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Lithotectonic elements and geological events in the Hengshan–Wutai–Fuping belt: a synthesis and implications for the evolution of the Trans-North China Orogen

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Abstract – The Hengshan–Wutai–Fuping belt is located in the middle segment of the Trans-North China Orogen, a Palaeoproterozoic continental collisional belt along which the Eastern and Western blocks amalgamated to form the North China Craton. The belt consists of the medium- to high-grade Hengshan and Fuping gneiss complexes and the intervening low- to medium-grade Wutai granite–greenstone terrane, and most igneous rocks in the belt are calc-alkaline and have affinities to magmatic arcs. Previous tectonic models assumed that the Hengshan and Fuping gneiss assemblages were an older basement to the Wutai supracrustal rocks, but recent studies indicate that the three complexes constitute a single, long-lived Neoarchaean to Palaeoproterozoic magmatic arc where the Wutai Complex represents an upper crustal domain, whereas the Hengshan and Fuping gneisses represent the lower crustal components forming the root of the arc. The earliest arc-related magmatism in the belt occurred at 2560–2520 Ma, marked by the emplacement of the Wutai granitoids, which was followed by arc volcanism at 2530–2515 Ma, forming the Wutai greenstones. Extension driven by widespread arc volcanism led to the development of a back-arc basin or a marginal sea, which divided the belt into the Hengshan–Wutai island arc (Japan-type) and the Fuping relict arc. At 2520–2480 Ma, subduction beneath the Hengshan–Wutai island arc caused partial melting of the lower crust to form the Hengshan tonalitic–trondhjemitic–granodioritic (TTG) suites, whereas eastward-directed subduction of the marginal sea led to the reactivation of the Fuping relict arc, where the Fuping tonalitic–trondhjemitic–granodioritic suite was emplaced. In the period 2360–2000 Ma, sporadic phases of isolated granitoid magmatism occurred in the Hengshan–Wutai–Fuping region, forming 2360 Ma, *c.* 2250 Ma and 2000–2100 Ma granitoids in the Hengshan Complex, the *c.* 2100 Ma Wangjiahui and Dawaliang granites in the Wutai Complex, and the 2100–2000 Ma Nanying granitoids in the Fuping Complex. At *c.* 1920 Ma, the Hengshan–Wutai island arc underwent an extensional event, possibly due to the subduction of an oceanic ridge, leading to the emplacement of pre-tectonic gabbroic dykes that were subsequently metamorphosed, together with their host rocks, to form medium- to high-pressure granulites. At 1880–1820 Ma, the Hengshan–Wutai–Fuping arc system was juxtaposed, intensely deformed and metamorphosed during a major and regionally extensive orogenic event, the Lüliang Orogeny, which generated the Trans-North China Orogen through collision of the Eastern and Western blocks. The Hengshan–Wutai–Fuping belt was finally stabilized after emplacement of a mafic dyke swarm at 1780–1750 Ma.

Keywords: Archaean, Palaeoproterozoic, magmatic arc, subduction, collision, Hengshan–Wutai–Fuping belt, Trans-North China Orogen.

1. Introduction

Major advancements in understanding the geological history of the North China Craton have been made in the past few years, following recognition of a major Palaeoproterozoic orogenic belt, called the Trans-North China Orogen (Fig. 1), which divides the craton into the Eastern and Western blocks (Zhao *et al.* 2001*b* and references therein). The Trans-North China Orogen is characterized by dominant Neoarchaean to Palaeoproterozoic arc-related juvenile crust with minor reworked basement rocks, fragments of ancient oceanic crust, mélanges, high-pressure granulites, retrograded eclogites, crustal-scale ductile shear zones, and linear fold belts with sheath folds (Li *et al.* 1990; Li & Qian, 1991; Zhai, Guo & Yan, 1992; Wang *et al.* 1996, 1997; Wu & Zhong, 1998; Zhao, Cawood & Lu, 1999; Zhao *et al.* 2000*b*; Guo, O'Brien & Zhai, 2002). These

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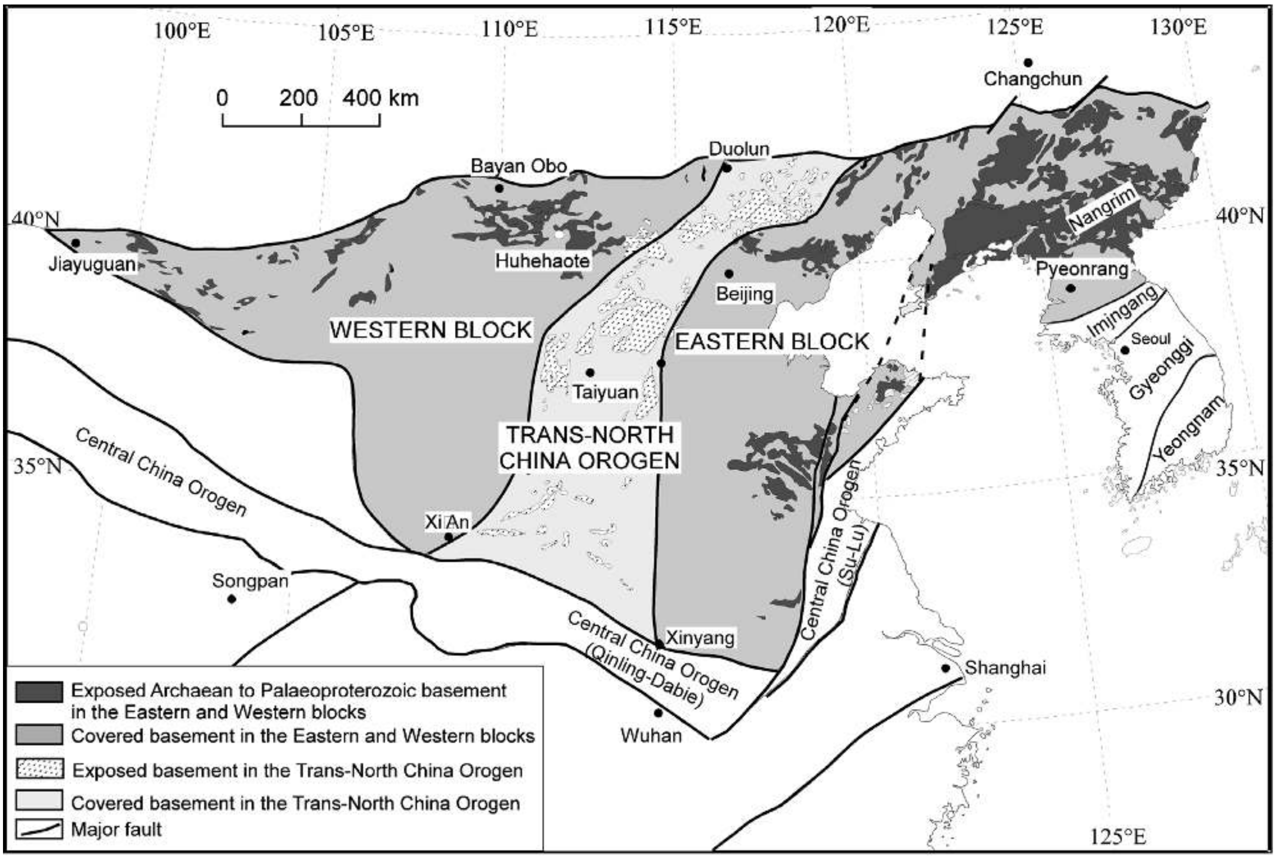

Figure 1. Three-fold tectonic subdivision of the North China Craton proposed by Zhao *et al.* (1998, 2001*b*).

lithotectonic elements contrast with the dominant Archaean tonalitic–trondhjemitic–granodioritic (TTG) gneiss domes surrounded by minor supracrustal rocks in the Eastern and Western blocks (Jahn & Zhang, 1984; Jahn *et al.* 1987, 1988; Jahn & Ernst, 1990; Kröner *et al.* 1998; Zhao *et al.* 1998; Ge *et al.* 2003; Wu *et al.* 2005; Xia *et al.* 2006*a*,*b*). In addition, petrographic and thermobarometric data have revealed a remarkable difference in metamorphic evolution between rocks in the Trans-North China Orogen and the Eastern and Western blocks (Zhao *et al.* 1998, 1999). The former underwent a major metamorphic event at *c.* 1.85 Ga with clockwise *P–T* paths involving isothermal decompression and suggesting a collisional environment (Zhao *et al.* 2000*a*), whereas the latter experienced a major metamorphic event at *c.* 2.5 Ga, with anticlockwise *P–T* paths involving isobaric cooling, possibly related to underplating of mantle-derived magmas (Zhao *et al.* 1998, 1999). These differences led Zhao *et al.* (2001*b* and references therein) to propose that the Trans-North China Orogen was a continental collisional belt along which the Eastern and Western blocks amalgamated to form the coherent North China Craton at about 1.85 Ga (Zhao, 2001; Zhao *et al.* 2005 and references therein). According to Zhao (2001), the western margin of the Eastern Block faced a major ocean during Neoarchaean to Early Palaeoproterozoic times, and eastward-directed subduction of the oceanic lithosphere beneath the western margin of the Eastern Block led to the formation of a magmatic arc that was subsequently incorporated into the Trans-North China Orogen during collision between the Eastern and Western blocks. There is now a coherent outline of timing and tectonic processes involved in the collision between the Eastern and Western blocks (Zhao *et al.* 1998, 1999; Wu *et al.* 2000; Wan *et al.* 2006), but the detailed tectonic architecture and pre-collisional history of the Trans-North China Orogen have not been well constrained, and a number of key geological issues related to the formation and evolution of this orogen are not well resolved. These issues include the relationships between the high-grade gneiss complexes and low-grade granite–greenstone terranes in the orogen, the nature of the magmatic arc system that was subsequently incorporated into the Trans-North China Orogen and the enigma of what magmatic and tectono-metamorphic events took place in the orogen following development of the 2.55 Ga arc and prior to collision of the Eastern and Western blocks at *c.* 1.85 Ga, a time span of around 700 million years.

As the largest and most lithologically representative basement exposure across the Trans-North China Orogen, the Hengshan–Wutai–Fuping belt is the most promising area for investigating the detailed magmatic, depositional, structural and metamorphic history of the orogen. Of particular significance is the presence of a low- to medium-grade granite–greenstone terrane

(Wutai Complex) intervening between two high-grade gneiss complexes (Hengshan and Fuping complexes). For these reasons, geologists from several countries have carried out extensive geological investigations in the Hengshan–Wutai–Fuping belt and obtained a wealth of new geochronological data and competing interpretations (e.g. Wilde, Cawood & Wang, 1997, 1998; Wilde, Zhao & Sun, 2002; Wilde *et al.* 2004*a*,*b*, 2005; Halls, 2000; Kröner, 2002; Kröner *et al.* 2001, 2005*a*,*b*, 2006; Kusky & Li, 2003; Passchier & Walte, 2002; Zhao *et al.* 2002*b*; Guan *et al.* 2002; Liu *et al.* 2000, 2002*a*,*b*, 2004*a*,*b*, 2005, 2006; Wang *et al.* 2001, 2003, 2004*a*,*b*; O'Brien, Walte & Li, 2005; P. Peng, unpub. Ph.D. thesis, Chinese Acad. Sciences, Beijing, 2005; Peng *et al.* 2005; Polat *et al.* 2005, 2006), which enable resolution of major lithotectonic elements and geological events that occurred in the belt. Here we present a summary and overview of these lithotectonic assemblages and geological events based on field relationships and recent geochronological data, especially SHRIMP U–Pb zircon ages, which provide important insights into understanding the above key issues related to the Neoarchaean to Palaeoproterozoic evolution of the Trans-North China Orogen.

2. Regional setting

The North China Craton is a general term used to refer to the Chinese part of the Sino-Korean Platform or Craton. It covers about 1.5 million square kilometres in most of northern China, the southern part of northeastern China, Inner Mongolia, the Bohai Bay and the northern part of the Yellow Sea. The craton is bounded by the Early Palaeozoic Qilianshan Orogen and late Palaeozoic to Mesozoic Central Asian Orogenic Belt to the west and north, respectively, and the Mesozoic Qinling–Dabie and Su–Lu ultrahigh-pressure metamorphic belts to the south and east, respectively (Fig. 1). As mentioned above, the basement of the North China Craton has been divided into the Archaean to Palaeoproterozoic Eastern and Western blocks, separated by the Palaeoproterozoic Trans-North China Orogen (Fig. 1). Lithological, geochemical, structural, metamorphic and geochronological differences between the basement rocks of the Eastern and Western blocks and the Trans-North China Orogen have been summarized by Zhao *et al.* (2001*a*) and are not repeated here. Recently, the three-fold subdivision and tectonic model of the North China Craton have been further refined and modified by new structural, petrological and geochronological data obtained over the past few years (Fig. 2; Zhao *et al.* 2005). These data indicate that the Western Block formed by amalgamation of the Ordos Terrane in the south and the Yinshan Terrane in the north along the EW-trending Khondalite Belt at some time prior to the collision of the Western and Eastern blocks (Fig. 2; Zhao *et al.* 2005). The data also suggest that the Eastern Block underwent Palaeoproterozoic rifting along its eastern continental margin in the period 2.2–1.9 Ga, and the closure of this rift basin at *c.* 1.9 Ga led to the formation of the Jiao-Liao-Ji Belt (Fig. 2; Li *et al.* 2001*a*,*b*, 2004*a*,*b*, 2005; Hao *et al.* 2004; Luo *et al.* 2004; Lu *et al.* 2006; Zhao *et al.* 2006). It remains unknown whether oceanic crust formed in the Jiao-Liao-Ji Belt during its rifting stage, though Du, Wang & Wang (1999) interpreted some ultramafic–mafic rocks as remnants of ophiolites.

The Trans-North China Orogen, a nearly NS-trending zone, about 1200 km long and 100–300 km wide (Fig. 3), is separated from the Eastern and Western blocks by the Xingyang–Kaifeng–Shijiazhuang–Jiianping Fault and the Huashan–Lishi–Datong–Duolun Fault, respectively. Both faults strike NS in the central and southern parts and NE in the north. The presence of voluminous mantle-derived basalts exposed along the two faults suggests that they are deep structures, possibly reaching into the lower crust or upper mantle (Ren, 1980). The main lithotectonic features of the Trans-North China Orogen include: (1) dominant Neoarchaean to Palaeoproterozoic arc-related juvenile crust with minor reworked basement rocks (Kröner *et al.* 1988; Sun, Armstrong & Lambert, 1992; Zhao *et al.* 2000*a*); (2) linear structural belts defined by strike-slip ductile shear zones, large-scale thrusting and folding, and transcurrent tectonics (Li & Qian, 1991; Zhang, Dirks & Passchier, 1994; Zhao *et al.* 1999); (3) sheath folds and mineral lineations (Wu & Zhong, 1998); (4) high-pressure granulites and retrograde eclogites (Zhai, Guo & Yan, 1992; Guo *et al.* 1999, 2001; Guo, O'Brien & Zhai, 2002; Guo, Sun & Zhai, 2005; Guo & Zhai, 2001; Zhao *et al.* 2001*a*; Zhang *et al.* 2006); (5) clockwise metamorphic *P–T* paths involving near-isothermal decompression (Liu, Shen & Geng, 1996; Zhao *et al.* 2000*a*; Guo, Sun & Zhai, 2005); (6) ancient oceanic fragments and ophiolitic mélange (Bai, 1986; Li *et al.* 1990; Bai, Wang & Guo, 1992; Wang *et al.* 1996, 1997; Wu & Zhong, 1998); (7) syn- or post-tectonic granites; and (8) post-collisional mafic dyke swarms (Halls *et al.* 2000; P. Peng, unpub. Ph.D. thesis, Chinese Acad. Sciences, Beijing, 2005; Peng *et al.* 2005). Most of these lithotectonic elements are classical indicators of collision tectonics.

