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GR Focus

The Paleoproterozoic North Hebei Orogen: North China craton's collisional suture with the Columbia supercontinent

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Abstract

Understanding the geologic history and position of the North China craton in the Paleoproterozoic Columbia supercontinent has proven elusive. Paleoproterozoic orogenic episodes (2.00–1.85 Ga) are temporally associated with ultimate stabilization of the North China craton (NCC), followed by the development of extensive craton-wide rift systems at 1.85–1.80 Ga. The age difference between the sedimentary cover and the metamorphic basement is up to 500–700 Ma, suggesting that uplift and doming of cratonic basement occurred in the latest Paleoproterozoic. Mafic dike swarms (1.80–1.77 Ga) and anorogenic magmatism (1.80–1.70 Ga) record the extensional breakup and dispersal of the North China craton during this stage. The late Paleoproterozoic tectonic framework and geological events documented provide important constraints for reconstruction of the NCC within the Late Paleoproterozoic supercontinent of Columbia.

An east-west striking thousand kilometer long belt of khondalites (granulite facies metapelites) stretches along the northern margin of the North China craton, on the cratonward side of the Northern Hebei orogenic belt. This granulite belt includes Mg–Al (sapphirine bearing) granulites that reached ultrahigh-temperature "peak" metamorphic conditions of ~1000 °C at 10 kbars at 1927±11 Ma. Following peak ultrahigh-temperature conditions, the rocks underwent initial isobaric cooling and subsequent isothermal decompression, and these trajectories are interpreted to be part of an overall anti-clockwise P-T evolution indicating that the northern margin of the craton experienced continental collision at 1.93–1.92 Ga. The position of the khondalite belt south of the Northern Hebei orogenic belt makes it analogous to Tibet, a continental collision-related plateau characterized by double crustal thicknesses and granulite facies metamorphism at depth. We suggest that the tectonic evolution of the NCC during this period was closely related to the assembly and break-up of the Columbia supercontinent, and that the NCC was adjacent to the Baltic and Amazonian cratons in the period 2.00–1.70 Ga. Craton-wide extension occurred within 100–150 Ma of collision along the northern margin of the craton at 1.93–1.92 Ga. It is concluded that mantle upwellings are chiefly responsible for the breakup of the NCC from the Paleoproterozoic supercontinent.
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Keywords: Rift-aulacogen; Mafic dike swarm; Domal uplift; Columbia supercontinent; Extensional tectonics; North China craton

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1. Introduction

The Late Paleoproterozoic (2.00–1.70 Ga) is the one of most important periods of deformation and metamorphism in the North China craton (NCC), and it is also the time span when significant changes occurred in the tectonic evolution of the craton (e.g., Bai et al., 1996; Kusky and Li, 2003; Wu et al., 2005; Xia et al., 2006; Zhao et al., 2006a,b; Kusky et al., 2006a, b). Soon after the major orogenic event felt across the craton at 2.0–1.85 Ga, extensional tectonics began to dominate, and thick sequences of Mesoproterozoic cover were deposited on the craton. This period coincides with the assembly of a major supercontinent in Earth history (Rogers and Santosh, 2003, 2004; Condie, 2003a,b, 2004; Zhao et al., 2006a,b), although the position of the NCC in this supercontinent is poorly constrained. To reconstruct and constrain the configuration of the Paleoproterozoic supercontinent, we need to document and correlate the collisional and later extensional episodes and regional tectonics of different cratonic blocks during the Proterozoic.

The NCC is bounded by Phanerozoic orogenic belts along both its southern and northern margins (Fig. 1). At the end of Paleoproterozoic, the stabilized NCC began to be buried under thick deposits of Mesoproterozoic clastic and carbonate rocks (younger than 1.80 Ga) in an extensive rift-graben system, accompanied by the emplacement of mafic dike swarms (between about 1.80–1.77 Ga) and intrusion of anorogenic magmas (rapakivi granite, gabbro, anorthosite, etc., 1.80–1.70 Ga) (Qian and Chen, 1987; Li et al., 2000a,b; Halls et al., 2000; Kusky and Li, 2003; Hou et al., 2003, 2005; Peng et al., 2005, 2007-this issue). The Mesoproterozoic sequences within the rifts commonly overly unconformably the cratonic Archean basement, with a break in the strata (except for in the khondalite belt, see below) between 2.5 and 1.8 Ga, which has been named the "Luliang Movement" (circa 1.80 Ga). Even though the "Luliang movement" has long been thought to be ultimately responsible for the cratonization of the North China craton, its tectonic framework and relevant tectonothermal episodes are ambiguous (Wilde et al., 2004; Zhao et al., 2005, 2006). Some of the outstanding questions include the following: (1) What major tectonothermal episodes did the NCC undergo in the late Paleoproterozoic? (2) What types of tectonic settings did the craton experience? (3) What is the relationship between extensional tectonics and the cratonic basement? (4) What is the tectonic setting and origin of the regional uplift marked by the Mesoproterozoic unconformity? (5) What are the relationships between crustal and mantle processes and features such as plumes?

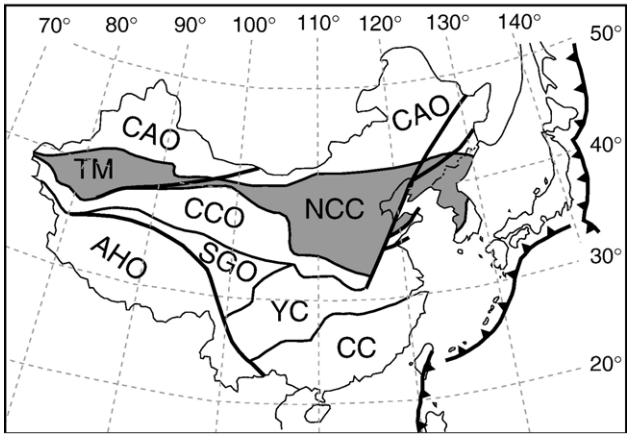


Fig. 1. Map of China showing the locations of the major Archean cratons and surrounding orogenic belts.

These questions have important implications to understand the final cratonization of the NCC and will also provide an important constraint for reconstruction of the NCC within the late Paleoproterozoic Columbia supercontinent (e.g., Rogers and Santosh, 2004). In this Focus paper, we synthesize new geological data, regional tectonic interpretations and isotopic ages and delineate the tectonic framework, geological setting and tectonothermal episodes of the NCC in the period of 2.1–1.70 Ga, to provide updated constraints for the reconstruction of Columbia.

2. Archean-early Proterozoic events in NCC

We begin with a review of older events that formed the craton between 3.8 and 2.0 Ga.

Beneath an extensive Phanerozoic cover, the North China craton (Fig. 2) is comprised dominantly of circa 3.8–2.5 Ga gneiss, tonalite–trondhjemite–granodiorite (TTG), granite,

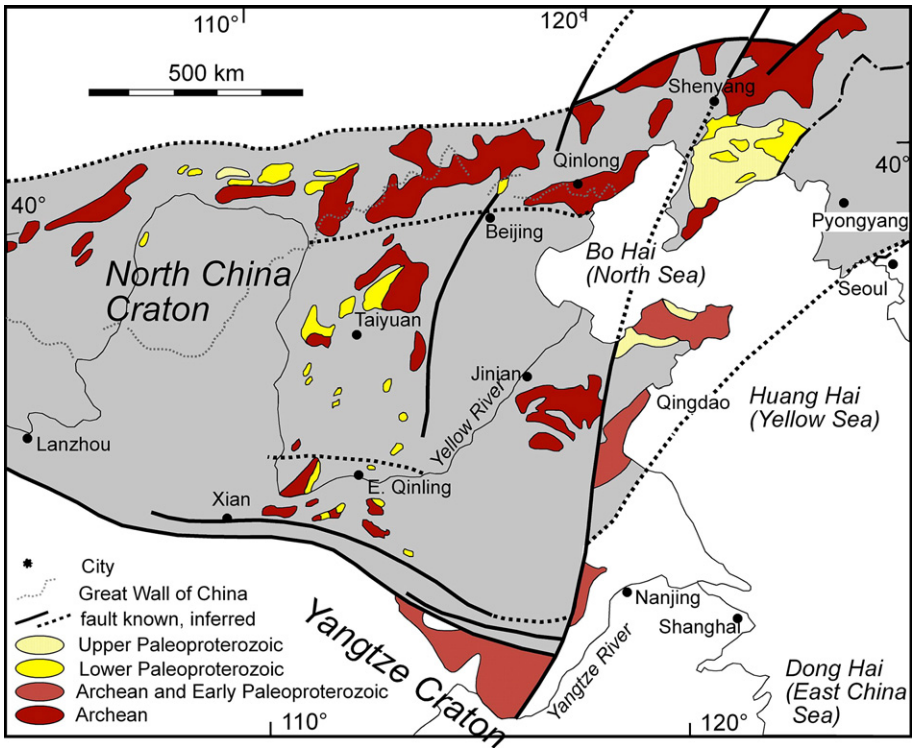


Fig. 2. Simplified geologic map of the North China craton showing the distribution of rocks of Archean, Proterozoic and younger ages.

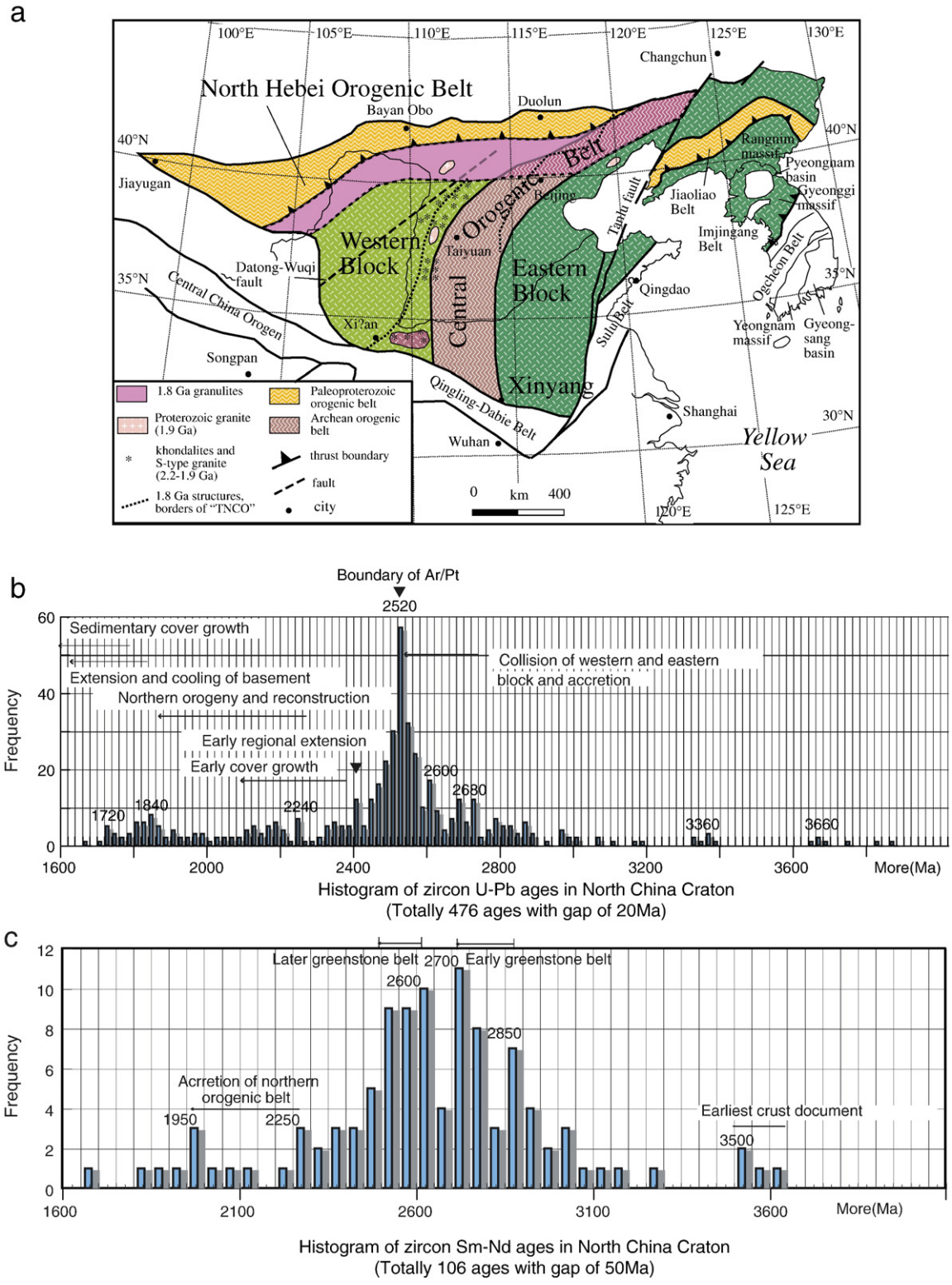
migmatite, amphibolite, ultramafite, mica schist and dolomitic marble, graphitic and sillimanitic gneiss (khondalites), banded iron formation (BIF) and metaarkose (Jahn and Zhang, 1984a,b; Bai et al., 1992, 1996; Wu et al., 1998a,b; Jahn et al., 1987; He et al., 1991, 1992; Shen et al., 1992; Shen and Qian, 1995; Wang et al., 1997). The most important period of crustal growth in the craton is between 2700 and 2520 Ma, based on a compilation of U–Pb and Sm–Nd ages, and Nd isotopic studies (Figs. 2 and 3a, c). The Archean rocks are overlain by the 1.85- to 1.40-Ga Mesoproterozoic Changcheng (Great Wall) system (Li et al., 2000a,b). In some areas in the central part of the NCC, 2.40–1.90 Ga Paleoproterozoic sequences deposited in cratonic graben are preserved (Kusky and Li, 2003).

The North China craton is divided into two major blocks (Fig. 3) separated by the Neoarchean Central Orogenic belt in which virtually all U–Pb zircon ages (upper intercepts) fall between 2.55 and 2.50 Ga (Zhao et al., 1998, 1999a,b, 2000, 2001a,b; Kröner et al., 1998, 2002; Wilde et al., 1998; Zhao, 2001; Kusky et al., 2006a,b; Kusky and Li, 2003; Polat et al., 2005a,b). The Western block, also known as the Ordos block (Zhang, 1989; Bai and Dai, 1998; Li et al., 1998), is a stable craton with a thick mantle root, no earthquakes, low heat flow and a lack of internal deformation since the Precambrian. The Western block contains a thick platform sedimentary cover intruded by a narrow belt of 2.55–2.50 Ga arc plutons along its eastern margin. Much of the Archean geology of the Western block is poorly exposed as it is covered by thick platform cover, ranging in age from Archean (?) to Cretaceous, typical of cratons.

