks; (7) the old rocks underwent metamorphism and anatexis between 2.52 and 2.48 Ga; (8) crustally derived late Neoarchean granites occur in all three blocks and are commonly younger than the TTGs; (9) crustal recycling of ~2.7 Ga rocks at ~2.5 Ga played an more important role than juvenile addition; and (10) young sediments in different areas commonly contain late Neoarchean and late Paleoproterozoic detrital zircons.

In general, it is difficult to determine the original relationships between the different blocks just by comparing rock types and ages. Considering the limited distribution of the ~2.5 Ga tectono-thermal event worldwide, however, the obvious similarity of the Eastern and Western blocks may suggest that they formed in a similar tectonic setting, supporting the conclusion that the NNC had already been a single unit at the end of the Neoarchean.

5 Summary and Conclusions

(1) The NCC underwent a long and complex evolution from 3.8 to 2.5 Ga. Rocks older than 2.8 Ga occur only locally, with Anshan and eastern Hebei being the most important areas where >3.8 Ga rocks and crustal components have been identified.

(2) The most important tectono-thermal event in the NCC occurred at ~2.5 Ga, and this is different from many other cratons worldwide. However, whole-rock Nd and Hf-in-zircon isotopic compositions indicate that the late Mesoarchean to early Neoarchean is the most important period for rapid production of continental crust. This is similar to several other cratons.

(3) The deep crust of the NCC shows similar evidence for the presence of ancient material as the surface exposures, and the available data suggest that the most important tectono-thermal events occurred in the late Neoarchean and late Paleoproterozoic, and juvenile material was added to the crust during the late Mesoarchean to early Neoarchean.
(4) We suggest that three ancient terranes older than 2.6 Ga can be delineated in the NCC, namely the Eastern, Southern, and Central Ancient Terranes.
(5) Vertical crustal growth is considered to have been the main mechanism of continental evolution prior to the Mesoarchean, and this is mainly based on geological features in the Anshan area. It is still uncertain whether magmatic underplating or arc magmatism played a decisive role in the evolution of the NCC during the late Neoarchean. We favor a multi-island arc model related to amalgamation through subduction/collision of different ancient terranes.
(6) The NCC may have been a single tectonic unit at the end of the late Neoarchean, due to cratonic stabilization as indicated by the formation of widespread and voluminous granites and extensive high-grade metamorphism and anatexis all over the craton, probably as a result of mantle underplating.

Acknowledgements We are grateful to the members of the Beijing SHRIMP Center for zircon separation, mount making, CL imaging, dating, and other help. Chunli Guo, Kejun Hou, Liewen Xie, Yueheng Yang, Honglin Yuan, Chunrong Diwu, and Hongying Zhou assisted in Hf-in-zircon isotopic analysis, and Suohan Tang, Jinhui Wang, Chaofeng Li, Jinghui Guo, Fukun Cheng, and Hongying Zhou assisted in whole-rock Nd isotopic analysis. We also thank Vickie Bennett, Michael Brown, Bin Chen, Yuelong Chen, Kent Condie, Xiaozhong Ding, Chunrong Diwu, Lilin Du, Clark R.L. Friend, Yuansheng Geng, Yongchang Gu, Jinghui Guo, Baofu Han, Jianmin Hu, Ping Jian, Wei Jin, Huaikun Li, Huimin Li, Houmin Li, Jianghai Li, Jinyi Li, Sanzhong Li, Tingdong Li, Xianhua Li, Xuping Li, Yanhe Li, Shoufa Lin, Fulai Liu, Junlai Liu, Shuwen Liu, Xiaochun Liu, Yongshun Liu, Zhihong Liu, Songnian Lu, Changqian Ma, Peisen Miao, Zhiyao Ni, Allen Nutman, Dominic Papineau, Peng Peng, Jishun Ren, M. Santosh, Qihan Shen, Min Sun, Yong Sun, Jeff D. Vervoort, Huichu Wang, Renmin Wang, Shijin Wang, Shiyan Wang, Tao Wang, Zejiu Wang, Chunjing Wei, Ian Williams, Simon A. Wilde, Chunming Wu, Fuyan Wu, Yuanbao Wu, Qinghui Xiao, Wenliang Xu, Zhongyuan Xu, Chonghui Yang, Jinhui Yang, Zhensheng Yang, Hongfu Zhang, Lianchang Zhang, Fengqing Zhao, Minggou Zhai, Guochun Zhao, Taiping Zhao, Yue Zhao, Jianping Zheng, Jianbo Zhou, Xiaodong Zhou, Xiangkun Zhu, and others for discussions and help in this study. We particularly thank Academician Minggou Zhai for originating this book. This paper is the result of long-term work in the NCC, supported financially by the Major State Basic Research Program of the People's Republic of China (2012CB416600, 2015FY310100), the National Natural Science Foundation of China (40172044, 40672127, 41002062, 41472167, 41472169, 49473172, 49872024), and the Key Program of the Ministry of Land and Resources of China (1212010711815, 1212011120151, 12120114021301, 12120113013700, 1212011220465, 1212011120142, 1212010811033, DKD2001020-3, DKD9904011, DKD20010209, J1.3.1). We express our sincere appreciation to the distinguished geologist Academician Yuqi Cheng who is one of the most important founders of metamorphic petrology, metamorphic geology, and geochronology in China and who has made significant contributions to the geology of China.

References

Abbott DH, Isley AE (2002) The intensity, occurrence, and duration of superplume events and eras over geological time. J Geodyn 34:265–307
Bureau of Geology Mineral Resources of Shandong Province (BGMRSP) (1991) Regional geology of Shandong Province. Geological Publishing House, Beijing, pp 1–595 (in Chinese with English abstract)
Bai J et al (1986) The early Precambrian geology of Wutaishan. Tianjing Publishing press, Tianjin, pp 1–46 (in Chinese with English abstract)
Bai J, Huang X-G, Wang H-C, Guo J-J (1996) The Precambrian evolution of China, 2nd edn. Geological Publishing House, Beijing, pp 1–259 (in Chinese)
Bai X, Liu S-W, Guo R-R, Zhang L-F, Wang W (2014) Zircon U-Pb-Hf isotopes and geochemistry of Neoarchean dioritic-trondhjemitic gneisses, Eastern Hebei, North China Craton: constraints on petrogenesis and tectonic implications. Precambr Res 251:1–20
Bédard J (2013) How many arcs can dance on the head of a plume? A 'comment' on: a critical assessment of Neoarchean 'plume only' geodynamics: evidence from the Superior Province, by Derek Wyman. Precambr Res 229:189–197
Black LP, Williams IS, Compston W (1986) Four zircon ages from one rock: the history of a 3930 Ma-old granulite from Mount Sones, Enderby Land, Antarctica. Contrib Miner Petrol 94:427–437
Bleeker W (2003) The late Archean record: a puzzle in ca. 35 pieces. Lithos 71:99–134
Bowring SA, Williams IS (1999) Priscoan (4.00-4.03 Ga) orthogneisses from northwestern Canada. Contrib Miner Petrol 134:3–16
Bouvier A, Vervoort JD, Patchett PJ (2008) The Lu-Hf and Sm-Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. Earth Planet Sci Lett 273:48–57
Cao G-Q et al (1996) Early Precambrian geology of western Shandong. Geological Publishing House, Beijing, pp 1–193 (in Chinese with English abstract)
Chadwick B, Vasudev VN, Hegde GV, Nutman AP (2007) Structure and SHRIMP U/Pb zircon ages of granites adjacent to the Chitradurga Schist Belt: implications for Neoarchean convergence in the Dharwar Craton, southern India. J Geol Soc India 69:5–24
Chen L (2007) Geochemistry and Geochronology of the Guyang Greenstone Belt. Postdoctoral Report. Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, pp 1–40 (in Chinese)
Chen T (1988) The geology and petrological characteristics of granitic rocks in the Caozhuang-Bailonggang area, Qian'an, Hebei. Bull Inst Geol, Chin Acad Geol Sci 18:82–97 (in Chinese with English abstract)
Chen B, Liu S-W, Geng Y-S, Liu C-Q (2006) Zircon U-Pb ages, Hf isotopes and significance of the late Archean-Paleoproterozoic granitoids from the Wutai-Lüliang terrain, North China. Acta Petrologica Sinica 22:296–304
Cheng Y-Q, Sheng Q-H, Wang Z-J (1982) Preliminary study of the metamorphosed basic Volcano-Sedimentary Yanlingguan formation of the Taishan Group of Xintai, Shandong. Geological Publishing House, Beijing, pp 1–72 (in Chinese)
Cheng Y-Q, Yang C-H, Wan Y-S, Liu Z-X, Zhang X-P, Du L-L, Zhang S-G, Wu J-S, Gao J-F (2004) Early Precambrain geological characters and anatectic reconstruction of crust in the north part of middle Taihang Mountain. Geological Publishing House, Beijing, pp 1–191 (in Chinese)
Clark C, Collins AS, Timms NE, Kinny PD, Chetty TRK, Santosh M (2009) SHRIMP U-Pb age constraints on magmatism and high-grade metamorphism in the Salem Block, southern India. Gondwana Res 16:27–36
Clark C, Kinny PD, Harley SL (2012) Sedimentary provenance and age of metamorphism of the Vestfold Hills, East Antarctica: evidence for a piece of Chinese Antarctica? Precambr Res 196–197:23–45