The Hengshan–Wutai–Fuping belt is situated in the middle segment of the Trans-North China Orogen (Fig. 3) and consists of three distinct tectonic complexes: the upper amphibolite to granulite facies Fuping and Hengshan complexes in the southeast and northwest, respectively, separated by the greenschist- to lower amphibolite-facies Wutai Complex (Fig. 4), which is interpreted as a typical granite–greenstone belt (Bai, 1986; Bai, Wang & Guo, 1992; Tian, 1991). The Hengshan Complex is bounded in the northwest by the valley of the Sanggan River and is separated from the Wutai Complex by the broad valley of the Hutuo River and thus the nature of the Hengshan–Wutai boundary is unclear. The Fuping Complex was previously considered

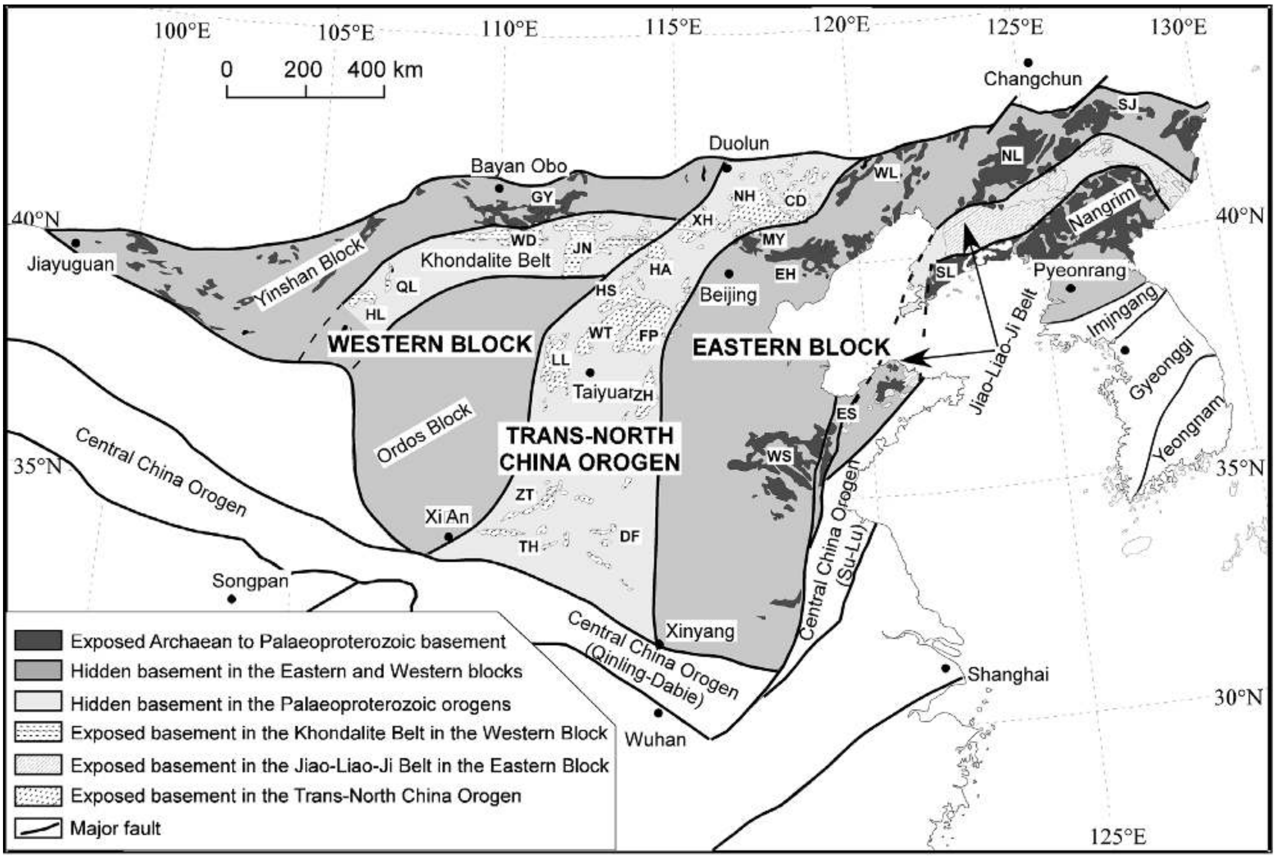

Figure 2. Tectonic subdivision of the North China Craton, modified by Zhao *et al.* (2005). Abbreviations for metamorphic complexes: CD – Chengde; DF – Dengfeng; EH – Eastern Hebei; ES – Eastern Shandong; FP – Fuping; GY – Guyang; HA – Huai'an; HL – Helanshan; HS – Hengshan; JN – Jining; LL – Lüliang; MY – Miyun; NH – Northern Hebei; NL – Northern Liaoning; QL – Qianlishan; SJ – Southern Jilin; SL – Southern Liaoning; TH – Taihua; WD – Wulashan–Daqingshan; WL – Western Liaoning; WS – Western Shandong; WT – Wutai; XH – Xuanhua; ZH – Zanhuang; ZT – Zhongtiao.

to be unconformably overlain by the Wutai Complex along the 'Tiebao unconformity' (Bai, 1986; Wu *et al.* 1989; Tian, 1991; Bai, Wang & Guo, 1992), but recent research revealed that the so-called 'Tiebao unconformity' is a regional-scale ductile shear zone, named the Longquanguan Ductile Shear Zone by Li & Qian (1991), and thus the nature of the boundary between the Fuping and Wutai complexes is a tectonic feature.

3. Major rock units of the Hengshan–Wutai–Fuping belt

3.a. Hengshan Complex

The Hengshan Complex is composed of four main rock units (Fig. 4): (1) the Hengshan granitoid gneisses, (2) the Hengshan mafic granulites, (3) the Yixingzhai gneisses, and (4) the Zhujiafang supracrustal assemblage (Tian, 1991; Zhao *et al.* 2001*a*).

The Hengshan granitoid gneisses are strongly deformed layered orthogneisses of dioritic–tonalitic–trondhjemitic–granodioritic–granitic composition. These rocks are extensively migmatized, and some of the migmatized zones show evidence of *in situ* melting and advanced anatexis, generating reddish granites. The compositional layering in the gneisses ranges from dark, hornblende-rich dioritic to tonalitic compositions to K-feldspar-dominated leucocratic granitoid varieties. Major element data show that the Hengshan granitoid gneisses belong to a high-alumina calc-alkaline suite (Li & Qian, 1994), and geochemical data suggest that they were emplaced in a magmatic arc environment (Fig. 5a; Kröner *et al.* 2005*a*,*b*).

Within the Hengshan granitoid gneisses there are discontinuous lenses or layers of amphibolite and high- and medium-pressure mafic granulite, ranging from 0.1 to 5 m in width and 0.1 to 50 m in length and interpreted as boudinaged gabbroic dykes (Kröner *et al.* 2005*a*,*b*, 2006). In the field, the high-pressure granulite lenses can be distinguished from the surrounding medium-pressure granulites by the presence of coarse-grained textures and lack of brown orthopyroxene in the former. The long axes of the granulite lenses are parallel to the regional foliation of the Hengshan granitoid gneisses. In some places, the interiors of amphibolites and mafic granulites preserve a relict igneous gabbroic/doleritic texture. There can be no doubt that these amphibolites and mafic granulites are remnants of mafic dykes that

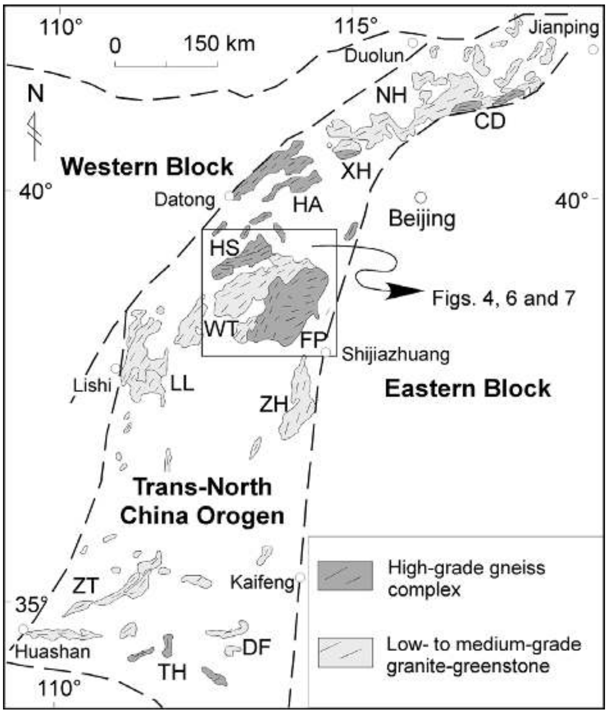

Figure 3. Simplified tectonic map showing the distribution of metamorphic complexes in the Trans-North China Orogen (after Zhao *et al.* 2000*a*). Area of Figures 4, 6 and 7 is outlined. Symbols and abbreviations as in Figure 2.

originally intruded into the granitoid rocks, as can still be observed at a few localities in low-strain zones (Kröner *et al.* 2005*a*,*b*, 2006).

The Yixingzhai gneisses occur in the southern part of the Hengshan Complex. They are chemically similar to the Hengshan granitoid gneisses, belonging to a high-alumina calc-alkaline suite and forming in a magmatic arc setting (Kröner *et al.* 2005*a*,*b*), but are only metamorphosed to greenschist to lower amphibolite facies and are less deformed, locally preserving igneous textures.

The Zhujiafang assemblage consists predominantly of amphibolite, felsic gneiss, mica schist, banded iron formation (BIF) and quartzite, which occur largely along two nearly EW-trending belts that cut across the regional layering/foliation of the Hengshan granitoid gneisses and Yixingzhai gneisses (Fig. 4). These rocks are characterized by strong ductile deformation and ubiquitous mylonite fabrics and are distinctively lower in metamorphic grade than the other supracrustal rocks within the Hengshan granitoid gneisses. Some Chinese workers have considered the Zhujiafang assemblage to be the equivalent of the Wutai greenstones in the Hengshan area (Tian, 1991; Li & Qian, 1994).

3.b. Wutai Complex

The Wutai Complex consists of Neoarchaean to Palaeoproterozoic granitic plutons and metamorphosed volcanic and sedimentary rocks, traditionally named the Wutai and Hutuo 'groups' in the Chinese literature.

The granitoid plutons in the Wutai Complex can be largely divided into three distinct types: the Wutai, Dawaliang and Fengkuangshan granites. The Wutai granites are the major components of the granitoid plutons in the Wutai Complex, including the Chechang–Beitai, Dazhaikou, Duyu, Ekou, Shifu, Lanzhishan, Guangmingshi and Wangjiahui bodies. They are composed of strongly deformed diorite–tonalite–trondhjemite–granodiorite suites with penetrative foliations, and thus are considered to be pre-tectonic granitoids (Tian, 1991). Geochemical data suggest that the Wutai granites were emplaced in a magmatic arc environment (Fig. 5a; Liu *et al.* 2004*b*, 2005; Kröner *et al.* 2005*b*). The Dawaliang-type granites, represented by the Dawaliang body and the younger phase of the Wangjiahui body, are composed of weakly deformed porphyric syenogranites. The Fengkuangshan-type granites, including the Fengkuangshan, Lianhuashan and Pingxingguan bodies, are composed of undeformed A-type granites with a massive structure, interpreted as post-orogenic or anorogenic granites (Tian, 1991).

Based on lithologies and metamorphic grades, the Wutai 'Group' is conventionally subdivided into three subgroups: Shizui, Taihuai and Gaofan subgroups. The Shizui Subgroup consists of peridotite, oceanic tholeiite, dacite, rhyolite, chert, banded iron formation (BIF), sandstone, siltstone, shale, calc-silicate rocks and minor limestone metamorphosed in lower amphibolite facies. Of these, the peridotites, oceanic tholeiites and cherts are considered to represent relict oceanic crust, whereas most sediments are interpreted as continental margin or back-arc basin deposits (Li *et al.* 1990; Bai & Dai, 1998; Wu & Zhong, 1998). The Taihuai Subgroup comprises felsic volcanic rocks and tholeiites metamorphosed in greenschist facies. On the Pearce (1976) major element discrimination diagram (Fig. 5b), most of the felsic and tholeiitic volcanics in the Wutai 'Group' have affinities to modern volcanic-arc assemblages or MORB (Bai, 1986; Wang *et al.* 2004*b*). On the Th/Ta v. La/Yb diagram (Condie, 1994, 1997, 2005), most of the amphibolite samples from the Wutai 'Group' plot in the arc field, though a few samples are located in the NMORB field and its adjacent areas (Fig. 5c; Wang *et al.* 2004*b*). The Gaofan Subgroup contains conglomerates, quartz greywackes, siltstones, limestones, and minor mafic to felsic volcanic rocks metamorphosed from subgreenschist to greenschist facies, which are interpreted as having developed in an intra-arc basin and/or a retro-arc foreland basin (Zhao *et al.* 2001*b*). Recent SHRIMP U–Pb zircon ages indicate that the Shizui, Taihuai and Gaofan subgroups are not a single lithostratigraphic sequence, the 'Wutai Group', as previously considered; instead, they are similar-aged volcanic-sedimentary formations that are

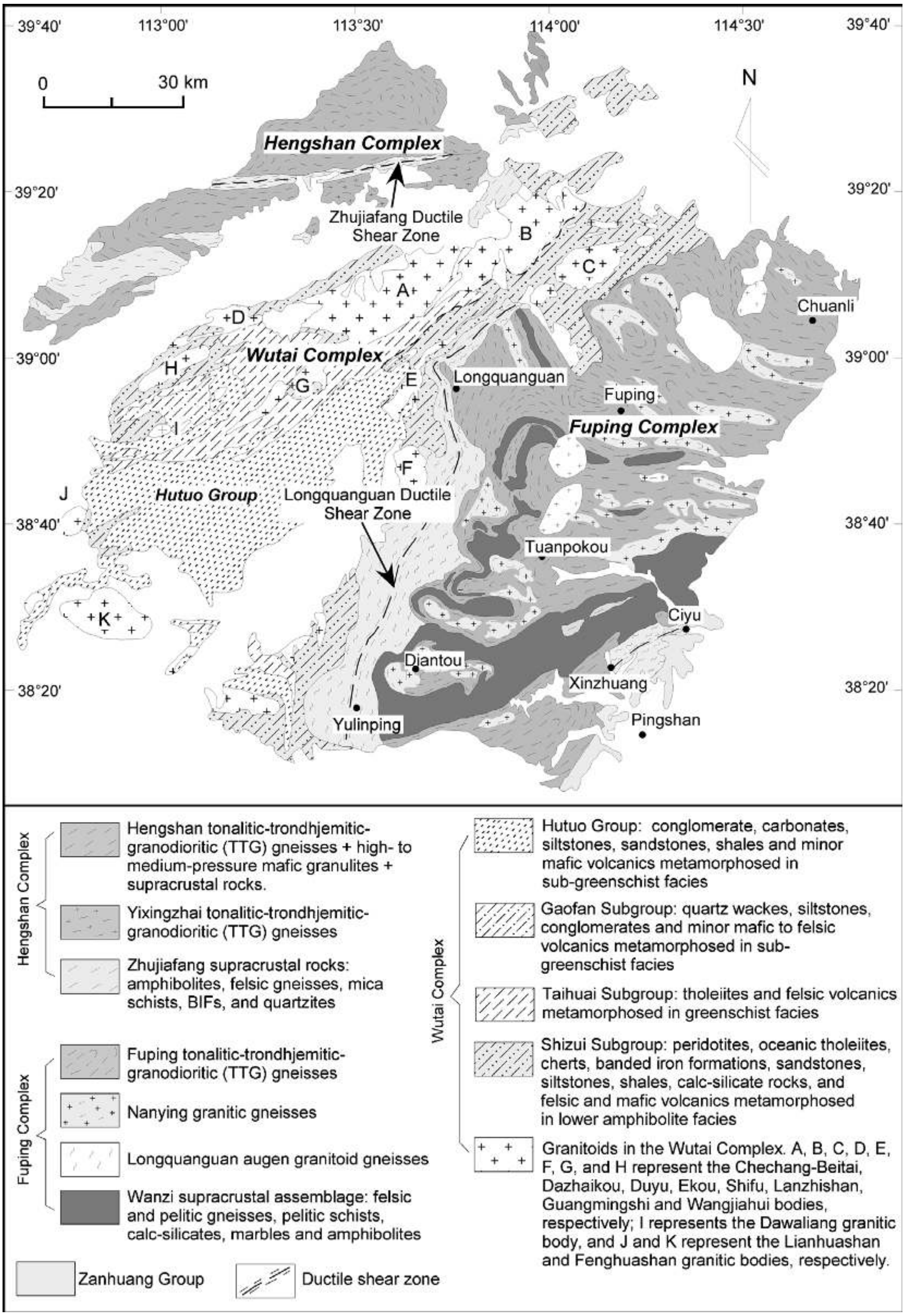

Figure 4. Simplified geological map of the Hengshan, Wutai and Fuping complexes.

structurally disrupted and juxtaposed along a series of NE–SW-trending ductile shear zones (see Section 3.c).

