Tectonic evolution of the North China Block: from orogen to craton to orogen

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Abstract: The North China Craton contains one of the longest, most complex records of magmatism, sedimentation, and deformation on Earth, with deformation spanning the interval from the Early Archaean (3.8 Ga) to the present. The Early to Middle Archaean record preserves remnants of generally gneissic meta-igneous and metasedimentary rock terranes bounded by anastomosing shear zones. The Late Archaean record is marked by a collision between a passive margin sequence developed on an amalgamated Eastern Block, and an oceanic arc–ophiolitic assemblage preserved in the 1600 km long Central Orogenic Belt, an Archaean–Palaeoproterozoic orogen that preserves remnants of oceanic basin(s) that closed between the Eastern and Western Blocks. Foreland basin sediments related to this collision are overlain by 2.4 Ga flood basalts and shallow marine–continental sediments, all strongly deformed and metamorphosed in a 1.85 Ga Himalayan-style collision along the northern margin of the craton. The North China Craton saw relative quiescence until 700 Ma when subduction under the present southern margin formed the Qingling–Dabie Shan–Sulu orogen (700–250 Ma), the northern margin experienced orogenesis during closure of the Solonker Ocean (500–250 Ma), and subduction beneath the palaeo-Pacific margin affected easternmost China (200–100 Ma). Vast amounts of subduction beneath the North China Craton may have hydrated and weakened the subcontinental lithospheric mantle, which detached in the Mesozoic, probably triggered by collisions in the Dabie Shan and along the Solonker suture. This loss of the lithospheric mantle brought young asthenosphere close to the surface beneath the eastern half of the craton, which has been experiencing deformation and magmatism since, and is no longer a craton in the original sense of the word. Six of the 10 deadliest earthquakes in recorded history have occurred in the Eastern Block of the North China Craton, highlighting the importance of understanding decratonization and the orogen–craton–orogen cycle in Earth history.

The Archaean North China (Sino-Korean) Craton (NCC) occupies about 1.7×10^6 km^2 in northeastern China, Inner Mongolia, the Yellow Sea, and North Korea (Bai 1996; Bai & Dai 1996, 1998; Fig. 1). It is bounded by the Central China orogen (including the Qinling–Dabie Shan–Sulu belts) to the SW, and the Inner Monglia–Daxinganling orogenic belt (the Chinese part of the Central Asian Orogenic Belt) on the north (Figs 1 and 2). The western boundary is more complex, where the Qilian Shan and Western Ordos thrust belts obscure any original continuity between the NCC and the Tarim Block. The location of the southeastern margin of the craton is currently under dispute (e.g. Oh & Kusky 2007), with uncertain correlations between the North and South China Cratons and different parts of the Korean Peninsula. The Yanshan belt is an intracontinental orogen that strikes east–west through the northern part of the craton (Davis *et al.* 1996; Bai & Dai 1998). The NCC includes several micro-blocks and these micro-blocks amalgamated to form a craton or cratons at or before 2.5 Ga (Geng 1998; Zhang 1998; Kusky *et al.* 2001, 2004, 2006; Li, J. H. *et al.* 2002; Kusky & Li 2003; Zhai 2004; Polat *et al.* 2005*a*, *b*, 2006), although others have suggested that the main amalgamation of the blocks did not occur until 1.8 Ga (Wu & Zhang 1998; Zhao *et al.* 2001*a*, 2005, 2006; Liu *et al.* 2004, 2006; Guo *et al.* 2005; Kröner *et al.* 2005*a*, *b*, 2006; Wan *et al.* 2006*a*, *b*; Zhang *et al.* 2006). Exposed rock types and their distribution in these micro-blocks vary considerably from block to block. All rocks >2.5 Ga in the blocks, without exception, underwent the 2.5 Ga metamorphism, and were intruded by 2.5–2.45 Ga granitic sills and related bodies. Nd T_{DM} models show that the main crustal formation ages in the NCC are between 2.9 and 2.7 Ga (Chen & Jahn 1998; Wu *et al.* 2003*a*, *b*). Emplacement of mafic dyke swarms at 2.5–2.45 Ga has also been

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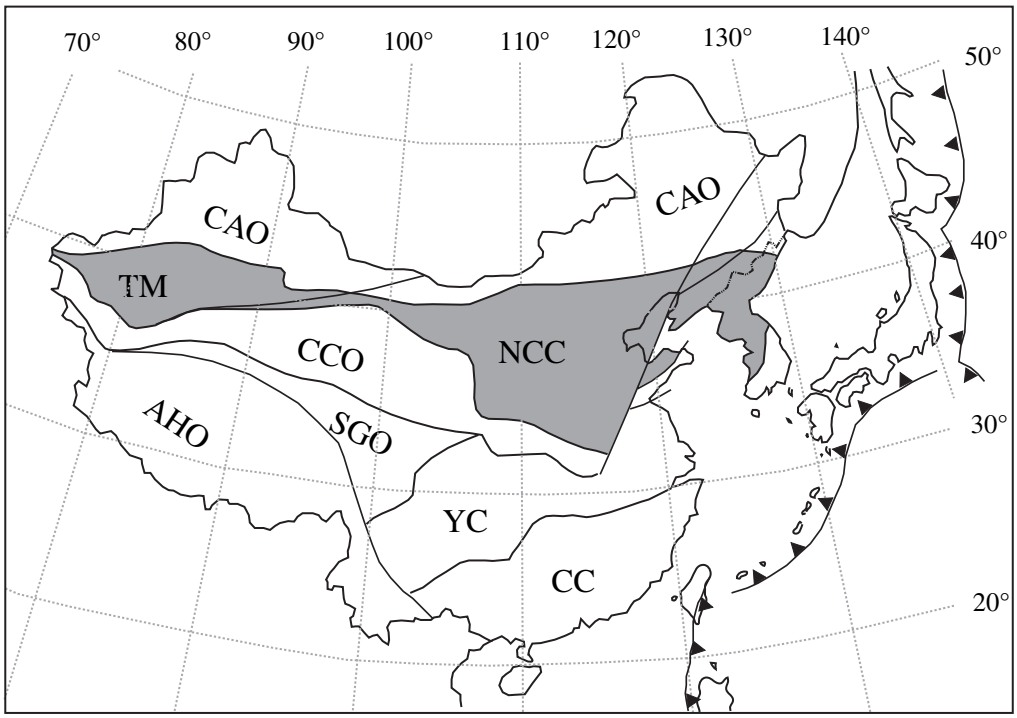

Fig. 1. Simplified map of Asia showing the major tectonic elements. NCC, North China Craton; TM, Tarim Block; CAO, Central Asia orogen; SGO, Songpan Ganzi orogen; CCO, Central China orogen; YC, Yangtze Craton; CC, Cathaysia Craton; AHO, Alpine–Himalaya orogen. Each province has many subdivisions, as discussed in the text.

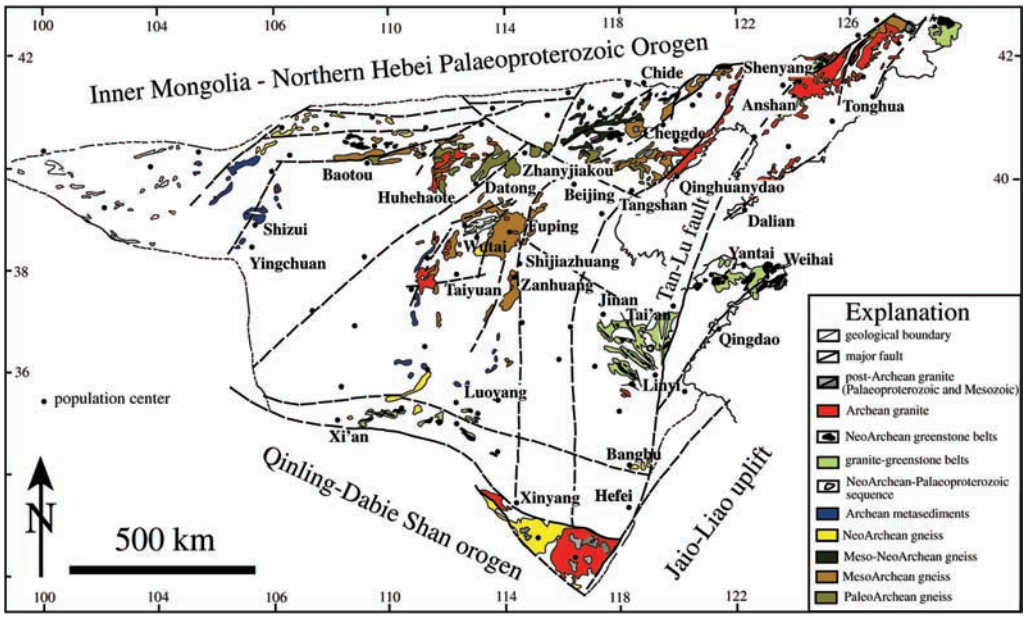

Fig. 2. Simplified geological map of the North China Craton (after Kusky & Li 2003).

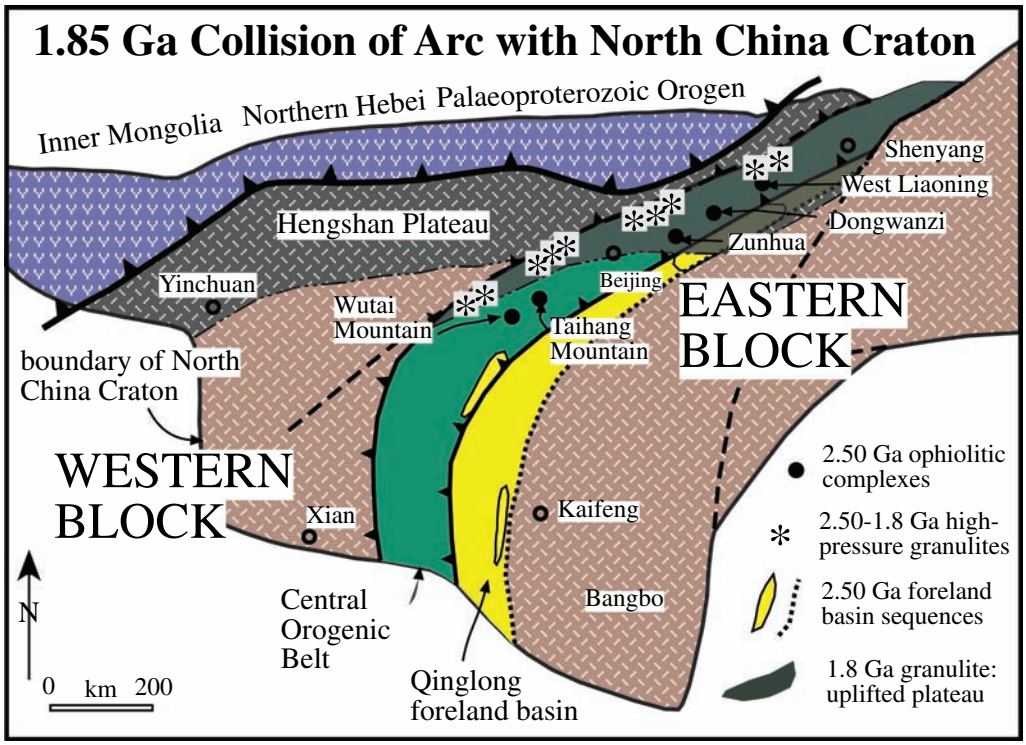

Fig. 3. Tectonic map of the North China Craton (modified after Kusky & Li 2003).

recognized throughout the NCC (Liu 1989; Li, J. H. *et al.* 1996; Li, T. S. 1999).

The craton consists of two major blocks (named the Eastern and Western Blocks), separated by the Central Orogenic Belt (Fig. 3). Other blocks, for example the Jiaoliao Block and Alashan Block, have been described (Geng 1998; Zhai 2004), and most appear to have been amalgamated by the time that the Eastern and Western Blocks collided at 2.5 Ga. Some of the boundaries, however, have been reactivated. Wu *et al.* (1998) suggested that a compositional polarity and diachronous intrusion history in the Eastern Block occurred because an ancient ocean basin between the blocks that now make up the Eastern Block was subducted eastward, beneath the continental block, forming an island arc, which evolved into an arc–continent collisional zone from Honghtoushan, via Qinhuangdao to eastern Shandong. The boundary between the Alashan Block and Western Block is the Western Ordos border fault, the nature of which is not clear.

The Western Block (also referred to as the Ordos Block) is a stable part of the craton that has a thick mantle root (based on depth to the low-velocity zone), low heat flow, and has experienced little internal deformation since the Precambrian (Yuan 1996; Zhai & Liu 2003). In contrast, the Eastern Block is unusual for a craton in that it is at present the site of numerous earthquakes, high heat flow, and a thin lithosphere reflecting the lack of a thick mantle root (Yuan 1996). The NCC is thus one of the world's most unusual cratons. At one time, it had a typical thick mantle root developed in the Archaean, locally modified at 1.8 Ga, and that was present through the mid-Palaeozoic as recorded by Archaean-aged mantle xenoliths carried in Ordovician kimberlites (Menzies *et al.* 1993; Griffin *et al.* 1998, 2003; Gao *et al.* 2002; Wu *et al.* 2003*a*, *b*). However, the eastern half of the root appears to have been removed during Mesozoic tectonism.

Below we outline the geology of the NCC and surrounding regions, starting with the amalgamation of the craton in the Archaean and/or Palaeoproterozoic and finishing with a summary of the evidence for the distinct behaviour of the Western and Eastern Blocks during Phanerozoic tectonism.

Precambrian geology

Major divisions and characteristics of blocks

The North China Craton includes a large area of locally well-exposed Archaean crust (Fig. 2),

including *c*. 3.8–2.5 Ga gneiss, tonalite–trondhjemite–granodiorite (TTG), granite, migmatite, amphibolite, ultramafic bodies, mica schist, dolomitic marble, graphite- and sillimanite-bearing gneiss (khondalite), banded iron formation (BIF), and meta-arkose (Jahn & Zhang 1984*a*, *b*; Jahn *et al.* 1987; He *et al.* 1991, 1992; Bai *et al.* 1992; Bai 1996; Wang 1991; Wang & Zhang 1995; Wang *et al.* 1997; Wu *et al.* 1998). The Archaean rocks are overlain by quartzites, sandstones, conglomerates, shales, and carbonates of the 1.85–1.40 Ga Mesoproterozoic Changcheng (Great Wall) Series (Li *et al.* 2000*a*, *b*). In some areas of the central part of the NCC, 2.40–1.90 Ga Palaeoproterozoic sequences that were deposited in cratonic graben are preserved (Kusky & Li 2003).