In contrast, the Eastern block is atypical for a craton in that it has numerous earthquakes, high heat flow and a thin lithosphere reflecting the lack of a thick mantle root (Menzies et al., 1993; Griffen et al., 1998; Wilde et al., 2003; Kusky et al., 2006a,b). The Eastern block contains a variety of ca. 3.80–2.50 Ga gneissic rocks and greenstone belts locally overlain by 2.60–2.50 Ga sandstone and carbonate units (Fig. 4). Deformation is complex, polyphase and indicates the complex collisional, rifting and underplating history of this block from the early Archean through the Mesoproterozoic (Zhai et al., 1992, 1995, 2002; Zhai and Liu, 2003; Zhou et al., 2002; Li et al., 2003, 2004; Kusky and Li, 2003; Kusky et al., 2001, 2004; Polat et al., 2005a,b; Wan et al., 2006).

Fig. 3. Sketch map showing the tectonic framework of NCC in the latest Paleoproterozoic (2.00–1.90 Ga). Note the location of the Northern Hebei orogen and related khondalites belt, related to collision on the north margin of the craton at that time. The Central Orogenic belt is an older orogen (2.5 Ga) that was reactivated largely as a strike-slip belt at this time. Map modified from Kusky and Li (2003). (b) Histogram showing compilation of all U–Pb ages >1600 Ma published (n=476) from rocks of the North China craton prior to 2006, divided into 20 Ma intervals (see also Wu et al., 2005). Note the peak in crustal formation ages of 2520, 2600 and 2680 corresponding to periods of major arc building and oceanic crust generation, especially in the central orogenic belt. 2400 Ma correlates with the main period of post-orogenic extension. Note also the paucity of ages between 2400 and 1850, showing that the model of Zhao et al. (2000-2006a,b) that claims 2400–1850 as the main period of arc magmatism and crustal growth in the NCC is not viable. The small peak of ages at 1840 corresponds to the post-orogenic extensional magmatism following collisional tectonics in the Northern Hebei orogen in the NCC at 1930–1850 Ma. (c) Sm–Nd histogram showing all Sm–Nd isotopic ages (n=106) published for rocks of the NCC prior to 2006. Note the mantle extraction ages for most greenstones and arc rocks in the range of 2600–2850 Ma. Note also the mantle extraction ages of arc magmas from the Northern Hebei orogen that cluster at 1950 Ma, prior to UHT metamorphism at 1930–1850 Ma. This plot also supports the idea that most crustal growth in the NCC was in the late Archean (e.g., Kusky and Li, 2003).

The Central Orogenic belt (COB) separates the Eastern and Western blocks (Fig. 3) and includes belts of TTG, granite and supracrustal sequences metamorphosed from granulite to greenschist facies. It can be traced for about 1,600 km from west Liaoning to west Henan (Fig. 3). [Note that the COB differs from the Trans North-China Orogen (TNCO) as defined by Zhao et al. (2004). The COB is an Archean orogen, with Archean structures defining its boundaries, whereas the TNCO is defined as a Proterozoic orogen, albeit one bound by Mesozoic and Cenozoic structures. Kusky et al. (2006a,b) and Polat et al. (2006) have suggested that the term TNCO be abandoned]. Widespread high-grade regional metamorphism including



magmatization occurred throughout the Central Orogenic belt between 2.60 and 2.50 Ga (Kröner et al., 1998; Zhai and Liu, 2003), with final uplift of the metamorphic terrain at circa 1.9–1.80 Ga associated with extensional tectonism (Li et al., 2000a) or a collision on the northern margin of the NCC (Kusky and Li, 2003). Amphibolite to greenschist grade metamorphism predominates in the southeastern part of the COB (Fig. 3), but the northwestern part of the COB is dominated by granulite facies to amphibolite facies rocks, including some high-pressure assemblages (10–13 kbars at 850±50 °C; Li et al., 2000b; Zhao et al., 2004; Kröner et al., 2002, 2005). The high-pressure assemblages form a wide belt across the northern part of the craton (Fig. 3) and are clearly not confined to the TNCO or COB, but related to Paleoproterozoic tectonism along the northern margin of the craton. O'Brien et al. (2005) note that metamorphic pressure–temperature (P-T) conditions increase to the north, generally across E-W striking shear zones such as the Zhujiafang shear zone (Fig. 5). This circa ~1.85 Ga structure separates medium pressure granulites on the south from high-pressure granulites on the north. Recently, Santosh et al. (in press) have documented ultrahigh-temperature granulite facies assemblages with extreme crustal metamorphism at temperatures exceeding 1000 °C from this northern belt as well. The high-pressure assemblages extend along an ENE striking linear belt for more than 700 km (Figs. 2, 6 and 7). We correlate these assemblages and structures to tectonism in the Northern Hebei orogenic belt and related collisional plateau/khondalites belt, as described below. Structures and metamorphic assemblages in this EW orogen overprint older, formerly NS structures in the Central Orogenic Belt, in some cases completely obliterating all the traces of older events. The discussion on Paleoproterozoic events by many workers in this terrane often fails to recognize the older, equally significant tectonic events.

The internal (western) domains of the Central Orogenic Belt are characterized by thrust-related subhorizontal foliations, flat-dipping shear zones, recumbent folds and tectonically interleaved high-pressure granulite migmatite and metasediments (Li and Kusky, 2007-this issue). These rocks are widely overlain by sediments deposited in graben and continental shelf environments, and intruded by several dike swarms (2.40–2.50 Ga, 1.80–1.90 Ga). Several large anorogenic granites with ages of 2.20–2.00 Ga are identified within the belt. Recently, two linear units have been documented within the belt, including the high-pressure granulite belt in the west and an Archean foreland-thrust fold belt in the east (Li et al., 2000a, 2002; Kusky and Li, 2003; Li and Kusky, 2007-this issue). The high-pressure granulite belt is separated by normal-sense shear zones from the western block, which is overlain by thick metasedimentary sequences (khondalite, younger than 2.40 Ga, and metamorphosed at 1862.7±0.4 Ma; A. Kroener, personal communication, 2003).

While most workers agree that the Central Orogenic Belt records the collision between Western and Eastern blocks of the NCC, the timing of this collision is debated. Zhao and co-workers (Zhao et al., 2000, 2001; Zhai and Liu, 2003) suggest that collision between the Western and Eastern blocks of the NCC occurred at 1.8 Ga, based on the metamorphic ages of high-pressure granulites and their inferred clockwise P-T paths. Clockwise P-T paths in regionally metamorphosed rocks are generally interpreted as reflecting double-thickening of crust followed by erosion and uplift. Thus, in the Zhao et al. scenario, an active continental arc developed on the western edge of the Eastern block by 2.5 Ga, and transformed to a continent–continent collision zone 650 million years later at ~1.85 Ga with the collision of the passive margin of the Western Block. However, many U–Pb and other metamorphic ages point to a major amphibolite-granulite facies event at 2.5 Ga (Kröner et al., 1998; Zhai and Liu, 2003; Li and Kusky, 2007-this issue). Kusky and co-workers suggest that the Eastern and Western Blocks collided at 2.5 Ga during an arc/continent collision, forming a foreland basin on the Eastern block, a granulite facies belt on the Western Block, and a wide orogen between the two blocks (Fig. 8). Evidence for this collision are found as remnants of 2.5 billion-year-old oceanic crust (Kusky et al., 2001, 2003, 2004; Kusky, 2004; Polat et al., 2005a,b), island arcs, accretionary prisms and deformed continental fragments that form a 2.5-Ga accretionary orogen in the Central Orogenic Belt (Figs. 2, 4 and 8). In their view, the collision was followed by post-orogenic extension and rifting that formed mafic dike swarms and extensional basins along the Central Orogenic Belt and led to the development of a major ocean along the northern margin of the North China craton (Kusky and Li, 2003). The northern margin of the craton remained episodically active as a convergent/accretionary margin for the next 2 billion years (Fig. 8), growing northward and accommodating the southward (?) subduction of thousands of kilometers of oceanic lithosphere (Kusky et al., 2006a,b). The circa 1.9–1.8 Ga event that formed the high-pressure granulites with clockwise P-T paths is interpreted by Kusky and Li (2003) to be related to a continental collision outboard of the Inner Mongolia-Eastern Hebei Orogen, and forming the east-west striking khondalite belt along the north margin of the craton (Fig. 8).

3. Late Paleoproterozoic tectonics (between 2.10 and 1.90 Ga)

The North China craton is bordered by Late Paleoproterozoic accretionary orogens. At least two major orogens of this period (between 2.10 and 1.90 Ga) have been identified. One is the Inner-Mongolia-North Hebei Orogenic Belt (or more simply the North Hebei Orogenic Belt: NHOB) along the northern margin of the craton, characterized by east-west striking composite folds and shear zones. It consists of belts of plutonic rocks (gabbro, diorite, granites, 2.10–1.90 Ga) and volcanic-sedimentary sequences. In the NHOB, the metamorphic ages (2.00 Ga) are commonly older than the crystallization ages of granites (1.90 Ga) (Li et al., 2000). They are interpreted to result from accretion and collision along the northern margin of the NCC (Li et al., 2000, 2001; Kusky and Li, 2003; Kusky et al., 2006a,b). Another orogenic belt is located in the Sino-Korea boundary area and is named the Jialiao Orogenic belt (Fig. 3). This belt forms a semi-circular band around the North Korean block (Bai et al., 1992; Li et al., 2006), and separates the eastern part of NCC from the North Korean massif. Since this belt is not yet well documented, it will not be discussed further in this paper.

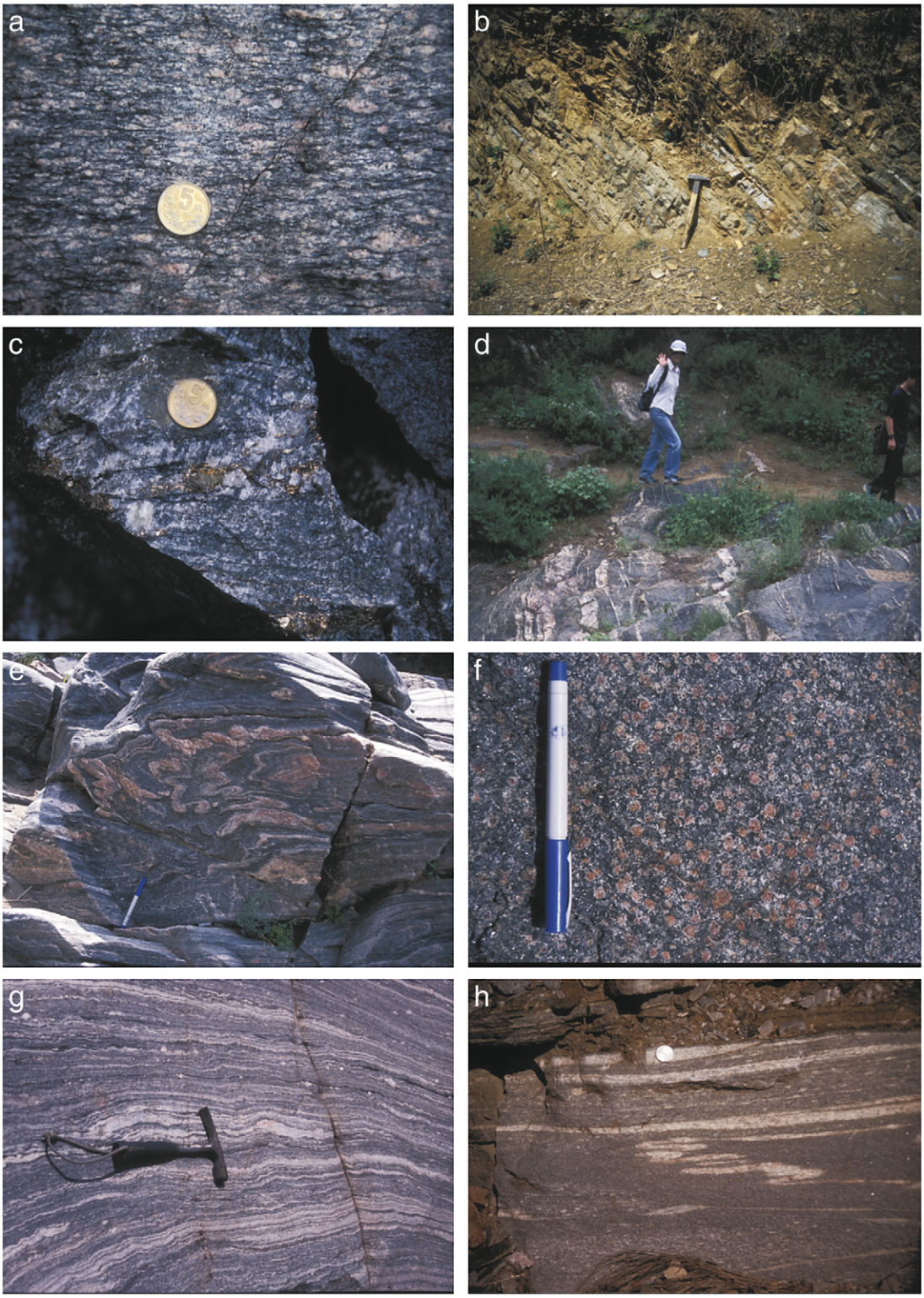


Fig. 4. Photographs of rocks from the North China craton: (a) strongly deformed porphyroclastic gneiss, eastern block; (b) Archean metasedimentary rocks including quartzite, metapelite and marble, with circa 3.5 Ga zircons; (c) massive sulfide deposits in 2.55 Ga mafic rocks in Wutai Mountains; (d) amphibolite facies greenstone intruded by circa 2.4 Ga granitoids, Eastern Hebei; (e) folded granite vein in granulite of the Hengshan; (f) plagioclase rims around garnet defining a corona texture in retrogressed granulite, Hengshan; (g) strongly deformed mylonitic shear zone of the Zhujifang shear zone; (h) mylonite with isoclinally folded granitoid vein, Dragon Spring (Longquanguan) shear zone.