The Hutuo Group is considered to be the youngest unit in the Hengshan–Wutai–Fuping belt and to unconformably overlie the Wutai Group, although in places it is tectonically interleaved with the Wutai sequence. The group ranges upward from an extensive basal sequence of conglomerate into quartzite and other clastic sediments, slate, dolomite and marble, with another unit of conglomerate at the top of the sequence. Rocks of the Hutuo Group are mostly metamorphosed in greenschist facies, although there may be an eastward increase in grade, reaching upper greenschist to amphibolite facies.

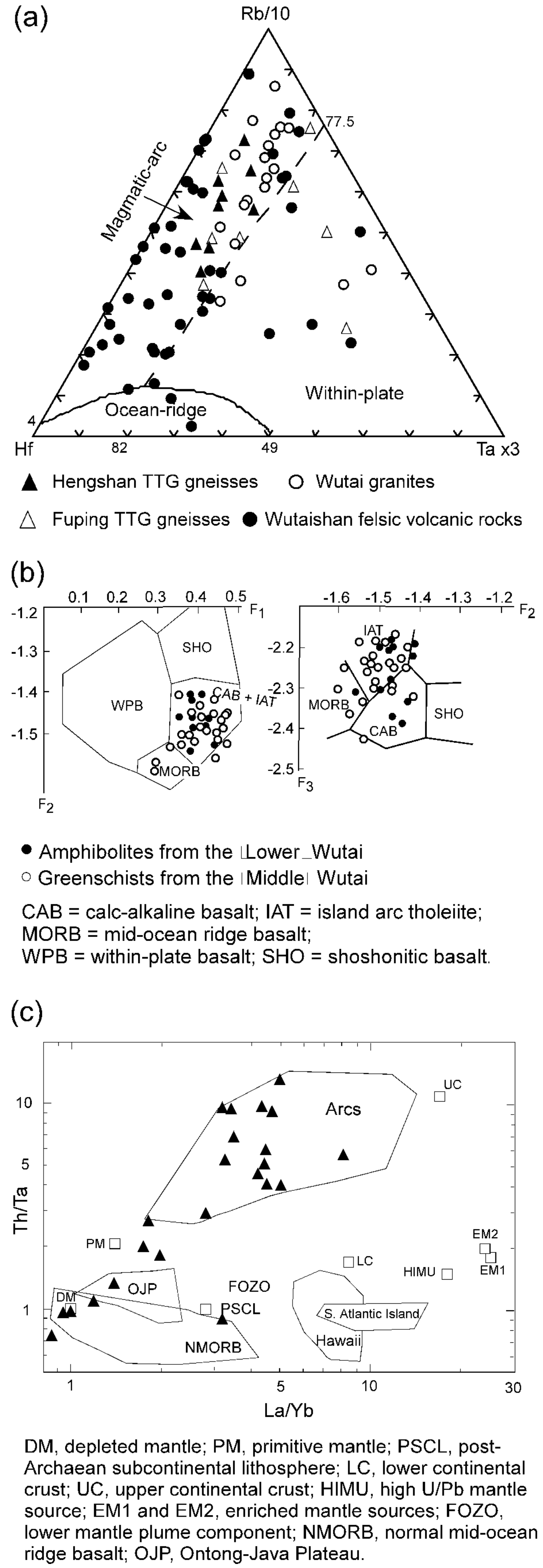

Figure 5. (a) Hf–Rb/10-Ta × 3 discrimination diagram (after Harris, Pearce & Tindle, 1986) for Hengshan TTG gneisses (Kröner *et al.* 2005*b*; Liu *et al.* 2005), Wutai volcanic and granitoid rocks (Wang *et al.* 2004*b*; Liu *et al.* 2005) and Fuping TTG gneisses (Liu *et al.* 2005). (b) Major element discrimination diagram (after Pearce, 1976) for Wutai amphibolites (Lower Wutai) and greenschists (Middle Wutai), based upon functions F_1, F_2 and F_3 (Bai, Wang & Guo, 1992). (c) Th/Ta v. La/Yb diagram (Condie, 1994, 1997, 2005) for the greenschist to amphibolite facies basaltic volcanics from the Wutai Complex (Wang *et al.* 2004*b*).

3.c. Fuping Complex

The Fuping Complex comprises four distinct rock units, herein called the Fuping granitoid gneisses, Longquanguan augen gneisses, Wanzi supracrustal assemblage, and Nanying granitic gneisses (Fig. 4; Liu *et al.* 2000; Zhao *et al.* 2002*b*).

The Fuping granitoid gneisses make up about 60 % of the complex and consist of medium-grained dioritic, tonalitic, trondhjemitic, granodioritic gneisses enclosing mafic granulite, amphibolite and hornblende gneiss that have undergone a complex history of upper amphibolite- to granulite-facies metamorphism and polyphase deformation. Petrological and geochemical data suggest that, like the Hengshan granitoid gneisses, the Fuping granitoid gneisses formed in a magmatic arc environment (Fig. 5a; Wang, Li & Liu, 1991).

The Longquanguan augen gneisses are mainly exposed along the Longquanguan ductile shear zone and are composed predominantly of coarse-grained to porphyritic granodioritic and monzogranitic gneisses and mylonitized granitic pegmatites containing K-feldspar phenocrysts, most of which have been intensely deformed to form augen. Enclosed in the Longquanguan augen gneisses are amphibolite and hornblende gneiss enclaves, similar to those in the Fuping granitoid gneisses. The Longquanguan augen gneisses display a tectonic contact with the Wanzi supracrustal assemblage and the Fuping gneisses (Wu *et al.* 1989; Li & Qian, 1991).

The Wanzi supracrustal assemblage forms a 100 km long, NE–SW-trending belt in the southern part of the complex (15 km wide) that swings northward to the central part of the complex, where it is extensively folded (Fig. 4). The supracrustal rocks are metamorphosed to amphibolite facies and comprise felsic and pelitic gneisses, pelitic schists, calc-silicate rocks, pure and impure marbles and amphibolites (Zhao *et al.* 2000*a*,*b*). Also associated with the supracrustal rocks are several small sillimanite-bearing granites which are considered to represent S-type granites derived from partial melting of pelitic gneisses and felsic paragneisses (Zhao *et al.* 2000*a*,*b*).

The Nanying granitic gneisses only occur within the Fuping granitoid gneisses and are dominated by medium- to fine-grained, weakly foliated, magnetite-bearing monzogranitic gneiss with minor granodioritic gneiss (Fig. 4; Zhao *et al.* 2000*a*,*b*). In addition to compositional differences, the Nanying gneisses are more massive in structure and more homogeneous in composition than the Fuping granitoid gneisses. In the field where contact relations are preserved, the Nanying granitic gneisses are clearly intrusive into the Fuping granitoid gneisses, but their relatively weak foliation is consistently parallel to the strong, penetrative foliation of the Fuping granitoid gneisses, suggesting that they most likely underwent the same deformational event that resulted in the development of the regional foliation in the Fuping Complex.

4. Major lithotectonic elements and geological events

In the last few years, the SHRIMP zircon dating technique, combined with single-grain zircon evaporation and mineral Sm–Nd and Ar/Ar methods, has been widely applied to date the major rock units of the Hengshan–Wutai–Fuping belt, producing a large number of precise age data for the mountain belt (see references in Table 1). These ages, in conjunction with structural, metamorphic and geochemical considerations, lead us to recognize the following major litho-tectonic assemblages and geological events in the Hengshan–Wutai–Fuping belt.

4.a. Remnants of an old (2.7–2.8 Ga) crustal component

The oldest known basement components in the Hengshan–Wutai–Fuping belt are rare medium-grained felsic gneisses that occur interleaved with the younger granitoid gneisses but are difficult to recognize as separate units in the field (Wilde, Cawood & Wang, 1997; Guan *et al.* 2002; Kröner *et al.* 2005*a*). In the Fuping Complex, xenocrystic zircons from a medium-grained hornblende gneiss enclosed in the Fuping granitoid gneisses were SHRIMP-dated by Guan *et al.* (2002) at 2708 ± 8 Ma (Fig. 6, Table 1). A sillimanite paragneiss from the Wanzi Supracrustal assemblage contains two ancient detrital zircons of ages 2827 ± 8 Ma and 2686 ± 8 Ma, of which the former, as far as we are aware, is the oldest single-grain zircon age so far reported from the Hengshan–Wutai–Fuping belt (Fig. 6, Table 1). In the Wutai Complex, Wilde, Cawood & Wang (1997) found four xenocrystic zircons in the 2553 ± 8 Ma Lanzhishan granites that yielded a weighted mean SHRIMP $^{207}Pb/^{206}Pb$ age of 2702 ± 10 Ma. Wilde (2002) also recognized 2763 ± 10 Ma and 2660 ± 7 Ma old xenocrystic zircons in the 2534 ± 10 Ma Longquanguan augen gneiss (Fig. 6), which is now considered to be part of the Wutai Complex (see Section 4.b). In addition, Wilde *et al.* (2004*a*) found two xenocrystic zircons with a weighted mean SHRIMP $^{207}Pb/^{206}Pb$ age of 2702 ± 10 Ma from a 2529 ± 10 Ma meta-andesite of the Zhuangwang Formation. In the Hengshan Complex, a grey trondhjemitic gneiss sample collected from a migmatite domain in Changchenggou (‘Great

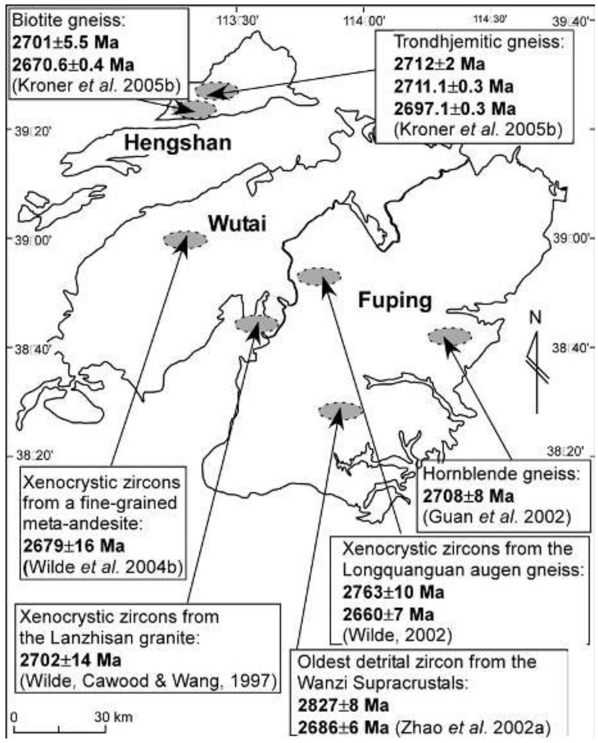

Figure 6. Distribution of 2.7–2.8 Ga xenocrystic zircons or gneisses in the Hengshan–Wutai–Fuping belt.

Wall Valley’ in English) and a grey biotite gneiss sample collected from Dashiyu (‘Big Stone Valley’ in English) were SHRIMP-dated by Kröner *et al.* (2005*b*) at 2712 ± 2 Ma and 2701 ± 5.5 Ma, respectively (Fig. 6). Kröner *et al.* (2005*b*) also used the single-grain evaporation technique to date a foliated grey gneiss from Changchenggou and a fine-grained biotite gneiss from Dashiyu at 2697.1 ± 0.3 Ma and 2670.6 ± 0.4 Ma, respectively. Taken together, these data, although sparse, confirm the existence of *c.* 2.7 Ga crustal components in the Hengshan–Wutai–Fuping region, now tectonically interleaved with the younger gneisses and most probably representing remnants of an older crustal domain whose history and evolution is difficult to reconstruct.

4.b. 2560–2520 Ma: emplacement of Neoarchaean Wutai granites and Longquanguan augen gneisses

The Wutai granites include the Ekou, Chechang–Beitai, Lanzhishan, Shifu, Guangmingshi and Wangjiahui plutons, of which the oldest is the Ekou pluton dated at 2566 ± 13 Ma and 2555 ± 6 Ma (Wilde, Cawood & Wang, 1997), and the youngest is the Wangjiahui pluton dated at 2517 ± 12 Ma (Wilde *et al.* 2005). As the largest exposure of the Wutai granites, the Chechang–Beitai pluton is composed of tonalites and granodiorites. Four samples collected from different phases of the pluton yielded SHRIMP zircon ages of 2552 ± 11, 2551 ± 5, 2546 ± 6 and 2538 ± 6 Ma (Table 1; Wilde *et al.* 2005), suggesting that the pluton was emplaced