Condie KC (2000) Episodic continental growth models: afterthoughts and extensions. Tectonophysics 322:153–162
Condie KC, Belousova E, Griffin WL, Sircombe KN (2009) Granitoid events in space and time: constraints from igneous and detrital zircon age spectra. Gondwana Res 15:228–242
Condie KC, Kröner A (2013) The building blocks of continental crust: evidence for a major change in the tectonic setting of continental growth at the end of the Archean. Gondwana Res 23:394–402
Corvino AF, Henjes-Kunst F (2007) A record of 2.5 and 1.1 billion year old crust in the Lawrence Hills, Antarctic southern Prince Charles Mountains. Terra Antartica 14:13–30
Cui M-L, Zhang L-C, Wu H-Y, Xu Y-X, Li W-J (2014) Timing and tectonic setting of the Sijiaying banded iron deposit in the eastern Hebei province, North China Craton: constraints from geochemistry and SIMS zircon U-Pb dating. J Asian Earth Sci 94:240–251
Cui P-L, Sun J-G, Sha D-M, Wang X-J, Zhang P, Gu A-L, Wang Z-Y (2013) Oldest zircon xenocryst (4.17 Ga) from the North China Craton. Int Geol Rev 55:1902–1908
Dai Y-P, Zhang L-C, Wang C-L, Liu L, Cui M-L, Zhu M-T, Xiang P (2012) Genetic type, formation age and tectonic setting of the Waitoushan banded iron formation, Benxi, Liaoning Province. Acta Petrologica Sinica 28:3574–3594 (in Chinese with English abstract)
Dai Y-P, Zhang L-C, Zhu M-T, Wang C-L, Liu L (2013) Chentaigou BIF-type iron deposit, Anshan area associated with Archean crustal growth: constraints from zircon U-Pb dating and Hf isotope. Acta Petrologica Sinica 29:2537–2550 (in Chinese with English abstract)
Davies GF (1995) Punctuated tectonic evolution of the earth. EarthPlanet Sci Lett 136:363–379
Deng H, Kusky T, Polat A, Wang J-P, Wang L, Fu J-M, Wang Z-S, Yuan Y (2014) Geochronology, mantle source composition and geodynamic constraints on the origin of Neoarchean mafic dikes in the Zanhuang Complex, Central Orogenic Belt, North China Craton. Lithos 205:359–378
Dey S, Pandey UK, Rai AK, Chaki A (2012) Geochemical and Nd isotope constraints on petrogenesis of granitoids from NW part of the eastern Dharwar craton: possible implications for late Archaean crustal accretion. J Asian Earth Sci 45:40–56
Diwu C-R, Sun Y, Lin C-L, Liu X-M, Wang H-L (2007) Zircon U-Pb ages and Hf isotopes and their geological significance of Yiyang TTG gneisses from Henan Province, China. Acta Petrologica Sinica 23:253–262 (in Chinese with English abstract)
Diwu C-R, Sun Y, Yuan H-L, Wang H-L, Zhong X-P, Liu X-M (2008) U-Pb ages and Hf isotopes for detrital zircons from quartzite in the Paleoproterozoic Songshan Group on the southwestern margin of the North China Craton. Chin Sci Bull 53:2828–2839
Diwu C-R, Sun Y, Dong Z-C, Wang H-L, Chen D-L, Chen L, Zhang H (2010a) In situ geochronology of Hadean zircon xenocryst (4.1 ~ 3.9 Ga) west of the Northern Qinling Orogenic Belt. Acta Petrologica Sinica 26:1171–1174 (in Chinese with English abstract)
Diwu C-R, Sun Y, Lin C-L, Wang H-L (2010b) LA-(MC)-ICP-MS U-Pb zircon geochronology and Lu-Hf isotope compositions of the Taihua complex on the southern margin of the North China Craton. Chin Sci Bull 55:2557–2571
Diwu C-R, Sun Y, Guo A-L, Wang H-L, Liu X-M (2011) Crustal growth in the North China Craton at ~2.5 Ga: evidence from in situ zircon U-Pb ages, Hf isotopes and whole-rock geochemistry of the Dengfeng Complex. Gondwana Res 20:149–170
Diwu C-R, Sun Y, Zhang H, Wang Q, Guo A-L, Fan L-G (2012) Episodic tectonothermal events of the western North China Craton and North Qinling Orogenic Belt in central China: constraints from detrital zircon U-Pb ages. J Asian Earth Sci 47:107–122
Diwu C-R, Sun Y, Wilde SA, Wang H-L, Dong Z-C, Zhang H, Wang Q (2013) New evidence for ~4.45 Ga terrestrial crust from zircon xenocrysts in Ordovician ignimbrite in the North Qinling Orogenic Belt, China. Gondwana Research 23:1484–1490
Diwu C-R, Sun Y, Zhao Y, Lai S-C (2014) Early Paleoproterozoic (2.45-2.20 Ga) magmatic activity during the period of global magmatic shutdown: Implications for the crustal evolution of the southern North China Craton. Precambr Res (in press)

Dong X-J, Xu Z-Y, Liu Z-H, Sha Q (2012a) 2.7 Ga granitic gneiss in the Northern Foot of Daqingshan Mountain, Central Inner Mongolia, and its geological implications. Earth Sci 37(Suppl.):45–52 (in Chinese with English abstract)
Dong X-J, Xu Z-Y, Liu Z-H, Sha Q (2012b) Zircon U-Pb geochronology of Archean high-grade metamorphic rocks from Xi Ulanbulang area, central Inner Mongolia. Sci China Ser D-Earth Sci 55:204–212
Dong C-Y, Wan Y-S, Zhang Y-H, Yang Z-Q, Liu D-Y (2013) 3.3-3.1 Ga magmatism recorded in an outcrop of the Dongshan Complex in the Anshan area, North China Craton: evidence from geochemistry and SHRIMP zircon dating. Acta Petrologica Sinica 29:414–420 (in Chinese with English abstract)
Dostal J, Mueller WU (2013) Deciphering an Archean mantle plume: Abitibi greenstone belt, Canada. Gondwana Res 23:493–505
Drüppel K, McCready AJ, Stumpfl EF (2009) High-K granites of the Rum Jungle Complex, N-Australia: insights into the Late Archean crustal evolution of the North Australian Craton. Lithos 111:203–219
Du L-L, Zhuang YX, Yang CH, Wan Y-S, Wang X-S, Wang S-J, Zhang L-F (2003) Characters of zircons in the Mengjiatun formation in Xintai of Shandong and their chronological significance. Acta Geol Sinica 77:359–366 (in English with Chinese abstract)
Du L-L, Zhuang Y-X, Yang C-H, Wan Y-S, Wang X-S (2005) SHRIMP U-Pb zircon chronology of fine-grained amphibolite in the Mengjiatun area, western Shandong. Acta Geoscientica Sinica 26:429–434 (in English with Chinese abstract)
Du L-L, Yang C-H, Zhuang Y-X, Wei R-Z, Wan Y-S, Ren L-D, Hou K-J (2010) Hf isotopic compositions of zircons from 2.7 Ga metasedimentary rocks and biotite-plagioclase gneiss in the Mengjiatun Formation Complex, western Shandong Province. Acta Geol Sinica 84:991–1001 (in Chinese with English abstract)
Duclaux G, Rolland Y, Ruffet G, Ménot RP, Guillot S, Peucat JJ, Fanning M, Rey P, Pêcher A (2008) Superimposed Neoarchaean and Paleoproterozoic tectonics in the Terre Adélie Craton (East Antarctica): Evidence from Th-U-Pb ages on monazite and $^{40}Ar/^{39}Ar$ ages. Precambr Res 167:316–338
Gao L-Z, Zhao T, Wan Y-S, Zhao X, Ma Y-S, Yang S-Z (2006) Report on 3.4 Ga SHRIMP zircon age from the Yuntaishan Geopark in Jiaozuo, Henan Province. Acta Geologica Sinica 80:52–57
Gao S, Rudnick RL, Yuan H-L, Liu X-M, Liu Y-S, Xu W-L, Ling W-L, Ayers J, Wang X-C, Wang Q-H (2004) Recycling lower continental crust in the North China craton. Nature 432:892–897
Garde AA, Hamilton MA, Chadwick B, Grocott J, McCaffrey KJW (2002) The Ketilidian orogen of South Greenland: geochronology, tectonics, magmatism, and fore-arc accretion during Paleoproterozoic oblique convergence. Can J Earth Sci 39:765–793
Geng Y-S, Wan Y-S, Shen Q-H (2002) Early Precambrian basic volcanism and crustal growth in the North China Craton. Acta Geol Sinica 76:199–202 (in Chinese with English abstract)
Geng Y-S, Liu F-L, Yang C-H (2006) Magmatic event at the end of the Archean in eastern Hebei Province and its geological implication. Acta Geol Sinica 80:819–833
Geng Y-S, Shen Q-H, Ren L-D (2010) Late Neoarchean to Paleoproterozoic magmatic events and tectonothermal systems in the North China Craton. Acta Petrologica Sinica 26:1945–1966 (in Chinese with English abstract)
Geng Y-S, Du L-L, Ren L-D (2012) Growth and reworking of the early Precambrian continental crust in the North China Craton: constraints from zircon Hf isotopes. Gondwana Res 21:517–529
Grant ML, Wilde SA, Wu F-Y, Yang J-H (2009) The application of zircon cathodoluminescence imaging, Th-U-Pb chemistry and U-Pb ages in interpreting discrete magmatic and high-grade metamorphic events in the North China Craton at the Archean/Proterozoic boundary. Chem Geol 261:155–171
Griffin WL, Pearson NJ, Belousova E, Jackson SE, Achterbergh EV, O'Reilly SY, Shee SR (2000) The Hf isotope composition of cratonic mantle: LAM-MC-ICPMS analysis of zircon megacrysts in kimberlites. Geochimica Cosmochimica Acta 64:133–147

Guan H, Sun M, Wilde SA, Zhou X-H, Zhai M-G (2002) SHRIMP U-Pb zircon geochronology of the Fuping Complex: implications for formation and assembly of the North China Craton. Precambr Res 113:1–18

Guo J-H, Sun M, Chen F-K, Zhai M-G (2005) Sm-Nd and SHRIMP zircon geochronology of high-pressure granulites in the Sanggan area, North China Craton: timing of Paleoproterozoic continental collision. J Asian Earth Sci 24:629–642

Guo L-S, Liu S-W, Liu Y-L, Tian W, Yu S-Q, Li Q-G, Lü Y-J (2008) Zircon Hf isotopic features of TTG gneisses and formation environment of Precambrian Sushui complex in Zhongtiao mountains. Acta Petrologica Sinica 24:139–148 (in Chinese with English abstract)

Guo R-R, Liu S-W, Santosh M, Li Q-G, Bai X, Wang W (2013) Geochemistry, zircon U-Pb geochronology and Lu-Hf isotopes of metavolcanics from eastern Hebei reveal Neoarchean subduction tectonics in the North China Craton. Gondwana Res 24:664–686

Fan H-R, Yang K-F, Hu F-F, Wang K-Y, Zhai M-G (2010) Zircon geochronology of basement rocks from the Bayan Obo area, Inner Mongolia, and tectonic implications. Acta Petrologica Sinica 26:1342–1350 (in Chinese with English abstract)

Frost CD, Bell JM, Frost BR, Chamberlain KR (2001) Crustal growth by magmatic underplating: isotopic evidence from the northern Sherman batholith. Geology 29:515–518

Halla J, Hunen JV, Heilimo E, Hölttäd P (2009) Geochemical and numerical constraints on Neoarchean plate tectonics. Precambr Res 174:155–162

Han B-F, Xu Z, Ren R, Li L-L, Yang J-H, Yang Y-H (2012) Crustal growth and intracrustal recycling in the middle segment of the Trans-North China Orogen, North China Craton: a case study of the Fuping Complex. Geol Mag 149:729–742

Han C-M, Xiao W-J, Su B-X, Chen Z-L, Zhang X-H, Ao S-J, Zhang J-E, Zhang Z-Y, Wan B, Song D-F, Wang Z-M (2014a) Neoarchean Algoma-type banded iron formations from Eastern Hebei, North China Craton: SHRIMP U-Pb age, origin and tectonic setting. Precambr Res 251:212–231

Han C-M, Xiao W-J, Su B-X, Sakyi PA, Chen Z-L, Zhang X-H, Ao S-J, Zhang J, Wan B, Zhang Z-Y, Wang Z-M, Ding J (2014b) Formation age and genesis of the Gongchangling Neoarchean banded iron deposit in eastern Liaoning Province: constraints from geochemistry and SHRIMP zircon U-Pb dating. Precambr Res 254:306–322

He Y-H, Sun Y, Chen L, Li H-P, Yuan H-L, Liu X-M (2005) Zircon U-Pb chronology of Longshan complex by LA-ICP-MS and its geological significance. Acta Petrologica Sinica 21:125–134 (in Chinese with English abstract)

Hildreth W, Moorbath S (1988) Crustal contributions to arc magmatism in the Andes of Central Chile. Contrib Miner Petrol 98:455–489

