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Paleoproterozoic tectonic evolution of the North China Craton

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Abstract

The Archean North China Craton consists of two major blocks, separated by the Central Orogenic Belt. The age of collision of the two blocks along the Central Orogenic Belt is controversial. Some models suggest that the Archean blocks collided at 1.8 Ga, during the Luliang Orogeny (1.7–1.9 Ga). In this model, high-pressure granulite facies metamorphism accompanied collision at 1.8 Ga. Other models have suggested that the Eastern and Western Blocks collided at 2.5 Ga, soon after 2.6–2.5 Ga ophiolitic and arc rocks throughout the orogen were formed. We synthesize the geology, geochronology, and tectonics of the Neoarchean through Mesoproterozoic evolution of the North China Craton. We 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, This collision was followed rapidly 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 north margin of the craton. An arc terrane developed in this ocean, and collided with the north margin of the craton by 2.3 Ga, forming a 1400 km long orogen known as the Inner Mongolia–Northern Hebei Orogen. A 1600 km long granulite-facies terrain formed on the southern margin of this orogen, representing a 200 km wide uplifted plateau formed by crustal thickening. The orogen was converted to an Andean-style convergent margin between 2.20 and 1.85 Ga, recorded by belts of plutonic rocks, accreted metasedimentary rocks, and a possible back-arc basin. A pulse of convergent deformation is recorded at 1.9–1.85 Ga across the northern margin of the craton, perhaps related to a collision outboard of the Inner Mongolia–Northern Hebei Orogen, and closure of the back arc basin. This event caused widespread deposition of conglomerate and sandstone of the basel Changcheng Series in a foreland basin along the north margin of the craton. At 1.85 Ga the tectonics of the North China Craton became extensional, and a series of aulacogens and rifts propagated across the craton, along with the intrusion of mafic dike swarms. The northern granulite facies belt underwent retrograde metamorphism, and was uplifted during extensional faulting. High pressure granulites are now found in the areas where rocks were metamorphosed to granulite facies and exhumed two times, at 2.5 and 1.8 Ga, exposing rocks that were once at lower crustal levels. Rifting led to the development of a major ocean along the southwest margin of the craton, where oceanic records continue until 1.5 Ga.

Keywords: Archean; China; Ophiolite; Granulite; Basin

1. Introduction

In many Precambrian orogenic belts worldwide, workers are faced with a paucity of temporal constraints on the timing of events and often construct simple tectonic models using only a few widely scattered geochronologic ages. This has led to the impression that many Precambrian orogenic belts have evolved slowly, with tectonic phases lasting hundreds of millions of years. This is in stark contrast to younger orogens, where orders-of-magnitude better age control has led workers to construct tectonic models recognizing individual tectonic phases that lasted several to tens of millions of years.

China's oldest continental fragment, the North China Craton (NCC), is composed of three main Archean elements including the Eastern Block, Western Block, and the intervening Central Orogenic Belt (Zhao et al., 2001a; Kusky et al., 2001; Li et al., 2002). Rock formation ages for the Eastern and Western Blocks cluster around 2.7–2.5 Ga (with small areas of older rocks, up to 3.5–3.8 Ga, in the Eastern Block) and at 2.5 Ga for the Central Orogenic Belt. There is a current disparity between tectonic models for the tectonic evolution of the North China Craton, with a 700 million-year difference in interpretations of when the craton amalgamated from its late Archean component parts. Some

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models suggest that the craton did not form until 1.85 Ga, when the Eastern and Western Blocks are postulated to have collided in a continent- continent collision (the Luliang Movement of earlier Chinese literature). These models are based primarily on a plethora of petrologic data on the timing of a high-grade metamorphic event, but do not have a solid geometric or kinematic model that explains the petrologic observations (Wu and Zhong, 1998; Zhao et al., 1998, 1999a,b, 2001a,b; Zhao, 2001; Kroener et al., 2002). These models also do not explain why high-pressure granulite rocks, one of the hallmarks of the postulated 1.85 Ga event, are confined to the northern one third of the orogen, and are elongate perpendicular to the strike of the orogen. They also do not account for data pointing to a 2.5 Ga metamorphic event that correlates between the Eastern and Western Blocks of the NCC. Furthermore, they do not explain how island arc and ophiolitic rocks that formed at 2.55 Ga could avoid being deformed and metamorphosed for 700 million years until 1.8 Ga.

Other models have suggested 2.5 Ga as the time of amalgamation of the component parts of the NCC, but have not attempted to explain the 1.85 Ga metamorphic event (Kusky et al., 2001; Li et al., 2002). These models have been based on regional field based stratigraphic, structural, and geochronological studies. The basic tenet of these models is that many of the rocks in the Central Orogenic Belt represent remnants of arcs, ophiolites, rifted margins, and accreted fragments that formed between 2.75 and 2.5 Ga. These were deformed and metamorphosed during closure of an ocean basin between the Eastern and Western Blocks at 2.5 Ga, then cut by mafic dikes that do not contain the older fabrics. Collision was followed closely at 2.5–2.4 Ga by rifting and associated sedimentation, intrusion of mafic dike swarms, and eruption of flood basalts. However, these models do not accommodate observations that led to the interpretations of a high-grade metamorphic event related to continental collision between the Eastern and Western Blocks at 1.85 Ga.

Much of the discrepancy between the different models for the timing of amalgamation of the Eastern and Western blocks hinges on the interpretation of single and multi-grain zircon populations plus sensitive high resolution ion microprobe (SHRIMP) ages from a granulite facies terrain in the Central Orogenic Belt. The oldest rocks in the Hengshan complex are 2701 ± 5.5 Ma biotite granitoid gneisses, which Kroener et al. (2002) interpret to be part of a 2700–2670 Ma igneous protolith to the metamorphic terrain. Alternatively, Kroener et al. note that these old rocks could be the oldest part of a circa 2700–2500 Ma igneous suite, but consider this unlikely since intermediate ages are currently unknown. Most gneissic rocks in the Hengshan yield U/Pb ages between 2526 and 2455 Ma, similar to the age range in the adjacent Wutai volcanic belt (Kroener et al., 2002). Upper-intercept U–Pb ages fall between 2.70 and 2.50 Ga, whereas lower intercept ages fall between 2.00 and 1.80 Ga, reflecting a major lead loss (metamorphic) event between 2.0 and 1.8 Ga. Additionally, ^{40}Ar/^{39}Ar ages on metamorphic hornblende and biotite, SHRIMP ages on metamorphic zircon rims, and Sm–Nd ages of garnets have led many to suggest that the lower intercept ages (2.00–1.80 Ga) represents the primary metamorphic event, and the upper intercept ages (2.50–2.70 Ga) represent the rock formation ages. We suggest that this is an oversimplification, and does not account for the presence of orogenic belts of several different ages, orientations, and significance in the North China Craton. Here, we present a new model for the Neoarchean–Mesoproterozoic evolution of the North China Craton that explains 2.5–1.7 Ga history of the craton, and is consistent with the petrologic, field, structural, stratigraphic, and geochronological data pointing to an earlier, more significant history of the craton.

2. Regional geology of the North China Craton

The North China Craton (Fig. 1) occupies about 1.7 million square kilometers in northeastern China, Inner Mongolia, the Yellow Sea, and Korea. It is bounded to the south by the Qinling-Dabie Shan orogen, the Yinshan-Yanshan orogen to the north, the Longshoushan belt to the west, and the Jiao-Liao belts to the east (Bai and Dai, 1996, 1998). The North China Craton includes a large area of intermittently-exposed Archean crust, including circa 3.8–2.5 Ga gneiss, TTG, granite, migmatite, amphibolite, ultramafite, mica schist and dolomitic marble, graphitic and sillimanititic gneiss (khondalites), banded iron formation (BIF), and metaarkose (Jahn and Zhang, 1984a,b; Zhai et al., 1985; Bai et al., 1992; Wu et al., 1998; Zhao, 1993; Jahn et al., 1987; Bai, 1996; He at al., 1991, 1992; Shen et al., 1992; Wang et al., 1997). The Archean rocks are overlain by the 1.85–1.60 Ga Mesoproterozoic Changcheng (Great Wall) Series (Li et al., 2000a,b). In some areas in the central part of the North China Craton, 2.40–1.90 Ga Paleoproterozoic–Mesoproterozoic sequences deposited in cratonic basins are preserved.