Table 1. Summary of isotopic ages for the Hengshan, Wutai and Fuping complexes

Sample	Description	Age (Ma)	Method	Sources
Ages of remnants of 2.7–2.8 Ga old continental crust				
Hengshan Complex				
990843	Grey trondhjemitic gneiss (Changchenggou)	2712 ± 2	SHRIMP	Kröner *et al*. (2005*b*)
	Same sample	2711.1 ± 0.3	EVAP	Kröner *et al*. (2005*b*)
990838	Well foliated grey biotite gneiss (Dashiyu)	2701 ± 5.5	SHRIMP	Kröner *et al*. (2005*b*)
980811	Grey granodioritic gneiss (Changchenggou)	2697.1 ± 0.3	EVAP	Kröner *et al*. (2005*b*)
980824	Finely layered, fine-grained biotite gneiss (Dashiyu)	2670.6 ± 0.4	EVAP	Kröner *et al*. (2005*b*)
Wutai Complex				
95-PC-114	Xenocrystic zircons from a meta-andesite (Ekou)	2679 ± 16	SHRIMP	Wilde *et al*. (2004*b*)
95-PC-94	Xenocrystic zircons from the Lanzhisan granite	2702 ± 14	SHRIMP	Wilde *et al*. (1997)
Fuping Complex				
95-PC-65	Xenocrystic zircons from the Longquanguan granite	2763 ± 10	SHRIMP	Wilde (2002)
	Same sample	2660 ± 7	SHRIMP	Wilde (2002)
FP50	Xenocrystic zircons from a biotite gneiss (Diebuan)	2708 ± 8	SHRIMP	Guan *et al*. (2002*a*)
FP260	Oldest detrital zircons from the Wanzi Supracrustals	2826 ± 8	SHRIMP	Zhao *et al*. (2002*a*)
	Same sample	2686 ± 6	SHRIMP	Zhao *et al*. (2002*a*)
Ages of late Archaean Wutai granitoids and Longquanguan augen gneisses (2560–2520 Ma)				
Ekou Pluton				
95-PC-34	Deformed, pink, medium-grained granitoid (Ekou)	2566 ± 13	SHRIMP	Wilde *et al*. (1997)
95–19	deformed, pink, medium-grained granitoid (Ekou)	2555 ± 6	SHRIMP	Wilde *et al*. (1997)
Chechang–Beitai pluton				
WC7	Foliated, coarse-grained tonalite (Shahe)	2552 ± 11	SHRIMP	Wilde *et al*. (2005)
95-PC-6B	Foliated, coarse-grained tonalite (Taipinggou)	2551 ± 5	SHRIMP	Wilde *et al*. (2005)
WC6	Deformed, fine-grained granodiorite (Taipinggou)	2546 ± 6	SHRIMP	Wilde *et al*. (2005)
WC5	Deformed, coarse-grained granodiorite (Taipinggou)	2538 ± 6	SHRIMP	Wilde *et al*. (2005)
Lanzhishan Pluton				
95-PC-94	Deformed, coarse-grained granitoid (Changjiagtan)	2553 ± 8	SHRIMP	Wilde *et al*. (1997)
95-PC-96	Deformed, coarse-grained granitoid (Changjiagtan)	2537 ± 10	SHRIMP	Wilde *et al*. (1997)
Shifo Pluton				
95-PC-98	Deformed medium-grained monzogranite (Nanliang)	2531 ± 4	SHRIMP	Wilde *et al*. (2005)
Guangmishi Pluton				
95-PC-76	Deformed, medium-grained granitoid (Guangmishi)	2531 ± 5	SHRIMP	Wilde *et al*. (2005)
Wangjiahui Pluton (Grey Phase)				
95-PC-62	Deformed medium-grained granodiorite (Shi Gang)	2520 ± 9	SHRIMP	Wilde *et al*. (2005)
95-PC-63	Deformed medium-grained granodiorite (Shi Gang)	2517 ± 12	SHRIMP	Wilde *et al*. (2005)
Longquanguan augen gneisses				
WL12	Sheared porphyritic granitoid (Longquanguan)	2543 ± 7	SHRIMP	Wilde *et al*. (1997)
WN11	Sheared tonaltic granitoid (Yushuwan Village)	2541 ± 14	SHRIMP	Wilde *et al*. (1997)
WL9	Sheared porphyritic granitoid (Longquanguan)	2540 ± 18	SHRIMP	Wilde *et al*. (1997)
Ages of late Archaean Wutai ‘Group’ (2530–2515 Ma)				
95PC-114	Meta-andesite, Zhuangwang ‘Formation’ (Ekou)	2529 ± 10	SHRIMP	Wilde *et al*. (2004*b*)
96PC-119	Meta-andesite, Zhuangwang ‘Formation’ (Ekou)	2513 ± 8	SHRIMP	Wilde *et al*. (2004*b*)
95-PC-115	Meta-andesite, Baizhiyan ‘Formation’ (Ekou)	2524 ± 10	SHRIMP	Wilde *et al*. (2004*b*)
WT13	Meta-rhyolite, Hongmenyan ‘Formation’ (S–T)	2533 ± 8	SHRIMP	Wilde *et al*. (2004*b*)
WT17	Meta-rhyodacite Hongmenyan ‘Formation’ (S–T)	2524 ± 8	SHRIMP	Wilde *et al*. (2004*b*)
WT9	Meta-dacite, Hongmenyan ‘Formation’ (S–T)	2523 ± 9	SHRIMP	Wilde *et al*. (2004*b*)
WT12	Meta-rhyodacite, Hongmenyan ‘Formation’ (S–T)	2516 ± 10	SHRIMP	Wilde *et al*. (2004*b*)
95-PC-55c	Meta-rhyolite, Gaofan ‘Subgroup’ (Xiazhuang)	2528 ± 6	SHRIMP	Wilde *et al*. (2004*b*)
Ages of late Archaean to Palaeoproterozic Hengshan, Yixingzhai and Fuping TTG gneisses (2520–2480 Ma)				
Hengshan TTG gneisses				
980814	Dioritic gneiss (Changchenggou)	2479 ± 3	SHRIMP	Kröner *et al*. (2005*b*)
	Same sample	2478.2 ± 0.3	EVAP	Kröner *et al*. (2005*b*)
990803	Dioritic gneiss with melt patches (Dashiyu)	2475 ± 2	SHRIMP	Kröner *et al*. (2005*b*)
990859	Dioritic gneiss (Xiaoshiyu)	2506 ± 5	SHRIMP	Kröner *et al*. (2005*b*)
	Same sample	2504.6 ± 0.3	EVAP	Kröner *et al*. (2005*b*)
980802	Homogeneous tonalitic gneiss (Dashiyu)	2500.5 ± 0.3	EVAP	Kröner *et al*. (2005*b*)
990871	Tonalitic gneiss, small side valley of Ruyuegou	2502.3 ± 0.3	EVAP	Kröner *et al*. (2005*b*)
HG1	Tonalitic gneiss (Dashiyu)	2520 ± 15	SHRIMP	Wilde *et al*. (unpub.)
HG5	Garnetiferous trondhjemitic gneiss (Yanmenguan)	2520 ± 10	SHRIMP	Kröner *et al*. (2005*b*)
HG6	Trondhjemitic gneiss, roadcut near Yanmenguan	2526 ± 12	SHRIMP	Kröner *et al*. (2005*b*)
HG7	Trondhjemitic gneiss, A roadcut near Yanmenguan	2507 ± 4	SHRIMP	Kröner *et al*. (2005*b*)
990845	Foliated trondhjemitic gneiss (Xiaoshiyu)	2504.4 ± 0.4	EVAP	Kröner *et al*. (2005*b*)
980838	Trondhjemitic gneiss (Ruyuegou)	2503.0 ± 0.3	EVAP	Kröner *et al*. (2005*b*)
990847	Grey, unveined trondhjemitic gneiss (Yanmenguan)	2524 ± 8	SHRIMP	Kröner *et al*. (2005*b*)
	Same sample	2521.7 ± 0.4	EVAP	Kröner *et al*. (2005*b*)
990854	Trondhjemitic gneiss (Xiaoshiyu)	2504.6 ± 0.3	EVAP	Kröner *et al*. (2005*b*)
980809	Foliated pegmatitic red granite-gneiss (Dashiyu)	2501 ± 3	SHRIMP	Kröner *et al*. (2005*b*)
	Same sample	2503.5 ± 0.3	EVAP	Kröner *et al*. (2005*b*)
980825	Fine-grained, strained granite-gneiss (Xiaoshiyu)	2496.3 ± 0.3	EVAP	Kröner *et al*. (2005*b*)
980833	Granitic gneiss (Xiaoshiyu)	2492.4 ± 0.3	EVAP	Kröner *et al*. (2005*b*)
990873	Foliated granite gneiss from migmatite (Guaner)	2499 ± 6	SHRIMP	Kröner *et al*. (2005*b*)
	Same sample	2497.6	EVAP	Kröner *et al*. (2005*b*)
980803	Homogeneous felsic gneiss (Dashiyu)	2502.3 ± 0.6	EVAP	Kröner *et al*. (2005*b*)

Table 1. Continued.

Sample	Description	Age (Ma)	Method	Sources
990821	Finely layered, fine-grained biotite gneiss (Dashiyu)	2526 ± 04.7	SHRIMP	Kröner *et al*. (2005*b*)
Yixingzhai TTG gneisses				
96PC153	Homogeneous tonalitic gneiss, near Yixingzhai	2513 ± 15	SHRIMP	Wilde (2002)
96PC154	Quartz dioritic gneiss, a roadcut near Yixingzhai	2499 ± 4	SHRIMP	Wilde (2002)
Fuping TTG gneisses				
FG1	Layered tonalitic gneiss, a roadcut near Xicaokou	2523 ± 14	SHRIMP	Zhao *et al*. (2002*a*)
FP50	Foliated, hornblende-rich tonalitic gneiss (Diebuan)	2520 ± 20	SHRIMP	Guan *et al*. (2002)
FP54	Trondhjemitic gneiss collected from Pingyang	2513 ± 12	SHRIMP	Guan *et al*. (2002)
FP217	Trondhjemitic gneiss collected from Tuanpokou	2499 ± 9.5	SHRIMP	Zhao *et al*. (2002*a*)
FP216	Granodioritic gneiss collected from Tuanpokou	2486 ± 8	SHRIMP	Zhao *et al*. (2002*a*)
FP08	Granodioritic gneiss collected from Xicaokou	2475 ± 8	SHRIMP	Guan *et al*. (2002)
FP236	Mylonitized monzongranitic gneiss (near Ciyu)	2510 ± 22	SHRIMP	Zhao *et al*. (2002*a*)
FP224	Mylonitized pegmatitic dyke (Xinzhuang)	2507 ± 11	SHRIMP	Zhao *et al*. (2002*a*)
Ages of Palaeoproterozoic (2360–2000 Ma) granitoids				
Hengshan Complex				
980806	Fine-grained granitic orthogneiss (Dashiyu)	2358.7 ± 0.5	EVAP	Kröner *et al*. (2005*b*)
990850	Layered trondhjemitic gneiss (Dashiyu)	2329.7 ± 0.6	EVAP	Kröner *et al*. (2005*b*)
HG4	Pegmatitic granite-gneiss (Dashiyu)	2331 ± 36	SHRIMP	Kröner *et al*. (2005*b*)
980881	Pegmatite cutting older gneisses (Xiaoshiyu)	2248.5 ± 0.5	EVAP	Kröner *et al*. (2005*b*)
980844	Red anatectic granite (Changchenggou)	2113 ± 8	SHRIMP	Kröner *et al*. (2005*b*)
	Same sample	2112.3 ± 0.6	EVAP	Kröner *et al*. (2005*b*)
Wutai Complex				
D2	Coarse-grained Dawaliang porphyritic granite	2176 ± 12	SHRIMP	Wilde (2002)
95-PC-50	Pink Phase of the Wangjiahui granite	2117 ± 17	SHRIMP	Wilde *et al*. (2005)
95-PC-51	Pink Phase of the Wangjiahui granite	2116 ± 16	SHRIMP	Wilde *et al*. (2005)
95-PC-60	Pink Phase of the Wangjiahui granite	2084 ± 16	SHRIMP	Wilde *et al*. (2005)
Fuping Complex				
FP188–2	Nanying granitoid gneisses, 10 km south of Fuping	2077 ± 13	SHRIMP	Zhao *et al*. (2002*a*)
FP204	Nanying granitoid gneisses near Dianfang	2024 ± 21	SHRIMP	Zhao *et al*. (2002*a*)
FP30	Nanying granitoid gneisses collected from Gangnan	2045 ± 64	SHRIMP	Guan *et al*. (2002)
Ages of Palaeoproterozoic pre-tectonic mafic dykes (now amphiolite or high-pressure granulites)				
Hengshan Complex				
Ch020901	High-pressure granulite facies mafic dyke (Dashiyu)	1915 ± 4	SHRIMP	Kröner *et al*. (2006)
Ch020902	High-pressure granulite facies mafic dyke (Dashiyu)	1914 ± 2	SHRIMP	Kröner *et al*. (2006)
Wutai Complex				
02SX009	Amphibolite facies mafic dyke (Hengling)	2147 ± 5	SHRIMP	Peng (2005)
Ages of the Palaeoproterozoic Hutuo Group and Wanzi supracrustal assemblage				
Hutuo Group in the Wutai Complex				
HTG-10	A felsic tuffaceous rock at Taihuai: an older group	2180 ± 4	SHRIMP	Wilde *et al*. (2004*a*)
	A younger population from the same sample	2087 ± 9	SHRIMP	Wilde *et al*. (2004*a*)
Wanzi Supracrustal assemblage in the Fuping Complex				
FP62	A paragneiss collected from Pingyang	2097 ± 46	SHRIMP	Guan *et al*. (2002)
FP249	The youngest concordant zircon from a paragneiss	2109 ± 5	SHRIMP	Zhao *et al*. (2002*a*)
FP260	One young discordant zircon from a paragneiss	2097 ± 6	SHRIMP	Zhao *et al*. (2002*a*)
FP014	Upper intercept age of igneous zircons cores	2099 ± 22	LA-ICP	Xia *et al*. (2006*c*)
FP037	Upper intercept age of igneous zircons cores	2110 ± 30	LA-ICP	Xia *et al*. (2006*c*)
FP053	Upper intercept age of igneous zircons cores	2112 ± 23	LA-ICP	Xia *et al*. (2006*c*)
Ages of metamorphism of the Hengshan, Wutai and Fuping complexes (1880–1800 Ma)				
Hengshan Complex				
990803	One euhedral zircon from a dioritic gneiss (Dashiyu)	1881 ± 8	SHRIMP	Kröner *et al*. (2005*b*)
M068	Meta-zircons from high-pressure granulite (Dashiyu)	1850 ± 3	SHRIMP	Kröner *et al*. (2006)
HG2	Meta-zircons from high-pressure granulite (Dashiyu)	1867 ± 23	SHRIMP	Kröner *et al*. (2006)
Ch990839	Coarse-grained pegmatitic melt (Xiaoshiyu)	1851 ± 5	SHRIMP	Kröner *et al*. (2006)
	Same sample	1856.1 ± 0.6	EVAP	Kröner *et al*. (2006)
HG1	Meta-zircons from a granitic gneiss (Dashiyu)	1872 ± 17	SHRIMP	Kröner *et al*. (2006)
Ch980871	Meta-zircons from a retro-eclogite (Xiaoshiyu)	1881.3 ± 0.4	EVAP	Kröner *et al*. (2006)
Ch990853	Meta-zircons from a retrograded eclogite (Dashiyu)	1859.7 ± 0.5	EVAP	Kröner *et al*. (2006)
Ch990886	Meta-zircons from a mafic granulite (Dashiyu)	1850.9 ± 0.4	EVAP	Kröner *et al*. (2006)
Ch990848	Meta-zircons from high-pressure granulite (Dashiyu)	1885.6 ± 0.4	EVAP	Kröner *et al*. (2006)
Wutai Complex				
Unknown	Garnet amphibolite from the Jingangku Formation	1851 ± 9	Sm–Nd	Wang *et al*. (2001)
S2010–2-1	Meta-monazites from a kyanite schist (Jingangku)	1822 ± 14	EPMA	Liu *et al*. (2006)
S2010–2-1	Meta-monazites from a kyanite schist (Jingangku)	1833 ± 8	EPMA	Liu *et al*. (2006)
SZ10	Meta-monazites from a kyanite schist (Jingangku)	1847 ± 62	EPMA	Liu *et al*. (2004*a*)
Fuping Complex				
FG1	Meta-zircons from a tonalitic gneiss (Xicaokou)	1802 ± 43	SHRIMP	Zhao *et al*. (2002*a*)
FP217	Meta-zircons from a trondhjemitic gneiss	1875 ± 43	SHRIMP	Zhao *et al*. (2002*a*)
FP216	Meta-zircons from granodioritic gneiss (Tuanpokou)	1825 ± 12	SHRIMP	Zhao *et al*. (2002*a*)
FP249	One meta-zircon rim from a paragneiss (Jiaan)	1821 ± 42	SHRIMP	Zhao *et al*. (2002*a*)
FP260	One meta-zircon rim from a paragneiss (Diaoyutai)	1891 ± 6	SHRIMP	Zhao *et al*. (2002*a*)
FP188–2	Meta-zircons from a Nanying granitoid gneisses	1826 ± 12	SHRIMP	Zhao *et al*. (2002*a*)
FP204	Meta-zircons from a Nanying granitoid gneisses	1850 ± 9.6	SHRIMP	Zhao *et al*. (2002*a*)

Table 1. Continued.

Sample	Description	Age (Ma)	Method	Sources
FP30	Two meta-zircon rims from a gneissic granite	1825 ± 18	SHRIMP	Guan *et al.* (2002)
FP08	Meta-zircons from a granodioritic gneiss (Xicaokou)	1817 ± 26	SHRIMP	Guan *et al.* (2002)
FP053	Meta-zircon rims from a paragneiss (Wuyuezhai)	1863 ± 30	LA-ICP	Xia *et al.* (2006*c*)
FP014	Meta-zircon rims from a paragneiss (Tuanpokou)	1822 ± 20	LA-ICP	Xia *et al.* (2006*c*)
Ages of Post-orogenic (1780–1750 Ma) mafic dyke swarms				
Hengshan Complex				
GU12	Unmetamorphosed mafic dyke (Near Tuling)	1769.1 ± 2.5	SGD	Halls *et al.* (2000)
Wutai Complex				
03WT08	Unmetamorphosed diabase dyke (Wutai County)	1754 ± 71	SGD	Peng (2005)
Fuping Complex (Taihangshan)				
99JX-16	Unmetamorphosed mafic dyke (Canyansi)	1765.3 ± 1.1	W–Ar–Ar	Wang *et al.* (2004*a*)
99JX-65	Unmetamorphosed mafic dyke (Huangbeiping)	1774.7 ± 0.7	W–Ar–Ar	Wang *et al.* (2004*a*)
99JX-71	Unmetamorphosed mafic dyke (Hujian'an)	1780.7 ± 0.5	W–Ar–Ar	Wang *et al.* (2004*a*)

SHRIMP – Sensitive high resolution ion microprobe; EVAP – Single grain evaporation. EPMA – Electron Probe Microanalysis; LA-ICP – LA-ICP-MS; SGD – Single grain dissolution; W–Ar–Ar – Whole rock ^{40}Ar–^{39}Ar. Meta-zircon – metamorphic zircons; S–T – Shahe–Taihuai Road. Note: In Kröner *et al.* (2005*a*,*b*, 2006*a*), Dashiyu, Xiaoshiyu and Changchenggou were translated into Big (or Large) Stone Valley, Little (or Small) Stone Valley and Great Wall Valley, respectively.

at about 2550–2540 Ma, slightly later than the Ekou pluton. The Lanzhishan pluton is divisible into older and younger phases with SHRIMP U–Pb zircon ages of 2553 ± 8 and 2537 ± 10 Ma, respectively (Wilde, Cawood & Wang, 1997). SHRIMP U–Pb zircon data also reveal that the Guangmingshi and Shifou plutons were simultaneously emplaced at *c.* 2531 Ma and probably belong to the same pluton. In summary, the above SHRIMP U–Pb zircon ages confirm the end-Archaean (2560–2520 Ma) emplacement of the Wutai granites which reflect the earliest arc-related magmatic event in the Hengshan–Wutai–Fuping belt.