The North China Craton is divided into two major blocks (Fig. 3) but the boundaries and ages of the intervening orogen have been the subject of some recent debate. One group (e.g. Kusky & Li 2003; Polat *et al.* 2006) has suggested that the boundary is a Late Archaean–Palaeoproterozoic orogen called the Central Orogenic Belt (COB), that underwent later deformation at *c*. 1.85 Ga. Other workers (e.g. Zhao *et al.* 2001*a*, 2006; Kröner *et al.* 2006) have suggested that the orogen is a *c*. 1.85 Ga feature called the Trans North China Orogen (TNCO) that represents collision of the two blocks at 1.85 Ga, and have defined the boundaries as Mesozoic faults. We believe that geological relationships, described below, favour the first division, which is followed here. However, most metamorphic ages demonstrate that strong metamorphism occurred at *c*. 1.85–1.8 Ga.

The Eastern and Western Blocks are separated by the Late Archaean Central Orogenic Belt, in which virtually all U–Pb zircon ages (upper intercepts) fall between 2.55 and 2.50 Ga (Zhang 1989; Zhai *et al*. 1995; Kröner *et al.* 1998, 2002; Wilde *et al.* 1998; Zhao *et al.* 1998, 1999*a*, *b*, 2000, 2001*a*, *b*, 2005; Li *et al.* 2000*b*; Kusky *et al.* 2001, 2004; Zhao 2001; Kusky & Li 2003; Polat *et al.* 2005*a*, *b*, 2006). The stable Western Block, also known as the Ordos Block (Bai & 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. It has a thick platform sedimentary cover intruded by a narrow belt of 2.55–2.50 Ga arc plutons along its eastern margin (Zhang *et al.* 1998). Much of the Archaean geology of the Western Block is poorly exposed because of thick Proterozoic and Palaeozoic to Cretaceous platformal cover. A platformal cover on an Archaean basement is typical of many Archaean cratons worldwide.

In contrast, the Eastern Block is atypical for a craton in that it has been tectonically active and has numerous earthquakes, high heat flow, and a thin lithosphere reflecting the lack of a thick mantle root. The Eastern Block contains a variety of *c*. 3.80–2.50 Ga gneissic rocks and greenstone belts locally overlain by 2.60–2.50 Ga sandstone and carbonate units (e.g. Bai & Dai 1996, 1998). Deformation is complex, polyphase, and indicates the complex collisional, rifting, and underplating history of this block from the Early Archaean to the Meso-Proterozoic (Zhai *et al.* 1992, 2002; Li *et al.* 2000*a*; Kusky *et al.* 2001, 2004; Kusky & Li 2003; Zhai 2004, 2005; Polat *et al.* 2005*a*, *b*, 2006), and again in the Mesozoic–Cenozoic (as described in the papers in this volume).

The Central Orogenic Belt includes belts of TTG, granite, and supracrustal sequences that were variably metamorphosed from greenschist to granulite facies. It can be traced for about 1600 km from west Liaoning in the north to west Henan Province in the south (Fig. 3). It should be noted that the COB differs from the TNCO defined by Zhao *et al.* (2001*a*). The COB is an Archaean orogen, with Archaean structures defining its boundaries, whereas the TNCO is defined as a Proterozoic orogen, albeit one bound by Mesozoic structures. High-grade regional metamorphism, including migmatization, occurred throughout much of the Central Orogenic Belt between 2.60 and 2.50 Ga (Zhai 2004), with final uplift of the metamorphic belt during *c*. 1.90–1.80 Ga extensional tectonism (Li *et al.* 2000*a*) or a collision on the northern margin of the NCC (Kusky & Li 2003). Greenschist- to amphibolite-grade metamorphism predominates in the southeastern part of the COB (such as in the Qinglong belt, Fig. 2), but the northwestern part is dominated by amphibolite- to granulite-facies rocks, including some high-pressure assemblages (10–13 kbar at $850 \pm 50\,^{\circ}$C; Li *et al.* 2000*b*; Zhao *et al.* 2001*a*, *b*; see additional references given by Kröner *et al.* 2002). The high-pressure assemblages occur in the linear Hengshan belt (Fig. 4), which extends for more than 700 km with a ENE–WSW trend. Internal (western) parts of the orogen are characterized by thrust-related subhorizontal foliations, shallow-dipping shear zones, recumbent folds, and tectonically interleaved high-pressure granulite migmatite and metasedimentary rocks. The COB is in many places overlain by sedimentary rocks deposited in graben and continental shelf environments, and is intruded by *c*. 2.5–2.4 and 1.9–1.8 Ga dyke swarms. Several large 2.2–2.0 Ga anorogenic granites have also been identified within the belt (Li & Kusky 2007).

Recently, two linear zones of deformation have been documented within the belt, including a high-pressure granulite belt in the west (Li *et al.*

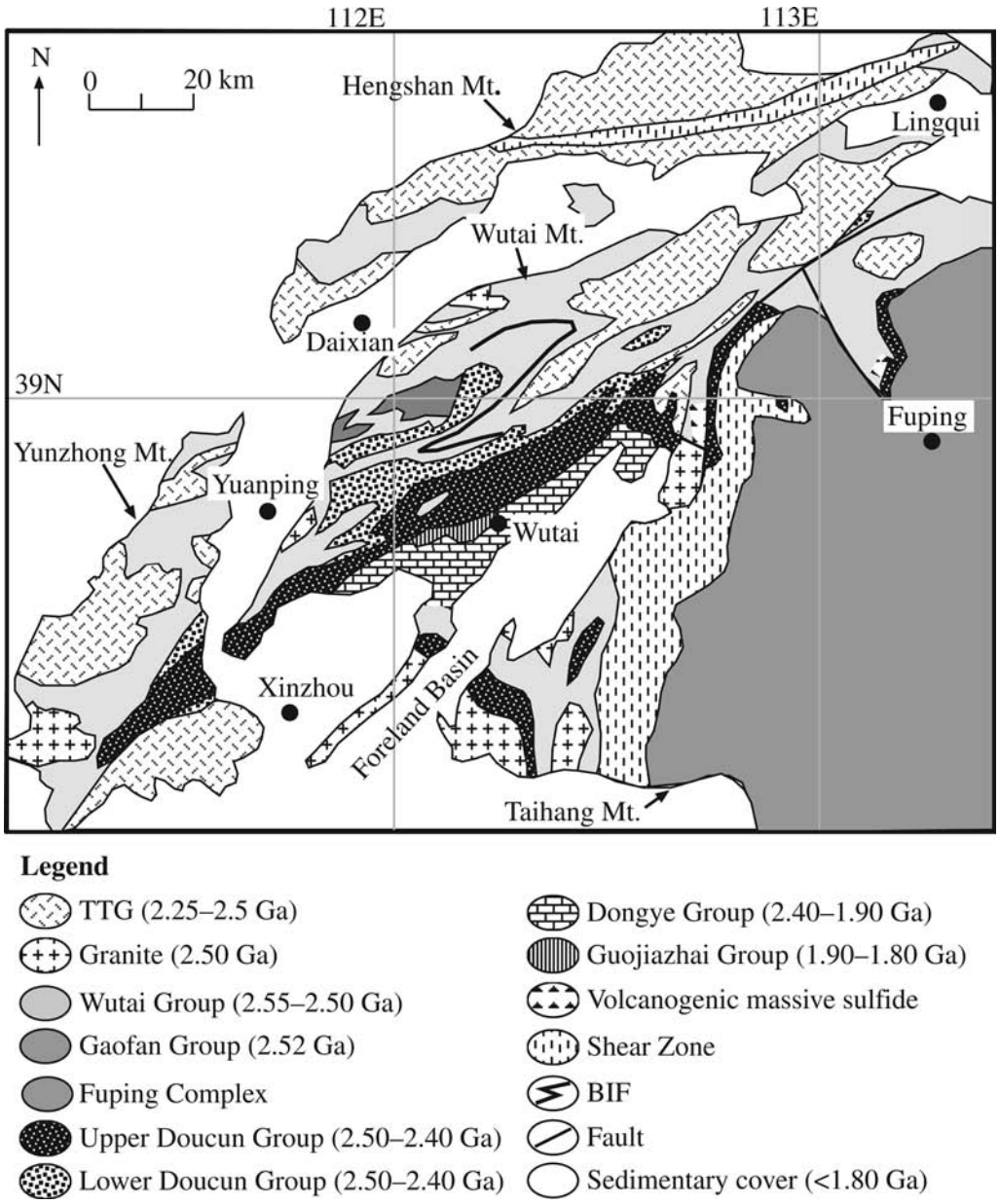

Fig. 4. Simplified geological map of the Hengshan–Wutaishan–Fuping area, showing relationships between high-pressure granulites and gneiss north of the shear zone on the north side of Hengshan Mountains, medium-pressure granulites to the south, and amphibolite- to greenschist-facies rocks of the Wutai Group and greenstone belt. Map modified after Yuan (1988) and Li *et al*. (2004).

2000*a*), and a foreland basin and fold–thrust belt in the east (Li, J. H. *et al.* 2002; Kusky & Li 2003; Li & Kusky 2006). The high-pressure granulite belt is separated by normal faults from the Western Block, which is overlain by thick metasedimentary rocks (khondalites) that are younger than 2.40 Ga, and were metamorphosed at 1.862.7 $\pm$ 0.4 Ga; A. Kröner, pers. commun.).

High-pressure granulites

The Hengshan high-pressure granulite (HPG) belt consists of several metamorphic terranes, including the Hengshan, Huaian, Chengde, West Liaoning, and Southern Taihangshan metamorphic complexes (Figs 2–4). The HPG commonly occurs as isolated pendants within intensely sheared TTG (2.60–2.50 Ga) and granitic gneiss (2.50 Ga), and is widely intruded by 2.20–1.90 Ga K-granite and mafic dyke swarms (2.45–2.40 Ga, 1.77 Ga) (Li *et al.* 2000*b*; Kröner *et al.* 2002; Peng *et al.* 2007). Locally, thrust slices of lower metamorphic grade khondalite and metamorphosed turbiditic sediments are interleaved with the high-pressure granulite rocks. The main rock type of the complexes is a garnet-bearing mafic granulite with characteristic plagioclase–orthopyroxene coronas surrounding the garnets, which show evidence for rapid exhumation-related decompression (at *c.* 1.9–1.8 Ga) from peak P–T of 1.2–0.9 GPa and 700–800 °C (Zhao *et al.* 2000; Kröner *et al.* 2002). At least three types of REE patterns are shown by the mafic rocks from flat to moderately light REE (LREE)-enriched, indicating original crystallization in a continental margin or island-arc setting (Li, J. H. *et al.* 2002). The subsequent high-pressure metamorphism occurred during pre-2.5 Ga partial subduction of the mafic rocks, which was then followed by collision and the rapid rebound–extension that is recorded by 2.50–2.40 Ga mafic dyke swarms and graben-related sedimentary rock sequences in the Wutai Mountains–Taihang Mountains areas (Kusky & Li 2003; Kusky *et al.* 2006). Another kind of high-pressure granulites occur as deformed and pulled-apart dykes. They yield sensitive high-resolution ion microprobe (SHRIMP) zircon ages of 1973 ± 4 Ma and 1834 ± 5 Ma, with a core residual age of 2.0–2.1 Ga (Peng *et al.* 2005, 2007).

Zhao *et al.* (2001*a*, *b*, 2005, 2006), Wilde *et al.* (2003), and Kröner *et al.* (2005*a*, *b*, 2006) have suggested that the *c.* 1.9–1.8 Ga granulite event in the NCC is related to the continent–continent collision between the Eastern and Western Blocks of the craton. This model is supported by the interpretation of clockwise metamorphic P–T–t paths that show crustal thickening related metamorphism at 1.85 Ga, in support of a collision at this time. However, Kusky & Li (2003) noted that the structural, sedimentological, and geological field data suggested collision of the Eastern and Western Blocks at 2.5 Ga, and that the 1.9–1.8 Ga granulite event occurs throughout rocks across the entire northern half of the craton, not just in the COB, and that it might be related to a collision along the northern margin of the craton, forming an east–west orogen by 1.8 Ga. O'Brien *et al.* (2005) recognized two main types of granulites, including high-pressure mafic granulites in the north, and medium-pressure granulites in the south, separated by the east–west-striking Zhujiafang shear zone. Further south, metamorphic facies are even lower grade, dominated by amphibolite to greenschist facies in the Wutaishan (O'Brien *et al.* 2005), providing evidence for north to south crustal staking of higher over lower grade rocks at *c.* 1.9–1.8 Ga. Santosh *et al.* (2006) have related ultrahigh-temperature metamorphism (975 °C at 9 kbar, and 900 °C at 12 kbar) at 1927 ± 11 Ma, and 1.1819 ± 11 Ma, to the formation of a 1.9–1.8 Ga collisional orogen along the north margin of the NCC during the amalgamation of the Columbia supercontinent.

2.5 Ga foreland basin

The Late Archaean Qinglong foreland basin and fold–thrust belt (Fig. 3) trends north–south to NE–SW, and is now preserved as several relict folded sequences (Kusky & Li 2003; Li & Kusky 2006). Its general sedimentary rock sequence from bottom to top can be further divided into three subgroups of quartzite–mudstone–marble, turbidite, and molasse. The lower subgroup, of quartzite–mudstone–marble, is well preserved in central sections of the Qinglong foreland basin (Taihang Mountains), which includes numerous shallowly dipping structures, and is interpreted to be a product of pre-2.5 Ga passive margin sedimentation on the Eastern Block. It is overlain by lower-grade turbidite and molasse-type sediments. The western margin of the Qinglong foreland basin is intensely reworked by thrusting and folding, and is overthrust by rocks of an active margin (TTG gneiss, ophiolite fragments, accretionary wedge type metasediments). To the east, rocks of the basin are less deformed, defining a gradual transition from high-grade metamorphism and ductile structures of the COB to an upper crustal level fold–thrust belt then foreland basin style structures to the east. The passive margin sedimentary rocks and the Qinglong foreland basin are intruded by a *c.* 2.40 Ga diorite and gabbroic dyke complex (Li & Kusky 2006), and are overlain by graben-related sedimentary rocks and 2.4 Ga flood basalts. In the Wutai and North Taihang basins, many ophiolitic blocks are recognized along the western margin of the foreland fold-and-thrust belt. These typically consists of pillow lava, gabbroic cumulates, and harzburgite, with the largest block being 10 km long in the Wutai–Taihang Mountains (Wang *et al.* 1997).