Hu J-M, Liu X-S, Li Z-H, Zhao Y, Zhang S-H, Liu X-C, Qu H-J, Chen H (2012) SHRIMP U-Pb zircon dating of the Ordos Basin basement and its tectonic significance. Chin Sci Bull 58:118–127

Huang D-M, Zhang D-H, Wang S-Y, Zhang Y-X, Dong C-Y, Liu D-Y, Wan Y-S (2012a) 2.3 Gamagmatism and 1.94 Ga metamorphism in the Xiatang Area, southern margin of the North China Craton. Geol Rev 58:565–573 (in Chinese with English abstract)

Huang X-L, Niu Y-L, Xu Y-G, Yang Q-J, Zhong J-W (2010) Geochemistry of TTG and TTG-like gneisses from Lushan-Taihua complex in the southern North China Craton: implications for late Archean crustal accretion. Precambr Res 182:43–56

Huang X-L, Wilde SA, Yang QJ, Zhong JW (2012b) Geochronology and petrogenesis of gray gneisses from the Taihua Complex at Xiong'er in the southern segment of the Trans-North China Orogen: implications for tectonic transformation in the Early Paleoproterozoic. Lithos 134–135:236–252

Huang X-L, Wilde SA, Zhong J-W (2013) Episodic crustal growth in the southern segment of the Trans-North China Orogen across the Archean-Proterozoicboundary. Precambr Res 233:337–357

Iizuka T, Komiya T, Johnson SP, Kon Y, Maruyama S, Hirata T (2009) Reworking of Hadean crust in the Acasta gneisses, northwestern Canada: evidence from in-situ Lu-Hf isotope analysis of zircon. Chem Geol 259:230–239

Jahn B-M, Auvray B, Cornichet J, Bai Y-L, Shen Q-H, Liu D-Y (1987) 3.5 Ga Old amphibolites from eastern Hebei province, China: field occurrence, petrography, Sm-Nd isochron age and REE chemistry. Precambr Res 34:311–346

Jahn B-M, Auvray B, Shen Q-H, Liu D-Y, Zhang Z-Q, Dong Y-J, Ye X-J, Zhang Q-Z, Cornichet J, Mace J (1988) Archean crustal evolution in China: the Taishan Complex, and evidence for juvenile crustal addition from long-term depleted mantle. Precambr Res 38:381–403

Jahn B-M, Zhou X-H, Li JL (1990) Formation and tectonic evolution of Southeastern China and Taiwan: isotopic and geochemical constraints. Tectonophysics 183:145–160

Jahn B-M, Liu D-Y, Wan Y-S, Song B, Wu J-S (2008) Archean crustal evolution of the Jiaodong peninsula, China, as revealed by zircon SHRIMP geochronology, elemental and Nd-isotope geochemistry. Am J Sci 308:232–269

Jayananda M, Moyen FF, Martin H, Peucat JJ, Auvray B, Mahabaleswar B (2000) Late Archaean (2550-2520 Ma) juvenile magmatism in the Eastern Dharwar Craton, Southern India: constraints from geochronology Nd-Sr isotopes and whole rock geochemistry. Precambr Res 99:225–254

Ji Z-Y (1993) New data on isotope age of the Proterozoic metamorphic rocks from northern Jiaodong and its geological significance.Shandong. Geology 9:40–51 (in Chinese with English abstract)

Jian P, Kröner A, Windley BF, Zhang Q, Zhang W, Zhang L-Q (2012) Episodic mantle melting-crustal reworking in the late Neoarchean of the northwestern North China Craton: Zircon ages of magmatic and metamorphic rocks from the Yinshan Block. Precambr Res 222–223:230–254

Jiang N, Guo J-H, Zhai M-G, Zhang S-Q (2010) ~2.7 Ga crust growth in the North China craton. Precambr Res 179:37–49

Jiang Z-S, Wang G-D, Xiao L-L, Diwu C-R, Lu J-S, Wu C-M (2011) Paleoproterozoic metamorphic P-T-t path and tectonic significance of the Luoning metamorphic complex at the southern terminal of the Trans-North China Orogen, Henan Province. Acta Petrologica Sinica 27:3701–3717 (in Chinese with English abstract)

Jin K, Xu W-L, Wang Q-H, Gao S, Liu X-C (2003) Formation time and sources of the Huaiguang "Migmatitic Granodiorite" in Bengbu, Anhui Provinece: evidence from SHRIMP zircon U-Pb geochronology. Acta Geoscientia Sinica 24:331–335 (in Chinese with English abstract)

Kinny PD (1986) 3820 Ma zircons from a tonalitic Amitsoq gneiss in the Godthab district of southern West Greenland. Earth Planet Sci Lett 79:337–347

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

Kröner A, Cui W-Y, Wang S-Q (1998) Single zircon ages from high-grade rocks of the Jianping Complex, Liaoning Province, NE China. J Asian Earth Sci 16:519–532

Kröner A, Wilde SA, O'Brien PJ, Li J-H, Passchier CW, Walte NP, Liu D-Y (2005a) Field relationships, geochemistry, zircon ages and evolution of a late Archaean to Palaeoproterozoic lower crustal section in the Hengshan terrain of northern China. Acta Geologica Sinica 79: 605–629

Kröner A, Wilde SA, Li J-H, Wang K-Y (2005b) Age and evolution of a late Archean to Paleoproterozoic upper to lower crustal section in the Wutaishan/Hengshan/Fuping terrain of northern China. J Asian Earth Sci 24:577–595

Kröner A, Wilde SA, Zhao G-C, O'Brien PJ, Sun M, Liu D-Y, Wan Y-S, Liu S-W, Guo J-H (2006) Zircon geochronology and metamorphic evolution of mafic dykes in the Hengshan Complex of northern China: evidence for late Palaeoprotero-zoic extension and subsequent high-pressure metamorphism in the North ChinaCraton. Precambr Res 146:45–67

Kröner A, Hoffmann JE, Xie H, Münker C, Hegner E, Wan Y, Hofmann A, Liu D, Yang J (2014) Generation of early Archaean grey gneisses through crustal melting of older crust in the eastern Kaapvaal craton, southern Africa. Precambr Res 255:833–846

Kusky TM, Li J-H (2003) Paleoproterozoic tectonic evolution of the North China Craton. J Asian Earth Sci 22:383–397

Kusky TM, Li J-H, Santosh M (2007) The Paleoproterozoic North Hebei Orogen: North China Craton's collisional suture with the Columbia supercontinent. Gondwana Res 12:4–28

Li B, Jin W, Zhang J-H, Wang Y-F, Cai L-B, Wang Q-L (2013) Composition and structural characteristics of Archean granite in Chentaigou area of Anshan. Global Geol 32:191–199 (in Chinese with English abstract)

Li C-D, Zhang F-Q, Miao L-C, Du Y-L, Hua Y-Q, Xu Y-W, Kang S-M (2009) Zircon SHRIMP U-Pb geochronology of the Zhangsangou Formation Complex in the northeastern margin of North China Craton and its geological significance. Acta Geol Sinica 83:642–650 (in Chinese with English abstract)

Li C-J, Bao Z-W, Zhao Z-H, Qiao Y-L (2012) Zircon U-Pb age and Hf isotopic compositions of the granitic gneisses from the Sanggan complex in the Zhangjiakouk area: constraints on the early evolution of North China Craton. Acta Petrologica Sinica 28:1057–1072 (in Chinese with English abstract)

Li J-H, Qian X-L, Hou G-T, Liu S-W, Chen J (2000) Late Paleoproterozoic to early Mesoproterozoic tectonic framework and major tectono-thermal episodes of north China: new interpretation of "Luliang orogeny". Earth Sci 25:15–20 (in Chinese with English abstract)

Li J-H, Kusky TM, Huang X-N (2002) Archean podiform chromitites and mantle tectonites in ophiolitic mélange, North China Craton: a record of early oceanic mantle processes. GSA Today 12:4–11

Li J-H, Yang C-H, Du L-L, Wan Y-S, Liu Z-X (2005) SHRIMP U-Pb geochronology evidence for the formation time of the Wanzi Group at Pingshan County, Hebei Province. Geol Rev 51:201–207 (in Chinese with English abstract)

Li S-X, Ji S-K, Ma Z-H, Huo G-P, Tian Y-Q, Yang W-K (1986) Geology of metasedimentary iron deposit in Wutaishan. Jilin Science and Technology Press, Changchun, pp 1–299 (in Chinese)

Li S-X, Liu X-S, Zhang L-Q (1987) Granite-greenstone belt in Sheerteng area, Inner Mongolia, China. J Changchun Univ Geol 17:81–102 (in Chinese with English abstract)

Li S-Z, Zhao G-C, Wilde SA, Zhang J, Sun M, Zhang G-W, Dai L-M (2010a) Deformation history of the Hengshan-Wutai-Fuping Complexes: implications for the evolution of the Trans-North China Orogen. Gondwana Res 18:611–631

Li T-S, Zhai M-G, Peng P, Chen L, Guo J-H (2010b) Ca. 2.5 billion year old coeval ultramafic-mafic and syenitic dykes in Eastern Hebei: implicaitons for cratonization of the North China Craton. Precambr Res 180:143–155

Liaoning Bureau of Geology and Mineral Resources Exploration (LBGMRE) (1975a) Geological map of Liaoyang sheet (1:200000)

Liaoning Bureau of Geology and Mineral Resources Exploration (LBGMRE) (1975b) Geological map of Yingkou sheet (1:200000)

Liaoning Bureau of Geology and Mineral Resources Exploration (LBGMRE) (1976) Geological map of Shenyang sheet (1:200000)

Liu C-H, Zhao G-C, Sun M, Zhang J, Yin C-Q (2012a) U-Pb geochronology and Hf isotope geochemistry of detrital zircons from the Zhongtiao Complex: constraints on the tectonic evolution of the Trans-North China Orogen. Precambr Res 222–223:159–172

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

Liu D-Y, Wilde SA, Wan Y-S, Wu J-S, Zhou H-Y, Dong C-Y, Yin X-Y (2008) New U-Pb and Hf isotopic data confirm Anshan as the oldest preserved segment of the North China Craton. Am J Sci 308:200–231

Liu D-Y, Wilde SA, Wan Y-S, Wang S-Y, Valley JW, Kita N, Dong C-Y, Xie H-Q, Yang C-X, Zhang Y-X, Gao L-Z (2009a) Late Mesoarchean-early Neoarchean tectonothermal events at the southern margin of the North China Craton: evidence of multiple events from SHRIMP U-Pb dating and hafnium isotope analysis of zircons from metamorphosed supracrustal rocks and tonalites. Chem Geol 261:140–154

Liu F, Guo J-H, Lu X-P, Diwu C-Y (2009b) Crustal growth at ~2.5 Ga in the North China Craton: evidence from whole-rock Nd and zircon Hf isotopes in the Huai'an gneiss terrane. Chin Sci Bull 54:4704–4713

Liu J-H, Liu F-L, Liu P-H, Wang F, Ding Z-J (2011a) Polyphase magmatic and metamorphic events from early Precambrian metamorphic basement in Jiaobei area: evidence from the Zircon U-Pb dating of TTG and granitic gneisses. Acta Petrologica Sinica 27:943–960 (in Chinese with English abstract)