The Longquanguan augen gneisses are restricted to the Longquanguan ductile shear zone and were previously interpreted as the youngest lithological unit in the Fuping Complex (Liu *et al.* 1985). However, recent SHRIMP U–Pb zircon ages reveal that the Longquanguan augen gneisses were emplaced at *c.* 2540 Ma (Wilde, Cawood & Wang, 1997), broadly simultaneous with the Wutai gneissic granites, but older than the 2520–2480 Ma Fuping TTG gneisses (see Section 4.d). Furthermore, magmatic zircons of the Longquanguan augen gneisses are not only identical in age to those of the Lanzhishan Granite, but both granitoids contain inherited zircons and zircon cores giving ages of *c.* 2700 Ma. Therefore, the Longquanguan augen gneisses most likely represent the equivalents of the Wutai granites but were structurally reworked during the development of the Longquanguan ductile shear zone. Similarities in fabric and petrographic features as well as the close spatial distribution between the Longquanguan augen gneisses and some of the Wutai granites (e.g. Lanzhishan granite) support this conclusion.

4.c. 2530–2515 Ma: formation of the Neoarchaean Wutai 'Group'

The volcano-sedimentary rocks of the Wutai 'Group' have long been considered to be either older than, or coeval with, the Wutai granites (Tian, 1991; Bai, Wang & Guo, 1992). However, SHRIMP U–Pb zircon ages show that the volcanic rocks of the Wutai 'Group' formed at 2530–2515 Ma (Wilde *et al.* 2004*a*), later than most of the Wutai granites. Traditionally, the Wutai 'Group' was subdivided into the lower, middle and upper sequences, represented by the Shizui, Taihuai and Gaofan subgroups, respectively (Bai, 1986; Bai, Wang & Guo, 1992; Tian, 1991). However, SHRIMP zircon ages reveal no difference between volcanic rocks previously considered to occupy different stratigraphic levels within the Wutai 'Group' (Table 1). For example, zircons from a felsic tuff of the Gaofan Subgroup provided a weighted mean ^{207}Pb/^{206}Pb age of 2528 ± 6 Ma, virtually the same as the age of 2529 ± 10 Ma obtained for a felsic tuff of the Shizui Subgroup (Wilde, 2002). A meta-andesite, collected from the Zhuangwang Formation of the Shizui Subgroup, yielded a SHRIMP U–Pb zircon age of 2513 ± 8 Ma (Wilde *et al.* 2005), which is the youngest age so far obtained for the Wutai 'Group'. Five rhyolite or rhyodacite samples collected from the Taihuai Subgroup yielded SHRIMP U–Pb zircon ages ranging from 2533 ± 8 Ma to 2516 ± 10 Ma (Wilde *et al.* 2005), suggesting that their eruption was largely coeval with that of the volcanic rocks in the Shizui and Gaofan subgroups. These results, together with field observations, suggest that the Wutai 'Group' is not a simple lithostratigraphic succession but constitutes a lithotectonic assemblage of volcano-sedimentary rocks that formed in the period 2530–2515 Ma. The volcanic rocks of the Wutai 'Group' have a close affinity to modern volcanic arc assemblages (Bai, 1986; Wang *et al.* 2004*b*; Polat *et al.* 2005) and may thus document the earliest arc-related volcanism in the Hengshan–Wutai–Fuping belt.

4.d. 2520–2480 Ma: emplacement of Neoarchaean to Palaeoproterozoic Hengshan, Yixingzhai and Fuping TTG gneisses

Granitoid gneisses are the major components of the Hengshan and Fuping complexes, making up 70–80 %

of the total exposures of both the complexes (Fig. 4). Conventionally, the high-grade Hengshan and Fuping complexes were assumed to be older than the low-grade Wutai Complex (Tian, 1991; Bai, Wang & Guo, 1992), and the Hengshan and Fuping TTG gneisses were considered to have been emplaced prior to intrusion of the Wutai granitoids (Tian, 1991; Bai, Wang & Guo, 1992). However, recent SHRIMP and evaporation zircon dating does not support these assumptions. As shown in Table 1, SHRIMP U–Pb ages for magmatic zircons indicate that the Fuping TTG gneisses were emplaced between 2523 and 2486 Ma (Guan *et al.* 2002; Zhao *et al.* 2002*b*). Similarly, SHRIMP and evaporation zircon ages show that the Hengshan TTG gneisses were also emplaced between 2524 and 2479 Ma (Table 1; Kröner *et al.* 2005*a*,*b*). An important conclusion from these data is that the Hengshan and Fuping tonalitic–trondhjemitic–granodioritic gneisses are younger than the Wutai granitoids; the latter were emplaced during Neoarchaean times, whereas the former were emplaced in the period between Neoarchaean and Early Palaeoproterozoic times. This conclusion contrasts with previous models that assumed the high-grade Fuping and Hengshan complexes to constitute an older basement below the lower grade Wutai Complex.

The amphibolite facies Yingxingzhai TTG gneisses in the southern Hengshan area have long been considered to be younger than the granulite facies Hengshan TTG gneisses in the northern area, but recent SHRIMP zircon ages do not support this assumption. Zircons from two Yingxingzhai TTG gneiss samples were SHRIMP-dated by Wilde (2002) at 2513 ± 5 Ma and 2499 ± 4 Ma (Table 1), which are similar to the age range (2526–2480 Ma) of the Hengshan TTG gneisses (Table 1; Kröner *et al.* 2005*a*,*b*). Therefore, the Yingxingzhai TTG gneisses most likely represent the upper crustal equivalent of the Hengshan TTG gneisses (Kröner *et al.* 2005*a*,*b*). This conclusion is consistent with the available geochemical data, which indicate that both the Hengshan and Yixingzhai TTG gneisses belong to calc-alkaline suites emplaced in a magmatic arc environment (Fig. 4; Kröner *et al.* 2005*a*,*b*).

4.e. 2350–2050 Ma: intermittent emplacement of Palaeoproterozoic granitoids

Palaeoproterozoic granitoids in the Hengshan–Wutai–Fuping belt have not been recognized until recently, following acquisition of new SHRIMP and evaporation zircon ages which indicate the widespread presence of Palaeoproterozoic granitoids in the belt. In the Wutai Complex, Palaeoproterozoic granitoids are represented by the Dawaliang pluton and the pink phase of the Wangjiahui pluton, of which the former yielded a SHRIMP zircon age of 2176 ± 12 Ma, whereas three samples of the latter were dated at 2117 ± 17, 2116 ± 16 and 2084 ± 20 Ma, respectively (Wilde *et al.* 2005). In the Fuping Complex, the Palaeoproterozoic granitoids are represented by the Nanying granitic gneisses which widely occur in the Fuping TTG gneisses (Fig. 4). SHRIMP data show that the Nanying gneissic granites were emplaced in the period 2077–2024 Ma (Table 1; Guan *et al.* 2002; Zhao *et al.* 2002*b*), slightly later than the Dawaliang granites. In the Hengshan Complex, similar-aged gneissic granites have been identified by Kröner *et al.* (2005*a*,*b*) using the SHRIMP and single-grain evaporation techniques (Table 1). They recognized three phases of Palaeoproterozoic gneissic granitoids that were emplaced at *c.* 2360 Ma, 2330 Ma and 2250 Ma, respectively (Table 1). It is particularly important to note that these Palaeoproterozoic granitoids in the Hengshan and Fuping complexes contain the same deformational features as the older Hengshan and Fuping granitoid gneisses and thus unambiguously demonstrate that the main deformational event is not Archaean but Palaeoproterozoic in age.

4.f. 2150–1915 Ma: emplacement of pre-tectonic mafic dykes

Pre-tectonic gabbro and diabase dykes are represented by numerous boudins and lensoid layers of mafic granulites or amphibolites in the Hengshan, Wutai and Fuping complexes. In some places, and in particular in low-strain zones such as those south of the Zhujiafang shear zone (Fig. 4), primary igneous fabrics (e.g. ophitic or subophitic texture) are well preserved in the amphibolite to granulite facies dykes (O'Brien, Walte & Li, 2005; Kröner *et al.* 2005*a*, 2006). In most cases, and especially in high-strain zones such as the areas north of the Zhujiafang shear zone (Fig. 4), the pre-tectonic gabbroic/diabase dykes occur as high-pressure granulites or retrograded eclogites, and strong ductile deformation has later rotated these dykes into parallelism with the layering in the enclosing gneisses and caused boudinage (Kröner *et al.* 2005*a*, 2006). In all of these cases the amphibolitic or granulitic layers and boudins are part of original gabbroic/diabase dykes that indicate an extensional event. In the Hengshan Complex, igneous zircons from two pre-tectonic mafic dykes (high-pressure granulites) yielded SHRIMP $^{207}Pb/^{206}Pb$ ages of 1915 ± 4 Ma and 1914 ± 2 Ma (Kröner *et al.* 2006), indicating that emplacement of the dykes occurred shortly before a major collisional (tectono-thermal) event at *c.* 1850 Ma (see Section 4.h). The deformed and metamorphosed mafic dykes are also found in the Wutai Complex, and one amphibolite facies mafic dyke yielded a SHRIMP $^{207}Pb/^{206}Pb$ age of 2147 ± 5 Ma (P. Peng, unpub. Ph.D. thesis, Chinese Acad. Sciences, Beijing, 2005; Table 1). These mafic dykes were most probably emplaced in back-arc or intra-arc basin environments.

4.g. 2100–1860 Ma: deposition of the late Palaeoproterozoic Hutuo Group and Wanzi supracrustal assemblage

The Hutuo Group is considered to be the youngest unit in the Hengshan–Wutai–Fuping belt and unconformably overlies both the Wutai and Fuping complexes (Tian, 1991). However, at several localities, the Hutuo rocks are tectonically interleaved with the Wutai 'Group', and at some localities the Hutuo Group shows the same deformational and metamorphic patterns as the Upper Wutai 'Subgroup'. This implies that deposition of the Hutuo Group rocks places a maximum age on the timing of the major deformational event in the Hengshan–Wutai–Fuping belt. A felsic tuffaceous rock collected from a metamorphosed sequence of volcanic rocks and sediments of the Hutuo Group contains two zircon populations with SHRIMP $^{207}Pb/^{206}Pb$ ages of 2180 ± 5 and 2087 ± 9 Ma, respectively (Wilde *et al.* 2004*b*). The older age is within error of the age of the Dawaliang granite in the Wutai Complex and is considered to be derived from a similar crustal magmatic source. The younger age is within the error of reported ages for the Nanying granitic gneisses in the adjacent Fuping Complex and is interpreted to reflect the timing of Hutuo volcanism. The age of 2087 ± 9 Ma also means that the Hutuo rocks must have been deformed and metamorphosed after this time, which further supports the conclusion, obtained from other recent studies (Kröner *et al.* 2005*a*, 2006*)*, that the main tectonism in the Hengshan–Wutai–Fuping belt occurred in the Palaeoproterozoic era and not in the late Archaean era as previously considered (Tian, 1991).

The Wanzi supracrustal assemblage in the Fuping Complex was previously considered to have been deposited between 2800 and 2560 Ma, constrained by conventional multigrain U–Pb zircon ages (Liu *et al.* 1985). However, recent SHRIMP data do not support this conclusion. Zhao *et al.* (2002*b*) obtained SHRIMP $^{207}Pb/^{206}Pb$ zircon ages of 2502 ± 7 Ma and 2507 ± 14 Ma from two Al-rich gneiss samples of the Wanzi supracrustal assemblage, interpreted as the crystallization ages of the igneous protolith. These authors also obtained a concordant zircon age of 2109 ± 5 Ma from one Al-rich gneiss sample, which suggests that the protoliths of the Wanzi assemblage must have been deposited after *c.* 2109 Ma. This conclusion is supported by Guan *et al.* (2002), who obtained a SHRIMP zircon age of 2097 ± 46 Ma from a fine-grained paragneiss of the Wanzi assemblage. Most recently, Xia *et al.* (2006*c*) applied the LA-ICP-MS technique to date the Wanzi supracrustal rocks and obtained three upper concordia intercept ages of 2099 ± 22 Ma, 2110 ± 30 Ma and 2112 ± 23 Ma for igneous zircon cores separated from a sillimanite paragneiss (Table 1). They also obtained metamorphic ages of 1863–1822 Ma for zircon rims that formed due to overgrowth or recrystallization. These data establish that (1) deposition of the Wanzi supracrustal assemblage occurred at some time between 2100 and 1860 Ma, and (2) that sedimentation of the Wanzi assemblage in the Fuping Complex was largely coeval with volcanism in the Hutuo Group of the Wutai Complex.

4.h. 1880–1820 Ma: Late Palaeoproterozoic continent–continent collision

In the Chinese literature, the high-grade Hengshan and Fuping complexes and the low-grade Wutai Complex have long been considered to be the products of two different tectono-metamorphic events, called the Fuping (*c.* 2.5 Ga) and Wutai (2.4–2.3 Ga) 'movements', respectively (Bai, 1986; Wu *et al.* 1989; Tian, 1991; Bai, Wang & Guo, 1992; Bai & Dai, 1998). This conclusion was based on a few 'unconformities', conventional multigrain zircon geochronology, and the common misconception that high-grade metamorphic rocks were older than low-grade ones. However, new geochronological data do not verify either the Fuping or Wutai 'movement'. In the Hengshan and Fuping complexes, SHRIMP U–Pb zircon studies combined with cathodoluminescence imaging and U–Th chemistry confirm the existence of metamorphic zircons in most lithologies (Guan *et al.* 2002; Zhao *et al.* 2002*b*; Kröner *et al.* 2005*a*,*b*, 2006). These zircons occur either as overgrowth rims surrounding older magmatic cores or as single, metamorphic grains, and are structureless, highly luminescent, multifaceted and very low in Th and U contents. These features make them distinctly different from the igneous zircons that are generally characterized by oscillatory zoning and comparatively high Th and U contents. Most metamorphic zircons from both Neoarchaean and Palaeoproterozoic rocks in the Fuping and Hengshan complexes yielded similar concordant ages in the range 1880 to 1820 Ma (Table 1), which are 700 Ma to 150 Ma younger than their igneous zircon cores. In the low- to medium-grade Wutai Complex, although metamorphic zircons have not yet been observed, a garnet-amphibole–whole rock Sm–Nd isochron age of 1851 ± 9 Ma was obtained for a garnet amphibolite collected from the Lower Wutai 'Subgroup' (Table 1; Wang *et al.* 2001). Most recently, Liu *et al.* (2004*b*, 2006) applied the electron probe microanalysis (EPMA) monazite dating technique to determination of metamorphic ages of the Wutai Complex. They obtained $ThO_2{*}/PbO$ ages of 1833 ± 8, 1822 ± 14 and 1846 ± 64 Ma for three monazite grains separated from a garnet–kyanite mica schist from the lower part (called the Jingangku Formation) of the 'Shizui Subgroup' (see Fig. 4). These data are consistent with the above mineral Sm–Nd isochron age of 1851 ± 9 Ma. Taken together, these results indicate that the main regional metamorphism of the Hengshan, Wutai and

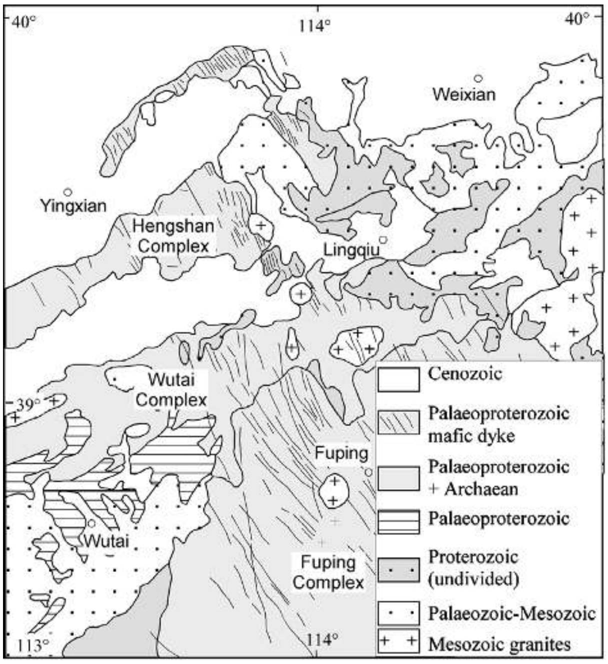

Figure 7. Spatial distribution of post-tectonic mafic dykes in the Hengshan–Wutai–Fuping belt (after Zhao *et al.* 2001*b*).