Timing of collisional orogenesis in the Central Orogenic Belt

Whereas it is well recognized that the Central Orogenic Belt records the collision between the Western and Eastern Blocks of the NCC, the timing of this collision is debated. Zhao and co-workers (Zhao *et al.* 2001*a*, *b*, 2005, 2006; Kröner *et al.* 2006) suggested 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 isothermal decompression (ITD) type clockwise $P–T$ paths. ITD type $P–T$ 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, a continental arc that had been active on the western edge of the Eastern Block since 2.5 Ga was transformed to a continent–continent collision zone at *c*. 1.85 Ga with the collision of the passive margin of the Western Block, indicating a life span for this margin of 650 Ma. 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 & Liu 2003; Kusky *et al*. 2006), a feature not accounted for in the Zhao *et al.* model. Several other aspects of the Zhao *et al.* model make it untenable. First, the proposition of having an active margin for 650 Ma is unlikely, especially when the geological record in the NCC shows little evidence for any accretionary activity in this period. Such a long-lived accretionary margin would be expected to produce an accretionary orogen on the scale of the Makran or the southern Alaska margin, yet the proposed location of the margin preserves no such rocks. Further, in the Zhao *et al.* (2006) interpretation, the granulites along the northern margin of the craton are explained by the unlikely scenario in which the two continental blocks both independently developed granulite-facies belts on one of their margins, which fortuitously became perfectly lined up to form one continuous belt along the northern margin of the craton at 1.8 Ga. The Zhao *et al.* model relies on the interpretation of the significance of *c*. 1.85 Ga metamorphic ages and $P–T–t$ paths from a major event at 1.85 Ga. Recent detailed mapping, analysis of structures, sedimentary basins, and the distribution of tectonic belts or rocks types in the craton suggest that there are other possible interpretations of the 1.85 Ga event. Furthermore, other workers (e.g. Li *et al.* 1996, 2000*a*, *b*; O'Brien *et al.* 2005; Santosh *et al.* 2006, and references therein) have shown that the ultra high-temperature and high-pressure granulites are distributed across the northern part of the craton, and not confined to the Central Orogenic Belt.

Kusky and coworkers (Kusky *et al.* 2001, Kusky 2004; Kusky & Li 2003; Polat *et al.* 2005*a*, *b*, 2006) suggested that the Eastern and Western Blocks collided at 2.5 Ga, forming a 200 km wide orogen that included development of a foreland basin on the Eastern Block, and a granulite-facies belt on the Western Block. Evidence for this collision is found as remnants of 2.5 Ga oceanic crust (Kusky *et al.* 2001; Kusky 2004; Polat *et al.* 2005*a*, *b*, 2006), island arcs, accretionary prisms, and deformed continental fragments, which show a consistent 2.5 Ga metamorphism. Late Archaean collision was, in this scenario, followed by post-orogenic extension and rifting that led to the emplacement of mafic dyke swarms and development of extensional basins along the COB, as well as to the opening of a major ocean along the northern margin of the NCC (Kusky & Li 2003).

1.85 Ga continent–continent collision on the northern margin of the craton

After collision at *c*. 2.5 Ga and post-collisional extension by 2.4 Ga, the North China Craton was in a relatively inactive tectonic stage with the exception of deformation, magmatic activity and metamorphism associated with an Andean-type margin that was active on the north margin of the craton from 2.2 to 1.85 Ga. Then an important metamorphic event happened between 1900 and 1800 Ma. As a result, all Precambrian rocks of the craton experienced the same metamorphic episode at 1900–1800 Ma, and associated migmatization and intrusion of crustal melt granites. Kusky & Li (2003) related this event to a continental collision on the northern margin of the craton, associated with the formation of a new east–west-striking foreland basin (in which the Changcheng Series of conglomerates, sandstones and shales was deposited), and was followed closely by a new period of post-orogenic extension. High-pressure granulites were developed in an east–west belt in the north (the Inner Mongolia–Eastern Hebei Palaeoproterozoic orogen), with polyphase granulites preserved from UHT processes in the Andean-type arc, and where the east–west belt crosses the COB. Alternatively, Zhai (2004) proposed that the *c*. 1.8 Ga event represents a continental geological process within the craton: an upwelling mantle plume caused uplift of the craton basement as a whole and was closely followed by the development of an aulacogen system. A series of continent rifts were developed, with alkalic volcanic eruption and intrusion of anorogenic magmatic association

(rapakivi–anorthosite–gabbro) and mafic dyke swarms. The Mesoproterozoic sedimentary sequences in the Yanshan rift are called the Changcheng–Jixian System, which was deposited at *c*. 1800–1500 Ma. However, the age of the upper Jixian System is not defined: it could extend to *c*. 1400–1100 Ma. Zhao *et al.* (2004) suggested that the volcanic eruption centre of the rift system was in western Henan Province. From *c*. 1800 Ma to 1700 Ma (the Xiong'er Group), the rift extended to the west, east and north, forming a triple junction. Finally, dioritic intrusions indicate rifting-end magmatic activity. The rift system mainly trends NE–SW to east–west and branches off into the Taihang Mountains to the south. The northern margin of the craton remained episodically active as a convergent–accretionary margin (separated by periods of passive margin sedimentation) for the next several hundred million years, growing northward and accommodating the southward(?) subduction of thousands of kilometres of oceanic lithosphere.

The 1.8 Ga event that formed the high-pressure granulites with clockwise P–T paths was interpreted by Kusky & Li (2003) as being related to a (continental?) collision outboard of the Inner Mongolia–Eastern Hebei orogen, and closure of a back-arc basin preserved along the north margin of the craton. Following collision at 1.85 Ga, extensional tectonics gave rise to a series of aulacogens and rifts that propagated across the craton, along with the intrusion of mafic dyke swarms. On the northern margin of the craton at Bayan Obo, a basement of migmatites is overlain unconformably by a 2 km thick shelf sequence of *c*. 2.07–1.5 Ga quartzites, shales, limestones, dolomites and conglomerates. Carbonatite dykes (Le Bas *et al.* 1992; Fan *et al.* 2002) emplaced into the sedimentary rocks are associated with the largest REE deposit in the world that has a Sm–Nd mineral age of 1426 ± 40 Ma and a monazite age of 1350 ± 149 Ma (Nakai *et al.* 1989). On the southwestern margin of the NCC the Western Block gneisses and migmatites are overlain by marbles and intruded by the Jinchuan lherzolite body, which contains the third largest nickel deposit in the world (Chai & Naldrett 1992). Troctolite associated with the lherzolite has a $^{206}Pb/^{238}U$ SHRIMP age on zircons of 827 ± 8 Ma, regarded by Li *et al.* (2004) as the crystallization age of the ultramafic intrusion. As Li *et al.* suggested, the Jinchuan intrusion may have been emplaced as a result of mantle plume activity during the break-up of the Rodinia supercontinent.

Many relationships between Palaeoproterozoic volcanosedimentary groups and basement blocks in the eastern part or the craton are still enigmatic. For instance, rocks of the Liaohe Group on the Jiadong Peninsula, and the Guanghua, Ji'an and Liaoling groups in Jilin Province, have been assigned various ages ranging from 2.5 to 1.9 Ga, and their tectonic environments have been interpreted as accretionary prism, collision-related, and rift related (e.g. see Zhai 2005; Li *et al.* 2006; Lu *et al.* 2006). Very little structural work has been published on these rocks, and it is clearly needed to understand the role of these rock groups in the tectonic evolution of the craton.

From the late Neoproterozoic until the end of the Palaeozoic, the NCC behaved as a coherent, stable continental block, as evidenced by deposition of shallow-marine carbonate platform sediments throughout the Palaeozoic (e.g. Metcalfe 1996, 2006). Breaks in sedimentation, however, were associated with deformation and orogeny along all margins of the craton and a regional disconformity between the Upper Ordovician and Upper Carboniferous units (Wang 1985). The latter may have resulted from the global eustatic lowstand of sea level following the early Palaeozoic orogeny or from double-vergent subduction beneath the north and south margins 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 & Nie 1996)). Moreover, it is during this interval that diamond-bearing kimberlites erupted in several areas of the Eastern Block of the NCC (Fig. 2; 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 that observed in Archaean cratons elsewhere (e.g. Kaapvaal, Slave, Siberia; see Menzies *et al.* 1993; Griffin *et al.* 1998, 2003).

Phanerozoic tectonics

Major orogenic belts, faults and basins

It is fair to say that the detailed geological and tectonic histories of the margins of the NCC are, for the most part, very poorly understood. Using current palaeomagnetic data, de Jong *et al.* (2006) suggested that in the Early Palaeozoic the NCC, South China (Yangtze) Craton and the Tarim Craton (Fig. 1) were microcontinents fringed by subduction–accretion complexes and island arcs along the northeastern Cimmerian margin of Gondwana (Fig. 5). Rifting in the Early Carboniferous was followed by drifting of the Precambrian blocks across the Palaeo-Tethys Ocean, and their amalgamation to form much of what is now China in Permo-Triassic times. The Solonker and Dabie sutures (see Figs 2, 6 and 7) record respectively

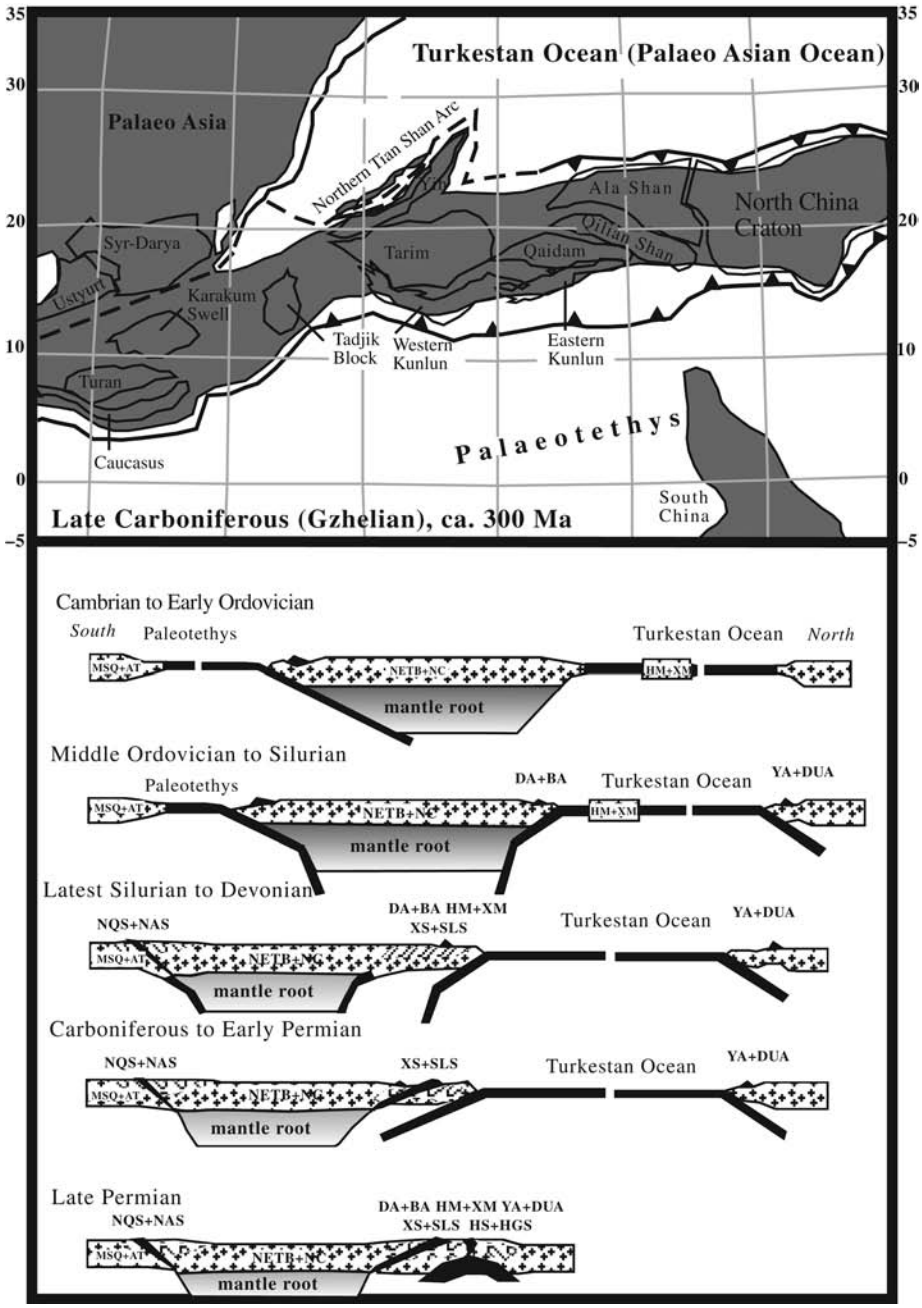

Fig. 5. Palinspastic map and schematic cross-sections showing the evolution of the North China Craton in the Palaeozoic. Modified after Heubeck (2001) and Yue *et al.* (2001). AT, Altyn Tagh; BA, Baoerhantu arc; DA, Dongqiyishan arc; DUA, Don Ujimqin arc; HGS, Hegenshan suture; HM, Hanshan microcontinent; HS, Hongshishan suture; MSQ, middle and south Qilian; NAS, North Altyn Tagh suture; NC, North China Craton; NETB, northeastern Tarim Block; NQS, north Qilian suture; SLS, Solon–Linxi suture; XM, Xilin Hot microcontinent; XS, Xiaohuangshan suture; YA, Yuanbaoshan arc. It should be noted that although the NCC and Tarim Block experienced craton margin tectonism throughout the Palaeozoic, the craton interior was relatively quiescent. However, subduction of thousands of kilometres of oceanic lithosphere under the craton from the Palaeotethys in the south, and Turkestan (Palaeoasian) Ocean strands in the north, significantly hydrated and weakened the subcontinental lithospheric mantle, perhaps creating conditions favourable for root loss in the Mesozoic.