3. Tectonic division of the North China Craton

We divide the North China Craton into two major blocks (Fig. 2) 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 (Kroener et al., 1998, 2002; Li et al., 2000b; Wilde et al., 1998; Zhao, 2001; Kusky et al., 2001). The Western Block, also known as the Ordos Block (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. 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. The North

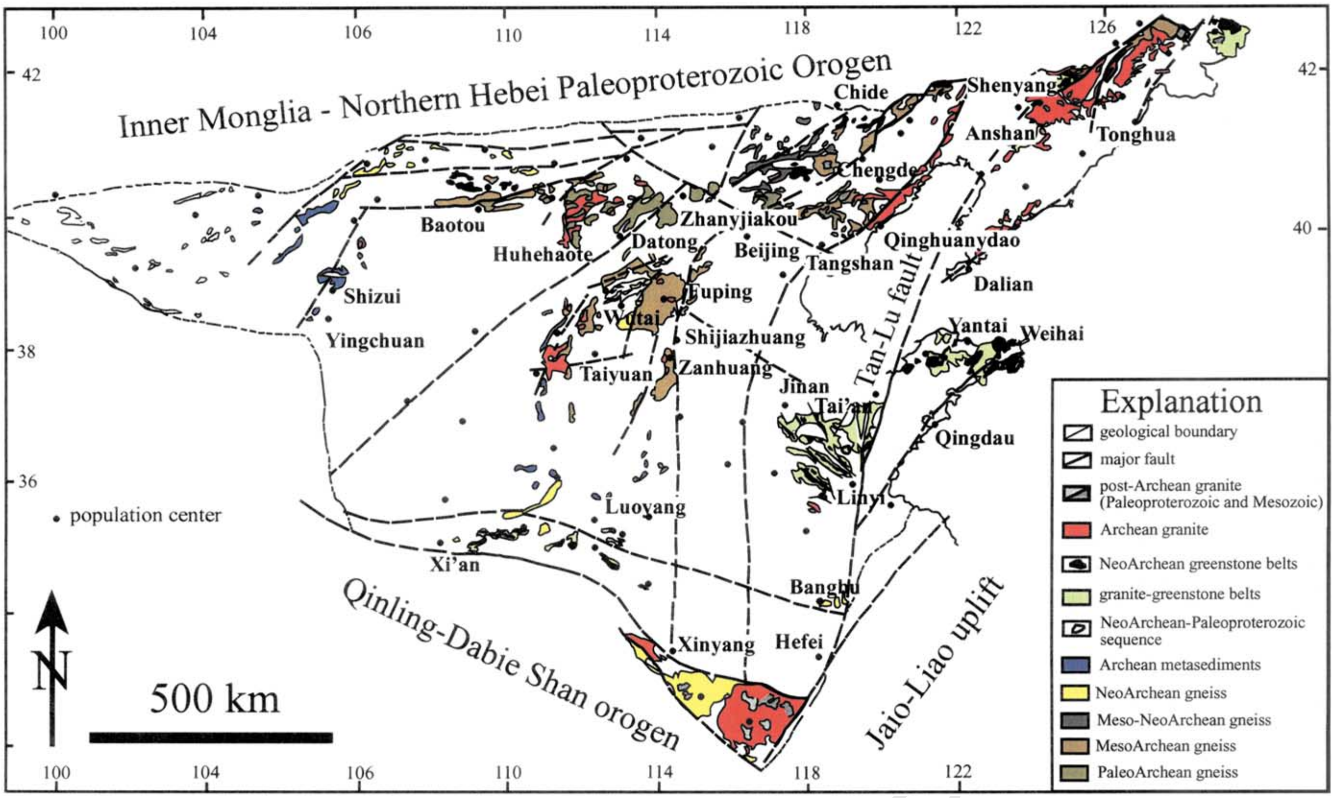


Fig. 1. Geologic map of the North China craton showing the distribution of major types of Precambrian rocks. Map modified from numerous sources.

China Craton is one of the world's most unusual cratons in that it had a thick tectosphere (subcontinental lithospheric mantle) developed in the Archean, which was present through the Ordovician as shown by deep xenoliths preserved in Ordovician kimberlites (Gao et al., 2002). However, the eastern half of the root appears to have delaminated or otherwise disappeared during Paleozoic, Mesozoic, or Cenozoic tectonism. This is demonstrated by Tertiary basalts that bring up mantle xenoliths of normal 'Tertiary mantle' with no evidence of a thick root (e.g. Menzies et al., 1993; Griffin et al., 1998; Zheng et al., 1998; Gao et al., 2002). The processes responsible for the loss of

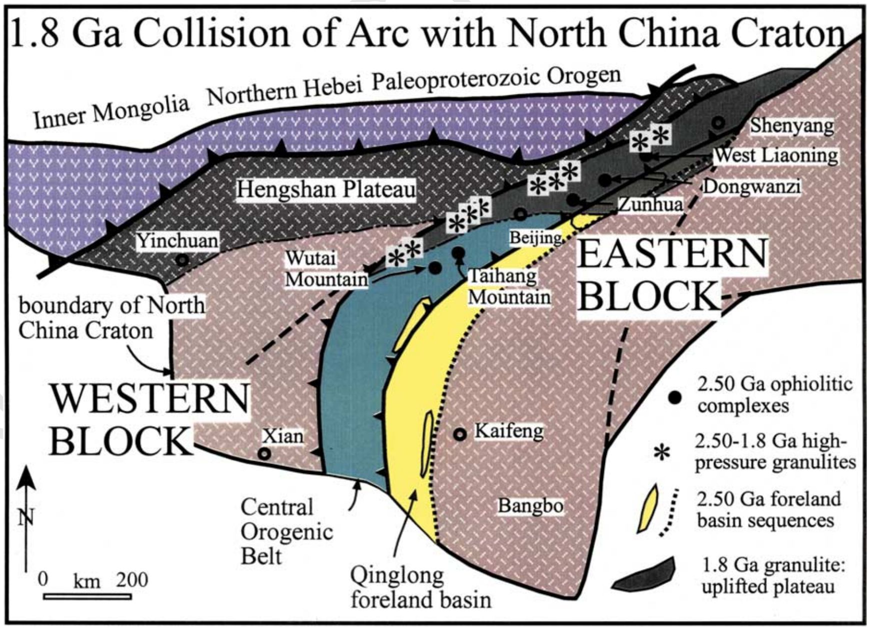


Fig. 2. Simplified tectonic map of the North China Craton, showing the main tectonic elements discussed in the text.