Fuping complexes occurred during the 1880–1820 Ma 'Lüliang Movement'. Based on these metamorphic ages, we conclude that this major tectonothermal event at *c.* 1.85 Ga is related to collision between the Eastern and Western blocks to form the North China Craton.

4.i. 1780–1750 Ma: emplacement of post-orogenic mafic dyke swarm

Late Palaeoproterozoic mafic dykes are widespread in the Hengshan–Wutai–Fuping belt, with a predominant NW–SE to NNW–SSE trend and, on a regional scale, constitute a dyke swarm (Fig. 7). Generally, they dip steeply, cutting both the Archaean and Palaeoproterozoic basement rocks and are covered by Mesoproterozoic and younger strata. Individual dykes range in width from 10 to 50 m to a maximum of about 100 m, and in length from 10 to 40 km, to a maximum of about 100 km. Most dykes are unmetamorphosed and undeformed, with chilled contacts. However, a few dykes were metamorphosed to upper amphibolite facies, indicated by garnet and amphibole reaction rims surrounding igneous plagioclase and clinopyroxene grains. Using the single-grain dissolution technique, Halls *et al.* (2000) obtained an upper concordia intercept zircon age of 1769.1 ± 2.5 Ma for an unmetamorphosed diabase dyke in the Hengshan Complex. Applying the same technique, Peng (P. Peng, unpub. Ph.D. thesis, Chinese Acad. Sciences, Beijing, 2005) obtained a similar upper intercept age of 1754 ± 71 Ma for an undeformed and unmetamorphosed mafic dyke in the Wutai Complex. The post-tectonic mafic dykes in the Fuping Complex have not been well dated, but Wang *et al.* (2004*a*) obtained whole-rock ^{40}Ar–^{39}Ar ages of 1765.3 ± 1.1 Ma, 1774.7 ± 0.7 Ma and 1780.7 ± 0.5 Ma for mafic dykes in the Zanhuang Complex, which is 50 km south of the Fuping Complex (Fig. 3), and the two together constitute the Taihang Mountain range. All of these data suggest that emplacement of undeformed and largely unmetamorphosed mafic dykes in the Hengshan–Wutai–Fuping belt occurred in the period 1780–1750 Ma. Controversy has surrounded the origin of these mafic dykes, with one school of thought believing that they were the products of a post-collisional extensional event (Zhao *et al.* 2001*b*), whereas others argued that they were produced from a mantle plume event that led to break-up of the hypothetical Palaeo-Mesoproterozoic supercontinent Columbia (Zhai, Bian & Zhao, 2000; P. Peng, unpub. Ph.D. thesis, Chinese Acad. Sciences, Beijing, 2005).

5. Discussion

Major lithotectonic assemblages and geological events in the Hengshan–Wutai–Fuping belt, as listed in Table 1, enable us to place rigorous constraints on a number of important geological issues regarding the Neoarchaean to Palaeoproterozoic evolution of this belt and the Trans-North China Orogen.

5.a. Relationships between the high-grade Hengshan and Fuping gneiss complexes and low-grade Wutai granite–greenstone terrane

Two contrasting tectonic models have previously been proposed for the evolution of the Hengshan, Fuping and Wutai complexes. One suggests that the first two developed as a single continental block that underwent Neoarchaean rifting associated with formation of the Wutai greenstones and closed upon itself in the Palaeoproterozoic era (Tian, 1991; Yuan & Zhang, 1993), while the other model proposes that the entire terrane is a Neoarchaean continent–arc–continent collision system, in which the Hengshan and Fuping complexes represent two exotic Archaean microcontinental blocks, and the Wutai granite–greenstone represents an intervening island arc (Bai, 1986; Li *et al.* 1990; Bai, Wang & Guo, 1992; Wang *et al.* 1996; Polat *et al.* 2005). Although these two models propose different tectonic settings and processes for the evolution of these complexes, they both assume that the Hengshan and Fuping gneisses are a crystalline basement to the Wutai granite–greenstone terrane. However, this assumption is not supported by the isotopic age data summarized above. As shown in Table 1, the Hengshan, Wutai and Fuping complexes are not remarkably different in age and all formed during Neoarchaean to Palaeoproterozoic times, although the Wutai granitoids are slightly older than major lithologies of the Hengshan and Fuping complexes. These three complexes seem to have experienced a common Neoarchaean to Palaeoproterozoic evolution, with the low- to medium-grade Wutai Complex representing an upper crustal calc-alkaline volcano-plutonic assemblage, probably generated above a subduction zone in a magmatic arc setting, whereas the Hengshan and Fuping complexes may be the lower crustal root zone of the arc. Thus, the tectonic evolution of the Hengshan–Wutai–Fuping belt may not be related to local interaction of the three complexes, either through closure of a Wutai rift (Tian, 1991; Yuan & Zhang, 1993) or collision between a Wutai arc and the putative Hengshan and Fuping microcontinental blocks (Bai, 1986; Bai, Wang & Guo, 1992; Li *et al.* 1990; Wang *et al.* 1996; Polat *et al.* 2005). Instead, we suggest that the three complexes represent elements of a single Neoarchaean to Palaeoproterozoic, long-lived magmatic arc that was subsequently incorporated into the Trans-North China Orogen during collision between the Eastern and Western blocks at around 1.85 Ga (Zhao *et al.* 2000*b*, 2001*b*, 2002*a*; Wilde, Zhao & Sun, 2002).

5.b. Nature of the Hengshan–Wutai–Fuping magmatic arc

Available geochemical data for rocks of the Hengshan, Fuping and Wutai complexes support an arc derivation (Geng & Wu, 1990; Li *et al.* 1990; Bai, Wang & Guo, 1992; Sun, Armstrong & Lambert, 1992; Wang *et al.* 1996; Liu *et al.* 2002*b*, 2004*a*,*b*, 2005; Wang *et al.* 2004*b*; Kröner *et al.* 2005*a*,*b*), with minor ultramafic to mafic rocks in the Lower Wutai that have been interpreted as remnants of ancient oceanic crust (Bai, Wang & Guo, 1992; Wang *et al.* 1996). Bai, Wang & Guo (1992) showed that the majority of amphibolites from the Lower Wutai and greenschists from the Middle Wutai have an affinity to calc-alkaline basalts or arc tholeiites (Fig. 5b). Wang *et al.* (2004*b*) also showed that the majority of amphibolites and greenschists in the Wutai 'Group' were derived from island arc-type basalts, though minor amounts have an affinity to MORB-type and back-arc basin basalts (Fig. 5c). Based on major and trace element features and Nd isotopes, Kröner *et al.* (2005*a*,*b*) showed that the Hengshan and Fuping TTG gneisses are characterized by a wide range in SiO_2 content, high Na_2O, Ba, Sr and low Y and HREE, and their selective enrichment in LIL elements and depletion in Nb, Ta and Ti can be derived from magmatic precursors with a strong mantle signature, modified by a subduction component and variable contributions from older crust. A particularly diagnostic discriminant for the tectonic setting is the Rb–Hf–Ta triangular plot for felsic to intermediate magmatic rocks, in which arc-derived assemblages occupy a field distinct from those generated in within-plate and ocean floor settings (Harris, Pearce & Tindle, 1986), though this diagram is useful only when Rb has not been mobilized. Figure 5a shows such a plot for the Hengshan TTG gneisses (Kröner *et al.* 2005*a*,*b*; Liu *et al.* 2004*a*), Wutai volcanic and granitoid rocks (Wang *et al.* 2004*b*; Liu *et al.* 2004*b*) and Fuping TTG gneisses (Liu *et al.* 2004*a*), clearly supporting their arc derivation. However, controversy still remains as to the nature of this magmatic arc. In most previous models, the Wutai Complex was considered to have formed in a Mariana-type arc system that was initiated by intra-oceanic subduction (Li *et al.* 1990; Bai, Wang & Guo, 1992; Wang *et al.* 1996). Based on the presence of minor MORB-type basalts and adakite-featured felsic volcanic rocks in the 'Wutai Group', Wang *et al.* (2004*b*) also preferred an intra-oceanic subduction process for the formation of the 2.6–2.5 Ga Wutai granite–greenstone terrane. However, the Mariana-type arc model is not supported by recent age data, which reveal the widespread existence of remnants of 2.66–2.82 Ga old continental crust in the Hengshan, Wutai and Fuping complexes. This is indicated by *c.* 2.7 Ga medium-grained grey biotite or hornblende gneisses that occur interlayered with the younger Hengshan and Fuping TTG gneisses (Guan *et al.* 2002; Kröner *et al.* 2005*b*), 2.67–2.76 Ga xenocrystic zircons from the Wutai and Longquanguan granitoid gneisses (Wilde, Cawood & Wang, 1997; Wilde *et al.* 2004*a*; Wilde, 2002), and 2.68–2.82 Ga detrital zircons from the Wanzi supracrustal rocks (Zhao *et al.* 2002*b*). More importantly, Wilde *et al.* (2004*a*) found a group of 2679 ± 16 Ma old xenocrystic zircons in a 2529 ± 10 Ma meta-andesite from the Zhuangwang 'Formation' that is considered part of the Shizui 'Subgroup'. These data suggest that the Hengshan–Wutai–Fuping belt was not an intra-oceanic arc but seems to have developed on a continental margin. The available data do not allow us to determine further whether it was a Japan-type island arc or an Andean-type continental margin magmatic arc. Although minor MORB-type basalts have been reported from the Wutai Complex (Wang *et al.* 2004*b*), it remains uncertain whether these erupted in a back-arc basin or a marginal basin environment.

5.c. Trans-North China Orogen: a long-lived (*c.* 700 Ma) accretionary magmatic arc?

As shown in Table 1, much of the juvenile crust of the Hengshan–Wutai–Fuping belt was accreted in the period 2560–2480 Ma, though a number of magmatic accretionary events occurred during Palaeoproterozoic times. However, more than 90 % of juvenile crust in other complexes (e.g. the Lüliang, Zhongtiao, Northern Hebei complexes; Fig. 3) in the Trans-North China Orogen was added in the period 2300–1900 Ma (Sun *et al.* 1993; Sun, 1997; Yu, Wang & Wang, 1997; Geng *et al.* 2000; Tian *et al.* 2005). This suggests that the Trans-North China Orogen records magmatic–tectonic evolution lasting for nearly 650 Ma. This is in contrast to most Phanerozoic collision belts where pre-orogenic sedimentation and magmatism are followed, within tens of millions of years, by orogenic deformation and metamorphism. The long-lived nature of the Trans-North China Orogen has been regarded as a major argument against the 1.85 Ga collision model, since few convergent continental-margin arcs in the world sat undisturbed for *c.* 700 Ma before being deformed and metamorphosed during accretionary and collisional events (Kusky & Li, 2003). However, such long-lived arcs have been documented or inferred in many other orogenic belts (Rivers & Corrigan, 2000), as summarized below. Kröner, Klemd & Zhao (2006) discussed the evolution of two such long-lived continental collisional belts, the Central Zone of the Limpopo belt in southern Africa and the Hengshan Complex of the Trans-North China Orogen, both of which consist predominantly of Archaean granitoid gneisses and minor shallow-water sediments with minor additions of early Palaeoproterozoic granites, and which were subjected to intense deformation and metamorphism in the late Palaeoproterozoic era, 500–700 Ma after their generation in arc-related settings. As pointed out by Kröner, Klemd & Zhao (2006), in both cases continental collision has been inferred, but there is no record of pre-collisional continental margin evolution and ocean closure; instead both terranes show evidence of having been generated in magmatic arc environments. These authors suggested that these terranes were rifted off from unknown Archaean active continental margins during Palaeoproterozoic times, similar to present-day Japan, and were then displaced before becoming attached, through terrane collision, to different Archaean blocks with which they share no common history.

Similar Palaeo-Mesoproterozoic long-lived magmatic arcs have also been found in southeastern Laurentia, southern Baltica, central Australia and western Amazonia (Karlstrom *et al.* 2001; Bingen *et al.* 2002; Brewer *et al.* 2002). In southeastern Laurentia and southern Baltica, a 1.8 to 1.3 Ga magmatic arc zone extends from Arizona through Colorado, Michigan, southern Greenland, Scotland, Sweden and Finland to western Russia, bordering the present southern margin of North America, Greenland and Baltica (Gower, Ryan & Rivers, 1990; Karlstrom *et al.* 2001). Petrological and geochemical studies indicate that this large magmatic arc zone includes dominantly juvenile volcanogenic sequences and granitoid suites resembling those of present-day island arcs and active continental margins (Nelson & DePaolo, 1985; Bennet & DePaolo, 1987) and may represent subduction-related episodic outgrowth along the continental margin of a Palaeo-Mesoproterozoic supercontinent (Karlstrom *et al.* 2001; Zhao *et al.* 2002*a*, 2004).

The Central Asian Orogenic Belt and the Kunlun Orogens are good examples of Phanerozoic long-lived magmatic arcs (Enkin *et al.* 1992; Sengör, Natalin & Burtman, 1993; Heubeck, 2001; Windley *et al.* 2002, 2007; Xiao *et al.* 2003, 2004, 2005; Jahn *et al.* 2004). The Central Asian Orogenic Belt, also called the Altaids (Sengör, Natalin & Burtman, 1993), is situated between the Siberian and Sino-Korean-Tarim cratons, and encompasses an immense area (*c.* 1000 km wide and *c.* 7000 km long) from the Urals in the west, through Kazakhstan, NW China, Mongolia, NE China to the Okhotsk Sea in the Russian Far East (Jahn *et al.* 2004). Available data show that the Central Asian Orogenic Belt was the world's largest site of Phanerozoic juvenile crust that developed from early Palaeozoic to early Mesozoic times (Sengör, Natalin & Burtman, 1993; Windley *et al.* 2002, 2007; Xiao *et al.* 2003, 2004; Jahn *et al.* 2004). A present-day example of long-lived magmatic arcs is the Andes, where the Pacific plate has been subducting under the west coast of South America for *c.* 500 million years since the Cambrian (Howell, 1995; Dalziel, 1997; Rivers & Corrigan, 2000). The Japanese arc has also existed since the Early Permian (Howell, 1995). These examples demonstrate that such long-lived arc magmatism is not unique, though the mechanism maintaining such long-lived arc magmatism remains enigmatic. Rivers & Corrigan (2000) argued that long-lived magmatic arcs are generally large geological features and may have faced a major open ocean, like the present-day Andes and Japanese arcs. This is consistent with our present model for the Trans-North China Orogen inferring a major ocean between the Eastern and Western blocks from before 2.55 Ga until its final closure at 1.85 Ga.