Reworking of the >2.5 Ga passive margin, circa 2.5 Ga foreland basin deposits, and 2.4–1.85 Ga platform sediments (Li and Kusky, 2007-this issue) is quite widespread in the Paleoproterozoic NHOB, in the northwestern part of NCC (Fig. 3) (Li et al., 2000; Kusky and Li, 2003). The NE-striking Datong-Wuqi Fault (DWF, Figs. 3, 5 and 6) is a major structure that cuts across the

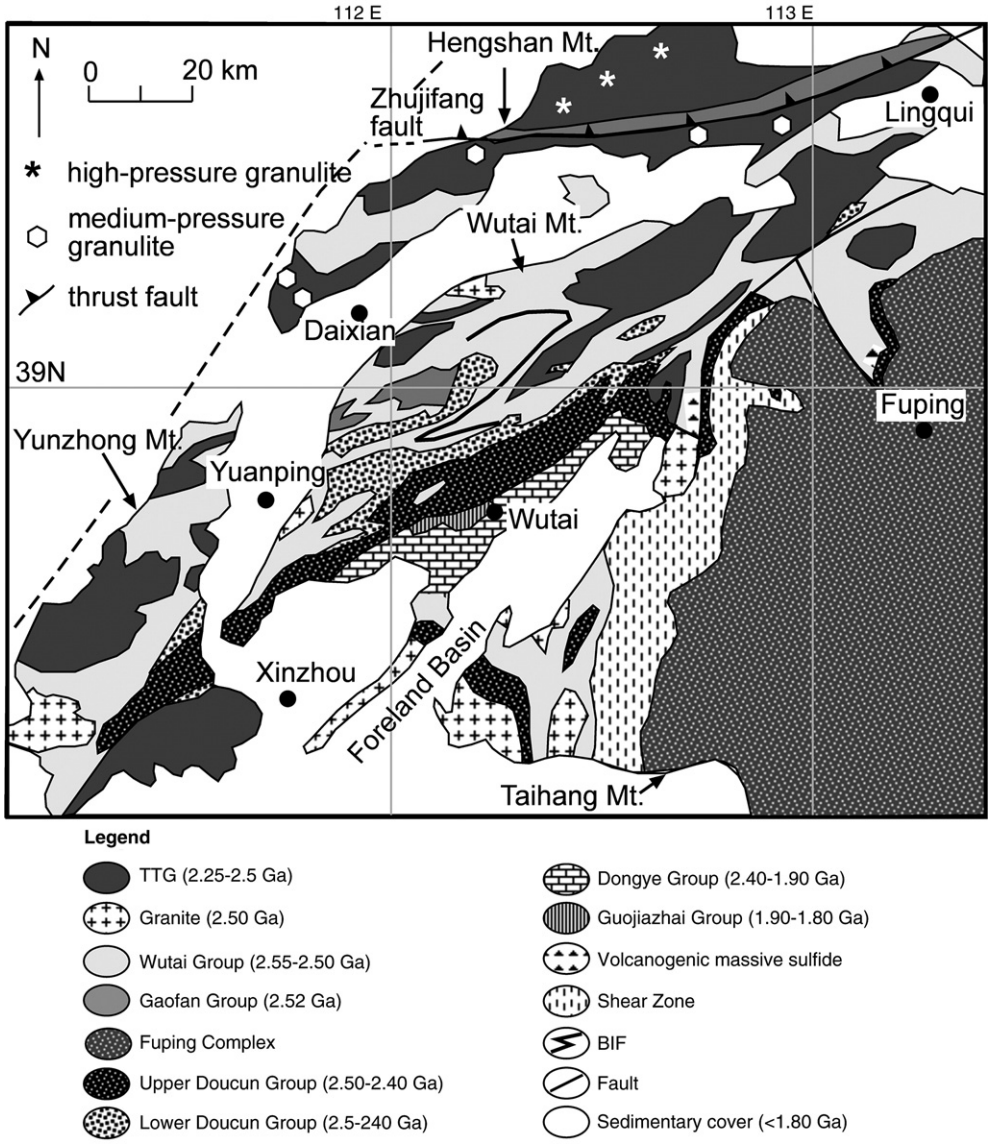


Fig. 5. Simplified map of the Wutai–Hengshan–Fuping area of the Central Orogenic belt, showing the relationship between Archean structures (NE striking) and Proterozoic structures (EW to ENE striking), and Mesozoic–Cenozoic faults (not shown) that strike NE parallel to the range fronts. Note that the circa 1.8- to 1.85-Ga Zhujiafang shear zone cuts the Archean fabrics and juxtaposes high-pressure (HP) granulites on the north over medium-pressure (MP) granulites on the south.

NHOB (Liu, 1992; Zhang et al., 1998) and apparently displaces belts of high-pressure granulites. It also cuts and displaces EW striking structures such as the Zhujiafang fault that have high-pressure assemblages on the north, as well as the medium pressure assemblages on the south (O'Brien et al., 2005). The sedimentary succession on the northwest side of DWF underwent high-grade metamorphism and penetrative deformation, with the formation of khondalites and S-type granites, characterized by NE-ENE-striking structures (Fig. 6), nearly parallel to the northern boundary of NCC. Deformation patterns in this orogen may be modeled by a northwest-directed transpression and thrusting between NCC and NHOB. On the southeast side of DWF, the outcrops are dominated by granite–greenstone belts that preserve distinct Neoarchean gneiss dome structures. Thus, the Datong-Wuqi fault represents a major structural feature within the cratonic basement, separating different tectonic and geological units on its two sides (Ma et al., 1979; Yuan et al., 1994; Zhang et al., 1998; Zhu, 2004).

3.1. The Northern Hebei Orogen: reworked cratonic sedimentary sequences and khondalites in the northwest part of the NCC

The 2.4- to 1.85-Ga cratonic cover, passive margin and foreland basin deposits were strongly reworked at 1.9–1.85 Ga. Deformation, metamorphism and magmatism are not fully understood along the northern margin of the craton and needs much more work before a comprehensive understanding is reached. Various authors have named different parts of the Paleoproterozoic orogen along the northern margin of the craton as the Inner Mongolia-Northern Hebei Orogen (IMNHO; Kusky and Li, 2003), the Northern Hebei Orogenic Belt (NHOB; Qian and Li, 1999) and the khondalite belt (Santosh et al., 2006a), after the distinctive granulite facies metapelitic rocks that characterize this belt.

The NHOB consists of granitoid gneisses (2.42–2.47 Ga), a gabbro-diorite complex, minor ultramafic rocks and voluminous

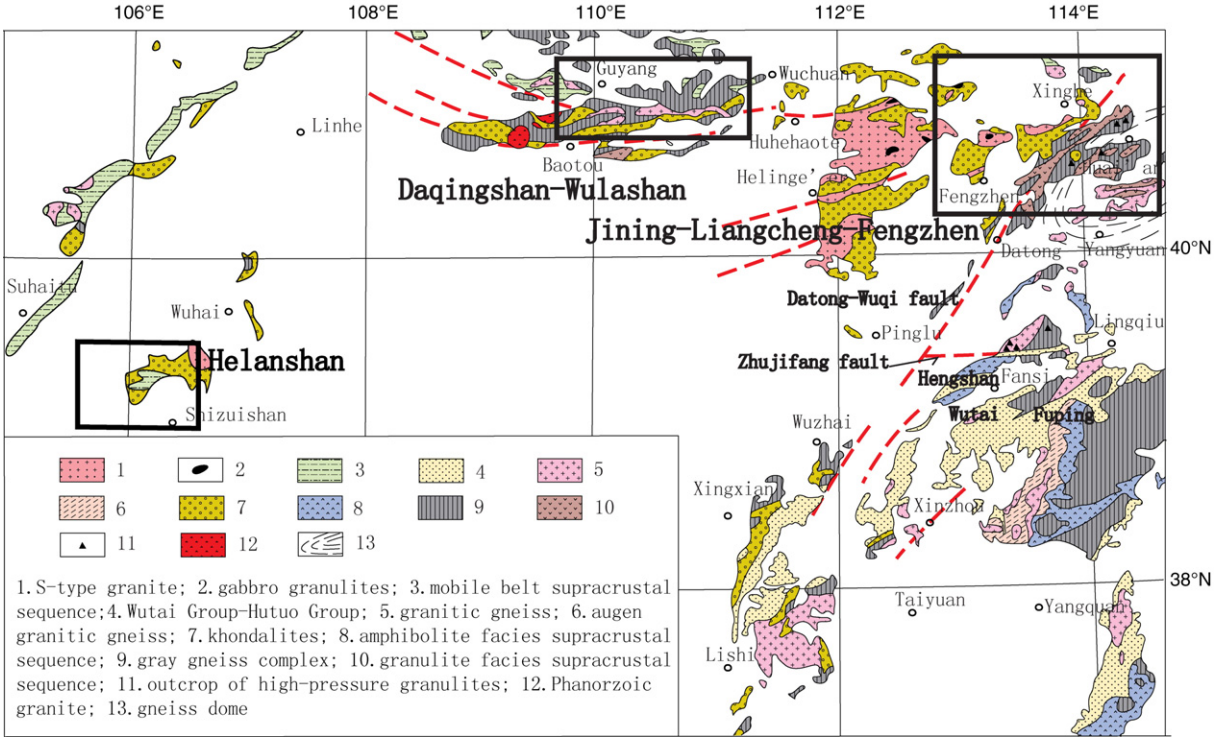


Fig. 6. Map of the northern margin of the North China craton showing the distribution of major outcrop belts of the Northern Hebei orogen, the khondalites belt and some of the major structures of the craton. Note how Archean structures strike NS to NE-SW, and Proterozoic structures related to collision on the north margin of the craton at 1.93 Ga generally strike EW. NE striking structures in the Central Orogenic belt include strike slip shear zones, showing that the Central Orogenic belt was re-activated as a shear belt kinematically linked to the collision at this time.

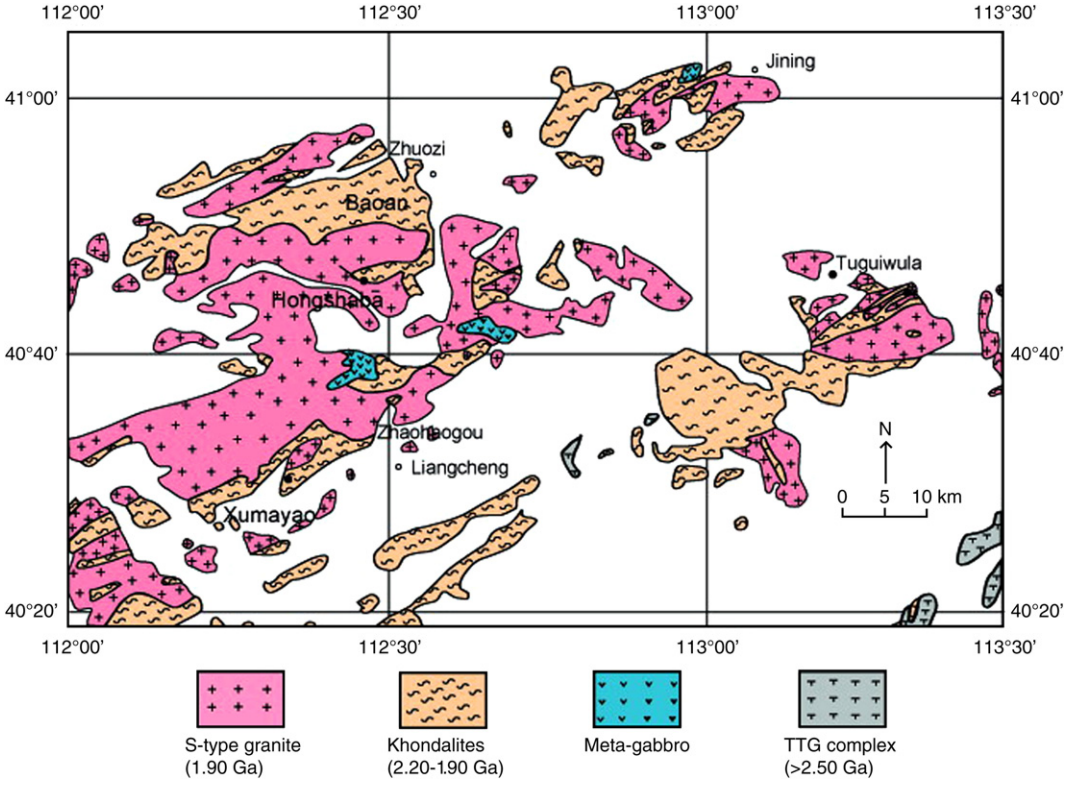


Fig. 7. Detailed map of the Tuguiwula–Baoan area, where UHT granulites have been discovered. The sapphirine-bearing Mg–Al granulites occur in the Tuguiwula towards the eastern part of the study area (Santosh et al., in press). Spinel+quartz was reported from khondalites in the Jining area in the northern part (Santosh et al., 2006a).

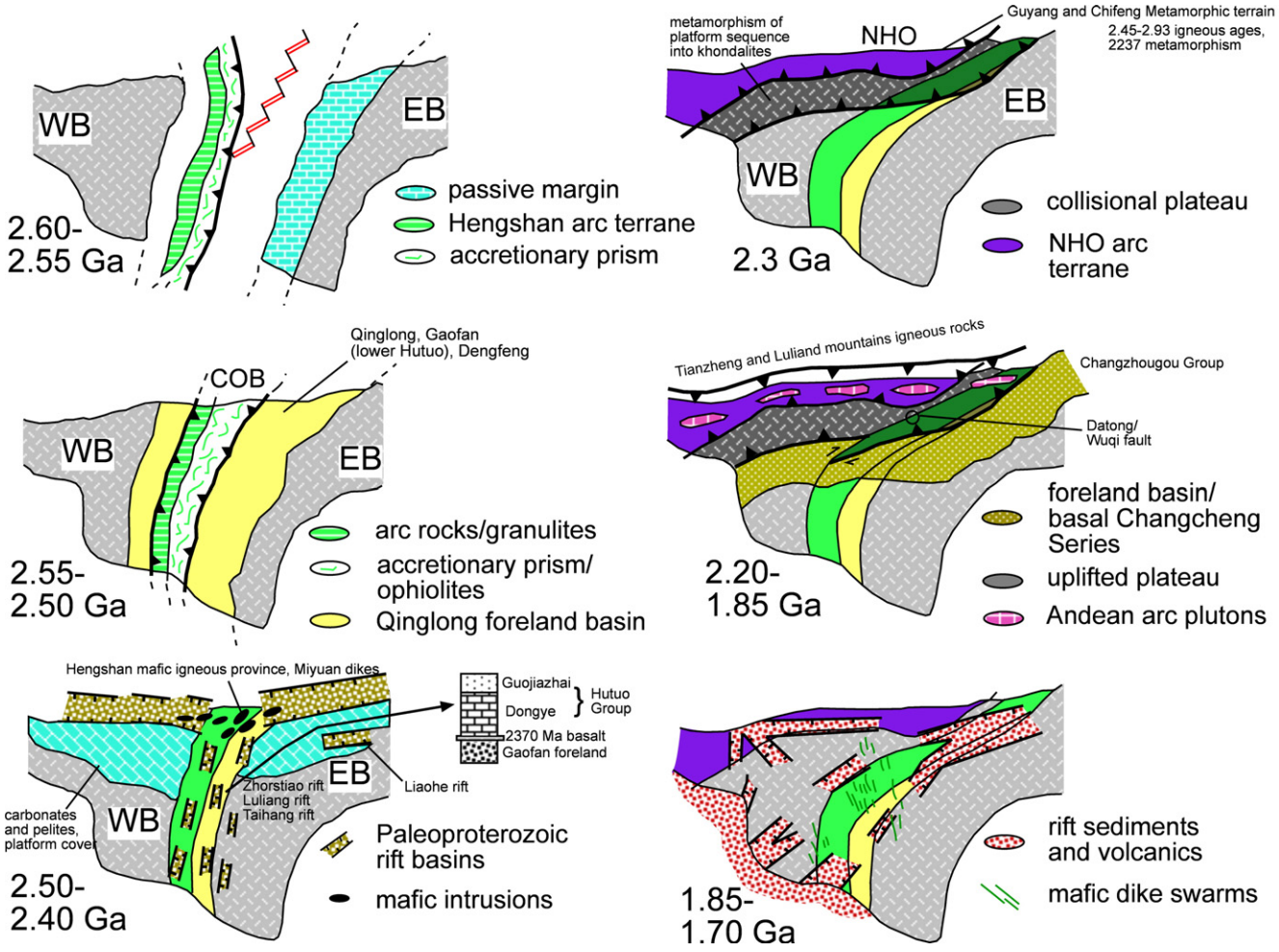


Fig. 8. Palinspastic maps showing the tectonic development of the North China craton from 2.6 to 1.7 Ga (modified after Kusky and Li, 2003). In this scenario, following collision along the northern margin of the craton at 1.85 Ga, extensional tectonics formed a series of aulacogens, rifts and mafic dikes that propagated across the craton. Rifting led to the development of an ocean along the southwest margin of the craton, where passive margin and cratonic sedimentation continued until 1.5 Ga. Throughout the rest of the Precambrian and until the end of the Paleozoic, the NCC behaved as a coherent, stable continental block, as evidenced by deposition of shallow marine carbonate platform sediments, with the only breaks in sedimentation being associated with deformation and orogeny along the margins of the craton, and a regional disconformity between the Upper Ordovician and Upper Carboniferous (Wang, 1985). The latter may have resulted from the global eustatic low stand of sea level following the Caledonian orogeny or from double-vergent subduction beneath the north and south margin of the craton (the Qaidam plate was subducted beneath the southern margin of the craton, and several oceanic plates subducted beneath the north margin of the craton (Yin and Nie, 1996). Moreover, it is during this interval that diamond-bearing kimberlites erupted in several areas of the eastern block of the NCC (Menzies et al., 1993; Griffin et al., 1998). The diamonds and the P-T array inferred from garnets carried in these kimberlites testify to the presence of a thick (≥170 km), lithospheric keel, similar to those observed in Archean cratons elsewhere (e.g., Kaapvaal, Slave, Siberia) (Menzies et al., 1993; Griffin et al., 1998).

supracrustal sequences (2.30–2.64 Ga), all of which are intruded by the late granites (2.38–2.44 Ga) (Geng et al., 1997; Li et al., 1998c) and exhibiting amphibolite to granulite facies prograde metamorphism. It forms an E-W-striking belt along the northern margin of the NCC and was probably generated by accretion along an active continental margin at the end of Neoarchean (Kusky and Li, 2003). To the south the NHO is thrust over the khondalites belt of the NCC.