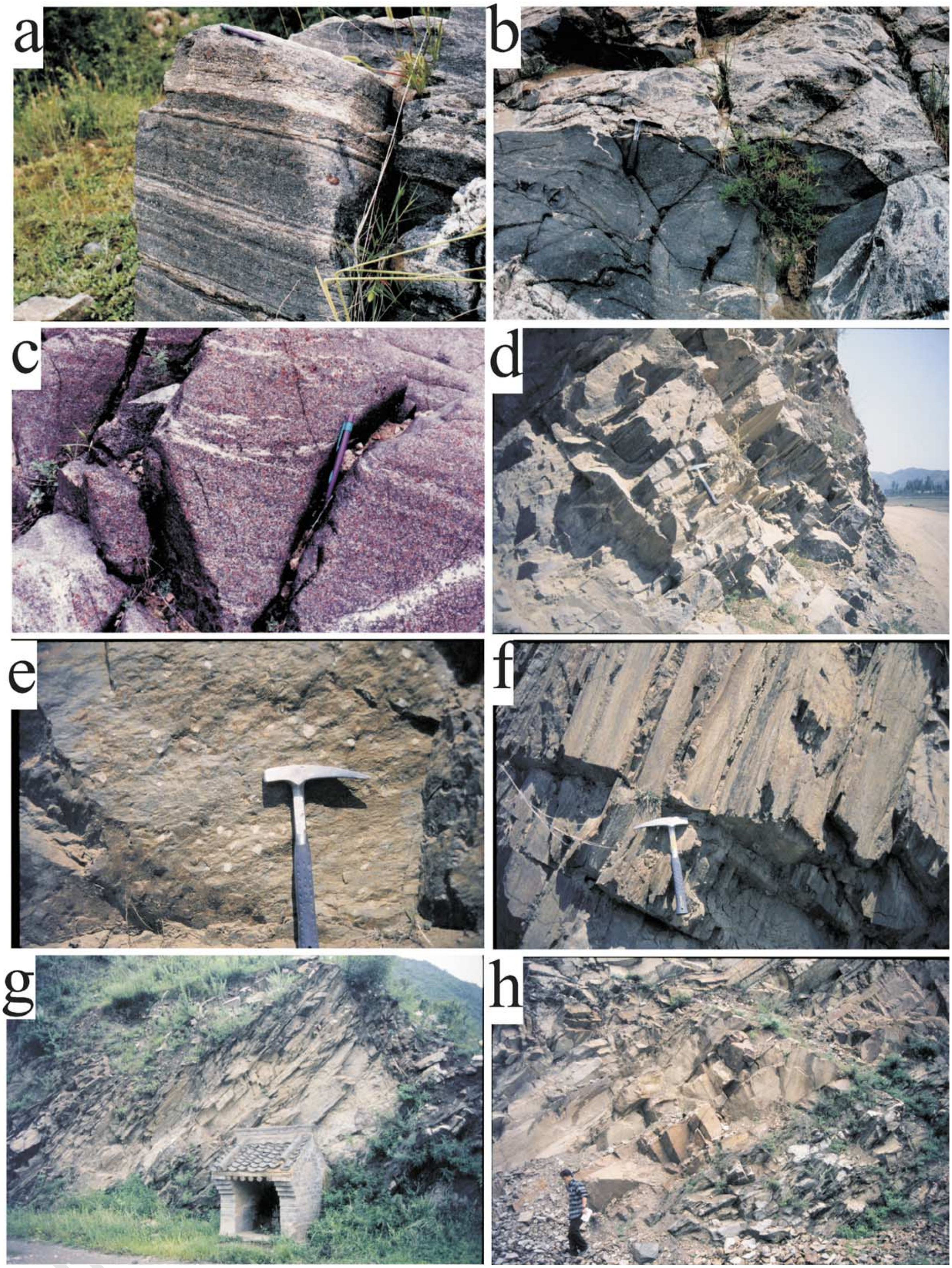


Fig. 3. Photographs of rocks in the Central Orogenic Belt. (a) High-grade gneiss with large garnet porphyroblasts exhibiting retrograde high-P granulite textures, Hengshan Complex; (b) mafic boudin in granulite gneiss, Hengshan Complex; (c) garnet-rich granulite gneiss, Hengshan Complex; (d) foreland basin flysch from the Qinglong basin; (e) conglomerate of the Hutuo Group, Wutai Mountains; (f) graywacke/shale beds in Hutuo Group, interpreted as flysch; (g) west-dipping flysch of Hutuo Group, Wutai Mountains (small temple for scale is 1.5 m tall); (h) thrust slice of arkose (Lower Wutai Group), interpreted as stable continental margin imbricated with foreland basin flysch, Wutai Mountains.

this root are enigmatic but are probably related to the present day high-heat flow, Phanerozoic basin dynamics and orogenic evolution.

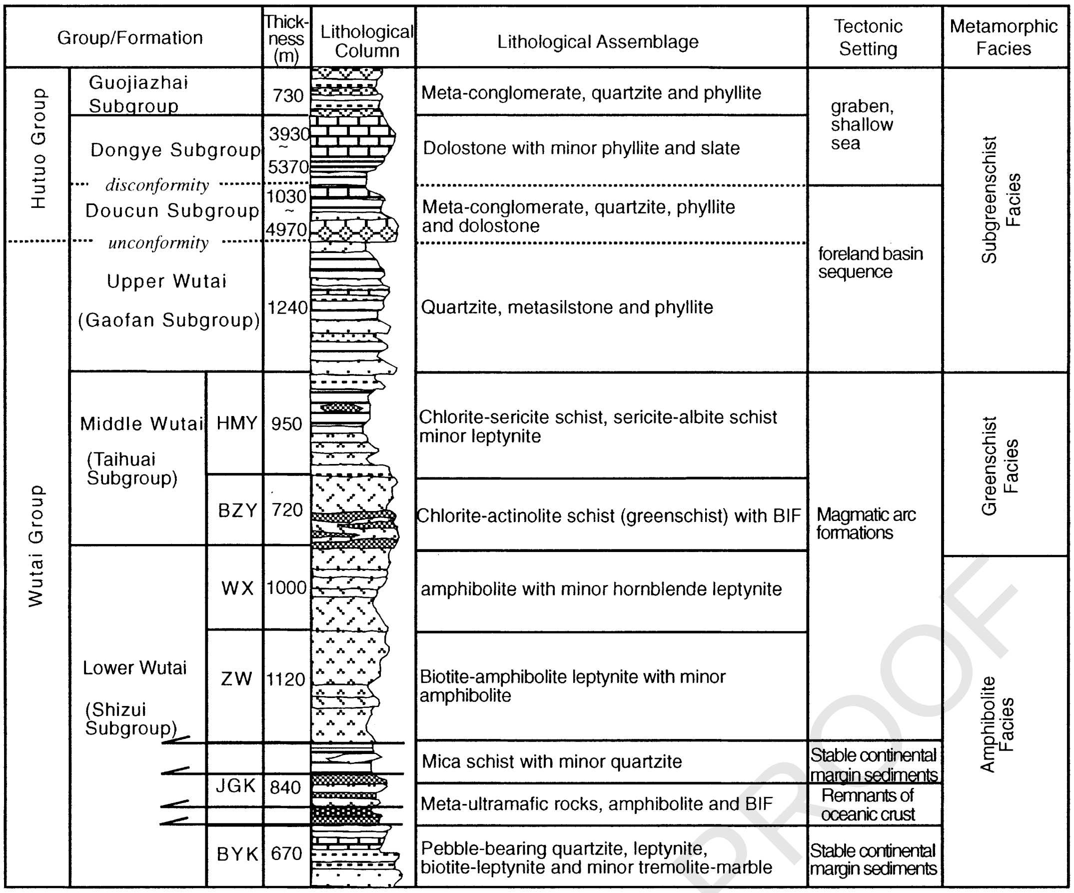
The Central Orogenic Belt (COB) includes belts of tonalite–trondhjemite–granodiorite (TTG), granite, and supracrustal sequences metamorphosed from greenschist to granulite-facies. It can be traced for about 1600 km from west Liaoning to west Henan (Fig. 2). Widespread high-grade regional metamorphism including migmatization occurred throughout the Central Orogenic Belt between 2.60 and 2.50 Ga, with final uplift of the metamorphic terrain at circa 1.80 Ga (Li et al., 2000a). Greenschist to amphibolite grade metamorphism predominates in the southeastern part of the COB, but the northwestern part of the COB is dominated by granulite-facies to amphibolite facies rocks (Fig. 3), including some high-pressure assemblages (10–13 kbars at 850 ± 50 °C); Zhao et al., 2001b; see additional references in Krorner et al., 2002). The high-pressure assemblages can be traced for more than 700 km along a linear belt trending ENE. Thrust-related subhorizontal foliation and shear zones, recumbent folds, and tectonically interleaved high-pressure granulite migmatite, and metasediments characterize internal (western) parts of the orogen. The western part of the orogen is widely overlain by sediments deposited in graben and continental shelf environments, and is intruded by several dike swarms (2.50–2.40, 1.90–1.80 Ga; Wu et al., 1998; Li et al., 2000a). Several large anorogenic granites with ages of 2.20–2.00 Ga are identified within the belt. Two linear units have been documented within the belt, including the Hengshan high-pressure granulite belt in the west (Li et al., 2000a, 2002) and a foreland-thrust fold belt in the east (Li et al., 2002). 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 1.8627 ± 0.4 (A. Kroener, pers. comm., 2003).