Liu J-H, Liu F-L, Ding Z-J, Liu P-H, Wang F (2012b) The zircon Hf isotope characteristics of ~2.5 Ga magmatic event and implication for the crustal evolution in the Jiaobei terrane, China. Acta Petrologica Sinica 28:2697–2704

Liu J-H, Liu F-L, Ding Z-J, Liu C-H, Yang H, Liu P-H, Wang F, Meng E (2013a) The growth, reworking and metamorphism of early Precambrian crust in the Jiaobei terrane, the North China Craton: constraints from U-Th-Pb and Lu-Hf isotopics ystematics, and REE concentrations of zircon from Archean granitoid gneisses. Precambr Res 224:287–303

Liu L, Zhang L-C, Dai Y-P, Wang C-L, Li Z-Q (2012) Formation age, geochemical signatures and geological significance of the Sanheming BIF-type iron deposit in the Guyang greenstone belt, Inner Mongolia: Acta Petrologica Sinica 28:3623–3637 (in Chinese with English abstract)

Liu L, Zhang L-C, Dai Y-P (2014) Formation age and genesis of the banded iron formations from the Guyang Greenstone Belt, Western North China Craton. Ore Geol Rev 63:388–404

Liu S-J, Wan Y-S, Sun H-Y, Nutman A, Xie H-Q, Dong C-Y, Ma M-Z, Du L-L, Liu D-Y, Jhan B-M (2013b) Paleo- to Eoarchean crustal materials in eastern Hebei, North China Craton: new evidence from SHRIMP U-Pb dating and in-situ Hf isotopic studies in detrital zircons of supracrustal rocks. J Asian Earth Sci 78:4–17

Liu S-W, Pan Y, Li J-H, Li G-G, Zhang J (2002) Geological and isotopic geochemical constraints on the evolution of the Fuping Complex, North China Craton. Precambr Res 117:41–56

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

Liu S-W, Lü Y-J, Feng Y-G, Zhang C, Tian W, Yan Q-R, Liu X-M (2007) Geology and zircon U-Pb isotopic chronology of Dantazi Complex, northern Hebei Province. Geol J China Univ 13:484–497 (in Chinese with English abstract)

Liu S-W, Santosh M, Wang W, Bai X, Yang P-T (2011b) Zircon U-Pb chronology of the Jianping Complex: implications for the Precambrian crustal evolution history of the northern margin of North China Craton. Gondwana Res 20:48–63

Liu S-W, Lü Y-J, Wang W, Yang P-T, Bai X, Feng Y-G (2011c) Petrogenesis of the Neoarchean granitoid gneisses in northern Hebei Province. Acta Petrologica Sinica 27:909–921 (in Chinese with English abstract)

Liu X-C, Zhao Y, Song B, Liu J, Cui J-J (2009c) SHRIMP U-Pb zircon geochronology of high-grade rocks and charnockites from the eastern Amery Ice Shelf and southwestern Prydz Bay, East Antarctica: constraints on Late Mesoproterozoic to Cambrian tectonothermal events related to supercontinent assembly. Gondwana Res 16:342–361

Liu Y-S, Gao S, Yuan H-L, Zhou L, Liu X-M, Wang X-C, Hu Z-C, Wang L-S (2004b) U-Pb zircon ages and Nd Sr, and Pb isotopes of lower crustal xenoliths from North China Craton: insights on evolution of lower continental crust. Chem Geol 211:87–109

Lu L-Z, Xu X-C, Liu F-L (1996) Early Precambrian Khondalite series of North China. Changchun Publishing House, Changchun, pp 1–272 (in Chinese)

Lu S-N, Chen Z-H, Xiang Z-Q (2008) The world geopark of Taishan: geochronological framework of Ancient Intrusives. Geological Publishing House, Beijng, pp 1–90 (in Chinese)

Lü B, Zhai M-G, Li T-S, Peng P (2012) Zircon U-Pb ages and geochemistry of the Qinglong volcano-sedimentary rock series in Eastern Hebei: implication for ~2500 Ma intra-continental rifting in the North China Craton. Precambr Res 208–211:145–160

Ma M-Z, Wan Y-S, Santosh M, Xu Z-Y, Xie H-Q, Dong C-Y, Liu D-Y (2012) Decoding multiple tectonothermal events in zircons from single rock samples: SHRIMP zircon U-Pb data from the late Neoarchean rocks of Daqingshan, North China Craton. Gondwana Res 22:810–827

Ma M-Z, Xu Z-Y, Zhang L-C, Dong C-Y, Liu S-J, Liu D-Y, Wan Y-S (2013a) SHRIMP dating and Hf isotope analysis of zircons from the early Precambrian basement in the Xi Ulanbulang area, Wuchuan, Inner Mongolia. Acta Petrologica Sinica 29:501–516 (in Chinese with English abstract)

Ma X-D, Fan H-R, Santosh M, Guo J-H (2013b) Geochemistry and zircon U-Pb chronology of charnockites in the Yinshan Block, North China Craton: tectonic evolution involving Neoarchaean ridge subduction. Int Geol Rev 55:1688–1704

Ma X-D, Guo J-H, Liu F, Qian Q, Fan H-R (2013c) Zircon U-Pb ages, trace elements and Nd-Hf isotopic geochemistry of Guyang sanukitoids and related rocks: implications for the Archean crustal evolution of the Yinshan Block, North China Craton. Precambr Res 230:61–78

Ma X-D, Fan H-R, Santosh M, Guo J-H (2014a) Chronology and geochemistry of Neoarchean BIF-type iron deposits in the Yinshan Block, North China Craton: implications for oceanic ridge subduction. Ore Geol Rev 63:405–417

Ma X-D, Fan H-R, Santosh M, Liu X, Guo J-H (2014b) Origin of sanukitoid and hornblendite enclaves in the Dajitu pluton from the Yinshan Block, North China Craton: product of Neoarchaean ridge subduction? Int Geol Rev. doi:10.1080/00206814.2014.929055

Manikyamba C, Kerrich R (2012) Eastern Dharwar Craton, India: Continental lithosphere growth by accretion of diverse plume and arc terranes. Geosci Front 3:225–240

McCready AJ, Stumpfl EF, Lally J, Ahmad M, Gee RD (2004) Polymetallic mineralization at the Browns deposit, Rum Jungle Mineral Field, Northern Territory, Australia. Econ Geol 99:257–277

Mei H-L (1991) P-T path of basic granulite in the Zhulagou complex, Inner Mongolia, China. Acta Petrologica et Minerlogica 10:133–142 (in Chinese with English abstract)

Miao P-S (2003) Tectonic style of the high-grade metamorphic terrain of Hengshan in the North China Craton. Tianjing Publishing press, Tianjing, pp 1–86 (in Chinese with English abstract)

Mohan MR, Piercey SJ, Kamber BS, Sarma DS (2013) Subduction related tectonic evolution of the Neoarchean eastern Dharwar Craton, southern India: new geochemical and isotopic constraints. Precambr Res 227:204–226

Moyen JF (2011) The composite Archaean grey gneisses: petrological significance, and evidence for a non-unique tectonic setting for Archaean crustal growth. Lithos 123:21–36

Moyen JF, Martin H, Jayananda M, Auvray B (2003) Late Archaean granites: a typology based on the Dharwar Craton (India). Precambr Res 127:103–123

North China Oilfield Company of PetroChina (NCOCP) (2012) Introduction on Drilling Cores Relating to Precambrian Basement in the Central Hebei Basin. Unpublished Ms, pp 1–18

Nutman AP, McGregor VR, Friend CRL, Bennett VC, Kinny PD (1996) The Itsaq Gneiss Complex of southern West Greenland: the world's most extensive record of early crustal evolution (3900-3600 Ma). Precambr Res 78:1–39

Nutman AP, Wan Y-S, Liu D-Y (2009) Integrated field geological and zircon morphology evidence for ca. 3.8 Ga rocks at Anshan: Comment on "Zircon U-Pb and Hf isotopic constraints on the Early Archean crustal evolution in Anshan of the North China Craton" by Wu et al. [Precambr Res 167 (2008) 339–362]. Precambr Res 172:357–360

Nutman AP, Wan Y-S, Du L-L, Friend CRL, Dong C-Y, Xie H-Q, Wang W, Sun H-Y, Liu D-Y (2011) Multistage late Neoarchaean crustal evolution of the North China Craton, eastern Hebei. Precambr Res 189:43–65

Nutman AP, Bennett VC, Friend CRL, Hidaka H, Yi K, Lee SR, Kamiichi T (2013) The Itsaq gneiss complex of Greenland: episodic 3900 to 3600 Ma juvenile crust formation and recycling in the 3600 to 3600 Ma Isukasian orogeny. Am J Sci 313:877–911

Nutman AP, Maciejowski R, Wan Y-S (2014) Protoliths of enigmatic Archaean gneisses established from zircon inclusion studies: case study of the Caozhuang quartzite, E. Hebei, China. Geosci Front 5:445–455

O'Neil J, Maurice C, Stevenson RK, Larocque J, Cloquet C, David J, Francis D (2007) The geology of the 3.8 Ga Nuvvuagittuq (Porpoise Cove) greenstone belt, northeastern Superior Province, Canada. In: van Kranendonk MJ, Smithies RH, Bennett VC (eds) Earth's oldest rocks, developments in Precambrian Geology, vol 15. pp 219–250

Pei F-P, Xu W-L, Yang D-B, Zhao Q-G, Liu X-M, Hu Z-C (2007) Zircon U-Pb geochronology of basement metamorphic rocks in the Songliao Basin. Chin Sci Bull 52:942–948

Peng M-S, Zhang P, Yang H-Z, Wang X-J, Qiao S-Y (2013a) Geochemical characteristics and geological significance of iron deposit in Nanfen, Liaoning. Sci Technol Rep 31:33–37 (in Chinese with English abstract)

Peng P, Li Y, Liu F, Wang F (2012) Geological relation of late Archean lithologic units in northwest Hebei, North China Craton: implication for building of early continental crust. Acta Petrologica Sinica 28:3531–3544 (in Chinese with English abstract)

Peng T-P, Wilde SA, Fan W-M, Peng B-X (2013b) Late Neoarchean potassic high Ba-Sr granites in the Taishan granite-greenstone terrane: petrogenesis and implications for continental crustal evolution. Chem Geol 344:23–41

Polat A, Li J, Fryer B, Kusky T, Gagnon J, Zhang S (2006a) Geochemical characteristics of the Neoarchean (2800-2700 Ma) Taishan greenstone belt, North China Craton: Evidence for plume-craton interaction. Chem Geol 230:60–87

Polat A, Herzberg C, Münker C, Rodgers R, Kusky T, Li J, Fryer B, Delaney J (2006b) Geochemical and petrological evidence for a suprasubduction zone origin of Neoarchean (ca. 2.5 Ga) peridotites, central osorgenic belt, North China Craton. Bull Geol Soc Am 118:771–784

Qian J-H, Wei C-J, Zhou X-W, Zhang Y-H (2013) Metamorphic P-T paths and new zircon U-Pb age data for garnet-mica schist from the Wutai Group, North China Craton. Precambr Res 233:282–296