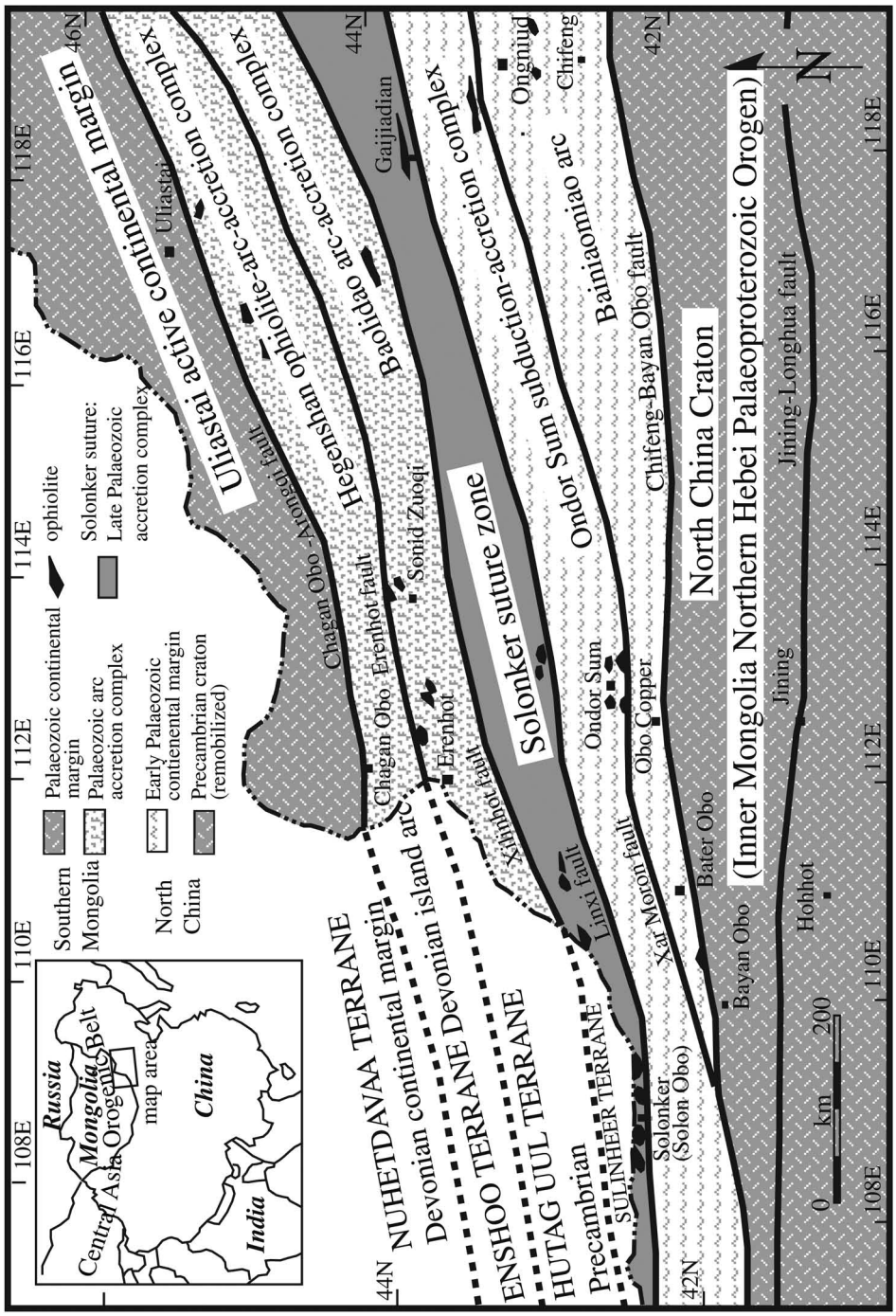

Fig. 6. Schematic map of the northern margin of the North China Craton, including the Inner Mongolia–Northern Hebei Palaeoproterozoic orogen, and the Central Asian orogen (modified after Xiao *et al.* 2003). The Solonker suture marks the composite suture between terranes accreted to the northern margin of the North China Craton, and terranes accreted to the southern margin of the Siberian Craton.

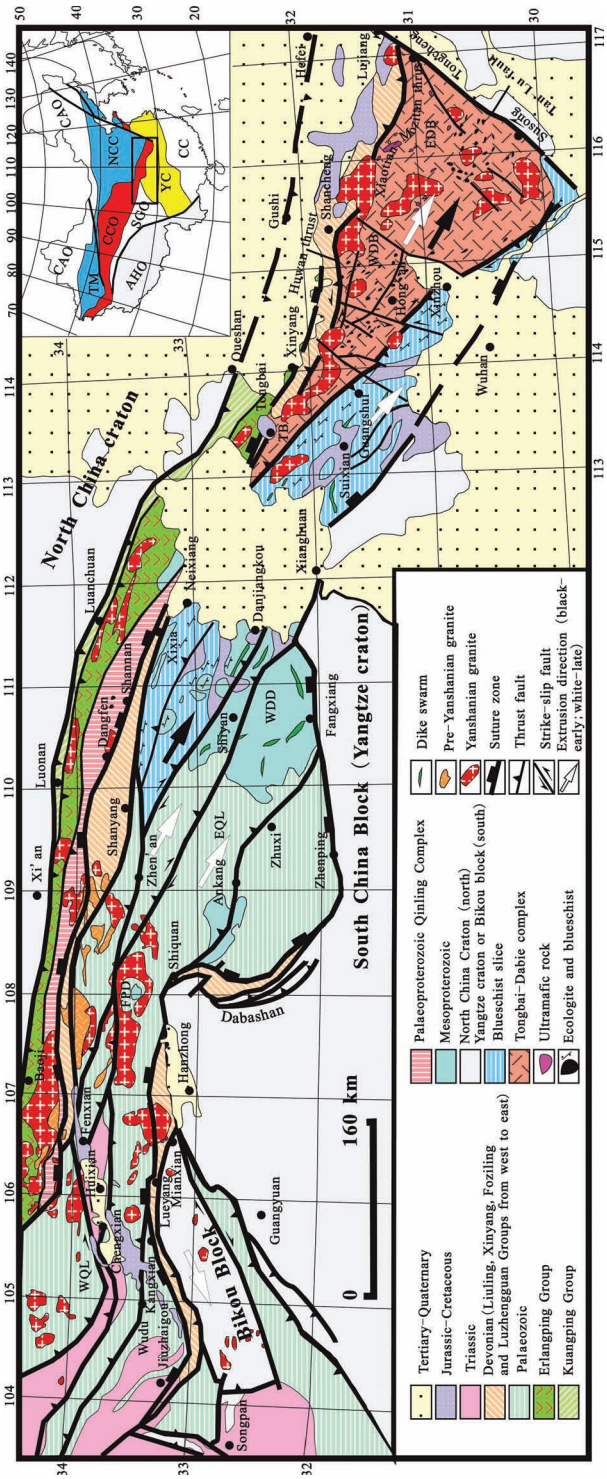

Fig. 7. Map of the Qingling–Dabie orogen (after Li, S. Z. *et al.* 2006). The two sutures in the orogen, including Shangdan suture in the north, and the Mianlue suture in the south, should be noted. The Shangdan suture resulted from Middle Palaeozoic closure of the Shangdan ocean and collision of the North China Craton and the Qinling–Dabie microplate. The Mianlue suture, however, resulted from Late Triassic closure of the Mianlue ocean and collision of the Qinling–Dabie microplate and the South China Craton. Map drawn by S. Z. Li. Abbreviations in inset map are as in Figure 1.

terrane accretion from the north (during closure of the Turkestan Ocean) and collision of the South China Craton with the NCC in the south (e.g. Li *et al.* 1995; Metcalfe 1996).

The main Mesozoic events to affect the NCC are traditionally referred to as the Late Triassic–Early Jurassic Indosinian orogeny, and the Late Jurassic–Early Cretaceous Yanshanian orogeny (Yang *et al.* 1986). Main surface features related to these events include major east–west and north–south fold belts, widespread plutonism, and extensional faults.

The structural history of the relatively flat-lying Palaeozoic sedimentary cover of the NCC shows that it was stable until Jurassic times (Wang 1985) although deformation on the craton margins began earlier. Kimberlites found in the Taihang–Luliang regions are Mesozoic–Tertiary in age and are related to uplift of the Shanxi highlands in the centre of the craton, which preceded and represents early stages of the young rifting in this area (Ke & Tian 1991; Dobbs *et al.* 1994; Zheng *et al.* 1998, 2001). On the eastern side of the craton, one of the world's largest continental margin transcurrent faults, the Tan-Lu fault, constitutes the most striking structural feature of the region (Fig. 2). It stretches more than 1000 km subparallel to the Pacific margin and probably extends into Russia (Xu & Zhu 1994). The timing of early motion and cause of formation of the Tan-Lu fault are controversial. Various workers have proposed Triassic (Okay & Sengör 1992; Yin & Nie 1993) or Cretaceous (Xu *et al.* 1987; Xu 1993; Xu & Zhu 1994) ages for initial motion, reflecting initiation either from collision between South China (Yangtze) Cratons and the NCC (Okay & Sengör 1992; Yin & Nie 1993) or from oblique convergence between the Pacific and Asian plates (Xu *et al.* 1987).

The apparent offset of the Dabie Shan and Su-Lu ultrahigh-pressure rocks suggests *c.* 500 km of initial sinistral motion on the Tan-Lu fault during the Triassic–Jurassic collision of the North and South China Cratons (Okay & Sengör 1992; Yin & Nie 1993). However, the central part of the fault indicates *c.* 740 km of sinistral displacement (Xu *et al.* 1987). Large-scale left-lateral strike-slip motion occurred on the Tan-Lu fault at *c.* 132–128 Ma (Early Cretaceous).

Geological evidence of Early Jurassic to mid-Cretaceous tectonism in the NCC is abundant, and not just recorded along the Tan-Lu fault system. Widespread 147–112 Ma magmatism included the intrusion of adakites, reflecting subduction of perhaps as many as three distinct slabs (Xu 1990; Zhang, L. C., *et al.* 2000; Davis *et al.* 2001; Wang *et al.* 2001; Zhang, Q., *et al.* 2001; Wei *et al.* 2002; Xu *et al.* 2002; Davis, 2003; see also Castillo 2006). The formation of China's most important gold vein deposits occurred at the same time along the northern, eastern, and southern margins of the Eastern Block (Mao *et al.* 1999; Zhou *et al.* 2002; Yang, J.-H. *et al.* 2003; Fan *et al.* 2007). Unroofing of many metamorphic core complexes (*c.* 140–105 Ma), products of SE–NE extension (Niu 2005; Zhang *et al.* 1994; Zheng *et al.* 1998, 2001; Zhang, Y. Q. *et al.* 1998; Webb *et al.* 1999; Zhang, Q., *et al.* 2001; Davis *et al.* 2002; Darby *et al.* 2006; Li *et al.* 2007), and major animal extinctions were also significant in this period (Chen *et al.* 1997; Wang *et al.* 2001).

These observations support a change from a relatively internally stable craton, from *c.* 1900 to 250 Ma, to a middle to late Mesozoic situation where the margins of the Eastern Block underwent significant Yanshanian orogenesis. This tectonism reflects three relatively contemporaneous collisional or subduction events, or both: (1) the collision of the Yangtze Craton to the south; (2) the closure of the Turkestan Ocean (forming the Solonker suture) and accretion of the oceanic arcs on the north; (3) and oblique subduction of Palaeopacific oceanic crust on the east (Fig. 5). Below, we discuss each of these settings.

Northern margin: the Solonker suture, and Palaeozoic subduction beneath the north margin of the NCC

The Palaeoasian or Turkestan Ocean was present on the northern side of the NCC throughout the Palaeozoic, with Palaeo-Tethys to the south (e.g. Metcalfe 1996, 2006). Several subduction zones were active during this interval, leading to continental growth through accretion of terranes along the northern margin of the craton and the generation of arc magmas (Davis *et al.* 1996, 2002, 2006; Yue *et al.* 2001; Xiao *et al.* 2003). These terranes north of the NCC (Fig. 6) host more than 900 Late Palaeozoic to Early Triassic plutons (Sengör *et al.* 1993; Sengor & Natal'in 1996; Xiao *et al.* 2003). Xiao *et al.* (2003) suggested that these plutons are related to closure of the Palaeoasian ocean at the end of the Permian. Closure is marked by the Solonker suture (Fig. 6) and 300–250 Ma south-directed subduction beneath the accreted terranes along the northern side and the northern margin of the NCC itself (Xiao *et al.* 2003). Continued convergence from the north during Triassic and Jurassic times caused post-collisional thrusting and considerable crustal thickening on the NW side of the craton (Xiao *et al.* 2003). The northeastern margin of the NCC with a Permian shelf sequence collided with the Khanka Block in Late Permian to Early Triassic times, as indicated by syncollisional granites (Jia *et al.* 2004). Many of the subsequent later Mesozoic

granitoids, metamorphic core complexes, and extensional basins, south of the Solonker suture in the northern part of the NCC and the adjacent Palaeozoic accretionary orogen (Fig. 6), may be related to post-collisional Jurassic–Cretaceous collapse of the massive Himalayan-style Solonker orogen and plateau (Ritts *et al.* 2001; Xiao *et al.* 2003; Gregory *et al.* 2006).

The south: Qingling–Dabie Shan–Sulu orogen

The Qinling–Dabie orogen is marked by the terranes forming the irregular suture between the NCC and South China Craton (Fig. 7). It is a major part of the east–west-trending Central China orogen (Jiang *et al.* 2001), which extends for 1500 km eastward from the Kunlun Range to the Qinling Range, and then 600 km farther east through the Tongbai–Dabie Range. Its easternmost extent, offset by movement along the Tan-Lu fault system, continues northeastward through the Sulu area of the Shandong Peninsula and then into South Korea. Ratschbacher *et al.* (2003) suggested that the Sulu belt continues through the Imjingang fold belt of Korea, yet the presence of 230 Ma eclogites in the southern Gyeonggi massif (Oh 2006; Oh & Kusky 2007) suggests that the Sulu belt may alternatively extend through South Korea. The intermittent presence of ultrahigh-pressure diamonds, eclogites and felsic gneisses indicates very deep subduction along a cumulative >4000 km long zone of collisional orogenesis (Yang, J. S., *et al.* 2003).

The rifting and collisional history throughout the Palaeozoic of the NCC with blocks and orogens to the south, such as the North Qinling terrane, the South Qinling terrane, and eventually (in the Triassic) the South China Precambrian block, is complicated and controversial (Meng & Zhang 1999). In the Early Palaeozoic, northward subduction of the Qaidam–South Tarim plate (possibly connected with the South China plate) took place beneath the active southern margin of the NCC (Li, S. Z. *et al.* 2002, 2006*b*). The NCC, probably together with the Tarim Block, collided with the South Tarim–Qaidam Block in the Devonian, then with the South China Block in the Permo-Triassic (Li, S. Z. *et al.* 2006*b*, and references therein). This latter collision resulted in exposure of ultrahigh-pressure rocks from *c.* 100 km depth in Dabie Shan, and westward escape of the South Tarim–Qaidam Block (e.g. Sengör 1985; Yang *et al.* 1986; Yin & Nie 1996; Hacker *et al.* 2000; Ratschbacher *et al.* 2000, 2003), and caused uplift of the large Huabei plateau in the eastern NCC (Fig. 7). Younger extrusion tectonics related to Himalayan collisions further west resulted in *c.* 500 km of left-lateral motion along the Altyn–Tagh fault, separating the NCC from the South Tarim–Qaidam Block, slicing and sliding to the west the arc that formed on the southern margin of the NCC during Early Palaeozoic subduction (Fig. 8).