Kusky and Li (2003) suggested that parts of the Northern Hebei orogen represent an arc/accretionary complex that initially grew in the ocean to the north of the NCC after rifting at 2.5–2.4 Ga and was accreted to the North China craton by 2.3 Ga (Fig. 8). These rocks include the low- to intermediate-grade Guyang and Chifeng metamorphic terranes, 2.49–2.45 Ga tonalitic–granitic gneiss, 2.48–2.40 Ga diorite-gabbro, scattered ultramafic rocks, 2.393 Ma trondhjemite and several 2.45–2.33 Ga supracrustal sequences including BIF, turbidites and biotite-hornblende gneiss, all intruded by 2.44–2.38 Ga granitoids. Multigrain analysis of zircons reveals that an early phase of metamorphism occurred at 2237 Ma (Kusky and Li, 2003).

Oblique collision along the khondalite belt (NHOB) was partitioned into left lateral strike-slip motion and southward thrusting in the area. The sedimentary cover of NCC underwent compressive to shearing deformation and high-grade metamorphism with clockwise P-T-t paths. Especially voluminous S-type granites with emplacement ages ranging from 2.00 to 1.90 Ga have been generated through anatexis and metamorphism. Ages of 2.00–1.85 Ga are recorded from metasediments in the northwestern part of the craton (Liu, 1994; Guo et al., 1993).

3.2. The Northern Hebei Orogen (NHO) and Khondalite Belt

The Inner-Mongolia-North Hebei Orogenic Belt (IMNHOB), NHO, or simply the khondalite belt, comprising a vast sequence of metasupracrustals, is distributed in a large area along the northwestern segment of the North China craton (e.g., Mei, 1997; Kusky and Li, 2003) forming the southern part of the Northern Hebei orogen (Fig. 3). The rocks occur broadly within three terrains namely, the Jining–Liangcheng–Fengzhen, Daqingshan–Wulashan and Helanshan (Fig. 6). The main rock associations in Jining–Liangcheng terrain are khondalites and S-type granites with minor metagabbro (Figs. 6 and 7). The S-type granite belts are largely controlled by ENE striking sinistral strike-slip shear zones. To the west, the Daqingshan–Wulashan terrain is made up of reworked granulite–charnockite complex, khondalites and granites (Fig. 6). The Daqingshan–Wulashan terrain is dominated by nearly west- to east-trending structural grains. Further to the west, the Helanshan terrain also consists of khondalites with an S-type granite association. This terrain is characterized by ENE-striking foliation, associated with a nearly EW- to WNW-trending structural dome. The common association of the khondalite terrains with sinistral shear zones that host syntectonic emplacement of S-type granites have been correlated with Paleoproterozoic reworking episodes along the northern margin of the North China craton. A molasse basin, older than 1.90 Ga, lies along the northern margin of the belt. The khondalite belt is succeeded to the south by amphibolite facies metasupracrustals and S-type granites. The Neoarchean structural patterns and metamorphic lithology and greenstone belts have been locally preserved in the weakly reworked basement. To the south, the nearly east to west-striking strike-slip to thrust shear zones are uniformly superimposed on the Neoarchean domains of the NCC. Mafic dike intrusions of ca. 1.80–1.76 Ga occur in all the three terrains.

The major rock types in the khondalite belt comprise garnet- and sillimanite-bearing granulite grade metapelites, garnet- and biotite-bearing leptynites, marbles and calc-silicate rocks, broadly identical with the lithologic units in the khondalite belt of southern Kerala in India metamorphosed during the Late Neoproterozoic-Cambrian times (cf. Santosh et al., 2006b). Condie et al. (1992) and Li et al. (2000) summarized the geochemical characteristics of the khondalites from North China craton, and described features typical of post-Archean shales. These rocks are characterized by enrichment of large ion lithophile elements, low Zr–Hf–Sr contents, significant enrichment in LREE and negative Eu anomalies. The khondalite suite of lithologies is thought to be derived from the high-grade metamorphism of interlayered psammitic, psammopelitic, pelitic and carbonaceous sediments deposited in a shallow sea upon a cratonic shelf. Graphite deposits are common in many localities within the khondalite belt. The voluminous S-type granites containing garnet in most places may represent extensive partial melting during the high-grade metamorphism of the thick sedimentary pile and melt movement. The metasedimentary sequence overlies a high-pressure granulite belt, the Hengshan belt, which extends over 700 km (cf. Kusky and Li, 2003).

Zircons from the Jining group khondalites have yielded two distinct age populations: 2.30–2.60 Ga and 1.85–2.00 Ga; the older ages are interpreted as the detrital zircon age and the younger ones as the metamorphic age (e.g., Kusky and Li, 2003). A number of granite bodies with ages ranging from 2.2 to 1.9 Ga are emplaced within the Jining khondalite terrain, particularly the voluminous S-type granites which were possibly generated through anatexis of the pelitic sediments. These S-type granites from the khondalite terrains of southern Inner Mongolia at the northwestern part of the North China craton have yielded zircon U–Pb ages of 1971±60 Ma and 1837±40 Ma, Pb–Pb ages of 1975±23 Ma and 1893±14 Ma and Rb–Sr isochron ages between 1970 and 1840 Ma (Guo et al., 1999). Among the granites, two types have been recognized, including garnet granite and leucogranite. The formation age of the garnet granite from the Sanggan area has been estimated as 1836±18 Ma from zircon U–Pb concordia; while the leucogranites gave an upper intercept age of 1912±98 Ma (Guo et al., 1999). Detrital zircons from the garnet–sillimanite–plagioclase gneiss (khondalite) yielded an age of 2130 Ma, while the metamorphic zircons are dated at 1872 Ma (Wu et al., 1998a,b). Monazite dating of khondalites with spinel+quartz UHT assemblage yielded two age peaks at 1927±11 Ma and 1819±11 Ma (Fig. 9), correlated to distinct thermal perturbation during the prograde and peak stages of extreme crustal metamorphism in this belt (Santosh et al., 2006a).

In a recent study, Santosh et al. (in press) reported U–Pb–Th electron microprobe analysis of monazites in textural association with ultrahigh-temperature (UHT) granulites occurring within the khondalite belt and constrained the timing of metamorphism as 1917±48 Ma. Since the khondalites as well as the Mg–Al granulites experienced extreme metamorphism at $T>950$–1000 °C, the monazite ages fix the timing of the UHT event in North China craton to be Paleoproterozoic. In another recent study, Wan et al. (2006) reported U–Pb zircon ages from various Paleoproterozoic metasedimentary units in the North China craton. These rocks contain detrital igneous zircon grains with ages ranging from 3.0 to 2.1 Ga, with the majority displaying an age between 2.3 and 2.0 Ga. According to these authors, the latter age group represents a series of magmatic events that occurred between the formation of the Archean basement and deposition of the sediments. The metasedimentary rocks analyzed by Wan et al. (2006) occur as two associations; older volcano-sedimentary units that formed between 2.37 and 2.0 Ma, and younger sedimentary units that formed mainly between 2.0 and 1.88 Ga. All these rock associations were then subjected to metamorphism during the Late Paleoproterozoic (1.88 and 1.85 Ga) tectonothermal event. Wan et al. (2006) correlate this age with a continent–continent collision event that led to the amalgamation of the North China craton. Wan et al. (2006) did not analyze any UHT rocks from the North China craton. However, the zircon SHRIMP ages for the Late Paleoproterozoic tectonothermal event (1.88–1.85 Ga) broadly correlate with the ca. 1819 Ma obtained from monazites by Santosh et al. (2006a,b) from the khondalite belt in North China craton.

Liu et al. (2006) analyzed U–Th–Pb in monazites from the low- to medium-grade Luliang and Wutai Complexes Central Orogenic Belt. The data revealed five age populations: (1) 1940–1938 Ma, (2) 1880–1847 Ma, (3) 1795–1755 Ma, (4) 1720–1703 Ma and (5) ~1648 Ma. Of these, the first four have also been recorded in

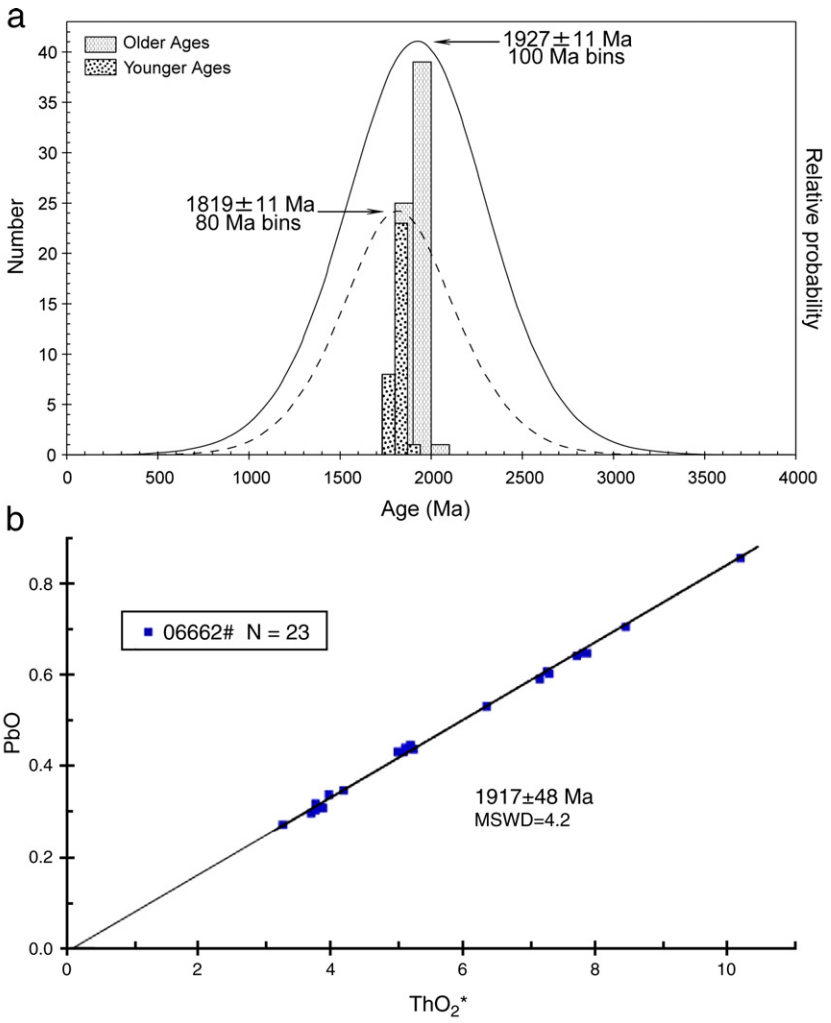


Fig. 9. (a) Probability density plots and histogram for monazites from khondalites of North China craton. Ages refer to prominent peaks in the probability density plots, n = number of analyses (after Santosh et al., 2006a). (b) PbO vs. ThO_2^* plots of monazite data from sapphirine-bearing Mg–Al granulites of North China showing linear data trend and isochron with an age 1917±48 Ma (after Santosh et al., in press).

the Wutai Complex. The oldest age range of 1940–1930 Ma is interpreted to record the widespread emplacement of mafic dikes in rocks of the Luliang and Wutai complexes. The age range of 1882–1822 Ma is interpreted by Liu et al (2006) as the age of the major metamorphic event caused by amalgamation between the Eastern and the Western Blocks. The age range of 1795–1755 Ma is consistent with emplacement of large scale unmetamorphosed mafic swarms at 1800–1765 Ma, interpreted as the time of post-orogenic extension. The 1720- to 1703-Ma and ca. 1648-Ma ages are considered to date later multiple stages of hydrothermal alteration, since monazites with such young ages occur only along fractures in older monazite grains and at the rims. Liu et al. (2006) considered their data to support a tectonic model for the evolution of the North China craton involving the collision of discrete Eastern and Western Blocks along the Trans-North China Orogen at ~1.85 Ga and post-collisional extension in the period 1795–1755 Ma. Although Liu et al. (2006) did not study any UHT granulite assemblages, it is interesting to note that some of their monazite ages overlap with the age ranges from monazites in the UHT granulites of North China craton reported in Santosh et al. (2006a,b, in press). Liu et al. (2006) also did not consider whether their data may be consistent with a continent–continent collision along the Northern Hebei Orogenic belt instead of in their Trans-North China orogen. Since the metamorphic P-T-t data can not distinguish the orientation of major shear and collisional belt, but only the relative depth of rock units in the crust, we agree with their general conclusion of a collision at that time but dispute the location of the collisional orogen.