Qian X-L, Cui W-Y, Wang S-Q, Wang G-Y (1985) Geology of Precambrian iron ores in eastern Hebei Province, China. Hebei Science and Tecnology Press, Shijiazhuang, pp 1–273 (in Chinese)

Qian X-L, Wang R-M et al. (1994) Geological evolution of the granulite terrain in north part of the North China Craton. Seismological Press, Beijing, pp 1–234 (in Chinese)

Ren K-X, Yan G-H, Cai J-H, Zou T-R, Mu B-L, Li F-T (2013) SHRIMP U-Pb zircon age and its implications of quartz syenite in Hadamengou, Inner Mongolia. Adv Geosci 3:42–47 (in Chinese with English abstract)

Ren R, Han B-F, Zhang Z-C, Li J-F, Yang Y-H, Zhang Y-B (2011) Zircon U-Pb and Hf isotopic studies of basement gneiss and overlying Meso-Neoproterozoic sedimentary rocks from the Changping area, Beijing, and their geological implications. Acta Petrologica Sinica 27:1721–1745 (in Chinese with English abstract)

Ren Y-W (2010) The study of granite-greenstone belt in Xihongshan Area, Inner Mongolia. Ms. Thesis, Jilin University, pp 1–64 (in Chinese with English abstract)

Rey PF, Philippot P, Thebaud N (2003) Contribution of mantle plumes, crustal thickening and greenstone blanketing to the 2.75-2.65 Ga global crisis. Precambr Res 127:43–60

Shan H-X, Zhai M-G, Wang F, Zhou Y-Y, Santosh M, Zhu X-Y, Zhang H-F, Wang W (2015) Zircon U-Pb ages, geochemistry, and Nd-Hf isotopes of the TTG gneisses from the Jiaobei terrane: Implications for Neoarchean crustal evolution in the North China Craton. J Asian Earth Sci (in press)

Shen B-F, Luo H, Li S-B, Li J-J, Peng X-L, Hu X-D, Mao D-B, Liang R-X (1994a) Geology and metallization of Archean Greenstone Belt in North China Plateform. Geological Publishing House, Bejing, pp 1–202 (in Chinese with English abstract)

Shen B-F, Luo H, Han G-G, Dai X-Y, Jin W-S, Hu X-D, Li S-B, Bi S-Y (1994b) Archean geolgy and metallization in northern Liaoning Province and southern Jilin Province. Geological Publishing House, Beijing, pp 1–255 (in Chinese with English abstract)

Shen Q-H, Zhang Y-F, Gao J-F, Wang P (1990) Study on Archaean metamorphic rocks in midsouthern Nei Mongol of China. In: Bulletin of Institute of Geology of Chinese Academy of Geological Scienes. Geological Publishing House, Beijing, pp 1–192 (in Chinese)

Shen Q-H, Xu H-F, Zhang Z-Q, Gao J-F, Wu J-S, Ji C-L (1992) Early Precambrain granulites of China. Geological Publishing House, Beijing, pp 1–237 (in Chinese)

Shen Q-H, Shen K, Geng Y-S, Xu H-F (2000) Compositions and geological evolution of Yishui Complex, Shandong. Geological Publishing House, Bejing, pp 1–179 (in Chinese)

Shen Q-H, Song B, Xu H-F, Geng Y-S, Shen K (2004) Emplacement and metamorphism ages of the Caiyu and Dashan igneous bodies, Yishui County, Shandong Province: zircon SHRIMP chronology. Geol Rev 50:275–284 (in Chinese with English abstract)

Shen Q-H, Geng Y-S, Song B, Wan Y-S (2005) New information from the surface outcrops and deep crust of Archean rocks of the North China and Yangtze Blocks, and Qinling-Dabie Orogenic Belt. Acta Geol Sinica 79:616–627 (in Chinese with English abstract)
Shen Q-H, Zhao Z-R, Song B, Song H-X (2007) Geology, petrochemistry and SHRIMP zircon U-Pb dating of the Mashan and Xueshan granitoids in Yishui County, Shandong Province. Geol Rev 53:180–186 (in Chinese with English abstract)
Shi Y-R, Wilde SA, Zhao X-T, Ma Y-S, Du L-L, Liu D-Y (2012) Late Neoarchean magmatic and subsequent metamorphic events in the northern North China Craton: SHRIMP zircon dating and Hf isotopes of Archean rocks from Yunmengshan Geopark, Miyun, Beijing. Gondwana Res 21:785–800
Song B, Nutman AP, Liu D-Y, Wu J-S (1996) 3800 to 2500 Ma crustal evolution in the Anshan area of Liaoning Province, northeastern China. Precambr Res 78:79–94
Song H-X, Zhao Z-R, Shen Q-H, Song B (2009) Study on petrochemistry and hafnium isotope in Yishui Complex, Shandong Province. Acta Petrologica Sinica 25:1872–1882 (in Chinese with English abstract)
Söderlund U, Patchett PJ, Vervoort JD, Isachsen CE (2004) The ^{176}Lu decay constant determined by Lu-Hf and U-Pb isotope systematics of Precambrian mafic intrusions. Earth Planet Sci Lett 219:311–324
Sun D-Z et al (1984) The early Precambrian geology of eastern Hebei. Tiangjing Science and Technology Press, Tianjing, pp 1–273 (in Chinese with English abstract)
Sun D-Z, Li H-M, Lin Y-X, Zhou H-F, Zhao F-Q, Tang M (1991) Precambrian geochronology, chronotectonic framework and model of chronocrustal structure of the Zhongtiao mountains. Acta Geol Sinica 65:216–231 (in Chinese with English abstract)
Sun D-Z, Hu H-F (1993) The tectonic framework of Precambrian in Zhongtiaoshan. Geological Publishing House, Beijing, pp 1–180 (in Chinese with English abstract)
Sun H-Y, Dong C-Y, Xie H-Q, Wang W, Ma M-Z, Liu D-Y, Nutman A, Wan Y-S (2010) The formation age of the Neoarchean Zhuzhangzi and Dantazi groups in the Qinglong area, eastern Hebei Province: evidence from SHRIMP U-Pb zircon dating. Geol Rev 56:888–898 (in Chinese with English abstract)
Sun M, Guan H (2001) Zircon U-Pb ages of the Fuping Complex and their implications: some comments on the geochronological study of the Precambrian high-grade metamorphic terranes. Acta Petrologica Sinica 17:145–156 (in Chinese with English abstract)
Sun X-H, Zhu X-Q, Tang H-S, Zhang Q, Luo T-Y (2014) Reprint of "The Gongchangling BIFs from the Anshan-Benxi area, NE China: petrological-geochemical characteristics and genesis of high-grade iron ores". Ore Geol Rev 63:374–387
Tang J, Zheng Y-F, Wu Y-B, Gong B, Liu X-M (2007) Geochronology and geochemistry of metamorphic rocks in the Jiaobei terrane: constraints on its tectonic affinity in the Sulu orogen. Precambrian Res 152:48–82
Tian W, Liu S-W, Liu C-Q, Yu S-Q, Li Q-G, Wang Y-R (2005) Zircon SHRIMP geochronology and geochemistry of TTG rocks of the Sushui Complex in the Zhongtiao area, and its geological significance. Nat Sci Prog 15:1476–1484 (in Chinese)
Trap P, Faure M, Lin W, Monié P (2007) Late Palaeoproterozoic (1900–1800 Ma) nappe stacking and polyphase deformation in the Hengshan-Wutaishan area: implication for the understanding of the Trans-North China Belt, North China Craton. Precambr Res 156:85–106
Trap P, Faure M, Lin W, Monié P, Bruguier O (2008) Contrasted tectonic styles for the Paleoproterozoic evolution of the North China Craton. Evidence for a ~2.1 Ga thermal and tectonic event in the Fuping Massif. J Struct Geol 30:1109–1125
Tsunogae T, Dunkley DJ, Horie K, Endo T, Miyamoto T, Kato M (2014) Petrology and SHRIMP zircon geochronology of granulites from Vesleknausen, Lützow-Holm Complex, East Antarctica: Neoarchean magmatism and Neoproterozoic high-grade metamorphism. Geosci Front 5:167–182
Van Kranendonk MJ, Smithies RH, Griffin WL, Huston DL, Hickman AH, Champion DC, Anhaeusser CR, Pirajno F (2014) Making it thick: a volcanic plateau origin of Palaeoarchean continental lithosphere of the Pilbara and Kaapvaal cratons. In: Roberts NMW, Van

Kranendonk M, Parman S, Shirey S, Clift PD (eds) Continent formation through time, vol 389. Geological Society, London, Special Publications, pages unknown
Wan Y-S (1993) The formation and evolution of the iron-bearing rock series of the Gongchangling area, Liaoning Province. Beijing Science and Technology Publishing House, Beijing, pp 1–108 (in Chinese with English abstract)
Wan Y-S, Zhang Z-Q, Wu J-S, Song B, Liu D-Y (1997a) Geochemical and Nd isotopic characteristics of some rocks from the Paleoarchaean Chentaigou supracrustal, Anshan area, NE China. Cont Dyn 2:39–46
Wan Y-S, Geng Y-S, Wu J-S (1997b) Geochemical compositions of early Precambrian meta-basaltic rocks in the North China Craton and its adjacent area. In: Cheng Y-Q (ed) Essay collection of early Precambrian geology of the North China Platform 39–59 (in Chinese)
Wan Y-S, Song B, Liu D-Y, Li H-M, Yang C, Zhang Q-D, Yang C-H, Geng Y-S, Shen Q-H (2001) Geochronology and geochemistry of 3.8-2.5 Ga ancient rock belt in the Dongshan scenic park, Anshan area. Acta Geologica Sinica 75:363–370 (in Chinese with English abstract)
Wan Y-S, Liu D-Y, Song B, Wu J-S, Yang C-H, Zhang Z-Q, Geng Y-S (2005a) Geochemical and Nd isotopic compositions of 3.8 Ga meta-quartz dioritic and trondhjemitic rocks from the Anshan area and their geological significance. J Asian Earth Sci 24:563–575
Wan Y-S, Song B, Yang C, Wu J-S (2005b) Zircon SHRIMP U-Pb geochronology of Archaean rocks from the Fushun-Qingyuan area, Liaoning Province and its geological significance. Acta Geol Sinica 79:78–87 (in Chinese with English abstract)
Wan Y-S, Song B, Geng Y-S, Liu D-Y (2005c) Geochemical characteristics of Archaean basement in the Fushun-Qingyuan area, northern Liaoning Province and its geological significance. Geol Rev 51:128–137 (in Chinese with English abstract)
Wan Y-S, Song B, Liu D-Y, Wilde SA, Wu J-S, Shi Y-R, Yin X-Y, Zhou H-Y (2006) SHRIMP U-Pb zircon geochronology of Paleoproterozoic metasedimentary rocks in the North China Craton: evidence for a major Late Paleoproterozoic tectonothermal event. Precambr Res 149:249–271
Wan Y-S, Liu D-Y, Yin X-Y, Wu J-S, Wilde SA (2007) SHRIMP geochronology and Hf isotope composition of zircons from the Tiejiashan granite and supracrustal rocks in the Anshan area, Liaoning province. Acta Petrologica Sinica 23:241–252 (in Chinese with English abstract)
Wan Y-S, Liu D-Y, Dong C-Y, Nutman A, Wilde SA, Wang W, Xie H-Q, Yin X-Y, Zhou H-Y (2009a) The oldest rocks and zircons in China. Acta Petrologica Sinica 25:1793–1807 (in Chinese with English abstract)
Wan Y-S, Liu D-Y, Dong C-Y, Xu Z-Y, Wang Z-J, Wilde SA, Yang Y-H, Liu Z-H, Zhou H-Y (2009b) The Precambrian Khondalite Belt in the Daqingshan area, North China Craton: evidence for multiple metamorphic events in the Palaeoproterozoic. In: Reddy SM, Mazumder R, Evans DAD, Collins AS (eds) Palaeoproterozoic supercontinents and global evolution: Journal of the London Geological Society, vol 323. Special Publications, pp 73–97
Wan Y-S, Liu D-Y, Wang S-Y, Zhao X, Dong C-Y, Zhou H-Y, Yin X-Y, Yang C-X, Gao L-Z (2009c) Early Precambrian crustal evolution in the Dengfeng area: constraints from geochemistry and SHRIMP U-Pb zircon dating. Acta Geol Sinica 83:982–999 (in Chinese with English abstract)
Wan Y-S, Miao P-S, Liu D-Y, Yang C-H, Wang W, Wang H-C, Wang Z-J, Dong C-Y, Du L-L, Zhou H-Y (2010a) Formation ages and source regions of the Palaeoproterozoic Gaofan, Hutuo and Dongjiao groups in the Wutai and Dongjiao areas of the North China Craton from SHRIMP U-Pb dating of detrital zircons: resolution of debates over their stratigraphic relationships. Chin Sci Bull 55:1278–1284
Wan Y-S, Dong C-Y, Wang W, Xie H-Q, Liu D-Y (2010b) Archaean basement and a Palaeoproterozoic collision orogen in the Huoqiu area at the southeastern margin of the North China Craton: evidence from SHRIMP U-Pb zircon geochronology. Acta Geol Sinica 84:91–104
Wan Y-S, Liu D-Y, Wang S-J, Dong C-Y, Yang E-X, Wang W, Zhou H-Y, Ning Z-G, Du L-L, Yin X-Y, Xie H-Q, Ma M-Z (2010c) Juvenile magmatism and crustalrecycling at the end of the