The terrane accretion and eventual continent–continent collision along the southern margin of the NCC are defined by a geometrically irregular suture, defining a diachronous convergence with a complex spatial and temporal pattern (e.g. Tapponnier *et al.* 1982; Yin & Nie 1993; Li, S. Z. *et al.* 2006*b*). Many models of extrusion tectonics, such as eastward, vertical (upward), and lateral, have been proposed in the last decade for the Qinling–Dabie orogen (Hacker *et al.* 2000; Li, S. Z. *et al.* 2002; Wang *et al.* 2003). Maruyama *et al.* (1994) proposed that vertical extrusion was important to Triassic exhumation of the ultrahigh-pressure rocks in the eastern part of the orogen. Hacker *et al.* (2000) pointed out that an orogen-parallel, eastward extrusion occurred diachronously between 240 and 225–210 Ma. Ratschbacher *et al.* (2000) described Cretaceous to Cenozoic unroofing that was initially dominated by eastward tectonic escape and Early Cretaceous Pacific back-arc extension, and then mid-Cretaceous Pacific subduction. Wang *et al.* (2003) proposed that the Triassic Dabie high-pressure–ultrahigh-pressure metamorphic rocks were originally beneath the Foping dome, which is in the narrowest part of the Qinling Belt, and that these rocks were extruded eastward to their present-day location. We also suggest that the root loss event beneath the adjacent NCC was related to the continental- scale tectonism in the Dabie–Qingling orogen. It is probably more than a coincidence that two of the most unusual tectonic events in the geological record (root loss under the NCC and ultrahigh-pressure metamorphism in Dabie Shan) are geographically and temporally coincident.

The east: Pacific plate subduction

Subduction along the Pacific margin of the NCC (Fig. 8) was active from 200 to 100 Ma, starting soon after closure of the ocean basins on the northern side of the craton (Heubeck, 2001; Xiao *et al.* 2003). Westward-directed oblique subduction was responsible for the generation of arc magmas, deformation, and possibly mantle hydration during this interval (Xu 1990). Although the duration and history of Mesozoic subduction beneath the eastern margin of the NCC is not well known, the active margin stepped outwards by Cenozoic times (Fig. 9), from when a better record is preserved. Numerous plate reconstructions (e.g. Engebretson *et al.* 1985; Stock & Molnar 1988; Hall 1997) for the Cenozoic of Asia and the

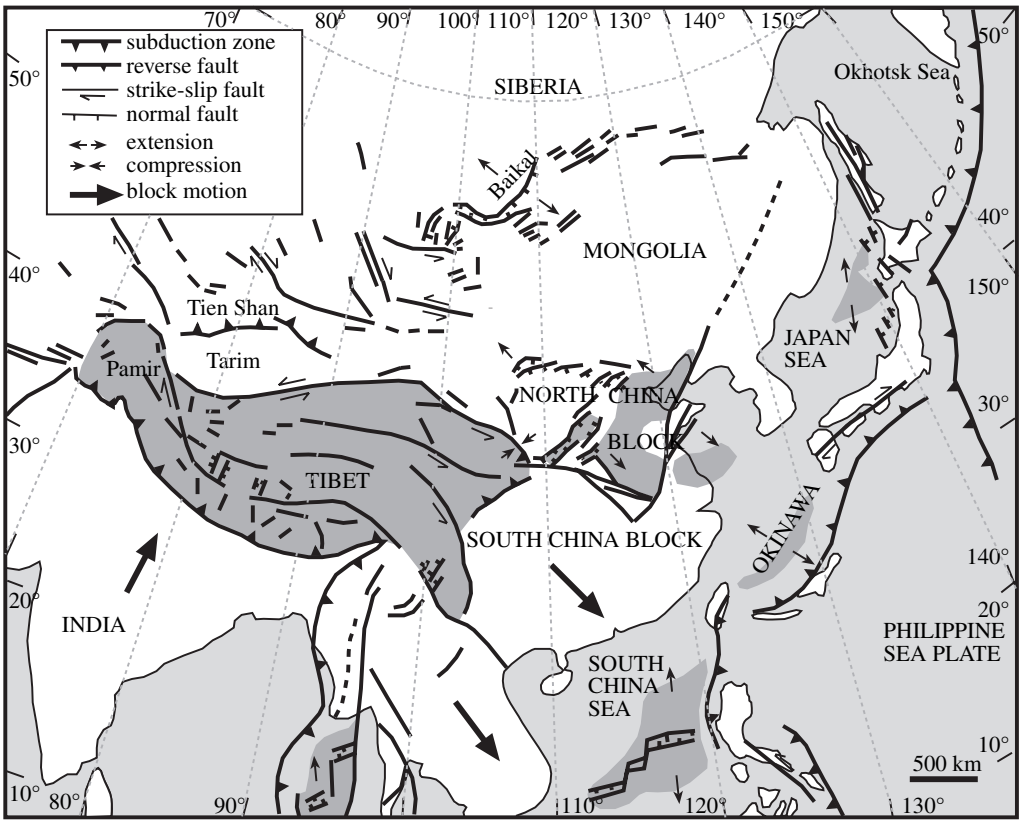

Fig. 8. Tectonic map of Asia (modified after Zhang, Y. Q. *et al.* 2003*a*), showing relationships between the India–Asia collision, escape of Indonesian and South China blocks seaward, and extension from Siberia to the Pacific margin. (Note also the opening of back-arc basins including the Sea of Japan and the South China Sea, and extension in the Bohai Basin and eastern part of the NCC.) The North China Craton is also strongly influenced by Pacific and palaeo-Pacific subduction, perhaps also inducing extension in the eastern NCC. The palaeo-Pacific and Pacific subduction zones developed in the Mesozoic, and also contributed to the hydration of the subcontinental lithospheric mantle beneath the NCC.

Eastern Pacific basin (Fig. 9) show that a wide scenario of different plates, convergence rates, and angles of subduction definitely relate to some of the processes of basin formation, magmatism, and deformation in the easternmost NCC (e.g. Northrup *et al.* 1995; Hall 1997; Li 2000; Li *et al.* 2007).

The implication of long-lived subduction beneath the NCC is important. When oceanic lithosphere subducts, it dehydrates and thereby weakens the upper mantle. It lowers the melting temperature (solidus), and decreases the mantle viscosity. Only 100–1000 ppm additional water decreases mantle viscosity by two orders of magnitude (Niu 2005; Komiya & Maruyama 2006). According to Komiya & Maruyama (2006) this is the principal cause of the fragmentation of the oceanic lithosphere in the Western Pacific. The idea that subduction of water into the mantle caused hydroweakening of the subcontinental lithosphere and was responsible for the thinning–delamination under the Eastern Block of the North China Craton came independently from Niu (2005) and Windley *et al.* (2005). However, whereas Niu (2005) considered that subduction by the Pacific plate was sufficient to carry water to the upper mantle, Windley *et al.* (2005), building on the ideas of Maruyama *et al.* (2004) and Komiya & Maruyama (2006) of double subduction, as summarized above, extended the process to include subduction zones sited on the Solonker, Dabie Shan and Mongol–Okhotsk sutures.

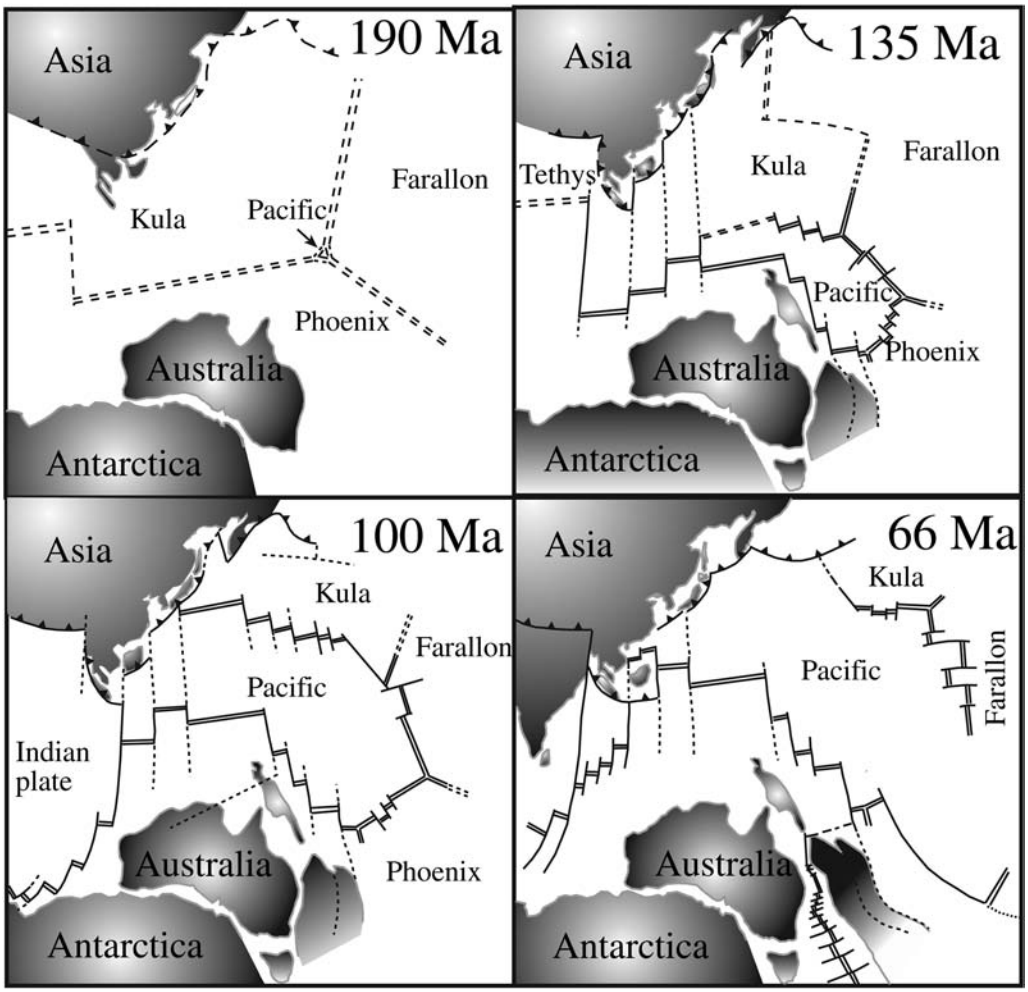

Fig. 9. Palinspastic maps showing the possible plate interactions along the Pacific margin of the NCC in the Mesozoic. (Note active subduction and episodes of ridge subduction).

Liu *et al.* (2001) established a connection between volcanic activity and extension in NE and Eastern China from *c*. 86 Ma to the present and the younger opening of the Japan Sea. However, the area of delamination under the Eastern Block of the NCC was also subjected to earlier subduction from the Solonker Ocean to the north and Dabie Ocean to the south, as described above, and the Cenozoic northerly subduction of the Indo-Australian plate. It is thus difficult to specifically target one major subduction event as the cause of many of the major deformational features. In fact, more different oceanic lithosphere fragments have probably been subducted under the eastern NCC than under any other Phanerozoic continental block, which may have extensively hydro-weakened the upper mantle (e.g. Niu 2005). Windley *et al.* (2005) suggested that Jurassic orogenic collapse at the northern and southern margins of the craton triggered the delamination. In a similar model, Zhang *et al.* (2003) proposed that Palaeozoic subduction of ocean crust beneath both the northern and southern margins of the NCC was responsible for destabilization of the eastern NCC and the resulting thinning and replacement of the lithospheric mantle. However, they envisaged the northern subduction zone as being sited on the margin of the Mongol–Okhotsk

Ocean, which would be hundreds of kilometres north of the Solonker Ocean and the preferred site in the present study.

From contraction to extension

The tectonics of much of Asia changed from contractional to extensional at *c.* 130–120 Ma, and this could be the best approximation for the time of the original subcontinental mantle root loss beneath the NCC.

Meng (2003) and Meng *et al.* (2003) suggested that the Jurassic collision of the amalgamated North China–Mongolia Block with the Siberian plate (Fig. 6) that gave rise to the Mongol–Okhotsk suture led to formation of a high-standing plateau. Gravitational collapse of the thickened crust led to Late Jurassic–Early Cretaceous crustal extension throughout the orogenic belts of Southern Mongolia and Northern China, and coeval thrusting to form the Yanshan belt on the northern margin of the NCC (e.g. Davis *et al.* 1996). This model, however, ignores the more southerly Solonker suture and associated Late Permian closure of the Palaeoasian Ocean near the Mongolia–China border. This Siberia–Mongolia collision with the simultaneously amalgamating Chinese Precambrian blocks gave rise to a major Himalayan-style orogen or even plateau, the post-collisional collapse of which was probably responsible for the Jurassic thrusting and for the formation of Cretaceous basins and metamorphic core complexes (Xiao *et al.* 2003).

The Late Jurassic Yanshanian orogen (Fig. 10) formed in response to the closure of the Palaeoasian Ocean along the north margin of the NCC, subduction of the palaeo-Pacific plate beneath the eastern margin of the NCC, and continued convergence between the NCC and South China Block in the south. This three-sided convergence in the Late Jurassic during the Yanshanian orogeny resulted in further uplift of the Huabei plateau, and widespread deformation and magmatism in the NCC. Widespread east–west Cretaceous extension represents the collapse of the Huabei collisional plateau (Zhang *et al.* 2001), and of the Yanshan belt in the northern NCC (Davis 2003), which led to the formation of the numerous metamorphic core complexes that are now widely recognized in the eastern North China Craton (Davis *et al.* 1996; Yang *et al.* 2004*b*; Cope & Graham 2007). These core complexes formed between 140 and 120 Ma (Cretaceous) and all seem to show a commonly oriented stretching lineation indicating extension or transport from NW to SE. Opening of the Bohai Sea (Allen *et al.* 1997) and many other marginal basins in the Tertiary shows that this extension was long-lived. Collision of India and Asia resulted in the uplift of numerous mountain ranges and large-scale crustal thickening throughout Asia since about 50 Ma, and some of the young extension in Eastern Asia, including within the NCC, may be related to escape away from this collision (Molnar & Tapponnier 1975; Yin & Nie 1996).