5.d. Palaeoproterozoic magmatic events and their regional significance

Most of the crust in the Hengshan–Wutai–Fuping belt was formed during Neoarchaean times, including the 2560–2520 Ma Wutai and Longquanguan granitoids, 2530–2515 Ma Wutai greenstone-type volcanics, and 2520–2480 Ma Hengshan, Yixingzhai and Fuping grey TTG gneisses (Table 1). These lithologies occupy more than 70 % of the total exposure of the Hengshan–Wutai–Fuping belt (Fig. 4). As discussed above, all these rocks have affinities to modern magmatic arcs and are considered to have formed in a long-lived Japan-type or Andes-type arc.

In the Chinese literature, all lithologies in the Hengshan–Wutai–Fuping belt, except for the Hutuo Group, were considered to be Archaean in age (Bai, 1986; Tian, 1991; Bai, Wang & Guo, 1992). However, the zircon ages summarized above and in Table 1 reveal the widespread presence of Palaeoproterozoic granitoids in the Hengshan, Wutai and Fuping complexes. The presence of these ductilely deformed Palaeoproterozoic granitoid gneisses in the Hengshan and Fuping complexes indicates that the major deformation in these complexes is not Archaean but Palaeoproterozoic in age. This is inconsistent with the models of Kusky & Li (2003) and Polat *et al.* (2005), which suggested that the collisional event leading to major deformation in these complexes occurred at *c.* 2.5 Ga.

Another important Palaeoproterozoic igneous event revealed by isotopic studies is the emplacement of pre-tectonic mafic dykes which were boudinaged and transformed to high- to medium-pressure mafic granulites in the Hengshan and Fuping complexes and garnet-bearing amphibolites in the Wutai Complex. The precursors of these mafic granulites have been considered to be Archaean in age because Tian *et al.* (1992) obtained a controversial Sm–Nd whole-rock isochron age of 2818 ± 86 Ma for these rocks from the Hengshan Complex. However, the new ages for igneous zircons from two metamorphosed mafic dykes in the Hengshan Complex (Table 1) undoubtedly indicate that they were emplaced in the Palaeoproterozoic era.

6. A tectonic scenario for the evolution of the Hengshan–Wutai–Fuping belt

On the basis of lithological, structural, metamorphic, geochemical and geochronological data summarized in this paper, we propose the following scenario for the evolution of the Hengshan–Wutai–Fuping belt, as shown in Figure 8.

(1) During Neoarchaean times, the Hengshan–Wutai–Fuping region was part of an Andean-type arc along the western margin of the Eastern Block, which was separated from the Western Block by a major ocean, with subduction of the oceanic lithosphere beneath the western margin of the Eastern Block (Fig. 8a). At 2560–2520 Ma, the release of water from the down-going slab caused partial melting of the lower crust in the overriding plate, producing large volumes of granitoid magma that were emplaced into the upper levels of the crust to form the Wutai and Longquanguan granitoid rocks (Fig. 8a).

(2) At 2530–2515 Ma, subduction of oceanic lithosphere and further release of fluids caused partial melting in the overriding mantle wedge, leading to underplating of mafic magmas in the lower crust and widespread mafic to felsic volcanism, forming part of the Wutai greenstone assemblage (Fig. 8b). Extension driven by widespread mafic to felsic volcanism led to the development of a back-arc basin or marginal sea which divided the region into the Hengshan–Wutai island arc (Japan-type) and the Fuping relict arc. Minor MORB-type basalts and ultramafic rocks from the Wutai greenstone assemblage were formed in the back-arc basin or marginal sea (Fig. 8b).

(3) At 2520–2480 Ma, subduction beneath the Hengshan–Wutai island arc triggered partial melting of the lower crust to form large amounts of TTG magmas that crystallized into the Hengshan and Yixingzhai TTG suites (Fig. 8c). Meanwhile, eastward-directed subduction of oceanic lithosphere of the marginal sea led to reactivation of the Fuping relict arc, where the Fuping TTG suite was emplaced (Fig. 8c).

(4) In the Palaeoproterozoic era (2360–2000 Ma), several phases of granitoid magmatism occurred in both the Hengshan–Wutai island arc and the Fuping reactivated arc (Fig. 8d), represented by the 2360 Ma, *c.* 2250 Ma and 2000–2100 Ma granitoid gneisses in the Hengshan Complex (Kröner *et al.* 2005*a*,*b*), *c.* 2100 Ma Wangjiahui and Dawaliang granites in the Wutai Complex (Wilde *et al.* 2005), and 2100–2000 Ma Nanying granitoid gneisses in the Fuping Complex (Zhao *et al.* 2002*b*; Guan *et al.* 2002; Liu *et al.* 2002*b*, 2005).

(5) At *c.* 1920 Ma, the Hengshan–Wutai island arc underwent an extensional event, possibly due to subduction of a mid-ocean ridge, leading to the emplacement of a major mafic dyke swarm (Fig. 8e). These dykes were subsequently metamorphosed to medium- to high-pressure granulites or retrograded eclogites in the Hengshan Complex and some amphibolites in the Wutai Complex.

(6) At 1880–1820 Ma, closure of the ocean between the Eastern and Western blocks led to continent–arc–continent collision (Fig. 8f). This collision induced large-scale thrusting, tectonic imbrication and isoclinal folding (Fig. 8f) and transported part of the Hengshan and Fuping lithologies into deep crustal levels where granulite and eclogite facies metamorphism occurred, whereas the Wutai Complex underwent greenschist- to lower amphibolite-facies metamorphism at higher crustal levels. Following peak metamorphism, the thickened crust underwent exhumation and near-isothermal decompression, forming widespread symplectic textures in the rocks. Further exhumation and inflow of fluids along ductile extensional shear zones led to cooling and retrogression, exemplified by widespread migmatization and *in situ* melting in the granitoid gneisses.

(7) The last magmatic event in the Hengshan–Wutai–Fuping belt was the emplacement of a 1780–1750 Ma mafic dyke swarm, probably as a result of orogenic collapse or post-orogenic extension.

Other metamorphic complexes in the Trans-North China Orogen document a Neoarchaean to Palaeoproterozoic history essentially similar to that of the Hengshan–Wutai–Fuping belt. For example, the Huai'an, Xuanhua, Chengde and Taihua complexes (Fig. 3) can be compared to the Hengshan or

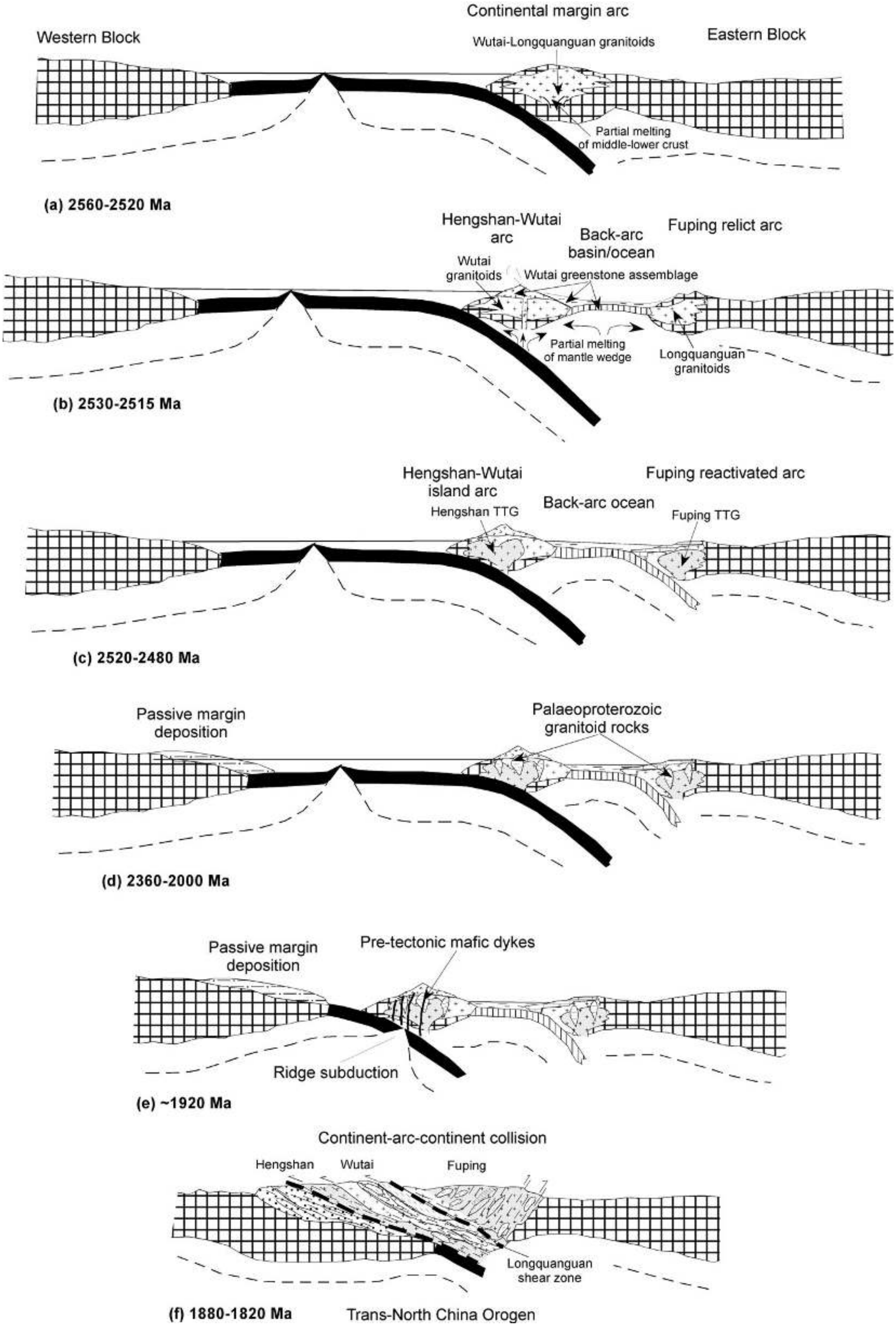

Figure 8. Schematic and speculative sections showing proposed geological evolution of the Hengshan–Wutai–Fuping belt and amalgamation of the North China Craton.

Fuping complexes, whereas the Zhongtiao, Dengfeng, Zanhuang and Northern Hebei complexes (Fig. 3) are similar to the Wutai Complex (Zhao *et al.* 2000*a*). Therefore, the magmatic, structural and metamorphic history of the Hengshan–Wutai–Fuping belt as summarized in this paper provides important insights for understanding the tectonic evolution of the Trans-North China Orogen.

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References

BAI, J. 1986. The Precambrian crustal evolution of the Wutaishan area. In *The Early Precambrian Geology of Wutaishan* (ed. J. Bai), pp. 376–83. Tianjing: Tianjin Science and Technology Press.

BAI, J. & DAI, F. Y. 1998. Archaean crust of China. In *Precambrian Crust Evolution of China* (eds X. Y. Ma & J. Bai), pp. 15–86. Beijing: Springer–Geological Publishing House.

BAI, J., WANG, R. Z. & GUO, J. J. 1992. *The Major Geologic Events of Early Precambrian and Their Dating in Wutaishan Region*. Beijing: Geological Publishing House (in Chinese), pp. 34–55.

BENNET, V. C. & DEPAOLO, D. J. 1987. Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping. *Geological Society of America Bulletin* **99**, 674–85.

BINGEN, B., MANSFELD, J., SIGMOND, E. M. O. & STEIN, H. 2002. Baltica–Laurentia link during the Mesoproterozoic: 1.27 Ga development of continental basins in the Sveconorwegian Orogen, southern Norway. *Canadian Journal of Earth Sciences* **39**, 1425–40.

BREWER, T. S., AHALL, K. I., DARBYSHIRE, D. P. F. & MENUGE, J. F. 2002. Geochemistry of late Mesoproterozoic volcanism in southwestern Scandinavia: implications for Sveconorwegian–Grenvillian plate tectonic models. *Journal of the Geological Society, London* **159**, 129–44.

CONDIE, K. C. 1994. Greenstones through time. In *Archean Crustal Evolution* (ed. K. C. Condie), pp. 85–120. Amsterdam: Elsevier.

CONDIE, K. C. 1997. Sources of Proterozoic mafic dyke swarms: Constraints from Th/Ta and La/Yb ratios. *Precambrian Research* **81**, 3–14.

CONDIE, K. C. 2005. High field strength element ratios in Archean basalts: a window to evolving sources of mantle plumes? *Lithos* **79**, 491–504.

DALZIEL, I. W. D. 1997. Neoproterozoic–Paleozoic geography and tectonics: review, hypothesis, environmental speculation. *Geological Society of America Bulletin* **108**, 16–42.

DU, W. W., WANG, R. M. & WANG, G. Y. 1999. Some clues to the presence of palaeo-ophiolites in the eastern part of the Dandong–Kuandian areas. *Journal of Peking University (Natural Science)* **35**, 254–8.

ENKIN, R. J., YANG, Z., CHEN, Y. & COURTILLOT, V. 1992. Paleomagnetic constraints on the geodynamic history of the major blocks of China from Permian to the present. *Journal of Geophysical Research* **97B**, 13953–89.

GE, W. C., ZHAO, G. C., SUN, D. Y., WU, F. Y. & LIN, Q. 2003. Metamorphic *P–T* path of the Southern Jilin complex: Implications for tectonic evolution of the Eastern block of the North China craton. *International Geology Review* **45**, 1029–43.

GENG, Y. S., WAN, Y. S., SHEN, Q. H., LI, H. M. & ZHANG, R. X. 2000. Chronological framework of the Early Precambrian important events in the Lüliang Area, Shanxi Province. *Acta Geologica Sinica* (English edition) **74**, 216–23.

GENG, Y. S. & WU, J. S. 1990. Geochemistry and evolution of the early Precambrian mafic rocks in the Wutai–Taihangshan area. *Precambrian Geology* **4**, 167–74 (in Chinese).

GOWER, C. F., RYAN, A. B. & RIVERS, T. 1990. Mid-Proterozoic Laurentia-Baltica: An overview of its geological evolution and summary of the contributions by this volume. In *Mid-Proterozoic Laurentia–Baltica* (eds C. F. Gower, T. Rivers & B. Ryan), pp. 1–20. Geological Association of Canada, Special Paper no. 38.

GUAN, H., SUN, M., WILDE, S. A., ZHOU, X. H. & ZHAI, M. G. 2002. SHRIMP U–Pb zircon geochronology of the Fuping Complex: implications for formation and assembly of the North China craton. *Precambrian Research* **113**, 1–18.

GUO, J. H., O'BRIEN, P. J. & ZHAI, M. G. 2002. High-pressure granulites in the Sangan area, North China Craton: metamorphic evolution, *P–T* paths and geotectonic significance. *Journal of Metamorphic Geology* **20**, 741–56.

GUO, J. H., SHI, X., BIAN, A. G., XU, R. H., ZHAI, M. G. & LI, Y. G. 1999. Pb isotopic compositions of feldspar and U–Pb age of zircons from early Proterozoic granites in the Sanggan area, North China Craton: metamorphism, crustal melting and tectonothermal events. *Acta Petrologica Sinica* **15**, 199–207.

GUO, J. H., SUN, M. & ZHAI, M. G. 2005. Sm–Nd and SHRIMP U–Pb zircon geochronology of high-pressure granulites in the Sanggan area, North China Craton: Timing of Palaeoproterozoic continental collision. *Journal of Asian Earth Sciences* **24**, 629–42.

GUO, J. H., WANG, S. S., SANG, H. Q. & ZHAI, M. G. 2001. Ar40–Ar39 age spectra of garnet porphyroblast: Implications for metamorphic age of high-pressure granulite in the North China Craton. *Acta Petrologica Sinica* **17**, 436–42.

GUO, J. H. & ZHAI, M. G. 2001. Sm–Nd age dating of high-pressure granulites and amphibolites from Sanggan area, North China Craton. *Chinese Science Bulletin* **46**, 106–11.