Neoarchean in Western Shandong Province, NorthChina Craton: evidence from SHRIMP zircon dating. Am J Sci 310:1503–1552
Wan Y-S, Liu D-Y, Wang W, Song T-R, Kröner A, Dong C-Y, Zhou H-Y, Yin X-Y (2011a) Provenance of Meso- to Neoproterozoic cover sediments at the Ming Tombs, Beijing, North China Craton: An integrated study of U-Pb dating and Hf isotopic measurement of detrital zircons and whole-rock geochemistry. Gandwana Res 20:219–242
Wan Y-S, Liu D-Y, Wang S-J, Yang E-X, Wang W, Dong C-Y, Zhou H-Y, Du L-L, Yang Y-H, Diwu C-R (2011b) ~2.7 Ga juvenile crust formation in the North China Craton (Taishan-Xintai area, western Shandong Province): further evidence of an understated event from U-Pb dating and Hf isotopic composition of zircon. Precambr Res 186:169–180
Wan Y-S, Liu D-Y, Dong C-Y, Liu S-J, Wang S-J, Yang E-X (2011c) U-Th-Pb behaviorof zircons under high-grade metamorphic conditions: a case study of zircon dating of meta-diorite near Qixia, eastern Shandong. Geosci Front 2:137–146
Wan Y-S, Liu D-Y, Nutman A, Zhou H-Y, Dong C-Y, Yin X-Y, Ma M-Z (2012a) Multiple 3.8–3.1 Ga tectono-magmatic events in a newly discovered area of ancient rocks (the Shengousi Complex), Anshan, North China Craton. J Asian Earth Sci 54–55:18–30
Wan Y-S, Dong C-Y, Liu D-Y, Kröner A, Yang C-H, Wang W, Du L-L, Xie H-Q, Ma M-Z (2012b) Zircon ages and geochemistry of late Neoarchean syenogranites in the North China Craton: a review. Precambr Res 222–223:265–289
Wan Y-S, Wang S-J, Liu D-Y, Wang W, Kröner A, Dong C-Y, Yang E-X, Zhou H-Y, Xie H-Q, Ma M-Z (2012c) Redefinition of depositional ages of Neoarchean supracrustal rocks in western Shandong Province, China: SHRIMP U-Pb zircon dating. Gondwana Res 21:768–784
Wan Y-S, Dong C-Y, Xie H-Q, Wang S-J, Song M-C, Xu Z-Y, Wang S-Y, Zhou H-Y, Ma M-Z, Liu D-Y (2012d) Formation ages of early Precambrian BIFs in North China Craton: SHRIMP zircon U-Pb dating. Acta Geol Sinica 86:1447–1478 (in Chinese with English abstract)
Wan Y-S, Xie H-Q, Yang H, Wang Z-J, Liu D-Y, Kröner A, Wilde SA, Geng Y-S, Sun L-Y, Ma M-Z, Liu S-J, Dong C-Y, Du L-L (2013) Is the Ordos Block Archean or Paleoproterozoic in age? Implications for the Precambrian evolution of the North China Craton. Am J Sci 313:683–711
Wan Y-S, Xie S-W, Yang C-H, Kröner K, Ma M-Z, Dong C-Y, Du L-L, Xie H-Q, Liu D-Y (2014a) Early Neoarchean (~2.7 Ga) tectono-thermal events in the North China Craton: a synthesis. Precambr Res 247:45–63
Wan Y-S, Zhao X-Z, Wang Z-J, Liu D-Y, Kröner A, Dong C-Y, Xie H-Q, Geng Y-S, Zhang Y-H, Fan R-L, Sun H-Y (2014b) SHRIMP zircon dating and LA-ICPMS Hf analysis of early Precambrian rocks from drill holes into the basement beneath the Central Hebei Basin, North China Craton. Geosci Front 5:471–484
Wan Y-S, Ma M-Z, Dong C-Y, Xie H-Q, Xie S-W, Ren P, Liu D-Y (2015a) Widespread late Neoarchean reworking of Meso- to Paleoarchean continental crust in the Anshan-Benxi area, North China Craton, as documented by U-Pb-Nd-Hf-O isotopes. Am J Sci (in press)
Wan Y-S, Dong C-Y, Wang S-J, Kröner A, Xie H-Q, Ma M-Z, Zhou H-Y., Xie S-W, Liu D-Y (2015b) Middle Neoarchean magmatism in western Shandong, North China Craton: SHRIMP zircon dating and LA-ICP-MS Hf isotope analysis. Precambr Res (in press)
Wang A-D, Liu Y-C (2012) Neoarchean (2.5-2.8 Ga) crustal growth of the North China Craton revealed by zircon Hf isotope: a synthesis. Geosci Front 3:147–173
Wang A-D, Liu Y-C, Gu X-F, Hou Z-H, Song B (2012a) Late-Neoarchean magmatism and metamorphism at the southeastern margin of the North China Craton and their tectonic implications. Precambr Res 220–221:65–79
Wang C-L, Zhang L-C, Lan C-Y, Dai Y-P (2014a) Petrology and geochemistry of the Wangjiazhuang banded iron formation and associated supracrustal rocks from the Wutai greenstone belt in the North China Craton: implications for their origin and tectonic setting. Precambr Res 255:603–626
Wang C-Q, Cui W-Y, Kröener A, Nemchin AA (2000) Zircon isotopic ages from magnetite quartzites of the Jianping metamorphic complex, western Liaoning Province. Chin Sci Bull 45:547–551

Wang E-D, Xia J-M, Fu J-F, Jia S-S, Men Y-K (2014b) Formation mechanism of Gongchangling high-grade magnetite deposit hosted in Archean BIF, Anshan-Benxi area, Northeastern China. Ore Geol Rev 57:308–321

Wang G-D, Wang H, Chen H-X, Lu J-S, Xiao L-L, Wu C-M (2012b) U-Pb dating of zircons from metamorphic rocks of the Taihua metamorphic complex, Mt. Huashan, southern margin of the Tans-North China Orogen. Acta Geol Sinica 86:1541–1551 (in Chinese with English abstract)

Wang H-L, Chen L, Sun Y, Liu X-M, Xu X-Y, Chen J-L, Zhang H, Diwu C-R (2007) 4.1 Ga xenocrystal zircon from Ordovician volcanic rocks in western part of North Qinling Orogenic Belt. Chin Sci Bull 52:3002–3010

Wang J, Kusky T, Polat A, Wang L, Deng H, Wang S (2013a) A late Archean tectonic mélange in the Central Orogenic Belt, North China Craton. Tectonophysics 608:929–946

Wang L-G, Qiu Y-M, McNaughton NJ, Groves DI, Luo Z-K, Huang J-Z, Miao L-C, Liu Y-K (1998) Constraints on crustal evolution and gold metallogeny in the Northwestern Jiaodong Peninsula, China, from SHRIMP U-Pb zircon studies of granitoids. Ore Geol Rev 13:275–291

Wang L-M, Yan T-M (1992) The Archaean tonalites in Qixia area, Shandong. Shandong Geol 8:80–87 (in Chinese with English abstract)

Wang Q-Y, Zheng J-P, Pan Y-M, Dong Y-J, Liao F-X, Zhang Y, Zhang L, Zhao G, Tu Z-B (2014c) Archean crustal evolution in the southeastern North China Craton: new data from the Huoqiu Complex. Precambr Res 255:294–315

Wang R-M, Wan Y-S, Cheng S-H, Feng Y-G (2009a) Modern-style subduction processes in the Archean: evidence from the Shangyi Complex in North China Craton. Acta Geol Sinica 83:535–543

Wang W, Yang E-X, Wang S-J, Du L-L, Xie H-Q, Dong C-Y, Wan Y-S (2009b) Petrography of Archean metamorphic pillow basalt in Taishan Rock Group, western Shandong, and SHRIMP U-Pb dating of zircons from intruding trondhjemite. Geol Rev 5:737–744 (in Chinese with English abstract)

Wang W, Wang S-J, Liu D-Y, Li P-Y, Dong C-Y, Xie H-Q, Ma M-Z, Wan Y-S (2010a) Formation age of the Neoarchaean Jining Group (banded iron formation) in the western Shandong Province: constraints from SHRIMP zircon U-Pb dating. Acta Petrologica Sinica 26:1171–1174 (in Chinese with English abstract)

Wang W, Liu S-W, Bai X, Yang P-T, Li Q-G, Zhang L-F (2011) Geochemistry and zircon U-Pb-Hf isotopic systematics of the Neoarchean Yixian-Fuxin greenstone belt, northern margin of the North China Craton: implications for petrogenesis and tectonic setting. Gondwana Res 20:64–81

Wang W, Liu S-W, Santosh M, Bai X, Li Q-G, Yang P-T, Guo R-R (2013b) Zircon U-Pb-Hf isotopes and whole-rock geochemistry of granitoid gneisses in the Jianping gneissic terrane, Western Liaoning Province: constraints on the Neoarchean crustal evolution of the North China Craton. Precambr Res 224:184–221