The granulite terranes of the North China craton show a common structural association. The oldest, Neoarchean structures strike generally north-northeast to northeast and are cut by circa 1.85–1.80 Ga east-west striking shear zones. One of the best examples of these cross-cutting relationship is the in the Hengshan (Fig. 5), where northeast striking foliations in circa 2.55 Ga gneisses are cut by the circa 1.8 Ga east-west striking Zhujiafang shear zone that emplaces high-pressure granulites on the north over medium pressure granulites to the south (O'Brien et al. 2005). The boundaries to the Hengshan uplift are controlled by the northeast striking faults of the Cenozoic Shaanxi graben system, perhaps re-activating older Mesozoic or Proterozoic

structures. These cross-cutting relationships show the complex structural history that these rocks have experienced, including orogenic events at 2.5 Ga, 1.9–1.85 Ga and Mesozoic to active tectonics related to Pacific subduction and the collision of India with Asia. Thus, the rock record does not support the contention of Zhao et al. (2000, 2002a,b, 2005) that the northeast striking shear zones are boundaries to an ocean that was open from the 2.5 to 1.8 Ga, but rather, strengthens the concept that the region records a complex history of several orogenic events with clear cross-cutting structural and superimposed stratigraphic relationships (e.g., Kusky and Li, 2003; Kusky et al., 2006a,b). At 1.9–1.85 Ga, the northern margin of the NCC was experiencing a major collisional and thickening event while the COB was behaving largely as a strike-slip belt in the orogenic foreland.

3.3. UHT metamorphism at 1.9 Ga in the NHO

High-pressure (HP) and ultrahigh-temperature (UHT) metamorphic assemblages have been described from granulites in the Bao'an, Hongshaba, Xumayao and Tuguiwula areas within the khondalite belt (Figs. 3, 6 and 7). In the Tuguiwula area interlayered aluminous metasediments outcrop in association with graphite-bearing garnet-biotite gneiss, garnet-bearing felsic gneiss and S-type granite (Santosh et al., 2006a, in press). The rocks show prominent compositional layering with garnet-sillimanite±cordierite±spinel-rich dark bands and quartzofeldspathic leucosome layers indicating partial melting. The khondalite layers commonly range in thickness from a few meters to several tens of meters and show polyphase deformational structures. Early NW trending and a later SW trending lineations are identified. The garnet–gneiss belts are strongly folded and the enclosing S-type granites also suffered strong ductile deformation with a sinistral sense of shear. At least four generations of deformation can be recognized with the khondalites involving D_1early thrusting; D_2 extension; D_3 strike-slip shear deformation (mainly sinistral); and D_4 intrusion of mafic dikes.

The Bao'an area (Fig. 7) is characterized mainly by S-type granites with abundant melanocratic residual bands of metapelites. At least four mafic dikes cut the S-type granites in this area, ranging in width from 1.5 to 5 m. The S-type granite–khondalite association is also exposed in the Honshaba area, where the khondalite band shows strong folding. Garnet bearing granites and khondalites underwent strong ductile shear deformation and were partly mylonitized in the Xumayao area. The felsic bands show stretching, folding and development of S_2 foliation. Garnet-bearing dark grey colored mylonitized gneiss appears in Zhaohaogou area, with large bands and relics of aluminous metapelites. Melanocratic residual bands rich in garnet and sillimanite occur within partially melted khondalites at Tuguiwula area.

Santosh et al. (in press) reported for the first time the occurrence of ultrahigh-temperature Mg–Al granulites from the Tuguiwula area, where these occur as several centimeter- to decimeter-sized concordant bands and layers within khondalites. The UHT indicator assemblages (Fig. 10) in these rocks include equilibrium sapphirine+quartz, high alumina orthopyroxene+sillimanite+quartz and high temperature perthites. The surrounding khondalites also carry spinel+quartz equilibrium assemblage. The history of prograde to peak metamorphism of these rocks is indicated by inclusions of sapphirine, spinel, quartz and sillimanite within garnet. Whereas the stability of sapphirine+quartz and orthopyroxene+sillimanite+quartz in the matrix assemblage suggests T>1000 °C and P>10 kbar peak metamorphism, conventional geothermobarometric estimates confirm the ultrahigh-temperature nature and also trace the retrograde conditions (930–970 °C at P>10 kbar—Al in Opx; 900–1000 °C—perthite; 930–990 °C—Grt-Opx; and 910–940 °C—sapphirine-spinel). An evaluation of the assemblages and textures using appropriate petrogenetic grids indicate that following peak ultrahigh-temperature conditions, the rocks underwent initial isobaric cooling and subsequent isothermal decompression. Santosh et al. (in press) interpreted these trajectories to be part of an overall anti-clockwise P-T evolution (Fig. 11). Dating of monazites in the UHT assemblage yielded ages of 1917±48 Ma, comparing well with other ages of 1927±11 on monazites from surrounding terranes (Fig. 9). Santosh et al. (in press) relate these features to collision of the northern margin of the NCC during assembly of the Paleoproterozoic supercontinent Columbia.

4. Archean granite–greenstone terrains southeast of the Datong-Wuqi fault

Neoarchean basements with overlying Paleoproterozoic cover sequences are well preserved southeast of the Datong-Wuqi fault at Wutai Mt., Luliang Mt., West Shandong, Songshan Mt. and Zhongtiao Mt. (Wu et al., 1998a,b; Li and Kusky, 2003; Kusky and Li, 2003; Li et al., 2001a; Zhang, 2002; Bai et al., 1996). Subgreenschist facies Paleoproterozoic sequences (2.40–2.0 Ga) rest unconformably on the cratonic basement in open folds. The early sedimentary cover in the Wutai area, represented by the Dongye Subgroup of the Hutou Group (2.45–2.0 Ga), was originally deposited in rift to shallow marine basins, with minor volcanic interlayers (Li and Kusky, 2007-this issue). Moreover, late Paleoproterozoic molasse (2.00–1.90 Ga) deposited in the foreland basin in southern to central parts of the NCC comprises the Guojiazhai, Yejishan and Danshanshi subgroups molasse, which are interpreted as distal deposits from the Paleoproterozoic orogeny in the NHOB (Bai et al., 1996; Li et al., 2001b; Kusky and Li, 2003).

In contrast, the Archean basement of the southeastern part of NCC was rarely affected by the late Paleoproterozoic orogenic episodes, such as Wutai–Taihang, Eastern Hebei, and Western Shandong metamorphic terrains. Whereas the Neoarchean greenstone belts and gneiss terrain are well preserved, their Paleoproterozoic sedimentary cover has not been completely preserved because of long-term uplift and erosion. Both granulite–gneiss terranes and granite–greenstone belts commonly yield zircon U–Pb ages older than 2.50 Ga, and rarely record late Paleoproterozoic events. They show characteristic Neoarchean gneiss domes and greenstone belt synforms (Zhang et al., 1998; Wu et al., 1998a,b), rarely reworked by the Paleoproterozoic tectonothermal episodes. As indicated on the map of aeromagnetic anomalies (Yuan, 1995), the southeastern

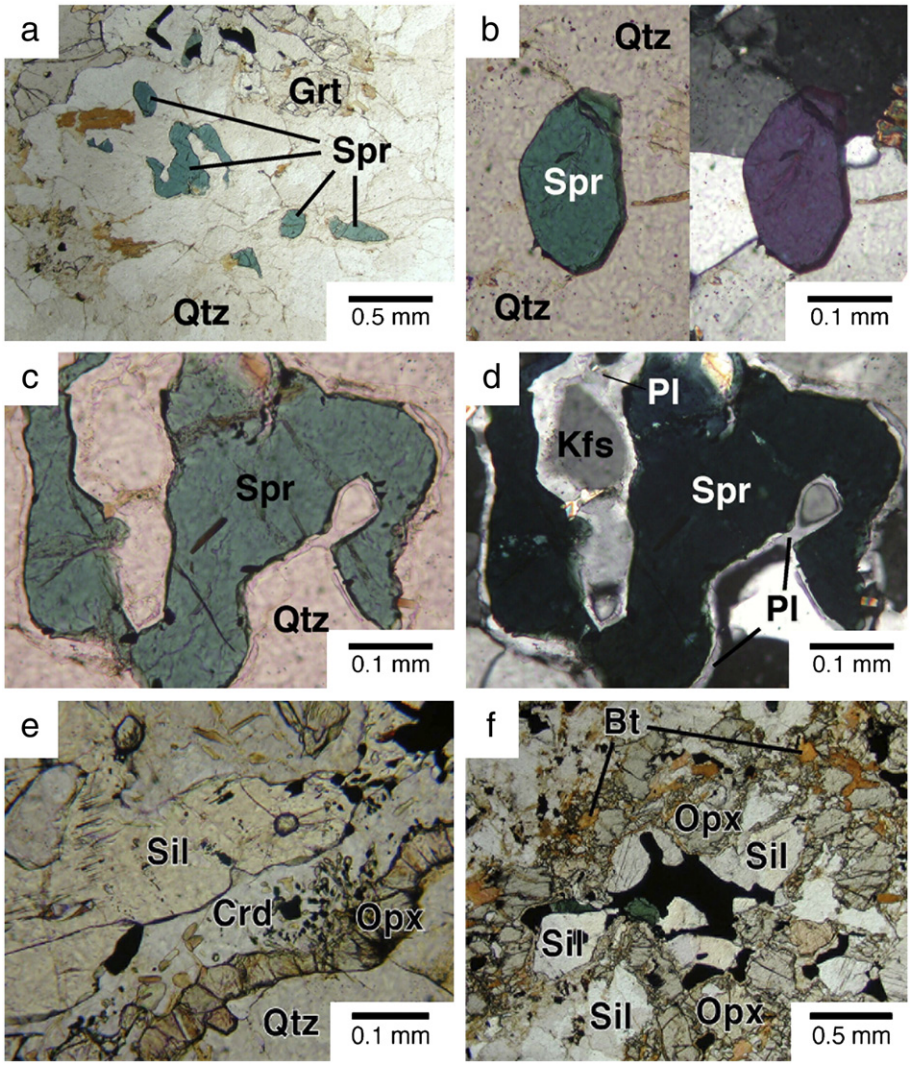


Fig. 10. Photomicrographs of sapphirine-bearing granulites from North China craton (after Santosh et al., in press). Mineral abbreviations are after Kretz (1983). (a) Bluish sapphirine scattered in quartzofeldspathic layer of Mg–Al granulite. (b) Left: Equilibrium sapphirine+quartz assemblage. Right: Same as the left photograph, crossed polars. (c) Sapphirine and quartz separated by K-feldspar and plagioclase. (d) Same as panel c, crossed polars. (e) Cordierite+orthopyroxene corona between sillimanite and quartz. (f) Orthopyroxene+sillimanite+ilmenite/magnetite assemblage surrounded by retrograde biotite.

part of the NCC basement preserves intact dome-like structures, rarely disturbed by late deformations.

In summary, depending on the amount of orogenic reworking, the early sedimentary cover exhibits different metamorphic facies spatially. Adjacent to the NHOB in the northwest, they are metamorphosed into granulite facies khondalites with synchronous intrusion of S-type granites. To the south, metamorphic grade decreases gradually, with the presence of amphibolite facies gneisses in the Luliang Mt. area (Li et al., 1999). In the Wutai–Taihang–Songshan Mountains, in the far southwest, it is characterized with only greenschist facies to barely metamorphosed successions.

5. Extensional setting and episode between 1.85 and 1.70 Ga in the NCC

At the end of the Paleoproterozoic (between 1.85 and 1.70 Ga), the NCC began to be dominated by an extensional tectonic regime, characterized by the development of several rift-aulacogen systems (Figs. 8 and 13), the emplacement of mafic dike swarms (1.80–1.77 Ga) on a large scale, and anorogenic magmatism (rapakivi granites, anorthosites, gabbros, ultramafic bodies, isolated granites and pegmatites). While in an extensional setting, the Archean metamorphic basement was ultimately uplifted to the Earth's surface, underwent cooling and retrograde metamorphism and the unmetamorphosed cratonic cover began to be deposited (Kusky and Li, 2003; Peng et al., 2005, 2007-this issue).

5.1. Graben-rift systems

The Mesoproterozoic aulacogen-rift systems (<1.85 Ga) cut across both the marginal areas and interior of the NCC (Figs. 8 and 13). At least five Mesoproterozoic aulacogen-rift systems have been identified in the NCC basement. In the northeastern part of the craton, the Yanliao-Taihang aulacogen (YTA) is well

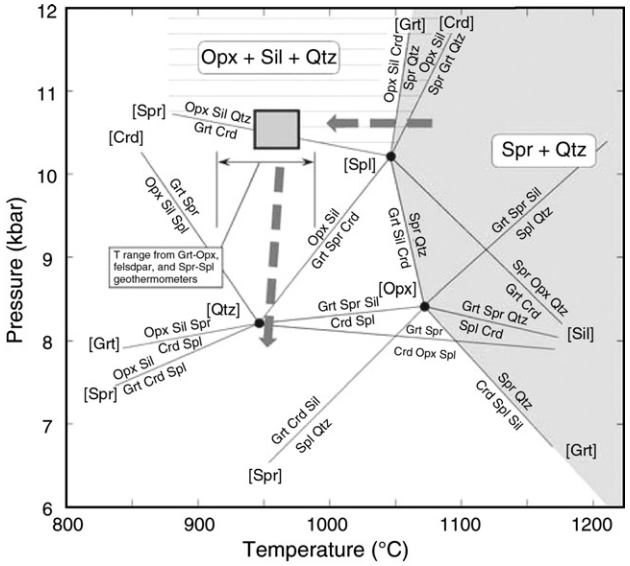


Fig. 11. Petrogenetic grid in the FMAS system (modified after Hensen and Harley, 1990; Harley, 1998). The stability fields of sapphirine+quartz and orthopyroxene+sillimanite+quartz are shown. Arrows indicate the approximate P-T trajectories inferred from sapphirine-bearing granulites reported in this study. The square indicates the P-T condition calculated from Al-rich orthopyroxene.

preserved, forming three distinct branches. Along the southern margin of the NCC three aulacogens have been identified, extending into the interior with narrow triangular shapes. Along the northern margin of the NCC, two rifts formed, with their boundaries parallel to its present northern limit of the craton.

(1) The Yanliao-Taihang aulacogen (YTA): As indicated by its thickness contours, it mainly consists of three branches, within which the 1.85- to 1.40-Ga-old Changcheng System was deposited (Figs. 8 and 12). Its western branch strikes ENE, the northeastern branch in a NE direction and the southern branch in a NNE direction. Rocks of the Changcheng System in the YTA were deposited mainly on the Archean basement, although at many sites (east Hebei and west Liaoning), are overlain unconformable by younger strata (Fig. 8; Table 2). The age difference between the aulacogen sequences and the metamorphic basement is up to 500–700 Ma. To the northeast, the YTA is truncated by a late ENE-trending fracture zone along the northern margin of the NCC, which may originally have been connected with an ocean northeast of the NCC. The southern branch of the YTA gradually narrows to the south.

(2) The Baiyun Obo rift (BR) and Zhaertai aulacogen (ZA): These east-west striking structures represent a boundary-parallel rift-aulacogen system that formed along the northern margin of the NCC. The Baiyun Obo and Zhaertai Groups (1.80–1.40 Ga) were deposited within these rifts respectively, unconformably overlying the Archean to Paleoproterozoic metamorphic basement (Qiao et al., 1991). To the north, the BR was truncated and reworked by the Paleozoic Mongolian-Central Asian orogenic belt. The ZA is characterized by development of volcanics but failed in the Mesoproterozoic (1.40 Ga), whereas the BR evolved into a passive continental margin in the late Mesoproterozoic.