Mesozoic to Cenozoic structural evolution and basin formation

Many large Mesozoic and Cenozoic basins cover the eastern North China Craton (Fig. 11). The development of these large basins was concentrated in two time periods, Jurassic to Cretaceous and Cretaceous to present (Griffin *et al.* 1998). Ren *et al.* (2002) proposed that the overall NW–SE-trending extensional stress field was related to changes in convergence rates of India–Eurasia and Pacific–Eurasia combined with some asthenospheric upwelling. Sass & Lachenbruch (1979) assumed that the two stages of basin formation were related to lithosphere erosion that began in Early Jurassic times. However, some workers have related the extension to subduction of the Kula plate beneath Eastern China in Jurassic–Cretaceous times and later subduction of the Pacific plate (Griffin *et al.* 1998). Geophysical and geochemical data (Figs 12 and 13) show that the areas of thinner lithosphere correspond to the deepest Cenozoic basins (Yuan 1996; Griffin *et al.* 1998). Kimberlites found in these basins (Fig. 14) provide the only direct source of information about the underlying mantle.

The Cretaceous–Tertiary Tieling basin in northern Liaoning Province (near Shenyang; Fig. 11) hosts Mesozoic–Tertiary kimberlites (Fig. 14; Griffin *et al.* 1998). Phanerozoic lithosphere beneath the Tan-Lu fault was replaced by hotter, more fertile material that may be related to the Tertiary rifting of the Shanxi highlands (Ke & Tian 1991; Dobbs *et al.* 1994; Zheng *et al.* 2001). Furthermore, the Eocene Luliang kimberlites imply that Phanerozoic-type mantle was in place by the end of the Cretaceous (Griffin *et al.* 1998). Another kimberlite within a narrow Cenozoic basin lying along the Tan-Lu fault in Tieling County (Fig. 14) shows similar Phanerozoic-type mantle that is related to rifting. Garnet temperatures at shallow depths indicate that significant cooling occurred after the Phanerozoic mantle was emplaced beneath this area (Griffin *et al.* 1998).

Cenozoic extension in the Shanxi graben and Bohai Sea basins

Cenozoic extensional deformation in the central NCC is localized in two elongate graben systems surrounding the Ordos Block (Fig. 11): the S-shaped Weihe–Shanxi graben system (Shanxi

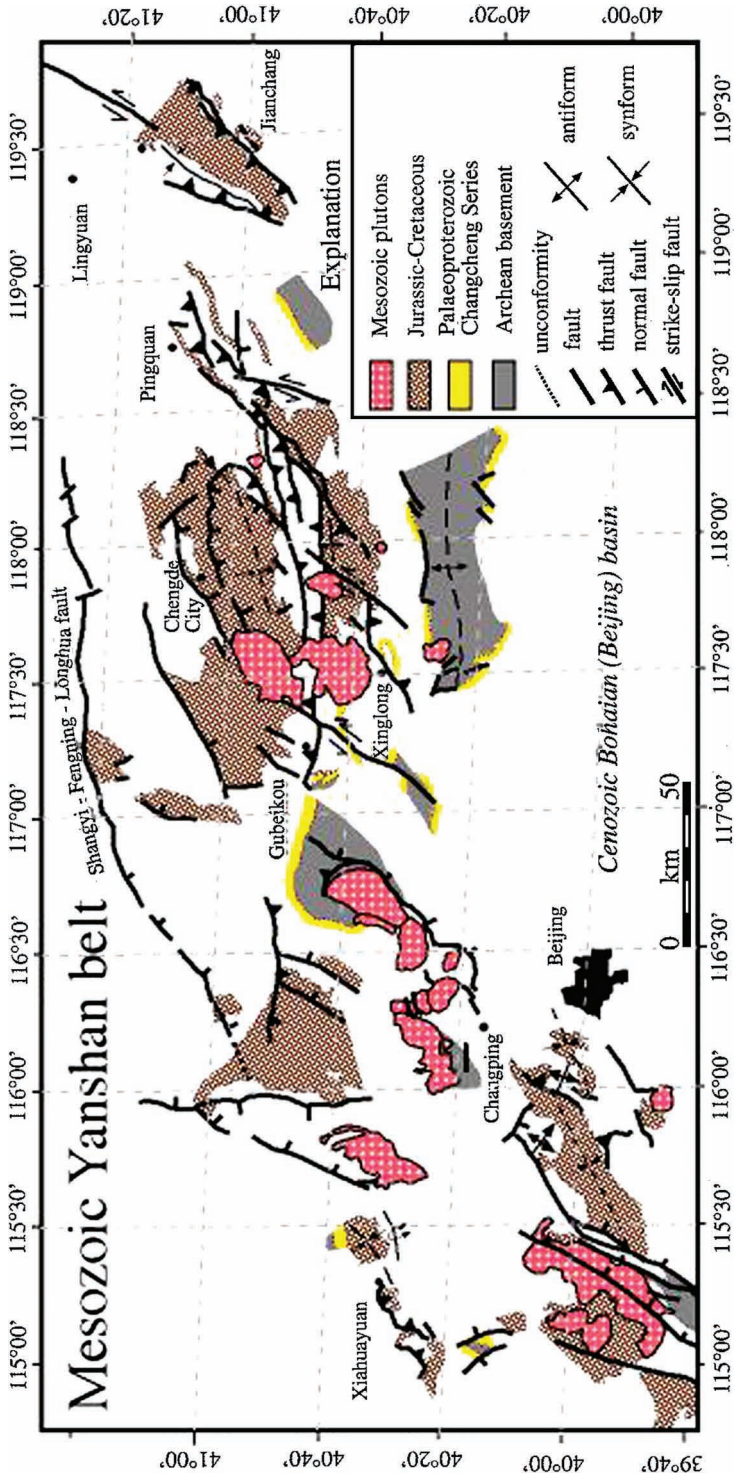

Fig. 10. Map of the Yanshan orogen, showing abundant normal faults and granitoid plutons.

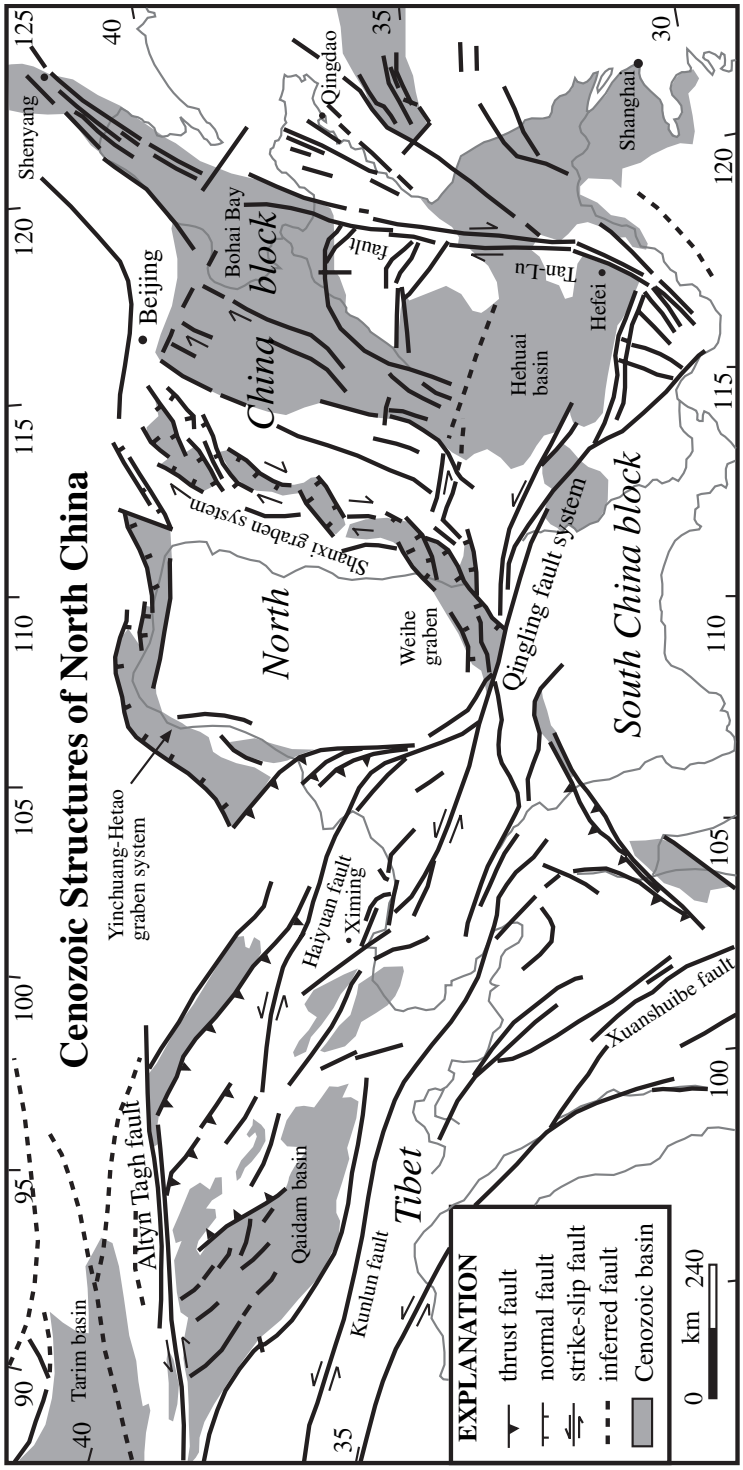

Fig. 11. Map of Northern China showing Cenozoic-active structures and basins in and around the North China Craton. Modified after Zhang, Y. Q. *et al.* (2003*a*).

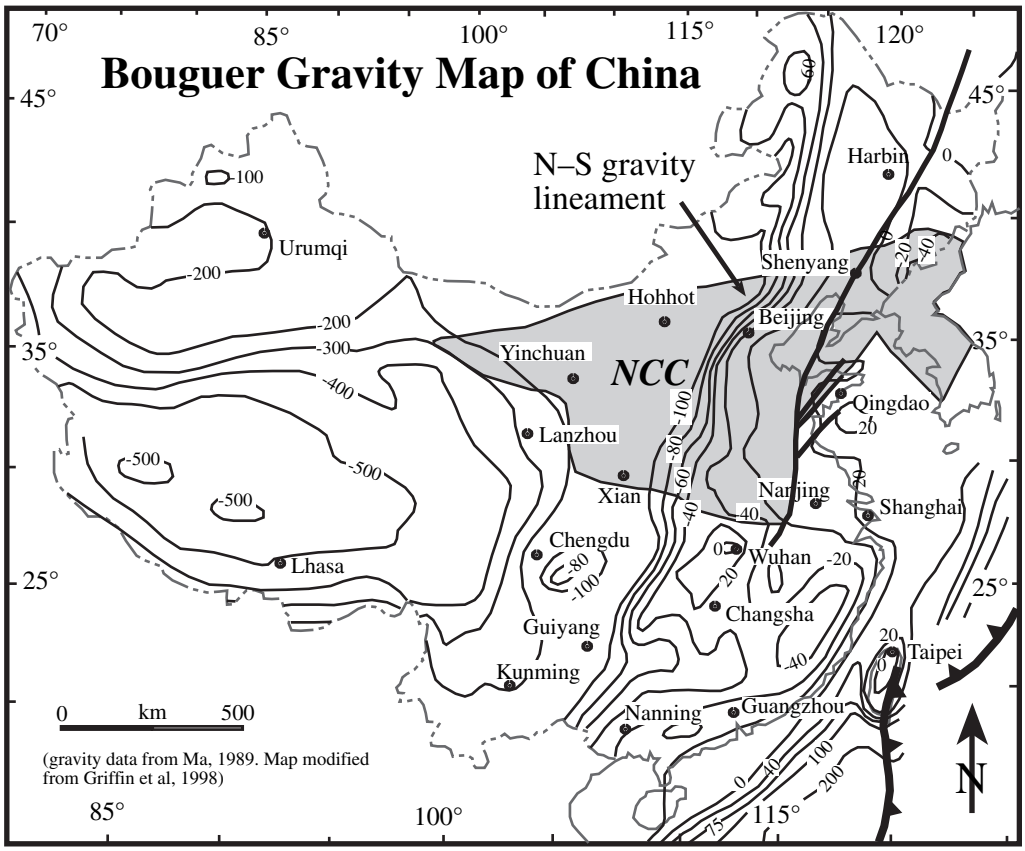

Fig. 12. Map showing Bouguer gravity and the prominent north–south gravity lineament that strikes across China, crossing the NCC along the approximate boundary between thick lithosphere to the west and thin lithosphere to the east. The north–south gravity lineament is parallel to the Pacific subduction margin, perhaps suggesting a causal link.

grabens for short) to the east and SE, and the arc-shaped Yinchuan–Hetao graben system to the NW (Zhang, Y. Q. *et al.* 1998; Morley 2002). The southwestern margin of this block corresponds to a zone of compression (Zhang 1989), through which the North China Craton is in direct contact with the Tibetan Plateau (Yin & Harrison 2001). Wang & Zhang (1995) determined that the subsidence in these grabens began during the Eocene, and extended to the whole graben system during the Pliocene. The Shanxi graben system was the last to be initiated in Northern China, at about 6 Ma. These two extensional domains show differences in the thickness of the crust and lithosphere; the thickness changes sharply across the eastern edge of the Taihangshan Massif (Ma 1989) on the eastern side of the Shanxi graben system. Zhang, Y. Q. *et al.* (2003) showed that the Shanxi graben system consists of a series of en echelon depressions bounded by normal faults. Xu *et al.* (1993) noted the S-shaped geometry of the Shanxi graben system, with two broad extensional domains in the north and south and a narrow transtensional zone in the middle. Both SPOT imagery interpretation and field analyses of active fault morphology show predominantly active normal faulting. Right-lateral strike-slip motion along faults that strike more northerly led Xu *et al.* (1993) to interpret the Shanxi graben system as a right-lateral transtensional shear zone, whereas Zhang *et al.* (1998, 2001) considered it to be an oblique divergent boundary between blocks within Northern China.