Wang W, Zhai M-G, Li T-S, Santosh M, Zhao L, Wang H-Z (2014d) Archean-Paleoproterozoic crustal evolution in the eastern North China Craton: zircon U-Th-Pb and Lu-Hf evidence from the Jiaobei terrane. Precambr Res 241:146–160

Wang W, Zhai M-G, Tao Y-B, Santosh M, Lü B, Zhao L, Wang S-J (2014e) Late Neoarchean crustal evolution of the eastern North China Craton: a study on the provenance and metamorphism of paragneiss from the Western Shandong Province. Precambr Res 255:583–602

Wang Z-H, Wilde SA, Wan J-L (2010b) Tectonic setting and significance of 2.3-2.1 Ga magmatic events in the Trans-North China Orogen: new constraints from the Yanmenguan mafic-ultramafic intrusion in the Hengshan-Wutai-Fuping area. Precambr Res 178:27–42

Wang Z-J, Shen Q-H, Wan Y-S (2004) SHRIMP U-Pb zircon geochronology of the Shipaihe "metadiorite mass" from Dengfeng County, Henan Province. Acta Geoscientica Sinica 25:295–298 (in Chinese with English abstract)

Warren RG, Ellis DJ (1996) Mantle underplating, granite tectonics, and metamorphic P-T-t paths. Geology 24:663–666

Wei C-J, Qian J-H, Zhou X-W (2014) Paleoproterozoic crustal evolution of the Hengshan-Wutai-Fuping region, North China Craton. Geosci Front 5:485–497

Wilde SA, Dorsett-Bain HL, Jinglan L (1997) The identication of a Late Pan-African granulite facies event in northeastern China: SHRIMP U-Pb zircon dating of the Mashan Group at Liu Mao, Heilongjiang Province, China. In: Proceedings of the 30th international geological congress. VSP International Science Publishers, Amsterdam, pp 59–74

Wilde SA, Cawood PA, Wang K-Y, Nemchin AA, Zhao G-C (2004a) Determining Precambrian crustal evolution in China: a case-study from Wutaishan, Shanxi Province, demonstrating the application of precise SHRIMP U-Pb geochronology. J Lond Geol Soc 226:5–25

Wilde SA, Zhao G-C, Wang K-Y, Sun M (2004b) First SHRIMP U-Pb ages for Hutuo Group in Wutaishan: further evidence for Palaeoproterozoic amalgamation of North China Craton. Chin Sci Bull 49:83–90

Wilde SA, Cawood PA, Wang K-Y, Nemchin AA (2005) Granitoid evolution in the Late Archean Wutai Complex, North China Craton. J Asian Earth Sci 24:597–613

Wilde SA, Valley JW, Kita NT, Cavosie AJ, Liu D-Y (2008) SHRIMP U-Pb and CAMECA 1280 Oxygen isotope results from ancient detrital zircons in the Caozhuang Quartzite, Eastern Hebei, North China Craton: evidence for crustal reworking 3.8 Ga ago. Am J Sci 308:185–199

Wu F-Y, Yang J-H, Liu X-M, Li T-S, Xie L-W, Yang Y-H (2005a) Hf isotopes of the 3.8 Ga zircons in eastern Hebei Province, China: implications for early crustal evolution of the North China Craton. Chin Sci Bull 50:2473–2480

Wu F-Y, Zhao G-C, Wilde S-A, Sun D (2005b) Nd isotopic constraints on crustal formation in the North China Craton. J Asian Earth Sci 24:523–545

Wu F-Y, Zhang Y-B, Yang J-H, Xie L-W, Yang Y-H (2008) Zircon U-Pb and Hf isotopic constraints on the Early Archean crustal evolution in Anshan of the North China Craton. Precambr Res 167:339–362

Wu J-S, Geng Y-S, Xu H-F, Jin L-G, He S-Y, Sun S-W (1989) Metamorphic geology of the Fuping Group. Bull Inst Geol Chin Acad Geol Sci 19:1–213 (in Chinese with English abstract)

Wu J-S, Geng Y-S, Shen Q-H, Wan Y-S, Liu D-Y, Song B (1998) Archaean geology characteristics and tectonic evolution of China-Korea Paleo-continent. Geological Publishing House, Beijing., pp 1–212 (in Chinese)

Wu M-L, Zhao G-C, Sun M, Li S-Z, He Y-H, Bao Z-A (2013) Zircon U-Pb geochronology and Hf isotopes of major lithologies from the Yishui Terrane: Implications for the crustal evolution of the Eastern Block, North China Craton. Lithos 170–171:164–178

Wu M-L, Zhao G-C, Sun M, Li S-Z, Bao Z-A, Yuk TP, Eizenhöefer PR, He Y-H (2014) Zircon U-Pb geochronology and Hf isotopes of major lithologies from the Jiaodong Terrane: implications for the crustal evolution of the Eastern Block of the North China Craton. Lithos 190–191:71–84

Wyman DA (2013a) A critical assessment of Neoarchean "plume only" geodynamics: evidence from the Superior Province. Precambr Res 229:3–19

Wyman DA (2013b) A reply to "How many arcs can dance on the head of a plume?" by Jean Bédard, Precambrian Research, 2013. Precambr Res 229:198–202

Xiang P, Cui M-L, Wu H-Y, Zhang X-J, Zhang L-C (2012) Geological characteristics, ages of host rocks and its geological significance of the Zhoutaizi iron deposit in Luanping, Hebei Province. Acta Petrologica Sinica 28:3655–3669 (in Chinese with English abstract)

Xie S-W (2012) Zircon chronology and geochemical characteristics of Jiaolai basin and its basement. China University of Geosciences (Wuhan), Wuhan, pp 1–142

Xie H-Q, Wan Y-S, Wang S-J, Liu D-Y, Xie S-W, Liu S-J, Dong C-Y, Ma M-Z (2013) Geology and zircon dating of trondhjemitic gneiss and amphibolite in the Tangezhuang area, eastern Shandong. Acta Petrologica Sinica 29:619–629 (in Chinese with English abstract)

Xie S-W, Wang S-J, Xie H-Q, Liu S-J, Dong C-Y, Ma M-Z, Liu D-Y, Wan Y-S (2014a) SHRIMP U-Pb dating of detrital zircons from the Fenzishan Group in eastern Shandong, North China craton. Acta Petrologica Sinica 30:2989–2998 (in Chinese with English abstract)

Xie S-W, Xie H-Q, Wang S-J, Kröner A, Liu S-J, Zhou H-Y, Ma M-Z, Dong C-Y, Liu D-Y, Wan Y-S (2014b) Ca. 2.9 Ga granitoid magmatism in eastern Shandong, North China Craton: zircon dating, Hf-in-zircon isotopic analysis and whole-rock geochemistry. Precambr Res 255:538–562

Yang C-H, Du L-L, Ren L-D, Wan Y-S, Song H-X, Yuan Z-L, Wang S-Y (2009) SHRIMP U-Pb ages and stratigraphic comparison of Angou group, on the southern margin of North China Craton. Acta Petrologica Sinica 25:1853–1862 (in Chinese with English abstract)

Yang C-H, Du L-L, Ren L-D, Song H-X, Wan Y-S, Xie H-Q, Liu Z-X (2011) Petrogenesis and geodynamic setting of Jiandeng potassic granite at the end of the Neoarchean in Zanhuang Complex, North China Craton. Earth Sci Front 18:62–78 (in Chinese with English abstract)

Yang C-H, Du L-L, Ren L-D, Song H-X, Wan Y-S, Xie H-Q, Geng Y-S (2013a) Delineation of the ca. 2.7 Ga TTG gneisses in the Zanhuang Complex, North China Craton and its geological implications. J Asian Earth Sci 72:178–189

Yang J-H, Wu F-Y, Wilde SA, Zhao G-C (2008) Petrogenesis and geodynamics of Late Archean magmatism in eastern Hebei, eastern North China Craton: geochronological, geochemical and Nd-Hf isotopic evidence. Precambr Res 167:125–149

Yang X-Q, Li H-M, Xue C-J, Li L-X, Liu M-J, Chen J (2013b) Geochemical characteristics of two iron ores from the Waitoushan Iron deposit, Liaoning Province: constraints on ore-forming mechanism. Acta Geol Sinica 87:1580–1592 (in Chinese with English abstract)

Yin X-Y, Wan Y-S, Liu D-Y, Wilde SA, Zhou H-Y, Wu J-S (2006) Formation time of supracrustal rocks in the Tiejiashan granite in the Anshan area: evidence from detrital zircon SHRIMP dating. Acta Petrologica et Mineralogica 25:282–286

Yin X-Y, Zhou H-Y, Liu D-Y, Gao L-Z, Dong C-Y, Wan Y-S (2015) Ancient Material Records in the North China Craton: SHRIMP U-Pb Dating and LA-MC-ICPMS Hf analysis of zircons from Archean Metamorphic Rocks in the Jiaozou Area, Henan. Geol Rev 61:183–194 (in Chinese with English abstract)

Ying J-F, Zhang H-F, Tang Y-J (2011) Crust-mantle interaction in the central North China Craton during the Mesozoic: evidence from zircon U-Pb chronology, Hf isotope and geochemistry of syenitic-monzonitic intrusions from Shanxi province. Lithos 125:449–462

Zhai M-G, Bian A-G, Zhao T-P (2000) The amalgamation of the supercontinent of North China Craton at the end of Neo-Archaean and its breakup during late Palaeoproterozoic and Meso-Proterozoic. Sci China Ser D-Earth Sci 43:219–232

Zhai M-G, Guo J-H, Liu W-J (2005) Neoarchean to Paleoproterozoic continental evolution and tectonic history of the North China Craton: a review. J Asian Earth Sci 24:547–561

Zhai M-G, Peng P (2007) Paleoproterozoic events in the North China Craton. Acta Petrologica Sinica 23:2665–2682 (in Chinese with English abstract)

Zhai M-G (2010) Tectonic evolution and metallogenesis of North China Craton. Miner Deposits 29:24–36 (in Chinese with English abstract)

Zhai M-G, Santosh M (2011) The early Precambrian odyssey of the North China Craton: a synoptic overview. Gondwana Res 20:6–25

Zhang H-F (2012) Destruction of ancient lower crust through magma underplating beneath Jiaodong Peninsula, North China Craton: U-Pb and Hf isotopic evidence from granulite xenoliths. Gondwana Res 21:281–291

Zhang H-F (2014) Neoarchean recycling of ^{18}O-enriched supracrustal materials into the lower crust: zircon record from the North China Craton. Precambr Res 248:60–71

Zhang H-F, Zhai M-G, Santosh M, Diwu C-R, Li S-R (2011a) Geochronology and petrogenesis of Neoarchean potassic meta-granites from Huai'an Complex: Implications for the evolution of the North China Craton. Gondwana Res 20:82–105

Zhang H-F, Ying J-F, Santosh M, Zhao G-C (2012a) Episodic growth of Precambrian lower crust beneath the North China Craton: a synthesis. Precambr Res 222–223:255–264

Zhang H-F, Yang Y-H, Santosh M, Zhao X-M, Ying J-F, Xiao Y (2012b) Evolution of the Archean and Paleoproterozoic lower crust beneath the Trans-North China Orogen and the Western Block of the North China Craton. Gondwana Res 22:73–85