(3) Helan aulacogen (HA): The Helan aulacogen strikes N-S, in the southwestern part of the NCC, and becomes narrow to the north. It is truncated by the early Paleozoic Qilian orogenic belt to the south. Its sedimentary infill unconformably overlies the Archean to Paleoproterozoic metamorphic terrain, with the thickness contours increasing from north to south. Gabbro-diabase dike swarms intrude the lower part of the sequence (Lin et al., 1995).

(4) The Shanxi-Shanxi aulacogen (SSA): The Shanxi-Shanxi aulacogen-graben system (note that this is not the same as the Cenozoic Weihe-Shanxi graben system that runs through the center of the craton) forms prominent topographic features that were confirmed by seismic exploration (Sun et al., 1985; Zhang et al., 1999). These graben strike NNE and tear apart the southern margin of the NCC, at right angles to the cratonic margin. To the south it is truncated by the late Proterozoic North Qinling orogenic belt, and in the interior of the NCC it becomes narrow in width and eventually disappears to the north. The SSA has two parallel branches, one in the east and one in the west. The thickness contours of the Mesoproterozoic sequences within the aulacogen trend NNE and are controlled by boundary faults. The eastern branch of the SSA is well developed with a thick sedimentary sequence (Wu et al., 1998a,b). Moreover, several NE- and NW-striking Mesoproterozoic graben were discovered by seismic exploration in the central part of NCC and correlate with the Mesoproterozoic aulacogen system (Wu et al., 1998a,b).

(5) The Xionger-Zhongtiao aulacogen (XZA): The XZA is preserved as a triangular form and is located in the southern portion of the NCC. To the interior of the NCC, the XZA becomes narrow and eventually disappears. The geological distribution of the Xiyanghe Group and Xionger Group within the aulacogen is controlled by fractures as indicated by thickness contours. Both groups are characterized by the development of intracontinental bimodal volcanics. The sequences rest unconformably upon the Archean–Paleoproterozoic metamorphic basement. Andesite from the lowermost volcanic-sedimentary formation, yields a U/Pb age of c.a. 1840±14 Ma (Sun et al., 1996; Sun and Hu, 1993), representing the age of initial extension with the XZA.

There are thick volcanic sequences in the Xionger-Zhongtiao aulacogen (Xiyanghe and Xionger Groups), that are different from the Yanliao-Taihang aulacogen that is dominated by sedimentary sequences. It is therefore suggested that the Xionger-Zhongtiao aulacogen must have undergone severe extension early in its development. Actually, the Xionger-Zhongtiao aulacogen is genetically related to the opening of the ancient North Qingling oceanic basin to the south (Sun et al., 1985). It represents a failed arm of a triple junction, as the other two rift segments opened as part of the oceanic basin.

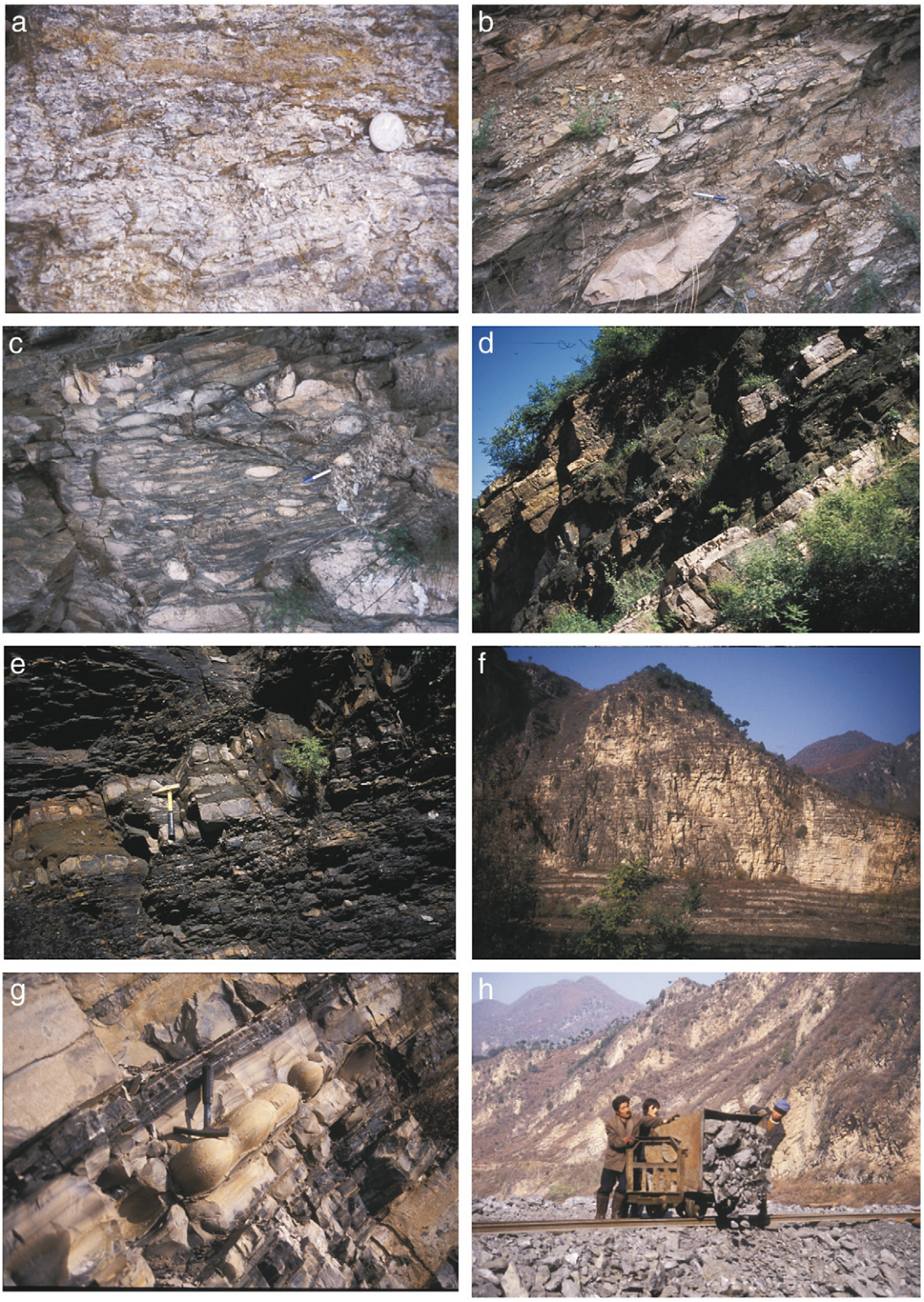


Fig. 12. Photographs of rocks discussed in text. (a) Circa 2.7–2.55 Ga metacarbonate and metapelites of the passive margin sequence developed on the western margin of the eastern block; (b, c) conglomerate of the Upper Wutai Group, deposited in the foreland basin related to circa 2.5 collision of the Eastern and Western blocks; (d) interbedded sandstones and shales of distal facies of 1.85 Ga foreland basin; (e) limestone interbedded with black shales of Chang Cheng Series, distal facies of basal Chang Cheng Series of circa 1.85–1.8 foreland basin; (f, g) deep-water continental rift facies deposits of the Gaoyuzhuang Formation of the Chang Cheng Series, including dolostone, sandstone, black shale, rhyolite, basalt and sulfide horizons dated at 1.425 Ga (Pb–Pb, see Li and Kusky, 2007-this issue) of the Chang Cheng Series; (h) local miners dumping sulfide ore, with Gaoyuzhuang Formation visible in strata dipping to left in background.

The five rift-aulacogen systems discussed above are associated with voluminous felsic extrusive magmatism. Sedimentary sequences deposited in the rift-aulacogens include mature clastic sediments, chiefly quartz arenites, shales and shallow marine carbonates, particularly in the upper, thermal subsidence phase deposits of these rifts. Currently, several ages older 1.80 Ga have been obtained on their basal formations, for example, an andesite of the Xiyanghe Group in the Xionger-Zhongtiao aulacogen yielded a U–Pb zircon age of 1840±14 Ma (Sun and Hu, 1993). It is therefore suggested that the Xionger-Zhongtiao aulacogen initiated at about 1.84 Ga. Since at least three aulacogens are present along the southern margin of the NCC (SSZ, XZA and HA) and strike into the interior of the NCC, they are regarded as different branches of the same aulacogen system that was initiated about 1.84 Ga ago. Furthermore, the shale-siltstone sequence from the basal formation in the Yanliao-Taihang aulacogen yielded a whole-rock Pb–Pb isochron age of 1848+57/−58 Ma (Yu et al., 1994), which provides an older age limit for the YLA. The Baiyun Obo rift it is not younger than 1728±5 Ma as constrained by the U–Pb zircon age for basalt in the BR (Wang et al., 1996).

5.2. Mafic dike swarms

Mafic dike swarms are mainly distributed at the junction between the northern and southern aulacogen systems mentioned above, in the central portion of the NCC (Fig. 8). At least three mafic dike swarms are recognized, the first striking WNW to EW, the second NW and the third NE (Halls et al., 2000; Hou et al., 2005; Peng et al., 2005, 2007-this issue). The NW-striking Taihang mafic dike swarm is the largest in scale, typically forming giant dike swarms over 20 km wide and 300 km long, which occur mainly in Taihang Mountain and extends to southern Inner Mongolia in the northwest. Mafic dike swarms also cut the western Shandong metamorphic terrain, where they also strike NW (Hou et al., 2003, 2005). Therefore, the Taihang–Hengshan mafic dike swarm is more than 1000 km long along strike, extending almost across the entire North China craton. The dikes are cut by late fractures at both ends, demonstrating that the NCC is part of a continuous ancient cratonic block.

NW-striking mafic dike swarms mainly intruded into the early Paleoproterozoic to Archean metamorphic basement, and locally into the lowermost sedimentary formations in the YTA, indicating their emplacement after the onset of extension. Isotopic ages of baddeleyite and zircon from several NW-striking mafic dikes of the Taihang swarm are bracketed between 1.80 and 1.77 Ga (Peng et al., 2004, 2007-this issue; Liao et al., 2003, Hou et al., 2005; Li et al., 2001a,b; Halls et al., 2000). The data provide key time constraints for their ages of emplacement, suggesting that their generation was associated with the development of the aulacogen-rift system at about 1.80 Ga. Linear mafic dike swarms are commonly related to continental rifting, which have been documented in many continents (Ernst and Buchan, 2001). The onset of rift-related basaltic magmatism is sometimes delayed as much as 15–30 Ma after the onset of extension as in North America (Ernst and Buchan, 2001)—the Taihang mafic dike swarm also falls within same age range (about 30 Ma) after rifting at about 1.80 Ga.

Lateral emplacement has been most clearly demonstrated for the Taihang mafic dike swarm (Fig. 8), where magnetic fabric data and field observations indicate horizontal (lateral) flow out to distances of more than 100 km (Halls et al., 2000; Hou et al., 2003). As their country rock is mainly metamorphic basement, these spectacular dike swarms are likely to have fed flood basalts in large igneous provinces, where the surface basalts have been diminished or removed by erosion. As their orientation is roughly parallel to the southwestern rifted margin of the NCC, their emplacement may be related to the stress field on a cratonic scale, rather than a local stress field. We summarize the isotopic ages of the Taihang NW-trending mafic dike swarm and anorogenic magmatism in Table 1.

5.3. Anorogenic plutonic belts

The early Mesoproterozoic anorogenic plutonic belts are distributed in the central portion of the Yanliao-Taihang aulacogen and its marginal basement (Fig. 13). Their distribution was controlled by aulacogen-related fractures. The anorogenic plutonic belts are mainly intrusive into Archean terrains of the NCC, with a large difference of age (0.6–0.8 Ga) between them. The relevant rock assemblages consist of rapakivi granite, granite, anorthositic–gabbroic–dioritic intrusions, which yield an age range of 1.80–1.70 Ma (Xie, 2005; 1994; Song, 1992; Hu et al., 1990; Sun and Hu, 1993, Li and Wang, 1997; Wang et al., 1996; Wang, 1991). Locally, ultramafic intrusions that were emplaced into its west branch yield a Sm–Nd whole-rock age of 1837±57 Ma (Chen et al., 1996). The apparent coupling between sedimentation in the aulacogen and intrusions within the basement proves that the tectonothermal episode at 1.80–1.70 Ga occurred in an extensional tectonic setting. As constrained by U/Pb dating, the duration of anorogenic magmatism is about 100 Ma, a longer time than that for the emplacement of the Taihang mafic dike swarms. So, the mafic dike swarms were associated with onset of rifting, followed by the intrusion of anorogenic plutonic belts associated with the initial development of rift-aulacogens or crustal thinning.

6. Paleoproterozoic tectonic framework of NCC (1.80 Ga)

The Paleoproterozoic rifting of the North China craton affected both the Archean craton and Paleoproterozoic Northern Hebei orogenic belt in the northwest. The distribution of the aulacogen-rift systems suggests that both its southwestern and northern margins formed strongly extended continental margins at about 1.80–1.70 Ga. Along its southwest margin, at least three failed branches of the aulacogens filled with thick volcanics ruptured the interior of the craton. Therefore, we suggest that the southwest part of NCC was a passive margin facing southwest at 1.8 Ga, resulting from intense break-up of a Paleoproterozoic continental land mass.

On the northern margin of the NCC, rift branches are nearly parallel to the cratonic boundary and structural grain of NHOB. In the interior of the NCC, the Yanliao-Taihang aulacogen with three complete arms cut across the basement. Moreover, the Taihang mafic dike swarm is aligned along a NW direction

Table 1
Isotopic ages of the Taihang NW-trending mafic dike swarm and anorogenic magmatism

Rock units and sites	Isotopic ages and dating methods	Country rocks and geological settings	References
Mafic dike swarm, in Hengshan	1769±2.5 Ma (conventional U–Pb zircon)	Neoarchean gneiss–granulite	Li et al. (2001a,b), Halls (2000)
Mafic dike swarm, at Datong	1778±3 Ma (SHRIMP U–Pb zircon)	Neoarchean gneiss and Paleoproterozoic khondalites	Peng et al. (2004, 2007-this issue)
Mafic dike swarm, in southern Taihang Mt.	1780.7±0.5 Ma (Ar–Ar)	Archean gneiss	Liao et al. (2003)
Mafic dike swarm in western Shandong	1844.3±8.9 Ma 1830±17 Ma 1790 Ma (all SHRIMP U–Pb zircon)	Neoarchean granite–greenstone	Hou et al. (2005)
Rapakivi granite, In North and northwest Beijing	1706±15 Ma 1691±2 Ma 1697±2 Ma (all conventional U–Pb zircon)	Neoarchean granulite–gneiss metamorphic terrain (2600–2500 Ma)	Song (1992), Yu et al. (1994)
Anorthosite complex in North Hebei	1715±6 Ma 1693±7 Ma 1730±16 Ma (all conventional U–Pb zircon)	Paleoproterozoic supracrustal sequence-pluton	Zhao et al. (2003)
Xionger Group volcanics Xiyanghe Group volcanics	1840±14 Ma (SHRIMP U–Pb zircon)	Rift	Sun and Hu (1993)

where many dikes intruded into the junction area of the rift-aulacogen systems mentioned above (Fig. 13), representing the aborted branches of rifts. As indicated by research on magnetic fabrics and magma flow structures in the field, it is suggested that magma moved laterally from southeast to northwest to feed the dikes. The magma chamber(s) center was roughly located at the southeast end of mafic dike swarm at Taihang (Hou et al., 2005), which coincides with the central part of the domal uplift of Yanliao-Taihang aulacogen before the 1.80-Ga extension, and/or to the south, centered in the Xionger area (Peng et al., 2005, 2007-this issue). Some layered mafic intrusions of the same age are preserved at Taihang Mt, supporting the interpretation of a plume head beneath that area. So, it is suggested that these rock complexes represent the initial plume impingement areas and extension within the NCC that enabled the emplacement of Taihang mafic dike swarms.