The Hengshan high-pressure granulite belt is about 700 km long, consisting of several metamorphic terranes, including the Hengshan, Huaian, Chengde, and west Liaoning complexes (Figs. 1 and 2). The high-pressure granulite commonly occurs as inclusions, some of which can be shown to be boudinaged dikes, within intensely sheared TTG (2.70–2.47 Ga) and granitic gneiss (2.50 Ga), and are widely intruded by K-granite (circa 1.90 Ga) and mafic dike swarms (2.40–2.45, 1.77 Ga) (Li et al., 2000a,b). Locally, khondalite and turbiditic slices are interleaved with the high-pressure granulite rocks, suggesting thrusting. The main rock type is garnet-bearing mafic granulite with characteristic Pl-Opx coronae around the garnet, which show evidence for rapid exhumation-related decompression. Isothermal decompressive P-T-t paths have been documented within the rocks; pressures and temperatures are in the range of 1.2–1.0 Gpa, and 700–800 °C, respectively. At least three types of REE patterns are shown by mafic rocks of the high-pressure granulites, from flat to LREE-moderately enriched, indicating a tectonic setting of active continental margin or island arc (Li et al., 2002). The high-pressure granulites were formed through subduction-collision, followed by rapid rebound-extension, recorded by 2.50–2.40 Ga mafic dyke swarms of (Wu et al., 1998; Li et al., 2000a) and graben-related sedimentary sequences in the Wutai Mountain–Taihang Mountain areas. They also show a younger, circa 1.85 Ga metamorphic signature, as discussed below.

The Qinglong foreland basin and fold-thrust belt (Figs. 2 and 3) is north- to northeast-trending, and is now preserved as several relict folded sequences including the Qinglong, Fuping, Gaofan (formerly the Upper part of the Wutai Group), and Dengfeng sequences. Its general sequence, from bottom to top, can be divided into three subgroups of quartzite–mudstone–marble, turbidite, and molasse, from bottom to top (Fig. 4). The lower subgroup of quartzite–mudstone–marble is well preserved in central sections of the Qinglong foreland basin (Taihang Mountain), with subhorizontal structures, supporting its interpretation as a passive margin developed prior to 2.5 Ga on the eastern block (Fig. 5). Lower-grade turbidite and molasse-type sediments overlie the lower subgroup. The western margin of the Qinglong foreland basin is intensively reworked by thrusting and folding and is overthrust by the overlying orogenic complex (TTG gneiss, ophiolite blocks, accretionary sediment). To the east its deformation becomes weaker in intensity. The Qinglong foreland basin is intruded by a gabbroic dike complex consisting of 2.40 Ga diorite, and overlain by graben-related sediments and flood basalts. In the Wutai and North Taihang basins, several ophiolitic blocks are recognized along the western margin of the foreland thrust-fold belt. These consist of pillow lava, gabbroic cumulates, and harzburgite. The largest ophiolitic thrust complex imbricated with foreland basin sedimentary rocks is up to 10 km long, and is preserved in the Wutai-Taihang Mountains (Wang et al., 1997).

4. Evidence for 2.75–2.5 Ga events

Nearly all of the volcanic, and most of the mafic plutonic rocks in the Central Orogenic Belt have igneous crystallization ages ranging between 2.75 and 2.50 Ga (Wilde et al., 1997, 1998; Zhao et al., 2001a,b; Kusky et al., 2001; Kusky et al., in review). Many of these rock sequences have been interpreted as parts of island arcs or ophiolites, and are associated with deformed continental margin sedimentary rocks (Kusky et al., 2001; Li et al., 2002). We do not know of any orogenic belt in the world where similar rocks have formed, then sat



Group/Formation			Thickness (m)	Lithological Assemblage	Tectonic Setting	Metamorphic Facies
Hutuo Group	Guojiazhai Subgroup		730	Meta-conglomerate, quartzite and phyllite	graben, shallow sea	Subgreenschist Facies
	Dongye Subgroup		3930 ~ 5370	Dolostone with minor phyllite and slate		
	disconformity					
	Doucun Subgroup		1030 ~ 4970	Meta-conglomerate, quartzite, phyllite and dolostone	foreland basin sequence	
	unconformity					
Wutai Group	Upper Wutai (Gaofan Subgroup)		1240	Quartzite, metasilstone and phyllite		
	Middle Wutai (Taihuai Subgroup)	HMY	950	Chlorite-sericite schist, sericite-albite schist minor leptynite	Magmatic arc formations	Greenschist Facies
		BZY	720	Chlorite-actinolite schist (greenschist) with BIF		
	Lower Wutai (Shizui Subgroup)	WX	1000	amphibolite with minor hornblende leptynite		Amphibolite Facies
		ZW	1120	Biotite-amphibolite leptynite with minor amphibolite		
		JGK	840	Mica schist with minor quartzite	Stable continental margin sediments	
				Meta-ultramafic rocks, amphibolite and BIF	Remnants of oceanic crust	
		BYK	670	Pebble-bearing quartzite, leptynite, biotite-leptynite and minor tremolite-marble	Stable continental margin sediments	

Fig. 4. Stratigraphic column showing Group and Formation names for different rock assemblages in the Wutai Mountain area, along with their tectonic interpretation. Modified after Tian, 1991. Abbreviations for formation names: BYK, Banyukou Formation; JGK Jingangku Formation; ZW, Zhuangwang Formation; WX, Wenxi Formation; BZY, Baizhiyan Formation; HMY, Hongmenyan Formation.

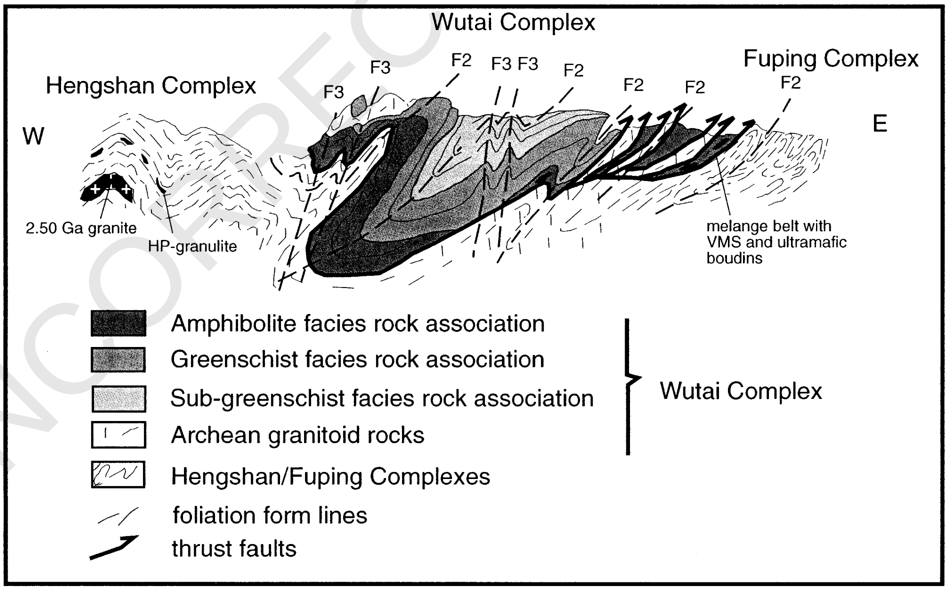


Fig. 5. Schematic structural cross-section through the Hengshan Complex, Wutai Complex, and Fuping Complex, showing Hengshan thrust over Wutai, and Wutai thrust over the Fuping Complex. Modified after Tian, 1991.

undisturbed for 700 million years before being deformed during accretionary tectonic events. Hence, we suggest that the arc and ophiolitic rocks of the Central Orogenic Belt were deformed during accretion soon after they formed at 2.50 Ga (Fig. 6). Deformation and metamorphism is associated with accretion of many of these fragments (Hu et al., 1999; Kusky et al., 2001), and metamorphism includes typical sea-floor alteration, regional greenschist to amphibolite facies belts, local granulite facies provinces (Kroener et al., 1998), and post-kinematic 2.50–2.40 Ga thermal aureoles around plutons.