Zhang, Y. Q. *et al.* (2003) suggested that NNE–SSW-oriented initial extension along the footwall of frontal range fault zones in northern Shanxi predates the Pliocene opening of the Shanxi graben and may be coincident with the Miocene Hannoba basalt flow (Figs 11 and 14). The direction of extension that prevailed during the initiation and evolution of the Shanxi graben system shows a northward clockwise rotation, from 300–330° along its southern and middle portion to 330–350°

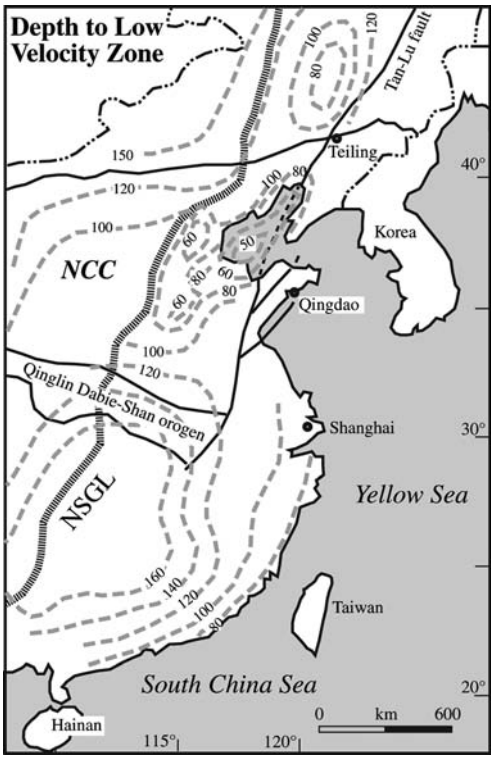

Fig. 13. Map showing depth to the low-velocity zone (modified after Griffin *et al.* 1998). NSGL, north–south gravity lineament.

across the northern part. SPOT imagery interpretation of late Quaternary active fault morphology by Zhang, Y. Q. *et al.* (1998) implies that the opening of the Shanxi graben system proceeded by northward propagation. This opening mode corroborates the kinematic interpretation by Zhang, Y. Q. *et al.* (2003*a*) and reflects a counterclockwise rotation of the Taihangshan Massif with respect to the Ordos Block around a pole located outside the block (Peltzer & Saucier 1996; Zhang, Y. Q. *et al.* 1998).

During the Miocene, the regions of rifting in Northern China were subjected to regional subsidence and the eruption of widespread basalt flows (Fig. 14) Yang *et al.* 2006*a*, *b*. Basalt volcanism, dated by Liu *et al.* (1992) at 25–10 Ma, was extensive in Mongolia and Eastern China, including the areas of the above grabens. According to Zhang, H. F. *et al.* (2003), this volcanism was related to extension in response to rollback of the subducted Pacific plate beneath Eastern Asia. Miocene normal faulting occurred particularly in the offshore part of the Bohai Sea basin, where this normal fault set strikes more easterly (Zhang, Y. Q. *et al.* 2003*b*).

Liu *et al.* (2001) and Zhang, Y. Q. *et al.* (2003*b*) inferred that the Miocene extension in North China may have shared a common mechanism with that of the opening of the Japan Sea. First, the opening of the Japan Sea began at the end of the Oligocene around 28 Ma or earlier, and continued to the Middle Miocene, at about 18 Ma (Tamaki *et al.* 1992; Jolivet *et al.* 1990; Fournier *et al.* 1994); the youngest dredged basaltic volcanic rocks were dated at 11 Ma (Kaneoka *et al.* 1990). Second, the spreading direction of the Japan Sea is roughly north–south to NNE–SSW (Sato 1994), consistent with the Miocene stretching direction in Northern China. Finally, the same extensional stress regime trending ENE–WSW to NE–SW has been documented in northeastern Japan (east of the Japan Sea) based on the direction of dyke swarms and dated at 20–15 Ma (Sato 1994).

Discussion: decratonization and the orogen to craton to orogen cycle

Major north–south-striking topographic and gravity gradients that strike across the NCC (e.g. Liu 1992; Niu 2005) correspond to a major change in lithospheric structure (Fig. 12). The north–south gravity lineament is a major gradient in Bouguer gravity anomalies that corresponds roughly to the border between the Eastern and Western Blocks (or areas with and without root loss). It also, however, extends further north and south for thousands of kilometres beyond the borders of the NCC (Fig. 12). Because the gravity lineament also corresponds to areas of Tertiary basin formation along major faults, it may represent a major crustal structure parallel to the Pacific subduction zone. The north–south gravity lineament is also interesting because it bounds areas that to the west have thick crust and 150–200 km thick lithosphere (Fig. 13), large negative Bouguer anomalies, and low heat flow. Sub-Moho seismic V_p values west of the lineament are high, in the range of *c.* 8.1–8.3 km s^{-1}. However, to the east the crust and lithosphere are generally thinner, there is high heat flow, and the regional Bouguer anomalies are zero to slightly positive. Sub-Moho seismic velocities are lower than to the west, ranging from 7.6 to 7.7 km s^{-1}, with some faster regions (implying partial root loss?). Tomographic profiles from the Eastern Block (Yuan 1996) show an irregular velocity structure for the lower lithosphere, suggesting only partial root loss.

The Eastern Block is seismically very active, experiencing many magnitude 8+ earthquakes that include six of the 10 most destructive events in recorded history (Kusky 2003), which killed more than one million people. From 3D P-wave velocity data Huang & Zhao (2004) established that in the lower crust and in the uppermost mantle under the source regions of the large earthquakes there

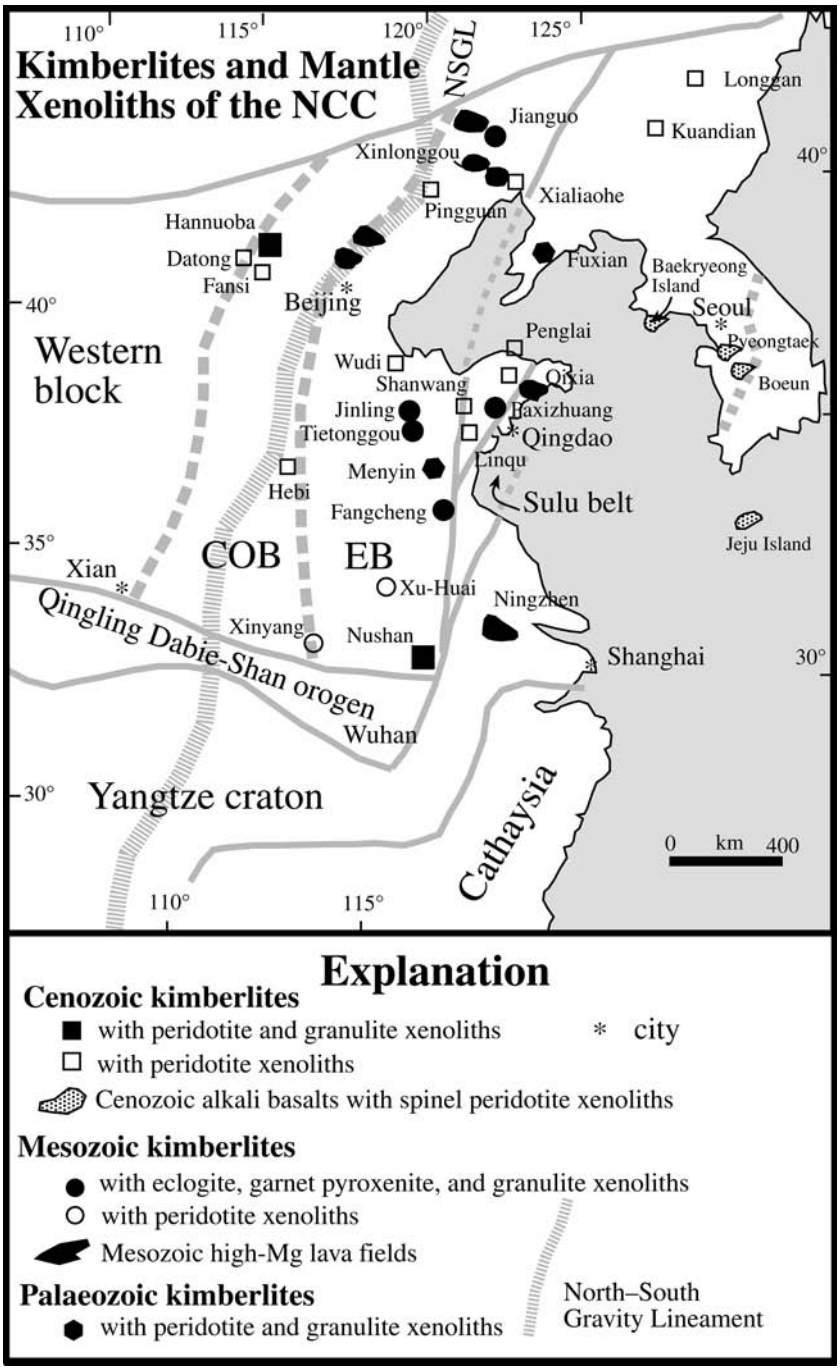

Fig. 14. Map of the eastern NCC showing distribution of kimberlites of different ages that entrain up mantle xenoliths.

are low-velocity and high-conductivity anomalies, which they considered to be associated with fluids. The fluids caused weakening of the seismogenic layer, contributing to the initiation of the large crustal earthquakes. These fluid data suggest that multiple subduction events beneath the zone of depleted lithosphere enriched the mantle in water, and hydro-weakened it. Whatever the

process of root loss (e.g. Menzies *et al.* 1993; Griffin *et al.* 1998; Wilde *et al.* 2003; Wu *et al.* 2003*a*, *b*; Yang 2003; Deng *et al.* 2004; Fan & Menzies 1992*a*, *b*), it appears to have caused continuing lithospheric instability.

Loss of the lithospheric root is also shown by the compositional data for mantle xenoliths brought up in early Palaeozoic and Mesozoic to Tertiary kimberlites and volcanic rocks (Fig. 14). The oldest kimberlites (490–450 Ma) are the Palaeozoic Fuxian and Mengyin pipes in the west, whereas the Tieling intrusions are Cretaceous to Tertiary in age (Fig. 14). Xenoliths in basalts from Nushan are only 0.8–0.5 Ma old, which, together with the older examples, provides a 500 Ma history of mantle samples from beneath the NCC. Geotherms based on mantle xenolith data (Ryan *et al.* 1996; Griffin *et al.* 1998; Xu *et al.* 1998) and garnet concentrates show that in Ordovician times, the Eastern Block had a low conductive cratonic geotherm, with many samples coming from beneath the diamond stability field. The Ordovician lithosphere–asthenosphere boundary is estimated to have been at about 180 km depth (Griffin *et al.*

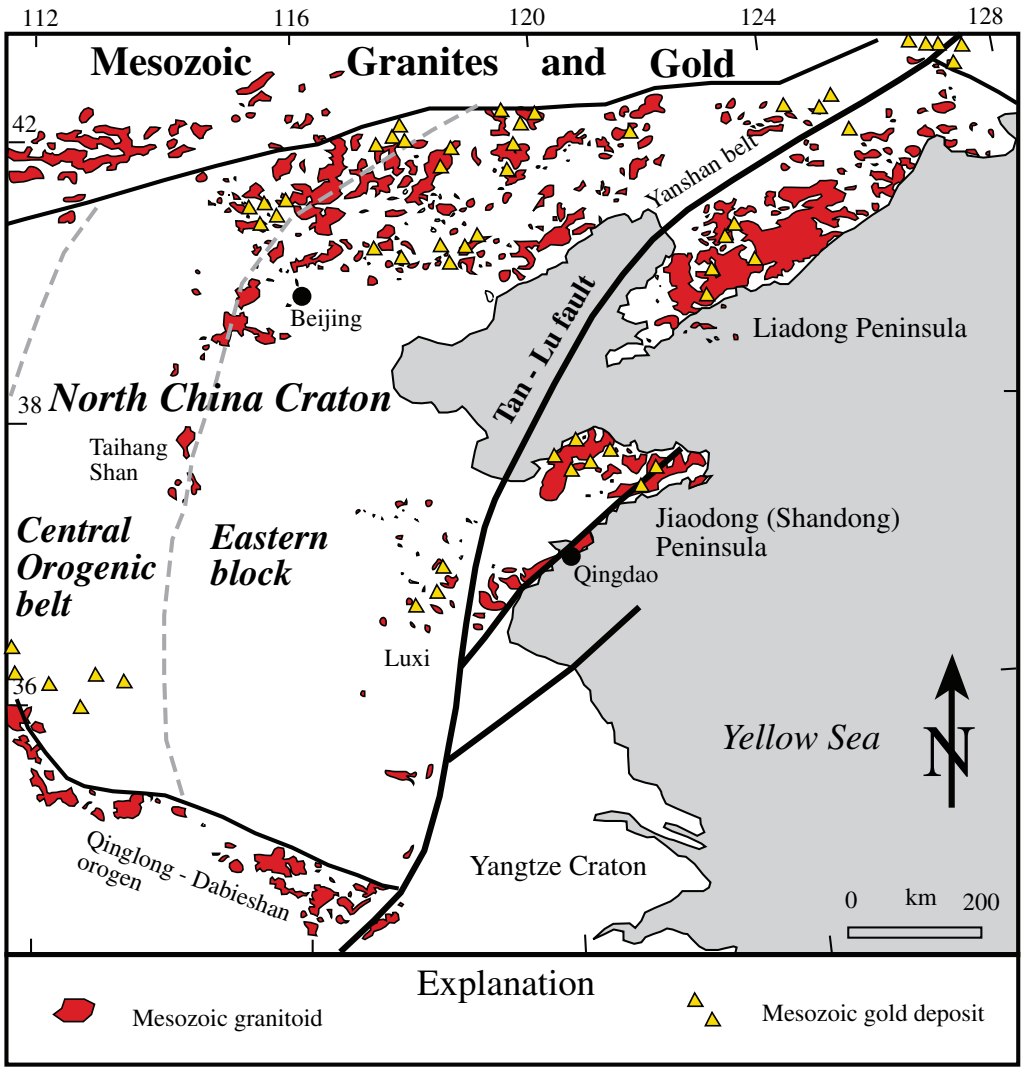

Fig. 15. Mesozoic gold and granite provinces of the NCC. (Note how the gold deposits and granites outline a ring around the Eastern block of the craton, suggesting that they may delineate the limits of the area of root loss). Modified after Goldfarb *et al.* (2001) and Wu *et al.* (2005).

1998). In contrast, compositional data from the younger mantle samples reveal a high geotherm and a lithosphere–asthenosphere transition that had risen to about 80 km depth. Compositional data from xenoliths thus clearly show the loss of the lithospheric root beneath the eastern NCC, but do not yield information on exactly when this loss may have occurred, why it occurred, or what the loss means for cratonic evolution. Basalts erupted through the crust of the Eastern Block (Fig. 14) also show a change in composition from Mesozoic to Tertiary, with high-Mg andesites or adakites interpreted as evidence for lower crustal foundering in Jurassic–Cretaceous times. From geochemical and isotopic data for Mesozoic lavas of the eastern NCC, Zhang, H. F. *et al.* (2003) concluded that there is thicker, less modified lithospheric mantle in the interior, and thinner, more heavily modified lithospheric mantle beneath the craton margins. They also demonstrated a secular change in the lithospheric mantle from a Palaeozoic refractory continental lithosphere to a Mesozoic enriched lithosphere.