7. Uplift of cratonic basement before extension at 1.80 Ga

Determining whether the NCC underwent appreciable uplift prior to Mesoproterozoic rifting is very important to constrain its tectonic history (e.g., Sengor and Burke, 1978) during this period, which can be analyzed from its stratigraphic sequences in the rift-aulacogens, and their basal unconformities. In the central area of Yanliao-Taihang aulacogen, such as eastern Hebei-northern Beijing, the basal formations (Changcheng system) commonly rest unconformably on the Archean high-grade metamorphic basement (Figs. 8, 12 and 13) and display a large age difference (>600–700 Ma) between their deposition and the age of the metamorphic basement. In the western and southern marginal areas of the Yanliao-Taihang aulacogen, the Neoarchean basement with Paleoproterozoic sequences was overlain unconformably by the Mesoproterozoic sedimentary sequences. The thickness of missing sequences along the unconformity between the Changcheng System and underlying Paleoproterozoic strata evidently decreases away from the center to the edges of a paleo-dome, centered in the center of the craton, as at the edges of the YTA the two sequences are only separated by a 100-Ma-long hiatus. Similar domal uplifts are shown by mafic dike swarms of this age, from central areas to outside of the YTA (Yanliao-Taihang aulacogen), their intruded country rocks change from Neoarchean high-grade metamorphic terrain to lower grade terrain with overlying Paleoproterozoic sequences (Table 1).

As documented by the unconformity at the base of the Mesoproterozoic sequences within the YTA (Yanliao-Taihang

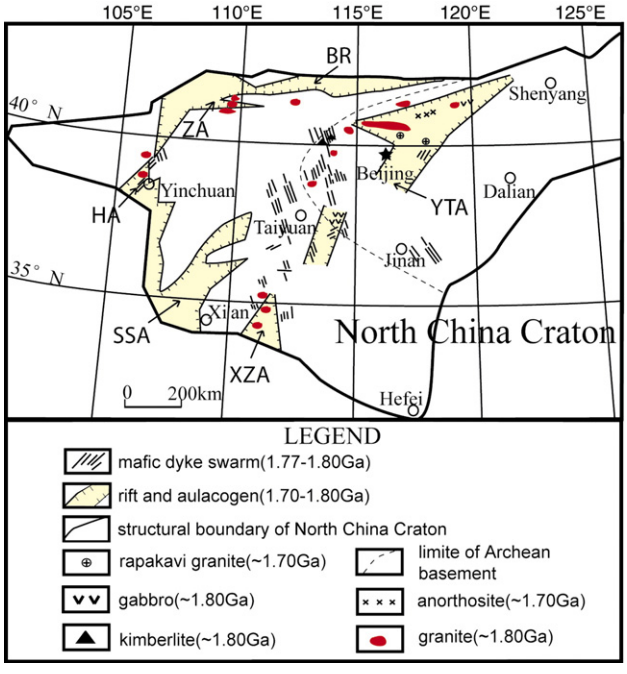


Fig. 13. Sketch map showing the tectonic framework of NCC in earliest Mesoproterozoic (1.85–1.70 Ga). (Modified from Li et al., 2000).

aulacogen) (Figs. 8 and 13), it is apparent that an extensive uplifted area coincided with its central part before rifting took place. The domal uplift reaches 1000 km or more in diameter, with a core area 600 km in diameter. The amplitude of the uplift decreased to the outside edge of the dome area, resulting in different erosion levels. From analysis of stratigraphic relationships it is suggested that the central area around the Yanliao-Taihang aulacogen, including Eastern Hebei, West Shandong and North Shanxi, etc., underwent significant uplift at the end of the Paleoproterozoic (1.80–1.70 Ga). Since Paleoproterozoic sequences were widely eroded in these areas, with Archean terrains exposed to the Earth surface. In the lower part of the Changcheng System succession, basal conglomerates about a thousand meters thick were deposited. On the outside of the Yanliao-Taihang aulacogen, lower grade metamorphic terrain and overlying Paleoproterozoic sequences have been preserved on a large scale, such as in the Wutai–Taihang Mountains, indicating that the erosion level became gradually shallower with time. Hence, the thickness of eroded sequences was up to 10 km prior to deposition of the Changcheng System in the core of the dome, based on the estimate of relict thickness of the Paleoproterozoic succession. The initial continental extension of the NCC occurred during the domal uplift at about 1.85–1.80 Ga.

The older age limit for rifting-related volcanic-sedimentary sequences in the XZA is 1840±14 Ma (Table 1), which represents the upper age limit for the uplift of the metamorphic basement to the surface. In the extensional setting, the North China metamorphic basement was extensively uplifted and cooled; it involves at least two stages of tectonic evolution:

(1) Regional doming and uplift prior to the initial rifting, interpreted to result from impingement of a mantle plume, throughout the region.
(2) The high mountain ranges can be very elevated, through considerable tilting in the marginal parts of rifts, followed by the onset of break-up and fragmentation with uplift of high-grade metamorphic rocks in gneiss domes beneath extensional detachments.

8. Regional tectonic setting of mafic dike swarm

The extensional break-up of the northwestern part of the North China craton at 1.80–1.70 Ga was influenced by the reactivation of preexisting orogenic structures, and was controlled by its nearly east-west to northeast-southwest structures.

In the interior of the craton, remote from the North Hebei Orogenic belt, rift trends change significantly, and the contemporaneous Taihang mafic dike swarms were intruded into the failed arms of triple junctions of Yanliao-Taihang aulacogen and Xionger-Zhongtiao aulacogen (Halls et al., 2000; Hou et al., 2003), which was at a high angle to the NHOB. As constrained by field observation and geochronology, the emplacement of the NW-striking Taihang mafic dike swarm occurred slightly later than deposition of the basal formations of the aulacogen-controlled sequences. Thus, it is suggested that their emplacement was controlled by the rift-aulacogen systems and marks the brittle fragmentation of the NCC. The continuous compression from earlier plate boundaries or doming from an underlying mantle plume played an important role for the initial extension of the NCC. The tectonic development of the craton at this time was controlled by the interaction between plumes and plate tectonics.

Furthermore, both the graben-rift system and Taihang mafic dike swarms are truncated by late fractures along the cratonic borders, and the rift-aulacogen systems mainly intruded in the marginal areas of the NCC. It is therefore proposed that the NCC is a fragmented block of a formerly larger craton or supercontinent that existed before the Mesoproterozoic extensional break-up. The fundamental changes within the NCC occurred at 1.85–1.80 Ga, characterized by extensional systems and emplacement of the Taihang mafic dike swarm across the whole craton, which marked the ultimate cratonization of North China (Li et al., 2000; Kusky and Li, 2003; Hou et al., 2005). These dikes may be an expression of a protracted, global episode of mafic magmatic activity and supercontinent breakup at ~1.80 Ga that has already been identified in several other cratons worldwide including North America, the Baltic shield, South America and Antarctica (e.g., Rogers and Santosh, 2004).

9. Tectonothermal episodes and tectonic models of the NCC between 2.00 and 1.70 Ga

As mentioned above, at around 2.00–1.70 Ga, the North China craton was involved in the tectonic assembly with other blocks and subsequent extension and break-up. This collision occurred after a prolonged and complex history of accretion and collisions through the Archean and early Paleoproterozoic, summarized in Fig. 14.

Between 2.00 and 1.90 Ga, the NCC collided with a block in the north (Fig. 14), which was responsible for the ultimate cratonization of North China (Kusky and Li, 2003). At the same time, the northwestern part of the craton underwent strong reworking adjacent to the Northern Hebei Orogenic belt, including intense shearing deformation, intrusion of granite and high-grade metamorphism of the early sedimentary cover (1.90–1.85 Ga). Simultaneously, the Central Orogenic belt was re-activated largely as a strike-slip orogen, with northeast-striking strike-slip shear zones offsetting and interacting with east-west, top to the south thrust sense ductile shear zones. Broadly similar Paleoproterozoic collision-related reworking (2.00–1.80 Ga) on the cratonic margins of other cratons has been also documented, such as for the Aldan shield, Baltic shield, Laurentia, Greenland and the Sao Francisco craton (Nutman et al., 1992; Condie et al., 1992; Gorbatschev and Bogdanova, 1993; Whitehouse et al., 1998; Jahn et al., 1998; Frost et al., 1998; Orrell et al., 1999; Scott, 1999).

Following continental collision at about 1.90 Ga, the NCC finished its continental cratonization, with a significant increase of its scale and thickness. The tectonics of the craton began to be dominated by extensional regimes at 1.8, some reflecting inherited structures from 1.9 Ga. On the surface, rift and graben systems were generated after a hiatus, with the rupturing of the craton, and local formation of a passive margin along its southwestern margin. The development of rifts was accompanied by coeval emplacement mafic dike swarms (1.80–

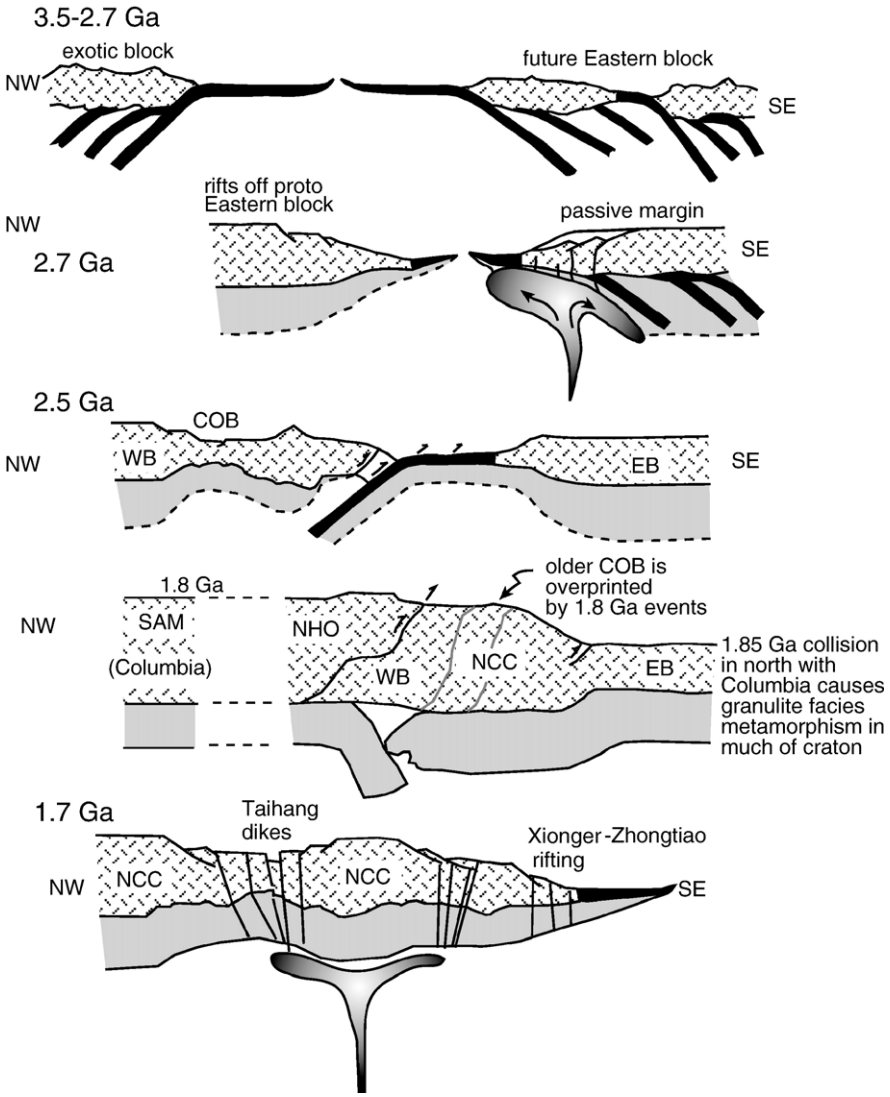


Fig. 14. Schematic diagrams illustrating the main tectonic events in the evolution of the North China craton (modified after Kusky et al., 2006a,b). From 3.5 to 2.7 Ga, the rocks that now comprise the craton formed a number of distinct arcs, microcontinents and accretionary orogens with an uncertain distribution. By 2.7 Ga, the present day Eastern block had formed, and experienced plume-induced rifting at 2.7 Ga that led to the formation of komatiites in Shandong, and a 1600-km-long passive margin sequence on the western margin of the eastern block. This Ocean, named the Dongwanzi Ocean, closed at 2.5 Ga with the emplacement of the accretionary orogen of the Central Orogenic belt (probably attached to the Western block) over the Eastern block. Rifting followed collision, forming an ocean on the north margin of the craton, that experienced arc accretions at 2.3–2.1 Ga, and a major continent–continent collision at 1.92–1.85 Ga, marking the suturing of the North China craton with Columbia, and the deposition of a major foreland sequence (the Chang Cheng Group). By 1.8 Ga, the craton had switched into an extensional mode, breaking out of Columbia.

1.77 Ga), followed by intrusion of anorogenic magmas (granites, anorthosite-gabbro suites, bimodal volcanic rocks) (1.80–1.70 Ga). The aulacogen systems and the anorogenic magmatic belts occur mainly in the marginal areas of the NCC, while mafic dike swarms were emplaced in the central portion of the NCC (Figs. 13 and 14).

From the isotopic age data constraints, we can outline the following major geological events in the NCC from 2.00 to 1.40 Ga (Table 2):

(1) The northwestern part of the North China craton underwent tectonothermal reworking at about 1.90 Ga and collided with other blocks. As a result, the platform sedimentary cover was metamorphosed to form khondalites with deposition of thick molasse in the foreland basin and in intermountain basins, such as those of the Guoijazhai subgroup at Wutai and Luliang Mountains (Li and Kusky, 2007-this issue). Remote from the NHOB, the southeastern part of North China craton is the least reworked Archean terrain in the Paleoproterozoic of the NCC.

(2) At about 1.85 Ga uplift and erosion occurred over a wide area in the eastern part of the North China craton, centered on the Taihang-eastern Hebei area. The doming reflects an underlying hot low-density mantle plume, which rose to high levels and caused the extension.