The 2.50 Ga rock units, tectonic belts, and structures are oriented north to northeast parallel to the Central Orogenic Belt. We correlate the first, 2.50 Ga, amphibolite to granulite facies event with this accretion event, and the 1.80 Ga granulite overprint to younger events. The igneous rocks of the COB are associated with 2.50 Ga foreland basin sequences, including the Qinglong, Gaofan (formerly Upper Wutai Group), and Dengfeng Groups (Fig. 4). Abundant amphibolite, gneiss and other metamorphic clasts in the 2.50–2.40 Ga Douchun (formerly basal Hutuo) conglomerate indicate that regional amphibolite (and higher) grade metamorphism occurred before 2.5–2.4 Ga. Metamorphic garnets in high-pressure granulites from the Sanggan area, NW Hebei, have yielded Ar–Ar laser isochron ages of 2510 ± 50 Ma, whereas metamorphic zircons from NW Hebei have yielded ages of 2438 Ma with protolith ages of 2530–2540 Ma (Sm–Nd) (Hu et al., 1999).

5. Evidence for 2.5–2.4 Ga rifting

Several N–S trending rifts formed in the central North China Craton between 2.50 and 2.40 Ga (Fig. 6), reflecting post-orogenic extension. A large area of mafic to ultramafic dikes, sheets and layered complexes has recently been identified in the Hengshan–Wutai–Taihang area. The Hengshan Mafic Igneous Province is mainly located in the granulite to upper amphibolite-facies terrain, in the northern part of the craton. It can be traced within lower-grade

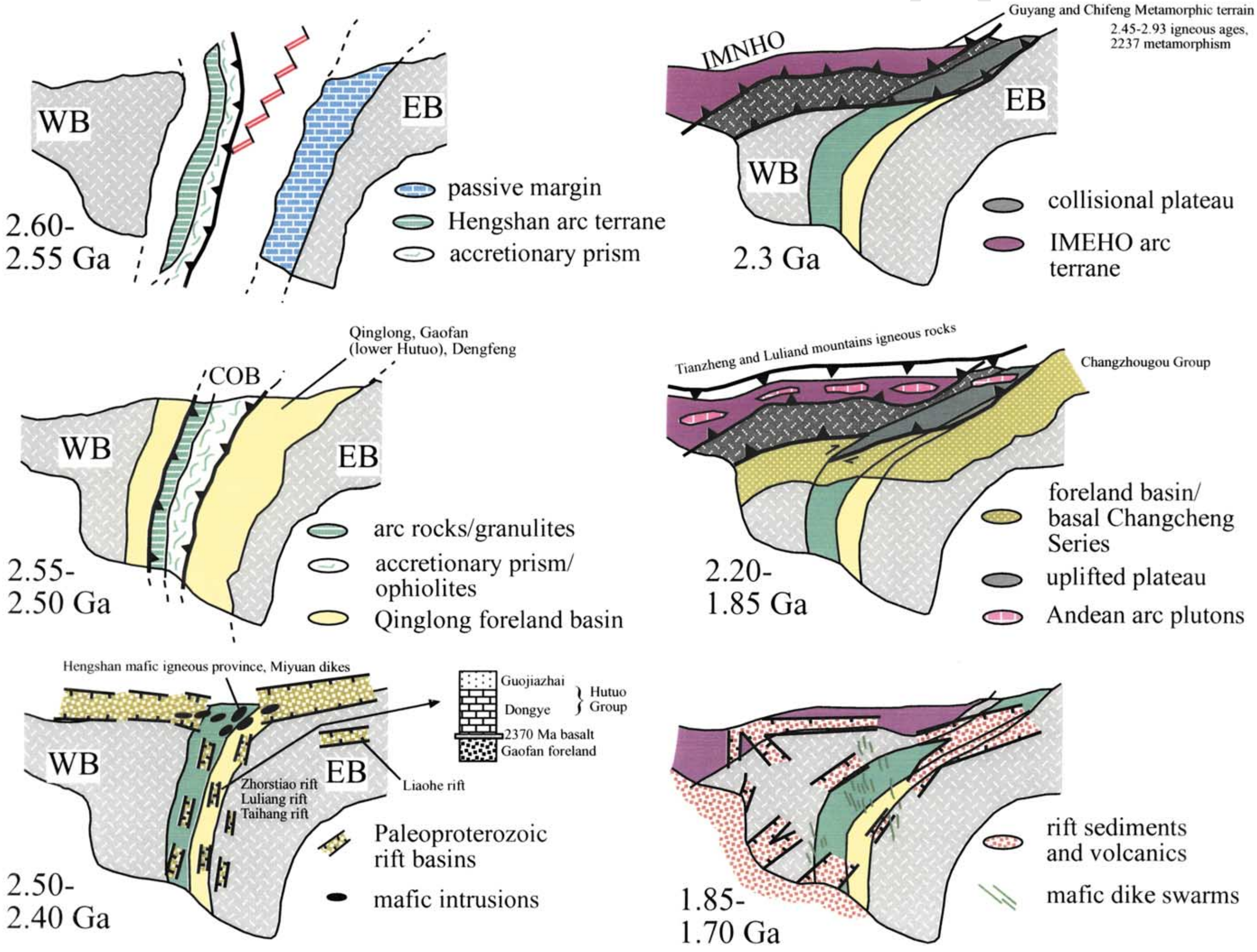


Fig. 6. Palinspastic maps showing the tectonic evolution proposed for the Neoarchean–Mesoproterozoic evolution of the craton.

terrains to the central to southern part of the Wutai–Luliang Mountains (Tian et al., 1998; Bai and Dai, 1996; Chen, 1990; Chen and Ji, 1996; He et al., 1993; Xu, 1990; Wu and Geng, 1991; Wang et al., 1997; Chen, 1996; Li et al., 2000a, b; Li et al., 1998). The mafic rocks intrude Neoarchaean TTG complex, greenstone belts, and khondalites. In the Wutai–Taihang metamorphic terrane, mafic plutonic rocks of the Hengshan Mafic Igneous Province intruded into the Wutai greenstone belt and Neoarchean TTG complex, but only rarely intrude the Hutuo Supergroup. Similar mafic intrusions are also reported from Neoarchean metamorphic basement in the southern and eastern parts of the North China Craton (Bai and Dai, 1996; Sun and Hu, 1993; Sun et al., 1996). Regionally, the Hengshan Mafic Igneous Province underlies the Paleoproterozoic Hutuo Group (2.40–1.90 Ga) of the Wutai–Taihang Mountains in the central part of North China Craton.

Most mafic intrusions and dikes strike NE to ENE (Fig. 6). Although they are commonly deformed along their margins, gabbroic textures are well preserved in their cores. Disequilibrium textures including garnet and amphibole coronas indicate that they underwent metamorphic overprinting. Preliminary age data (including mainly Sm–Nd whole-rock and single-grain zircon U–Pb analyses) yield ages in the range of 2.50–2.40 Ga (Wu et al., 1998; Li et al., 2000a), or 1.90–1.80 Ga for rocks of the Mafic Igneous Province. These age clusters are interpreted as ages of emplacement, and metamorphic reworking, respectively (Li et al., 2000a,b; Shen et al., 1992, 1994; Jin and Guan, 1999). A SHRIMP age of 2455 ± 2 Ma from a dioritic gneiss at Dashiyu (Kroener et al., 2002), in the Hengshan, may be related to this suite. U–Pb (zircon) dating of mafic dikes in the Miyuan granulite-facies terrane north of Beijing suggests that the mafic magmatism occurred at ca. 2.52–2.362 Ga (Jin and Guan, 1999). The mafic dykes commonly display LREE-enrichment, consistent with generation of the dikes in a rift setting.