Although extending for thousands of kilometres along the Pacific rim, Mesozoic granitoids and gold deposits (Goldfarb *et al.* 2001; Hart *et al.* 2002; Mao *et al*. 2002; Wu *et al.* 2005) that are contemporaneous with the lithospheric thinning form a ring (Fig. 15) around the Eastern Block (Yang, J. H. *et al.* 2003). The removal of the lithospheric mantle and upwelling of new asthenospheric mantle induced partial melting and dehydration of the

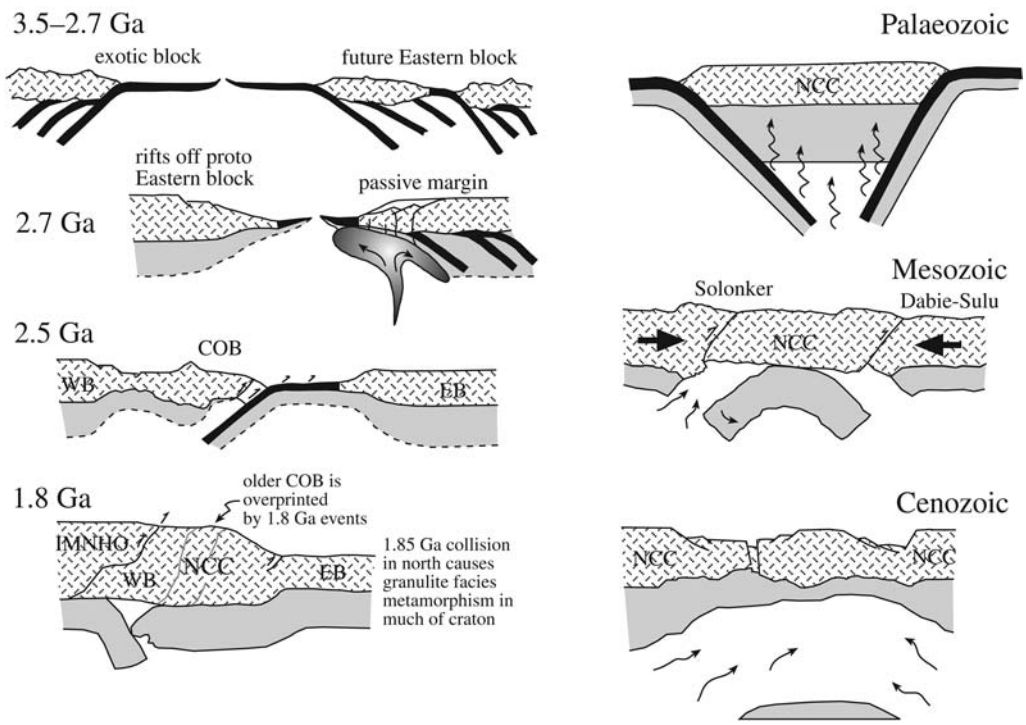

Fig. 16. Model showing simplified evolution of the North China Craton, from orogen to craton to orogen, and how crustal and mantle root processes may be linked (note that the root is not to scale). Growth of the craton by subduction–accretion in arc settings probably involved the underplating of buoyant oceanic slabs (e.g. Kusky 1993), which would eventually become the subcontinental mantle root. Plume-influenced rifting at 2.7 Ga broke apart the future Eastern Block, and led to the development of a passive margin sequence on the western side of the Eastern block. This margin collided with a convergent margin at 2.5 Ga, amalgamating the craton. At 1.85 the craton experienced a major collision event along its northern margin, which resulted in partial replacement of the mantle root and widespread high-grade metamorphism, and the formation of a collisional plateau and foreland basin. For much of the Palaeozoic the craton was relatively internally stable, but accommodated about 18 000 km of cumulative subduction along its northern, southern, and eastern margins. Subduction-related dehydration reactions in the slab released fluids that hydrated the mantle, weakening its rheology and lowering its melting point, which allowed the root to release a low-density melt phase during Mesozoic tectonism, become denser, and sink into the asthenosphere after being triggered by near-simultaneous collisions along its northern (Solonker) and southern (Dabie–Sulu) margins. IMNHO, Inner Mongolia–Northern Hebei Orogen.

lithospheric mantle and lower crust, and the derived fluids deposited the gold (Yang, J. H. *et al.* 2003, 2004). The granitoids and associated ore-bearing fluids may contain one of the best and most detailed records of the history of root loss beneath the NCC, perhaps preserving a history of the chemical and physical environments associated with foundering of subcrustal lithosphere. Additional research on these granitoids and mineral deposits may yield considerable insights into the physical and chemical processes associated with root loss.

Many models and constraints have been proposed to explain the delamination of lithospheric roots in orogens, and we apply some of these models to loss of the lithospheric root beneath the NCC (see Fig. 16). Marotta *et al.* (1998) defined four major stages during a mantle 'unrooting' process: orogenic growth; initiation of gravitational instability until lithospheric failure; sinking of the detached lithosphere; relaxation of the system. Meissner & Mooney (1998) suggested that the basic driving force for delamination is the negative buoyancy of the continental lower crust and subcrustal lithosphere with respect to the warm, mobile asthenosphere. A likely cause of such negative buoyancy is a phase transformation in the lower crust from mafic granulite facies to eclogite (Morgan 1984; e.g. Kaban *et al*. 2003). Thus weakness in the lower crust during continental compression and extension is a key to the process of delamination. According to Schott & Schmeling (1998), full detachment of a delaminated lithospheric slab occurs only if the viscosity of the lower crust is greater than *c*. 10^{21} Pa s. Lithospheric roots or unsupported slabs of at least 100–170 km depth extent are needed to provide sufficient negative buoyancy to allow delamination and detachment. Gao *et al.* (1998*a*, *b*) applied geochemical data to the problem of delamination under the eastern NCC. They found that the lower crust in Eastern China contains *c*. 57% SiO_2, which contrasts with the generally accepted models of mafic lower crust. They further suggested that eclogite from the Dabie–Sulu UHP belt is the most likely candidate as the delaminated material, and that a cumulative 37–82 km thick eclogitic lower crust is required to have been delaminated to explain the relative Eu, Sr and transition metal depletions in the crust of East–Central China. Delamination of eclogites can also explain the significantly higher than eclogite Poisson's ratio in the present Dabie lower crust and upper mantle and the lack of eclogite in Cenozoic xenolith populations of the lower crust and upper mantle in Eastern China.

However, considering that the lower crust contains *c*. 57% SiO_2, and that xenoliths of lower crust in Cenozoic basalts in Hanuoba, North Hebei are garnet gabbro and two-pyroxene granulites, Zhai *et al.* (2004) suggested that delamination of eclogites possibly occurred only at the northern and southern edges of the eastern North China Block. The thinning of the lithosphere could be related to thermal–chemical erosion with a mantle upwelling under the joint grip of the surrounding blocks, although its mechanism is not clear, and we favour the hydro-weakening mechanism discussed above (e.g. Niu 2005; Windley *et al.* 2005; Komiya & Maruyama 2006).

Conclusion

The North China Craton has experienced one of the longest and most complex histories of any geological terrane on the planet (Fig. 16). Events from *c*. 3.5 to 2.7 Ga primarily reflect the extraction of melts from the mantle, probably in arc settings, and the amalgamation of many arcs to form some of the distinctive blocks in the craton. By 2.7 Ga the Eastern Block of the craton apparently was affected by a plume, associated with rifting of another block off the current western edge of the craton, which led to the opening of an ocean and deposition of a passive margin sequence on the western edge of the Eastern Block from 2.7 to 2.5 Ga. At 2.5 Ga the Eastern Block collided with a convergent margin now preserved in the Central Orogenic Belt, and apparently attached to the Western Block, obducting ophiolites and depositing a thick foreland basin sequence on the Eastern Block. This 2.5 Ga event culminated in the amalgamation of the North China Craton, and the intrusion of 2.4 Ga dykes and plutons across much of the central part of the craton.

These Archaean–Palaeoproterozoic events are responsible for the initial formation of the root of the North China Craton, and we speculate that the first stages of root formation may have involved underplating of buoyant oceanic lithospheric slabs beneath convergent margins, as described by Kusky (1993). Interestingly, this mechanism would result in different parts of the subcontinental lithospheric mantle having different properties such as orientation of slabs (and internal olivine crystals), perhaps leading to a different susceptibility to delamination or root loss in the events later in the craton's history.

The craton experienced its strongest metamorphic event at 1.85–1.8 Ga, related to continent–continent collision, which overprinted and obscured earlier events. Metamorphic evidence shows that the crustal thickness doubled, and pressures of metamorphism increase from south to north. Although the location of the collision has been disputed, sedimentological, structural, igneous, metamorphic and tectonic patterns clearly show that the collision was along the north margin of the craton (Fig. 16). This collision was so strong that

Table 1. *Summary of geological evolution of the North China Craton*

Age	Event	Signature in crust	Signature in SCLM	References
3.5–3.1 Ga	Cratonic blocks form; remnants preserved	TTG, gneiss, fuchsitic quartzite, pelite	Melt extraction	Zhai *et al.* 2004
2.7; 2.55–2.5 Ga	Rifting then arcs active in Dongwanzi Ocean	Formation of TTG, CA arc suite, accretionary prisms, ophiolites, continental arc in Hengshan	Possible underplating of slabs beneath Western (± Eastern) Blocks; mantle hydration	Kusky *et al.* 2001; Li *et al.* 2002; Kusky 2004
2.5 Ga	Closure of Dongwanzi ocean	Formation, deformation, metamorphism of Central Orogenic Belt	Collision-related deformation of SCLM; formation of depleted root	Kusky *et al.* 2001; Gao *et al.* 2002, 2006
2.4 Ga	Post-collision extension	Formation of regional mafic dyke swarms, flood basalts	Melt extraction	Kusky & Li 2003; Kusky *et al.* 2006
2.4–2.3–2.1 Ga	Ocean opening, N margin craton	Passive margin sediment, N margin; continental sediment, interior; collision of arcs at 2.3 and 2.1 Ga	Isotherm relaxation	Zhao, et al. 2002; Kusky & Li 2003; Zhao, T. P. *et al.* 2004
1.9–1.85 Ga	Major continent–continent collision, final amalgamation of NCC	Formation of granulite plateau N part of craton, widespread metamorphism; deposition of S-prograding wedge of Changcheng clastic foreland basin	Possible collision-related delamination in part of craton? Replacement of part of root	Gao *et al.* 2002, 2006; Kusky & Li 2003
1.8 Ga	Post-collision extension	Mafic dyke swarms	Mantle melting	Peng, Li, Kusky, etc.
1800–700 Ma	Quiescence?	Period of root stability, when craton acts like a craton; platform sediments?	Stability	
700–250 Ma	Subduction under Dabie Shan	Cambro-Ordovician limestones deposited on platform, active margin on south	Hydration owing to ingress of slab fluids?	S. Z. Li, Hacker, Rathsburger, Rowley, Sengör, Niu
500–250 Ma	Subduction under Solonker	405–207 Ma, orogeny in NCC involves terrane accretion on N margin craton, and in Central Asia Orogenic Belt	Hydration owing to ingress of slab fluids?	Xiao *et al.* 2003
270–208 Ma	Indosinian Orogeny	Scissor-like closure of Solonker Ocean	Shortening of N edge of SCLM	
200–100 Ma	Subduction under Pacific margin	Remelting of lower crust in Jiao-Liao massif	Hydration owing to ingress of slab fluids?	Li, S. Z. *et al.* 2006*a*

(*Continued*)

Table 1. Continued

Age	Event	Signature in crust	Signature in SCLM	References
200–150 Ma	Collision and post-collision thrusting in both Solonker and Dabie Shan collision zones	Thrust belts on craton margins, foreland sediments	Thickening of crust–mantle system; loss of additional root?	Gao *et al.* 2002, 2004; Li, S.Z. *et al.* 2006*a*, *b*
165–90 Ma	Yanshanian Orogeny	Formation of circum-Pacific magmatic belts, Tan-Lu fault	Hydration owing to ingress of slab fluids	
140–105 Ma	Regional extension	Formation of many metamorphic core complexes, most have SE–NW extension directions; from 132 to 128 Ma, large-scale left-lateral motion on Tan-Lu fault (Zhu *et al.* 2001)	Decompression?	Niu *et al.* 1994; Zhang 1989; Zhang *et al.* 1997; Zhang *et al.* 1998; Webb *et al.* 1999; Davis *et al.* 2002
160–106 Ma	Adakites	A-type magmatic rocks	Overlaps with Yanshanian	Wei 2002; Xu *et al.* 2002; Davis 2003; Gao *et al.* 2006
134–103 Ma	Gold, etc. mineralization	Fluid flow on regional scales, gold mineralization	Overlaps with Yanshanian	Mao *et al.* 1999; Goldfarb *et al.* 2001; Yang *et al.* 2003
147–112 Ma	Major volcanism		Overlaps with Yanshanian	Zhang *et al.* 2000; Wang *et al.* 2001
50–O Ma	Himalayan Orogeny	Collision of India–Asia, uplift and exposure, extension	Extrusion	Yin & Harrison 2001
Present		Active normal faults, hot springs, volcanism in Eastern Block; quiet, low heat flow, no earthquakes in Western Block		Liu *et al.* 2001; Zhang, Y. Q. *et al.* 2003*a*

SCLM, subcontinental lithospheric mantle.

in many places, particularly along the northeastern margin of the craton (Fig. 16), the 2.5 Ga subcontinental lithospheric mantle was apparently replaced by 1.8 Ga asthenosphere.

For much of the Palaeozoic, the North China Craton was internally relatively stable, but *c*. 18 000 km of subduction along its northern, southern, and eventually its eastern margins led to extensive hydration of the mantle root, and pre-weakening of the root before massive Himalayan-style collisions along the northern (Solonker) and southern (Dabie Shan) margins of the craton. These nearly simultaneous collisions in the Triassic strongly affected the mantle root, and when the upper crust entered a phase of orogenic collapse in the Jurassic and Cretaceous, the root appears to have similarly responded by somehow detaching and sinking into the asthenosphere, and/or being thermally eroded perhaps after the root was lost. Palaeopacific subduction also involved at least one episode of ridge subduction, and the role that the thermally pulse associated with this event may have played in the loss of the lithospheric root beneath the North China Craton has yet to be analysed.

Analysis of the geological history of the craton thus clearly shows that crustal and mantle processes are linked, and that a better understanding of surface tectonic evolution can lead to a better understanding of the processes that trigger root formation, root loss, and decratonization. Recognition of the process of decratonization and the orogen to craton to orogen cycle in the North China Craton, which is still experiencing the terminal consequences of the loss of its root, lead us to consider how important this process may have been through Earth history. If the North China Craton has lost its root and essential properties of being a craton, is it possible that other cratons have been 'decommissioned' and incorporated into mountain belts as isolated fragments or terranes of Archaean rocks so common in younger orogens? If so, we may have to reconsider current models of continental growth.

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