Table 2
Tectonothermal episodes in the period 2.00–1.70 Ga

2.00–1.90 Ga	Collision along the northwestern margin of NCC
1.85–1.80 Ga	Mantle plume resulted in widespread uplift and erosion, followed by development of rift system. The extensional events initial fragmentation of continent
1.80 Ga, 1.77–1.80 Ga, 1.70–1.75 Ga	The initial breakup of NCC, accompanied by the emplacement of granites in basement, deposition of Changcheng System and outbreak of Xionger Group volcanics, emplacement of mafic dike swarms, anorogenic magmatism (anorthosite, layered gabbros, rapakivi granite), eruption of basalt rhyolites
1.60 Ga	With post-plume thermal subsidence, rifts developed into continental depressions, accompanied with marine transgressions, with deposition of late sedimentary cover

(3) At about 1.85–1.80 Ga aulacogen-rift systems were generated across the entire craton, and high-grade metamorphic terrains were rapidly uplifted to the surface or to shallow crustal levels in areas of extreme extension. U–Pb systematics of Archean high-grade rock samples show evidence of substantial disruption in the Paleoproterozoic, with lower intercepts falling in the range of zircon growth at 1.80–1.85 Ga. The Ar–Ar hornblende and biotite isotopic ages of 1.80 Ga have been also widely documented from Archean rocks of the North China craton (e.g., Zhai et al., 2005).

Within the aulacogen-rift systems sediments and volcano-sedimentary sequences (<1.85 Ga-1.70 Ga) were deposited, accompanied by coeval intrusion of ultramafic rocks, charnockites and alkaline granites at 1.80 Ga. With the continuing extension of the craton, the Taihang mafic dike swarm (1.80–1.77 Ga) was emplaced. Subsequently, rapakivi granites, anorthosites and gabbros (1.79–1.75 Ga) were emplaced in the Yanliao-Taihang aulacogen, followed by volcanic eruption of Tuanshanzi and Dahongyu Formations (1.68–1.62) of the Changcheng Group.

The 1.85–1.70 Ga time interval is one of the two most important Precambrian episodes within the NCC (the other being 2.55–2.5 Ga), as widely documented by isotopic age peaks both for the basement and magmatic intrusions (Li et al., 2000). The peak of granite intrusions (1.83–1.82 Ga) is revealed by zircon U–Pb methods, and the peak of retrograde metamorphism (1.82–1.79 Ga) with basement by multi-methods (U–Pb, mineral Ar–Ar, mineral-rock Sm–Nd). Clearly, the intrusion of granites (1.83–1.82 zircon U–Pb) occurred prior to the retrograde metamorphism of the basement. It supports the explanation of the active extensional model, i.e., the magmatic activity leading to the extension and ultimate exposure of metamorphic basement to the Earth's surface.

In the northwest part of the NCC, the initial development of extensional tectonics was controlled by the post-orogenic collapse and reactivation, with formation of NE-ENE trending rift-aulacogen systems (Figs. 8 and 13). The east-west trending Baiyun Obo rift is parallel to the structural grains of the NHOB and controlled by the post-orogenic extension.

In the central to eastern part of NCC, rift-aulacogen systems clearly cut across cratonic basement and boundaries. They were not limited to Paleoproterozoic metamorphic terrains; actually they are widely developed upon the Archean high-grade metamorphic basement (>2.5 Ga) and cut structural trends in the metamorphic basement. As mentioned above, the rift-aulacogen systems seem to be independent of the basement structures, but coincide with the extent of domal uplift around the Yanliao-Taihang aulacogen above a mantle plume. For instance, the NW striking Taihang mafic dike swarm truncates the structural grain of both the reworked margin adjacent to the NHOB and Archean basement. It is thus suggested that the stress field associated with their emplacement was controlled by mantle plumes rather than the tectonic margins of the NCC.

In summary, the effects of a mantle plume interaction with the North China craton are expressed by regional unconformities, crustal extension, development of rift systems, emplacement of mafic dike swarms and anorogenic magmatism. The mantle plume and NHOB interacted temporally and spatially in the late Paleoproterozoic, with development of complicated extensional structures and related magmatism.

10. Discussion and conclusions: implications for reconstruction of supercontinent and mechanism for break-up

10.1. Implications for reconstruction of the Columbia supercontinent

Global similarities of ages of high-grade metamorphism associated with continental collision suggests that there was a peak in the amalgamation of land masses into a supercontinent in the late Paleoproterozoic (Condie, 2003a,b; Zhao et al., 2002a,b, 2000, 2006a,b). Rogers and Santosh (2002, 2004) proposed the framework of a supercontinent, Columbia, that formed and was broken up during the period between 1.9 and 1.5 billion years ago. Rogers and Santosh (2004) proposed that Columbia may have contained nearly all of the Earth's continental blocks during this period when eastern India, Australia and attached parts of Antarctica were apparently sutured to western North America, and the eastern margin of North America, southern margin of Baltica/North China and western margin of the Amazon shield formed a continuous zone of continental outbuilding. Fragmentation began at circa 1.6 Ga, when rifting occurred in North China. Rifting continued until about 1.4 Ga in most of Columbia, and a similar age of rifting north of the Zimbabwe craton of southern Africa suggests that an entire continental block stretching from Australia to South Africa separated from Columbia at this time. Further separation of North America from South America/Africa and rotation of the different blocks ultimately led to the fragmentation of Columbia and its reorganization to Rodinia.

It is uncertain where the NCC might have been located in the Paleoproterozoic supercontinent, although preliminary reconstructions have been suggested based on petrological evidence (Wilde et al., 2002; Rogers and Santosh, 2004; Zhai et al., 2005). The late Paleoproterozoic to early Mesoproterozoic tectonic framework and tectonothermal episodes of the NCC outlined

here, and their correlation with other cratons (2.00–1.70 Ga) provide important tectonic constraints and insight for the reconstruction of the NCC within the Columbia supercontinent. Most importantly, we have shown that the circa 2.0–1.85 Ga orogenic belt associated with incorporation of the NCC into the Columbia supercontinent is located along the present northern margin of the craton, and not in the center of the craton as assumed by earlier workers (Wilde et al., 2002; Zhao et al., 2006a,b). This belt of 1.93–1.85 Ga deformation can now be shown to extend another 2,000 km from along the northern margin of the NCC through the northern margin of the adjacent Tarim block (Zhang et al., 2007-this issue), extending the known length of the North Hebei Orogen in China to more than 3,000 km. Deformation in the Central Orogenic belt at this time includes far-field north over south thrusting, and strike-slip shear zones that merge with the orogen in the north. Reconstructions of Columbia that assume that the eastern and western blocks of the NCC amalgamated at 1.85 during Columbia assembly are clearly incorrect.

Collisions of the NCC with other blocks in the north at about 2.00 Ga-1.90 Ga resulted in reworking of the foreland in the northwestern part of the NCC. Comparable orogenic-reworking events at the same time have been also widely documented in the foreland and hinterland of other cratonic blocks, including the Aldan shield, Laurentia, Baltica, Greenland and Sao Francisco cratons (Teixeira and Figueiredo, 1991; Nutman et al., 1992; Whitehouse et al., 1998; Jahn et al., 1998; Frost et al., 1998; Orrell et al., 1999; Scott, 1999; Teixeira et al., 1999). Most continental collisions during this period were in connection with the assembly of the supercontinent.

At about 1.85 Ga, the NCC switched from collision and reworking to cratonic extension, culminating with the development of rift-aulacogen systems and intrusion of mafic dike swarms at about 1.80–1.70 Ma. It is important to note that the present southwestern and northern margins of the NCC began to form by the breakup of a larger craton, with development of oceanic basins, as extension continued at 1.80 Ga.

As indicated by its two distinct rifted margins and extensional regime at about 1.80 Ga, the major part of the NCC was far from a collisional setting during that period. With development of rifts and oceanic basins along both its northern and southwestern margins, the NCC was broken from a supercontinent, and then drifted to form widely separated fragments. The age of rifting-break up (1.80 Ga) of the NCC was clearly early than those of the Laurentia and Baltica.

Both the northern and the southwestern rifted margins of the NCC formed an acute angle on its northwestern corner at about 1.80 Ga. This distinct geometry of the cratonic block and relevant rifted margins is similar to RRR (rift-rift-rift) triple junction margins commonly associated with supercontinent fragmentation, consistent with the observation that the NCC split from the hinterland of a supercontinent at 1.80 Ga. Similar acute angles and paired rifted margins have been preserved on the southern ends of several cratonic fragments, such as Africa and India, associated with fragmentation of Gondwana (e.g., Rogers and Santosh, 2004).

Moreover, the timing of extensional-anorogenic magmatism of the NCC mainly shows a range from 1.80 to 1.70 Ga. The Taihang mafic dike swarms, and the rapakivi granite of North China can be correlated with those of Aldan shield, Amazonian craton and Urayualagua shield (Fig. 15). In the Aldan shield and Amazonian craton, the rapakivi granites with ages of 1.90–1.70 Ga are reported. In the Amazonian craton and Urayualagua shield, a mafic dike swarm of 1.75–1.72 Ga has been identified (Chaves and Neves, 2005). The Archean basement was also intruded by both rapakivi granite and mafic dike swarms in the Aldan shield, as has the eastern part of the Amazonian craton. All the evidence suggests a possible connection of the NCC with the Aldan shield and Amazonian craton in the late Paleoproterozoic. Fig. 15 shows our proposed reconstruction of Columbia based on these data.

In summary, the NCC records a sequence of comparable tectonothermal episodes (2.00–1.70 Ga) with those of Baltic shield, Amazonian and Sao Francisco cratons and has a close tectonic relation with these cratons. The tectono-magmatic and metamorphic evolution of the Northern Hebei orogen is remarkably similar to the Svecofennian of Baltica, and the Transamazonian and Eburnian belts of Africa and South America. These continental blocks and orogens may have belonged to a single supercontinent or continent at 1.80–1.70 Ga. All these blocks

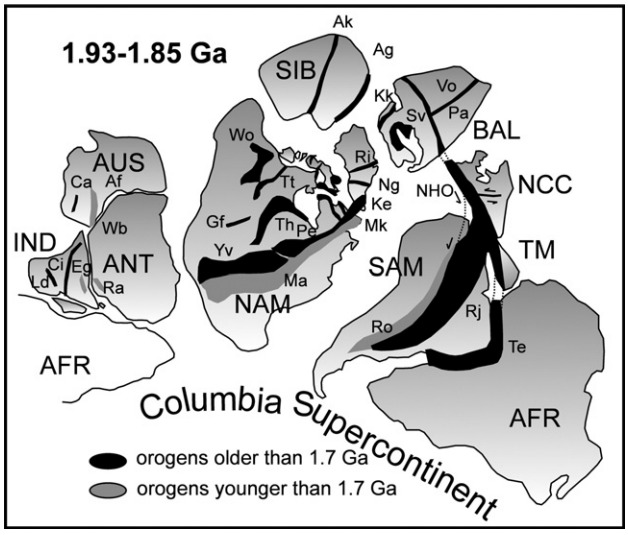


Fig. 15. Reconstruction of the Columbia Supercontinent at 1.93–1.85 Ga, modified after Rogers and Santosh (2004). Note that the timing of events in the North China craton coincides with those in adjacent cratons when the collisional orogen that brought the NCC into Columbia is recognized as the Northern Hebei orogen. This orogen continues for 3000 km across the NCC and through the Tarim block, and then connects with the Tansamazonian-Eburnian and Rio Negro belts of Africa and South America, and the Svecofennian belt of Baltica. Abbreviations of cratons as follows; AFR, Africa; IND, India; AUS, Australia; ANT, Antarctica; NAM, North America; SIB, Siberia; BAL, Baltica; NCC, North China craton; SAM, South America. Abbreviations of orogens as follows: Af; Albany-Fraser; Ad, Aravalli-Delhi; Ag, Angara; Ak, Akitkan; An, Angara; NHO, Ca, Capricorn; Ci, Central Indian; Eg, Eastern Ghats; Fo, Fox; Gf, Great Falls; Ke, Ketilidian; Kg, Konisbergian-Gothian; Kk, Kola-Karelia; La, Labradorian; Li, Limpopo; Ln, Lurio-Namama; Ma, Mazatzal; Mk, Makkovikian; Ng, Nagssugtoqidian; Northern Hebei; Nq, New Quebec; Pa, Pachemel; Pe, Penokian; Ra, Rayner; Ri, Rinkian; Rj, Rio Negro-Juruena; Ro, Rondonian; Sv, Sveckofennian; Te, Transamazonian-Eburnian; Th, Trans-Hudson; TM, Tarim; Tt, Thalston-Thelon; To, Torngat; Un, Ungava; Vo, Volhyn; Wb, Windmill Islands-Bunger Hills; Wo, Wopmay; Yv, Yavapai.

were associated with extensional tectonics and breakup of a possible supercontinent over a time interval from 1.80 to 1.70 Ga, in contrast to the dominantly accretion and collision tectonics of Laurentia and North Atlantic craton during the same period. Therefore, we suggest that the NCC in the latest Paleoproterozoic was far from Laurentia and Greenland, and located between the Baltic Shield, and the Amazonian and Sao Francisco cratons (Fig. 15). Interestingly, the age of collision in the NHO (1.93 Ga) correlates remarkably well with the events in the Trans-Amazonian orogens, which experienced sinistral transpression from 2.1 to 2.0 Ga, and late magmatic stages from 2.0 to 1.9 Ga (Rogers and Santosh, 2004). Activity continued in the older part of the Rio Negro-Juruena Belt from 1.8 to 1.6 Ga (Rogers and Santosh, 2004) and may be related to the extensional event recoded in the Baiyun Obo rift on the north side of the NCC at that time (Fig. 13).

10.2. Origin of rifting and breakup of NCC at 1.80 Ga

There has not been much discussion about what initiated rifting of the NCC at 1.85–1.80 Ga, although a plume model has been postulated (Zhai et al., 2005; Peng et al., 2005). A mantle plume can account for the domal uplift and subsequent continental extension and fragmentation within the North China craton documented in this paper (Fig. 14). Prior to continental rifting at 1.80 Ga, uplift during this stage extended across a dome hundreds of kilometers in diameter, beyond the Yanliao-Taihang aulacogen, in response to underlying mantle upwelling. It resulted in erosion of the subcontinental lithospheric mantle. The domal uplift and cracking caused radial fracturing with the lithosphere, and initiated the break-up of the NCC, with the formation of three branches of Yanliao-Taihang aulacogen, Xionger-Zhongtiao aulacogen and emplacement of mafic dike swarms. However, beyond the uplift, rift-aulacogen systems, such as BR, ZA, were also controlled by regional (i.e., plate-boundary) stresses.

Evidence for domal uplift and branched rifting is compatible with mantle plume or mantle diapir models (Condie, 2002). The plume model is also supported by anorogenic magmatism within rift-aulacogen systems and emplacement of related mafic dike swarms. The total duration of magmatism and associated rifting is up to 100–150 Ma (between 1.85 and 1.70 Ga), comparable to those of long-lived plumes (Condie, 2003a,b). We suggest therefore that a mantle plume initiated the uplift, extension, and subsidence that formed the extensive passive margin along the southwestern side of the North China craton, accompanied by the development of oceanic basins at about 1.80 Ga.

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