Several NE-trending rift systems formed in the central to southern part of the North China Craton at the same time as the emplacement of the Hengshan Mafic Igneous Province (2.50–2.40 Ga). These rifts include the Luliang, Zhongtiao, South Taihang, and Hutuo rifts (Fig. 6). Within them, the Paleoproterozoic sequence overlies Neoarchaean basement with the eruption of continental flood basalt and bimodal volcanics recorded in the lower parts of the rift sequences (2.50–2.30 Ga; Yu et al., 1997; Bai and Dai, 1996; Sun et al., 1996). The redefined Hutuo Supergroup consists of the Dongye Group and the Guojiazhai Group. The lowermost formation of Hutuo Supergroup, the Qingshichun Formation, is separated from the underlying Gaofan Group, which consists of foreland basin sediments, by a late fault or unconformity, but in many places it disconformably overlies Neoarchean basement.

Several layers of flood basalt occur within the lower formations of the Hutuo Supergroup. These basalts give a Sm–Nd whole-rock isochron age of 2369 ± 30 Ma, and U–Pb (zircon) ages of 2366 + 103–94 Ma (Qingshichun basalt) and 2358 Ma (Hebianchun basalt). Comparable basalts from Taihang Mountain give Pb–Pb zircon ages of 2300 Ma. These ages are interpreted as igneous crystallization ages (Wang et al., 1997; Wu et al., 1986). The upper part of the Dongye Group records the transition to a passive continental margin setting, with deposition of widespread marine carbonates.

The Paleoproterozoic sequences in the Luliang rift, in the central part of the North China Craton (Fig. 2), are comparable with the Hutuo Supergroup, and are dominated by northeast-trending clastic sediments and mafic volcanics (Sm–Nd whole-rock age of 2471 Ma (Zhang et al., 1988)). The thickness of volcanics increases to the north. In the Zhongtiao rift (Fig. 6) the Zhongtiao and Jiangxian Groups are characterized by bimodal volcanics, and correlate with the Hutuo Group to the north. In the Taihang rift, the Paleoproterozoic Gantaohe Group mainly consists of mafic volcanics (zircon Pb–Pb age of 2.30 Ga), which developed in the northeast-trending rift overlying the Neoarchean basement (Tan et al., 1993).

The Hutuo and related rift systems structurally truncate the underlying Central Orogenic Belt and the eastern part of the Ordos Block, suggesting that they formed after the regional tectonic assembly of the craton in the Neoarchean. To the north, the Hutuo rift disappears, but is replaced by the numerous mafic intrusions of the Hengshan Mafic Igneous Province, within the high-grade metamorphic basement. The ages of mafic intrusions within the high-grade metamorphic basement are slightly older or close to those of mafic volcanics in the lowermost formation in the Hutuo rift. They have geochemical compositions of continental basalt. These relationships suggest that mafic magmatism may be associated with the same extensional episode across the entire craton. The flood basalts, mafic intrusions, and rift sedimentation record continental rifting and breakup of the North China Craton after its initial amalgamation in the Neoarchean (2.50–2.40 Ga). These rocks may be associated with post-orogenic extension after Neoarchean assembly of the Eastern and Western Blocks.

2.70–2.50 Ga gray gneisses of the Western Block are overlain unconformably by the circa 2.40 (or younger) Ga khondalite series, consisting of a 1–3 km thick sequence of shallow-water quartzite, feldspathic arenite, sandstone, siltstone, graphitic schist, and carbonate (Qian and Li, 1999; Zhao et al., 2000). Geochemical studies of the khondalites show that they were derived from cratonic sources and are similar to Phanerozoic shales (Condie et al., 1992; Qian and Li, 1999). Granulite facies metamorphism of the khondalite series records clockwise P-T-t paths, with metamorphic zircon ages falling between 2.1 and 1.8 Ga (Qian and Li, 1999; Kroener, pers. comm., 2003). This granulite facies event is similar to the second-generation granulite P-T-t path in the underlying gneisses, suggesting that the khondalites experienced one period of granulite facies metamorphism at 1.8 Ga, whereas the underlying gneisses experienced two. The older event in the underlying gneisses records an anticlockwise, P-T-t path (Qian and Li, 1999) associated with crustal thickening possibly associated with emplacement of a TTG suite. Metamorphic ages for the older event in the gray gneisses fall between 2.57 and 2.35 Ga (Qian and Li, 1999; Kroener et al., 1998). We suggest that blanketing of the Western (Ordos) block by these shallow water sediments may be related to regional thermal subsidence following rifting in the Central Orogenic Belt. Alternatively, if the younger ages are correct, then the khondalites may represent early distal shales deposited in the Changcheng foreland basin.

Rocks associated with 2.50–2.40 Ga rifting in the Wutai–Taihang–Luliang sequences include immature elastic sediments, mafic dikes, continental flood basalts, and bimodal volcanic rocks overlain by a thermal subsidence phase sequence of shallow water sediments (now khondalites). These grade upward into a cratonic platform sequence of carbonates and shales. We suggest that the N–S rift in the Central Orogenic Belt connected with a more successful rift that formed an ocean on the northern margin of the North China Craton (Fig. 6). The history of this ocean is now recorded by the continental margin and deep-water sediments preserved in the Inner Mongolia–Eastern Hebei Paleoproterozoic Orogenic Belt (Figs. 2 and 6).

A Paleoproterozoic rift system also developed in the eastern part of the North China Craton, as recorded by Liaohe Group and Kuandian complex in Eastern Liaoning. This rift system is located at the eastern side of the Tanlu fault. It trends roughly E–W and consists of supracrustal sequences, bimodal volcanics and anorogenic granite assemblages (Kuandian complex, 2.40–2.30 Ga) (Sun et al., 1996). This rift is parallel to the main eastern arm of the 2.50–2.40 Ga triple junction and is interpreted as a graben parallel to the main ocean. Similar structures are known from younger rifted margins adjacent to successful oceans, including the Newark rift adjacent to the Atlantic Ocean.

6. 2.4–2.3 Ga events

The Inner Mongolia–North Hebei Paleoproterozoic orogenic belt (IMNHO: Fig. 2) marks the northern margin of the North China Craton. This belt includes 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, 2393 ± 3 Ma trondhjemite, and several 2.45–2.33 Ga supracrustal sequences (BIF, turbidites, and biotite-hornblende gneiss), all intruded by 2.44–2.38 Ga granites (Li et al., 1998, 2000a,b). Metamorphic zircons have ages of approximately 2237 Ma (multigrain analysis, Wang and Zhang, 1995). We interpret this belt as an arc/accretionary wedge complex that grew in the ocean to the north of the North China Craton after 2.50 Ga rifting, and accreted to the north margin of the craton by 2.3 Ga.

To the south of the Inner Mongolia–North Hebei Paleoproterozoic orogen is the North China granulite facies belt (Fig. 2). This belt includes an accretionary belt derived from the ocean to the north of the NCC during convergence and collision with the Inner Mongolia–North Hebei arc terrane. South of this, older parts of the NCC were strongly deformed and reworked at 2.3 Ga, forming a 1600 km-long E–W striking granulite facies terrain (Figs. 2 and 6). High-pressure granulites are preserved as boudins within large, E–W striking Paleoproterozoic shear zones (Li et al., 1998b). We interpret this belt as a collisional plateau bounded by E–W strike-slip shear zones that may have accommodated lateral escape of parts of the northern part of the NCC. This lateral escape is now partially recorded in the arcuate pattern of the North China granulite facies belt wrapping around the indentor-style Inner Mongolia–North Hebei Paleoproterozoic arc terrane (Figs. 2 and 6). The plateau may have been converted to a convergent margin plateau after initial collision with the Inner Mongolia–Northern Hebei arc terrane, as discussed below.