Zhang H-F, Ying J-F, Tang Y-J, Li X-H, Feng C, Santosh M (2012c) Phanerozoic reactivation of the Archean North China Craton through episodic magmatism: evidence from zircon U-Pb geochronology and Hf isotopes from the Liaodong Peninsula. Gondwana Res 19:446–459

Zhang H-F, Wang J-L, Zhou D-W, Yang Y-H, Zhang G-W, Santosh M, Yu H, Zhang J (2014a) Hadean to Neoarchean episodic crustal growth: Detrital zircon records in Paleoproterozoic quartzites from the southern North China Craton. Precambr Res 254:245–257

Zhang J, Zhao G-C, Sun M, Wilde SA, Li S-Z, Liu S-W (2006a) High-pressure mafic granulites in the Trans-North China Orogen: tectonic significance and age. Gondwana Res 9:349–362

Zhang J, Zhao G-C, Li S-Z, Sun M, Liu S-W, Wilde SA, Kröner A, Yin C-Q (2007) Deformation history of the Hengshan Complex: implications for the tectonic evolution of the Trans-North China Orogen. J Struct Geol 29:933–949

Zhang J, Zhao G-C, Li S-Z, Sun M, Wilde SA, Liu S-W, Yin C-Q (2009) Deformational history of the Fuping Complex and new U-Th-Pb geochronological constraints: implications for the tectonic evolution of the Trans-North China Orogen. J Struct Geol 31:177–193

Zhang J, Zhang H-F, Lu X-X (2013) Zircon U-Pb age and Lu-Hf isotope constraints on Precambrian evolution of continental crust in the Songshan area, the south-central North China Craton. Precambr Res 226:1–20

Zhang J-J, Zhao L, Liu S-W (2006b) Structures of syn-deformational granites in the Longquanguan shear zone and their monazite electronic microprobe dating. Acta Geol Sinica 80:864–874 (in Chinese with English abstract)

Zhang L-C, Zhai M-G, Zhang X-J, Xiang P, Dai Y-P, Wang C-L, Franco P (2012d) Formation age and tectonic setting of the Shirengou Neoarchean Banded iron deposit in eastern Hebei Province: constrains from geochemistry and SIMS zircon U-Pb dating. Precambr Res 222–223:325–388

Zhang L-C, Zhai M-G, Wan Y-S, Guo J-H, Dai Y-P, Wang C-L, Liu L (2012e) Study of the Precambrian BIF-iron deposits in the North China Craton: progreese and problems. Acta Petrologica Sinica 28:3431–3445 (in Chinese with English abstract)

Zhang Q-S, Yang Z-S, Wang Y-J (1988) Early crust and mineral deposits of Liaodong Peninsula. China Geological Publishing House, Beijing, pp 1–451 (in Chinese with English abstract)

Zhang R-Y, Zhang C-L, Diwu C-R, Sun Y (2012f) Zircon U-Pb geochronology, geochemistry and its geological implications for the Precambrian granitoids in Zhongtiao Mountain, Shanxi Province. Acta Petrologica Sinica 28:3559–3573 (in Chinese with English abstract)

Zhang X-J, Zhang L-C, Xiang P, Wan B, Francon P (2011) Zircon U-Pb age, Hf isotopes and geochemistry of Shuichang Algoma-type banded iron-formation, North China Craton on the ore-forming age and techonic setting. Gondwana Res 20:137–148

Zhang X-H, Yuan L-L, Xue F-H, Zhai M-G (2014b) Neoarchean metagabbro and charnockite in the Yinshan block, western North China Craton: petrogenesis and tectonic implications. Precambr Res 255:563–582

Zhang Y-Q, Wang T, Jia H-Y, Zhang Z-X (2003) U-Pb ages of zircons from the Xiulanbulang hypersthene-plagioclase granulite in the north Daqing Mountains, Central Inner Mongolia. Geol China 30:394–399 (in Chinese with English abstract)

Zhang Y-Q, Liu Y-J (2004) Zircon U-Pb age of the quartz diorite in North Daqing Mountains, central Inner Mongolia. Geol Miner Resour South China 4:22–27 (in Chinese with English abstract)

Zhao G-C (2014) Precambrian evolution of the North China Craton. Elsevier, Amsterdam, pp 1–194

Zhao G-C, Wilde SA, Cawood PA, Lu L-Z (1998) Thermal evolution of Archean basement rocks from the eastern part of the North China carton and its bearing on tectonic setting. Int Geol Rev 40:706–721

Zhao G-C, Wilde SA, Cawood PA, Lu L-Z (1999) Thermal evolution of two types of mafic granulites from the North China craton: implications for both mantle plume and collisional tectonics. Geol Mag 136:223–240

Zhao G-C, Wilde SA, Cawood PA, Sun M (2001) Archean blocks and their boundaries in the North China Craton: lithological, geochemical, structural and P-T path constrains and tectonic evolution. Precambr Res 107:45–73

Zhao G-C, Wilde SA, Cawood PA, Sun M (2002) SHRIMP U-Pb zircon ages of the Fuping complex: implications for Late Archean to Paleoproterozoic accretion and assembly of the North China Craton. Am J Sci 302:191–226

Zhao G-C, Sun M, Wilde SA (2003) Correlations between the Eastern Block of the North China Craton and the South Indian Block of the Indian Shield: an Archaean to Palaeoproterozoic link. Precambr Res 122:201–233

Zhao G-C, Sun M, Wilde SA, Li S-Z (2005) Late Archean to Paleoproterozoic evolution of the North China Craton: key issues revisited. Precambr Res 136:177–202

Zhao G-C, Wilde SA, Sun M, Guo J-H, Kröner A, Li S-Z, Li X-P, Zhang J (2008a) SHRIMP U-Pb zircon geochronology of the Huai'an Complex: constraints on late Archean to Paleoproterozoic magmatic and metamorphic events in the Trans-North China Orogen. Am J Sci 308:270–303

Zhao G-C, Zhai M-G (2013) Lithotectonic elements of Precambrian basement in the North China Craton: review and tectonic implications. Gondwana Res 23:1207–1240

Zhao R-F, Guo J-H, Peng P, Liu F (2011) 2.1 Ga crustal remelting event in Hengshan Complex: evidence fom U-Pb dating and Hf-Nd isotopic study on potassic granites. Acta Petrologica Sinica 27:1607–1623 (in Chinese with English abstract)

Zhao, Z.-P., et al., 1993. Precambrian crustal evolution of the Sino-Korean Paraplatform. Beijing: Science Press: 1–444 (in Chinese)

Zhao Z-R, Song H-X, Shen Q-H, Song B (2008b) Geological and geochemical char acter istics and SHRIMP U-Pb zircon dating of the Yinglingshan granite and its xenoliths in Yishui County, Shandong, China. Geol Bull China 27:1551–1558 (in Chinese with English abstract)

Zhao Z-R, Song H-X, Shen Q-H, Song B (2009) The petrogeochemiscal characters and SHRIMP U-Pb zircon ages of the meta-mafic rocks from the Yushui Complex, in Yishui County, Shandong Province. Geol Rev 55:286–299 (in Chinese with English abstract)

Zheng J-P, Griffin WL, O'Reilly SY, Lu F-X, Wang C-Y, Zhang M, Wang F-Z, Li H-M (2004a) 3.6 Ga lower crust in central China: new evidence on the assembly of the NCC. Geology 32:229–232

Zheng J-P, Griffin WL, O'Reilly SY, Lu F-X, Yu C-M, Zhang M, Li H-M (2004b) U-Pb and Hf-isotope analysis of zircons in mafic xenoliths from Fuxian kimberlites: evolution of the lower crust beneath the North China craton. Contrib Miner Petrol 148:79–103

Zheng J-P, Lu F-X, Yu S-M, Tang H-Y (2004c) An in situ Zircon Hf isotopic U-Pb age and trace element study of banded granulite xenolith from Hannuoba basalt: tracking the early evolution of the lower crust in the North China Craton. Chin Sci Bull 49:3277–3285

Zheng J-P, Griffin WL, O'Reilly SY, Hu B-Q, Zhang M, Tang H-Y, Su Y-P, Zhang Z-H, Pearson N, Wang F-Z, Lu F-X (2008) Continental collision and accretion recorded in the deep lithosphere of central China. Earth Planet Sci Lett 269:496–506

Zheng J-P, Griffin WL, Ma Q, O'Reilly SY, Xiong Q, Tang H-Y, Zhao J-H, Yu C-M, Su Y-P (2012) Accretion and reworking beneath the North China Craton. Lithos 149:61–78

Zhou H-Y, Liu D-Y, Wan Y-S, Wilde SA, Wu J-S (2007) 3.3 Ga magmatic events in the Anshan area: new SHRIMP age and geochemical constraints. Acta Petrologica et Mineralogica 26:123–129 (in Chinese with English abstract)

Zhou H-Y, Liu D-Y, Wan Y-S, Dong C-Y (2009a) 3.3-3.1 Ga magmatism in the Dongshan Complex, Anshan: evidence from SHRIMP U-Pb zircon dating. Geol Bull China 27:2122–2126 (in Chinese with English abstract)

Zhou J-B, Wilde SA, Zhao G-C, Zheng C-Q, Jin W, Zhang X-Z, Cheng H (2008) SHRIMP U-Pb zircon dating of the Neoproterozoic Penglai Group and Archean gneisses from the Jiaobei Terrane, North China, and their tectonic implications. Precambr Res 160:323–340

Zhou Y-Y, Zhao T-P, Xue L-W, Wang S-Y, Gao J-F (2009b) Petrological, geochemical and chronological constraints for the origin and geological significance of Neoarchean TTG gneiss in the Songshan area, North China Craton. Acta Petrologica Sinica 25:331–347 (in Chinese with English abstract)

Zhou Y-Y, Zhao T-P, Wang C-Y, Hu G-H (2011) Geochronology and geochemistry of 2.5 to 2.4 Ga granitic plutons from the southern margin of the North China Craton: implications for a tectonic transition from arc to post-collisional setting. Gondwana Res 20:171–183

Zhou Y-Y, Zhao T-P, Zhai M-G, Gao J-F, Sun Q-Y (2014) Petrogenesis of the Archean tonalite-trondhjemite-granodiorite (TTG) and granites in the Lushan area, southern margin of the North China Craton: implication for crustal accretion and transformation. Precambr Res 255:514–537

Zhu M-T, Zhang L-C, Dai Y-P, Wang C-L (2015) In situ zircon U-Pb dating and O isotopes of the Neoarchean Hongtoushan VMS Cu-Zn deposit in the North China Craton: implication for the ore genesis. Ore Geol Rev 67:354–367

Zhu X-Y, Zhai M-G, Chen F-K, Lü B, Wang W, Peng P, Hu B (2013) ~2. 7 Gacrustal growth in the North China Craton: evidence from zircon U-Pb ages and Hf isotopes of the Sushui Complex in the Zhongtiao terrane. J Geol 121:239–254

http://www.springer.com/978-3-662-47884-4

Precambrian Geology of China
Zhai, M. (Ed.)
2015, VIII, 390 p. 156 illus., 119 illus. in color.,
Hardcover
ISBN: 978-3-662-47884-4