A second, apparently younger group of high-pressure granulites is located slightly south of the granulites in the North China granulite facies belt, and separated from it by shear zones. The southern, or Hengshan-Chengde high-pressure granulites also occur as boudins within ENE–NE striking shear zones. The granulites in the Hengshan area have younger metamorphic ages, interpreted to be about 1.86–1.83 Ga (Li et al., 1996, 1998b, Kroener et al., 2002). Crystallization ages for most igneous rocks in this zone range between 2503 and 2478 Ma, with one zircon phenocryst age of 2697 Ma (Li et al., 2000a,b). One foliated granite has an age of 2331 ± 36 Ma, with metamorphic ages of 1872 ± 17 and 1827 ± 10 Ma (Kroener et al., 2002). Many of the boudins are located in extensional shear zones that overprint older contractional structures. Some boudins have pressure-shadow tails composed of granitic melts, suggesting partial melts. The granulites are cut by NNW-striking undeformed and unmetamorphosed mafic dikes with one U/Pb age of 1769 ± 2.5 Ma (Li et al., 2000a,b). They are truncated to the southwest by a large E–W striking strike-slip shear zone that juxtaposes the HP granulite terrain with the 2.5 Ga Wutai greenstone belt.

In contrast, age relations in the Chengde part of the Southern Granulite Province preserve evidence for different timing of intrusive and metamorphic events. TTG gneisses and gabbros were emplaced into older volcanosedimentary sequences, with gabbro recording HP metamorphism between 2490 and 2485 Ma (Kroener et al., 1998), which we interpret to reflect the Neoarchean collision of the East and West blocks at 2.5 Ga. Diorite was emplaced into the metamorphic suite, then deformed and metamorphosed again between 2279 and 2237 Ma (Li et al., 2000a). Extensional faults, mafic dikes, and rift-type sedimentary sequences mark formation of a rift between 1900 and 1700 Ma.

The structural evolution of the southern belt of high-pressure granulites includes early sub-horizontal thrusting, during which the HP granulites were interleaved with gray gneiss and supracrustal sequences, and intruded by syn-tectonic granites. During the second stage of deformation, extensional exhumation occurred along shallowly SE-dipping extensional shear zones, followed by third generation folding that produced open to recumbent folds that plunge NNE and SSW, with SE dipping axial surfaces. During the fourth phase of deformation, strike slip faulting and rotation of older structures occurred.

The location of the southern high-pressure granulites to the south of the older uplifted plateau, along with their structural position within ENE–NE striking shear zones, suggest to us that they formed in response to a younger, circa 1.9–1.8 Ga collision outboard of the Inner Mongolia–Northern Hebei arc terrane. The contact between the two terranes is strongly reworked. We do not see evidence that these high-pressure granulites are related to collision of the Eastern and Western Archean blocks of the North China Craton in the N–S striking Central Orogenic Belt (c.f. Zhao et al., 1998, 1999a,b, 2001a,b; Zhao, 2001; Kroener et al., 2002).

7. 2.20–1.85 Ga events

The North China Craton experienced additional regional deformation, possible accretion of exotic terranes, and Andean-style arc magmatism between 2.20 and 1.85 Ga. At least two major late Paleoproterozoic orogens (2.1–1.90 Ga) have been identified in the North China Craton. The Inner Mongolia–North Hebei Orogenic Belt along the northern margin of the craton was intruded by a belt of plutonic rocks (gabbro, diorite, and granite) upon which volcanic-sedimentary sequences were deposited. Deformation in this belt caused strong reworking of the northern and western parts of the North China Craton between 2.20 and 1.90 Ga. Another, poorly understood orogenic belt is located in the Sino-Korea boundary area (Bai et al., 1992; Cao, 1996), separating the eastern part of North China Craton from the North Korean massif. It crops out mainly in Eastern Liaoning and Jilin, extending northeast of North Korea.

The Inner Mongolia–North Hebei Orogen (Figs. 2 and 6) consists of voluminous TTG to dioritic gneisses, granite, metavolcanics, metasediments, and a minor mount of gabbroic-ultramafic intrusions. It is characterized by east to west-trending composite folds and shear zones. We recognize three distinct belts that formed in the orogen in this time period. From north to south, these include a metasedimentary belt, deposited originally in shallow water; a plutonic belt, consisting of TTG–quartz diorite complexes and late granodiorite–granite, with amphibolite–greenschist facies metamorphism, and, in the south, a supracrustal belt including metavolcanics and metasediments intruded by diorite-gabbro, with amphibolite-facies metamorphism. We interpret these as an accretionary margin, Andean-style arc, and back are basin, respectively.

The Inner Mongolia–North Hebei Orogenic Belt was thrust over the Archean craton to the south, resulting in the retrograde metamorphism of granulites. The Paleoproterozoic nearly east–west strike-slip to thrust shear zones cut across the Neoarchean domains of the reworked Archean craton. The reworked Archean cratonic margin occurs as a granulite-facies belt approximately 1600 km long, along the northern margin of the North China Craton. We name this belt of granulite facies rocks the Hengshan plateau (Fig. 2), after excellent exposures in the Hengshan area, and our inference that the granulite facies metamorphism indicates crustal thickness suggestive of the formation of a large uplifted plateau. Igneous crystallization ages within this belt range from 3.8–3.5 to 2.5 Ga (mainly 2.8–2.5 Ga). The southern limit of the Hengshan Plateau is marked by a nearly E–W trending Opx isograd, across which Archean geologic features appear to be continues with those of the interior of the North China Craton, without major tectonic breaks.

A large number of granites with ages ranging from 2.2 to 1.90 Ga were emplaced into the Inner Mongolia–Eastern Hebei Orogenic Belt. Circa 2.0 Ga granite intrusions are recognized in Tianzheng, and in the Luliang Mountains. A 1.90 charnockite intruded the khondalite terrain in the Luliang area. Voluminous S-type granites were generated through anatexis and metamorphism of the Jining khondalites in the western part of the North China Craton. The khondalites were strongly deformed and thrust southward, causing thickening, and leading to the mainly lower-pressure metamorphism, with synchronous intrusion of S-type granite.

Two U–Pb (zircon) age groups are widely documented within the Hengshan Plateau granulite facies province (2.50 Ga, and 2.00–1.85 Ga). Lower intercepts of 2.00–1.85 Ga represent lead loss (metamorphic) events, with older Archean ages representing the ages of the protoliths (crystalline zircon) of TTG, or earlier metamorphic ages (overgrowth of zircon). The 2.00–1.85 Ga ages are recorded and distributed in the Hengshan, Inner Mongolia, and Luliang areas, and demonstrate that the western part of the North China Craton has been reworked. Formation of charnockite and enderbite in the northern Shanxi-northwestern Hebei region correlates with the second metamorphic episode within the TTG complex of the granulite facies province.

The structural grain in the Hengshan Plateau is ENE to NE, associated with thrusting and strike-slip shearing. Locally, the shear zones in the southern part of the Hengshan Plateau mark the southern boundary of the granulite facies province. The regional deformation may be the result of dextral transpression in the area. Several EW or

Fig. 7. Photographs of the Changcheng Series. (a–d) Quartzites near the Great Wall, (e) ripple marks in Changchang sandstones in rock wall, (f) concentric folds in Changcheng quartzites, (g) interbedded sandstones and shales in more distal facies of Changcheng Series, (h) limestone interbedded with black shales of Changcheng Series.

NE-trending shear zones have been identified in the central to western parts of NCC.

The 1.90 Ga Longquanguan shear zone marks the eastern boundary of reworking and high-grade metamorphism in the west. Some thrust and strike-slip faults occur in the Hengshan and Luliang. To the east are the lower to intermediate-grade TTG-greenstone terrains of Taihang and West Shangdong. The strike-slip shear zones in the south Hengshan led to the juxtaposition of the granulite facies province with the greenstone belt-gneiss terrain in the central part of the North China Craton.

The North China Craton south of the Hengshan Plateau was minimally affected by the late Paleoproterozoic orogenic events. Greenstone belts and gneiss terrains with lower metamorphic grades are well preserved. Zircons from these terrains yield ages older than 2.50 Ga. A major dextral/thrust shear zone in the southern Hengshan dips west, marking the structural boundary between the 1.90 Ga reworked granulite facies terrain and the lower-grade Wutai greenstone belt. Therefore, the shear zone may mark the transition from the uplifted Hengshan Plateau to the Proterozoic foreland. It may be modeled by a northwest-directed transpression and thrusting between the Inner Mongolia- Northern Hebei orogen and the North China Craton, resulting in dextral shear zones trending NE to ENE.

8. 1.85–1.6 Ga: deposition of the Changcheng (Great Wall) Series

Thick sequences of predominantly clastic sedimentary rocks were deposited across the northern part of the North China Craton between 1.85 and 1.6 Ga, forming the Changcheng Series (Fig. 6). The sedimentary sequence is largely undeformed, but some sections show shallow-level concentric folds and thrusts (Fig. 7) similar to those found in foreland thrust belts and basins worldwide. The contact between the Changcheng Series and underlying basement is interpreted to be an unconformity in most places, though in many places the contact is faulted.

There is very little geochronological data on the precise ages of and correlation between different sections of the Changcheng Series. However, a five-fold stratigraphic division of the Changcheng Series has emerged, from the lowermost Changzhougou Formation, up through the Chuanlinggou, Tuanshanzi, Dahongyu, and Gaoyuzhuang Formations (Hebei Bureau, 1989; Sun et al., 1984; Zhu and Chen, 1992; Fang et al., 1998). The Changzhougou Formation is approximately 450 m thick, consisting of sandstone and conglomerate. The base of the formation includes boulder and cobble conglomerates with well-rounded, 45 cm diameter clasts of underlying basement, vein quartz, and metamorphic rocks (Fig. 7). These are interbedded with graded beds of coarse-grained sandstone and grade up into quartz-sandstone with low-angle trough-cross beds and then into fluvial quartz-sandstone (Fig. 7). Toward the south on Taihang Mountain, the sandstones are interbedded with, and grade laterally into, dolostones (Fig. 7), suggesting that the source of the sandstone and conglomerate was to the north, and that the Changzhougou Basin was relatively free of clastic influx a few hundred kilometers from the north margin of the craton. Such relationships are reminiscent of younger foreland basins, where clastic rocks grade laterally into shallow water carbonates from the orogen toward the craton. Yu and Zhang (1984) and Li et al. (1985) reported a Pb–Pb age of 1848 ± 39 Ma for clay minerals in the Changzhougou Formation in the Yanshan Mountains.

The Chuanlinggou Formation rests conformably on the Changzhougou Formation and ranges from 900 m thick in the east to 50 m thick in the west (Zhu and Chen, 1992). It consists mainly of thinly-bedded siltstone, interlayered with micrite and dolostone. Stromatolites are locally well-developed (Zhu, 1980; Liang et al., 1985a,b). To the south, the formation consists predominantly of thinly-bedded siltstone, shale, and fine-grained sandstone. Yu and Zhang (1984) and Li et al. (1985) report a Pb–Pb age of 1785 ± 19 Ma for illite in the upper part of the formation. The lack of conglomerates and coarse-grained sandstone in the Chuanlinggou Formation suggests that the main denudation of the mountains to the north had been completed by the time this formation was deposited. We accordingly interpret the Chuanlinggou Formation to mark the transition of the northern margin of the North China Craton from a foreland basin from 1850 to approximately 1790 Ma, to a rift and cratonic cover sequence from 1785 Ma through approximately 1600 Ma.

The upper three formations of the Changcheng Series, including the Tuanshanzi, Dahongyu, and Gaoyuzhuang Formations, include predominantly micrites, dolostones, stromatolitic dolostone, quartzite, and shale. We interpret these formations to represent a continuation of cratonic sedimentation. The Tuanshanzi Formation has yielded a U–Pb whole rock isochron of 1776 Ma (no error reported, Zhong, 1977), and a Rb–Sr whole rock isochron age of 1606 ± 19 Ma has been suggested for a volcanic flow within the formation (Lu and Li, 1991). The Dahongyu Formation has several interbedded potassic lava flows, one of which has yielded a U–Pb zircon age of 1626 ± 6 Ma (Lu and Li, 1991).

9. 1.85–1.6 Ga aulacogens and continental rifts

The North China Craton became dominated by extension by 1.85 Ga (Fig. 6), with the intrusion of anorogenic rapakivi granite, anorthosite, and mafic dike swarms. Rift and graben systems propagated across the craton. In the south, the Xionger Group shows characteristics of a bimodal volcanic sequence possibly related to the opening of the Qingling Ocean (Sun et al., 1985). Throughout the late Paleoproterozoic to early Mesoproterozoic (1.85–1.40 Ga), the North China Craton was characterized by extensional structures such as aulacogens and mafic dyke swarms. The aulacogen systems and the anorogenic magmatic belts occur mainly in the marginal areas of the North China Craton, whereas mafic dike swarms were emplaced in the central portion of the craton. At this time, the granulite facies terrain in the north was finally exposed. The extensional episode resulted in rapid cooling of the basement and final uplift and exposure of the metamorphic basement.

The aulacogen systems are not limited to Paleoproterozoic metamorphic terrains but were widely developed upon the Archean high-grade metamorphic basement and cut structural trends in the metamorphic basement. The basal formations within the aulacogens commonly rest unconformably on high-grade metamorphic basement (such as in northwest Hebei, eastern Hebei-northern Beijing, Helan Mountains, and the Zhongtiao Mountains), and are commonly much younger (>600–700 Ma) than the metamorphic basement. The graben-rift systems are superimposed mainly on the Archean basement in the eastern part of the craton, typically following order structural trends. Subsequent events mostly record cooling after 1.80 Ga. The present SW margin of the North China Craton began to break up during extensional events between 1.85 and 1.70 Ga. Graben systems evolved to a passive continental margin, and records of oceanic sedimentary deposition continued to 1.50 Ga. Along the southwest margin of the craton, several aulacogens with thick volcanic sequences are well developed. Recently, Paleoproterozoic ophiolites (1.80 Ga; Ma, 1989) were identified in the Qianlian Mountain, on the southwestern side of the craton (Fig. 6), apparently marking an oceanic basin or back arc basin. Therefore, we suggest that a SW-facing continental margin formed on the North China Craton at the end of Paleoproterozoic.

10. Reconciliation of data with a new model for the Paleoproterozoic evolution of the NCC

Major deformation and metamorphism of the northern part of the North China Craton occurred between 1.9 and 1.85 Ga (Li et al., 1998). Many recent metamorphic studies have been carried out in the Hengshan, where exposures are abundant and fresh (Wang, 1991; Zhai et al., 1992, 1995; Zhang and Cong, 1982; Zhang et al., 1991, 1994; Li et al., 1996, 1998b; Zhao, 2001; Zhao et al., 1998, 1999a,b, 2000; Kroener et al., 2002). The observation that the Hengshan is located within the N–S striking Central Orogenic Belt has led several workers to postulate that the 1.9–1.8 Ga metamorphic events are related to the N–S structures. We suggest alternatively that the N–S structures are late Archean, whereas the 1.9–1.8 Ga metamorphic events are related to events in the 1400 km long Paleoproterozoic to Mesoproterozoic Inner Mongolia–Hebei orogenic belt (Figs. 2 and 6). This orogen forms a series of E–W striking structures that crop out across the northern part of the North China Craton. A 1600 km long and 200 km wide granulite facies province is located south of the Inner Mongolia–Northern Hebei Orogen and overprints the northern part of the Central Orogenic Belt, including the Hengshan. We suggest that this represents a Paleoproterozoic–Mesoproterozoic uplifted plateau related to the collision of an arc terrane at 2.3 Ga, and its conversion to an active, Andean style convergent margin. The granulite facies province does not extend south of Luliang–Hengshan–northern Taihang Mountains, and E–W striking granulite facies structures overprint earlier N–S structures. High pressure granulites are confined to the part of the granulite facies province that experienced both 2.5 Ga uplift and erosion from collision of the E and W blocks, as well as uplift in the 1.8 Ga events related to the Paleo-Mesoproterozoic collision. It is possible, therefore, that the location of the high-pressure granulites (retrograded eclogites) is restricted to regions that experienced uplift and denudation from mid-crustal levels two times, effectively exposing rocks that were once at lower crustal levels.

11. Uncited reference

Li et al., 1998c.

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