HALLS, H. C., LI, J. H., DAVIS, D., HOU, G., ZHANG, B. X. & QIAN, X. L. 2000. A precisely dated Proterozoic palaeomagnetic pole from the North China craton, and its relevance to palaeocontinental reconstruction. *Geophysical Journal International* **143**, 185–203.

HAO, D. F., LI, S. Z., ZHAO, G. C., SUN, M., HAN, Z. Z. & ZHAO, G. T. 2004. Origin and its constraint to tectonic evolution of Palaeoproterozoic granitoids in the eastern Liaoning and Jilin province, North China. *Acta Petrologica Sinica* **20**, 1409–16.

HARRIS, N. B. W., PEARCE, J. A. & TINDLE, A. G. 1986. Geochemical characteristics of collision-zone magmatism. In *Collision tectonics* (eds M. P. Coward & A. C. Ries), pp. 67–81. Geological Society of London, Special Publication no. 19.

HEUBECK, C. 2001. Assembly of central Asia during the middle and late Paleozoic. In Paleozoic and Mesozoic tectonic evolution of central and eastern Asia (eds M. S. Hendrix & G. A. Davis), pp. 1–22. Geological Society of America, Memoir no. 192.

HOWELL, D. G. 1995. *Principles of terrane analysis: new applications for global tectonics*. 2nd ed. London: Chapman and Hall.

JAHN, B. M., AUVRAY, B., CORNICHET, J., BAI, Y. D., SHEN, Q. H. & LIU, D. Y. 1987. 3.5 Ga old amphibolites from eastern Hebei Province, China: field occurrence, petrography, Sm–Nd isochron age and REE geochemistry. *Precambrian Research* **34**, 311–46.

JAHN, B. M., AUVRAY, B., SHEN, Q. H., LIU, D. Y., ZHANG, Z. Q., DONG, Y. J., YE, X. J., ZHANG, Q. Z., CORNICHET, J. & MACE, J. 1988. Archaean crustal evolution in China: the Taishan Complex and evidence for Juvenile crustal addition from long-term depleted mantle. *Precambrian Research* **38**, 381–403.

JAHN, B. M. & ERNST, W. G. 1990. Neoarchaean Sm–Nd Isochron Age for Mafic–Ultramafic Supracrustal Amphibolites from the Northeastern Sino-Korean Craton, China. *Precambrian Research* **46**, 295–306.

JAHN, B. M., WINDLEY, B., NATAL'IN, B. & DOBRETSOV, N. 2004. Phanerozoic continental growth in central Asia – Preface. *Journal of Asian Earth Sciences* **23**, 599–603.

JAHN, B. M. & ZHANG, Z. Q. 1984. Archaean granulite gneisses from eastern Hebei Province, China: rare earth geochemistry and tectonic implications. *Contributions to Mineralogy and Petrology* **85**, 224–43.

KARLSTROM, K. E., HARLAN, S. S., ÅHÄLL, K. I., WILLIAMS, M. L., MCLELLAND, J. & GEISSMAN, J. W. 2001. Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia. *Precambrian Research* **111**, 5–30.

KRÖNER, A. 2002. Zircon ages of the Hengshan Complex. In *A Neoarchaean to Palaeoproterozoic Lower to Upper Crustal Section in the Hengshan–Wutaishan Area of North China* (eds A. Kröner, G. C. Zhao, S. A. Wilde, M. G. Zhai, C. W. Passchier, M. Sun, J. H. Guo, P. J. O'Brien & N. Walte), pp. 28–32. Guidebook for Penrose Conference Field Trip, September 2002. Beijing: Chinese Academy of Sciences.

KRÖNER, A., COMPSTON, W., ZHANG, G. W., GUO, A. L. & TODT, W. 1988. Ages and tectonic setting of Neoarchaean greenstone–gneiss terrain in Henan Province, China, as revealed by single-grain zircon dating. *Geology* **16**, 211–15.

KRÖNER, A., CUI, W. Y., WANG, W. Y., WANG, C. Q. & NEMCHIN, A. A. 1998. Single zircon ages from high-grade rocks of the Jianping Complex, Liaoning Province, NE China. *Journal of Asian Earth Sciences* **16**, 519–32.

KRÖNER, A., KLEMD, R. & ZHAO, G. C. 2006. Rates of orogenic processes in two unusual Palaeoproterozoic high-grade terrains of southern Africa and northern China, EUG, Vienna. *Geophysical Research Abstract* **8**, 2796–7.

KRÖNER, A., WILDE, S. A., LI, J. H. & WANG, K. Y. 2005*a*. Age and evolution of a Neoarchaean to early Palaeozoic upper to lower crustal section in the Wutaishan/Hengshan/Fuping terrain of northern China. *Journal of Asian Earth Sciences* **24**, 577–95.

KRÖNER, A., WILDE, S., O'BRIEN, P. J. & LI, J. H. 2001. The Hengshan and Wutai complexes of northern China: lower and upper crustal domains of a Neoarchaean to Palaeoproterozoic magmatic arc and significance for the evolution of the North China Craton. In *4th International Archaean Symposium 2001, Extended Abstracts* (ed. K. F. Cassidy), p. 327. AGSO, Geoscience Australia, Record 37.

KRÖNER, A., WILDE, S. A., O'BRIEN, P. J., LI, J. H., PASSCHIER, C. W., WALTE, N. P. & LIU, D. Y. 2005*b*. Field relationships, geochemistry, zircon ages and evolution of a Neoarchaean to Palaeoproterozoic lower crustal section in the Hengshan Terrain of Northern China. *Acta Geologica Sinica* **79**, 605–29.

KRÖNER, A., WILDE, S. A., ZHAO, G. C., O'BRIEN, P. J., SUN, M., LIU, D. Y., WAN, Y. S., LIU, S. W. & GUO, J. H. 2006. Zircon geochronology of mafic dykes in the Hengshan Complex of northern China: evidence for late Palaeoproterozoic rifting and subsequent high-pressure event in the North China Craton. *Precambrian Research* **146**, 45–67.

KUSKY, T. M. & LI, J. H. 2003. Palaeoproterozoic tectonic evolution of the North China Craton. *Journal of Asian Earth Sciences* **22**, 383–97.

LI, J. H. & QIAN, Q. L. 1991. A study on the Longquanguan shear zone in the northern part of the Taihang Mountains. *Shanxi Geology* **6**, 17–29 (in Chinese).

LI, J. H. & QIAN, X. L. 1994. *Early Precambrian crustal Evolution of the Hengshan Metmaorphic Terrain, North China Craton*. Tianyuan: Shanxi Science and Technology Press.

LI, J. L., WANG, K. Y., WANG, C. Q., LIU, X. H. & ZHAO, Z. Y. 1990. An Early Proterozoic collision belt in the Wutaishan area, China. *Scientia Geologica Sinica* **25**, 1–11 (in Chinese).

LI, S. Z., HAN, Z. Z., LIU, Y. J. & YANG, Z. S. 2001*a*. Geological and geochemical constraints on Palaeoproterozoic pre-Orogenic deep processes in the Jiao-Liao Block. *Scientia Geologica Sinica* **36**, 184–94 (in Chinese).

LI, S. Z., HAN, Z. Z., LIU, Y. J., YANG, Z. S. & MA, R. 2001*b*. Regional metamorphism of the Liaohe Group: implications for continental dynamics. *Geological Review* **47**, 9–18 (in Chinese).

LI, S. Z., HAO, D. F., ZHAO, G. C., SUN, M., HAN, Z. Z. & GUO, X. Y. 2004*a*. Geochemical features and origin of Dandong granite. *Acta Petrologica Sinica* **20**, 1417–23.

LI, S. Z., ZHAO, G. C., SUN, M., WU, F. Y., HAO, D. F., HAN, Z. Z., LUO, Y. & XIA, X. P. 2005. Deformational history of the Palaeoproterozoic Liaohe Group in the Eastern Block of the North China Craton. *Journal of Asian Earth Sciences* **24**, 654–69.

LI, S. Z., ZHAO, G. C., SUN, M., WU, F. Y., LIU, J. Z., HAO, D. F., HAN, Z. Z. & LUO, Y. 2004*b*. Mesozoic, not Palaeoproterozoic SHRIMP U–Pb zircon ages of two Liaoji granites, Eastern Block, North China Craton. *International Geology Review* **46**, 162–76.

LIU, D. Y., PAGE, R. W., COMPSTON, W. & WU, J. S. 1985. U–Pb zircon geochronology of Neoarchaean metamorphic rocks in the Taihangshan–Wutaishan area, North China. *Precambrian Research* **27**, 85–109.

LIU, S. W., LI, J. H., PAN, Y. M., ZHANG, J. & LI, Q. G. 2002*a*. An Archaean continental block in the Taihangshan and Hengshan regions: Constraints from geochronology and geochemistry. *Progress in Natural Science* **12**, 568–76.

LIU, S. W., LIANG, H. H., ZHAO, G. C., HUA, Y. G. & JIAN, A. H. 2000. Isotopic chronology and geological events of Precambrian complex in the Taihangshan region. *Science in China (Series D)* **43**, 386–93.

LIU, S. W., PAN, P. M., LI, J. H., LI, Q. G. & ZHANG, J. 2002*b*. Geological and isotopic geochemical constraints on the evolution of the Fuping Complex, North China Craton. *Precambrian Research* **117**, 41–56.

LIU, S. W., PAN, Y. M., XIE, Q. L., ZHANG, J. & LI, Q. G. 2004*a*. Archaean geodynamics in the Central Zone, North China Craton: Constraints from geochemistry of two contrasting series of granitoids in the Fuping and Wutai Complexes. *Precambrian Research* **130**, 229–49.

LIU, S. W., PAN, Y. M., XIE, Q. L., ZHANG, J. & LI, Q. G. 2005. Geochemistry of the Palaeoproterozoic Nanying Granitoid Gneisses: constraints on the tectonic setting of the Central Zone, North China Craton. *Journal of Asian Earth Sciences* **24**, 643–58.

LIU, S. W., SHEN, Q. H. & GENG, Y. S. 1996. Metamorphic evolution of two types of garnetiferous granulites from the northwestern Hebei Province and P–T estimation by the Gibbis method. *Acta Petrologica Sinica* **12**, 261–75.

LIU, S. W., SHU, G. M., PAN, Y. M. & DANG, Q. N. 2004*b*. Electronic microprobe dating and metamorphic age of Wutai Group, Wutai Mountains. *Geological Journal of Chinese Universities* **10**, 356–63 (in Chinese with English abstract).

LIU, S. W., ZHAO, G. C., WILDE, S. A., SHU, G. M., SUN, M., LI, Q. G., TIAN, W. & ZHANG, J. 2006. Th–U–Pb monazite geochronology of the Lüliang and Wutai Complexes: constraints on the tectonothermal evolution of the Trans-North China Orogen. *Precambrian Research* **148**, 205–25.

LU, X. P., WU, F. Y., GUO, J. H., WILDE, S. A., YANG, J. H., LIU, X. M. & ZHANG, X. O. 2006. Zircon U–Pb geochronological constraints on the Palaeoproterozoic crustal evolution of the Eastern block in the North China Craton. *Precambrian Research* **146**, 138–64.

LUO, Y., SUN, M., ZHAO, G. C., LI, S. Z., XU, P., YE, K. & XIA, X. P. 2004. LA-ICP-MS U–Pb zircon ages of the Liaohe Group in the Eastern Block of the North China Craton: constraints on the evolution of the Jiao-Liao-Ji Belt. *Precambrian Research* **134**, 349–71.

NELSON, B. K. & DEPAOLO, D. J. 1985. Rapid production of continental crust 1.7–1.9 b.y. ago: Nd and Sr isotopic evidence from the basement of the North American mid-continent. *Geological Society of America Bulletin* **96**, 746–54.

O'BRIEN, P. J., WALTE, N. & LI, J. H. 2005. The petrology of two distinct granulite types in the Hengshan Mts, China, and tectonic implications. *Journal of Asian Earth Sciences* **24**, 615–27.

PASSCHIER, C. W. & WALTE, N. 2002. Deformation of the Hengshan Complex. In *A Neoarchaean to Palaeoproterozoic Lower to Upper Crustal Section in the Hengshan–Wutaishan Area of North China* (eds A. Kröner, G. C. Zhao, S. A. Wilde, M. G. Zhai, C. W. Passchier, M. Sun, J. H. Guo, P. J. O'Brien & N. Walte), pp. 11–13. Guidebook for Penrose Conference Field Trip, September 2002. Beijing: Chinese Academy of Sciences.

PEARCE, J. A. 1976. Statistical analysis of major element patterns in basalts. *Journal of Petrology* **17**, 15–43.

PENG, P., ZHAI, M. G., ZHANG, H. F. & GUO, J. H. 2005. Geochronological constraints on the Palaeoproterozoic evolution of the North China craton: SHRIMP zircon ages of different types of Mafic dikes. *International Geology Review* **47**, 492–508.

POLAT, A., HERZBERG, C., MUNKER, C., RODGERS, R., KUSKY, T. M., LI, J. H., FRYER, B. & DELANEY, J. 2006. Geochemical and petrological evidence for a supra-subduction zone origin of NeoArchaean (2.55–2.50 Ga) peridotites, central orogenic belt, North China Craton. *Geological Society of America Bulletin* **118**, 771–84.

POLAT, A., KUSKY, T. M., LI, J. H., FRYER, B., KERRICH, R. & PATRICK, K. 2005. Geochemistry of NeoArchaean (ca. 2.55–2.50 Ga) volcanic and ophiolitic rocks in the Wutaishan greenstone belt, central orogenic belt, North China craton: Implications for geodynamic setting and continental growth. *Geological Society of America Bulletin* **117**, 1387–99.

REN, J. S. 1980. *Tectonic evolution of China*. Beijing: Science Press.

RIVERS, T. & CORRIGAN, D. 2000. Convergent margin on southeastern Laurentia during the Mesoproterozoic: tectonic implications. *Canadian Journal of Earth Sciences* **37**, 359–83.

ŞENGÖR, A. M. C., NATAL'IN, B. A. & BURTMAN, V. S. 1993. Evolution of the Altaid tectonic collage and Paleozoic crustal growth in Eurasia. *Nature* **364**, 299–307.

SUN, D. Z. 1997. The Jiangxian Group. In *Paleoproterozoic Era* (ed. Committee of Lexicon of China Stratigraphy), pp. 28–9. Beijing: Geological Publishing House.

SUN, D. Z., HU, W. X., TANG, M. & ZHAO, F. Q. 1993. *The geochronological framework and crustal structures of Precambrian basement in the Zhongtiaoshan area*. Beijing: Geological Publishing House.

SUN, M., ARMSTRONG, R. L. & LAMBERT, R. ST. J. 1992. Petrochemistry and Sr, Pb and Nd isotopic geochemistry of Early Precambrian rocks, Wutaishan and Taihangshan areas, China. *Precambrian Research* **56**, 1–31.

TIAN, W., LIU, S. W., LIU, C. H., YU, S. Q., LI, Q. G. & WANG, Y. R. 2005. SHRIMP U–Pb zircon ages and geochemistry of the Sushui TTG gneisses in the Zhongtiao Complex and their geological significance. *Progress in Natural Science* **15**, 1476–84.

TIAN, Y. Q. 1991. *Geology and Mineralization of the Wutai–Hengshan Greenstone Belt*. Taiyuan: Shanxi Science and Technology Press.

TIAN, Y. Q., LIANG, Y. F., FAN, S. K., ZHU, B. Q. & CHEN, L. W. 1992. Geochronology and Nd isotopic geochemistry of the Hengshan Complex. *Geochemica Sinica* **3**, 255–63.

WAN, Y. S., WILDE, S. A., LIU, D. Y., YANG, C. X., SONG, B. & YIN, X. Y. 2006. Further evidence for ~1.85 Ga metamorphism in the central Zone of the north China Craton: SHRIMP U–Pb dating of zircons from metamorphic rocks in the Lushan area, Henan Province. *Gondwana Research* **9**, 189–97.

WANG, K. Y., LI, J. L., HAO, J., LI, J. H. & ZHOU, S. P. 1996. The Wutaishan mountain belt within the Shanxi Province, Northern China: a record of Neoarchaean collision tectonics. *Precambrian Research* **78**, 95–103.

WANG, K. Y., LI, J. L., HAO, J., LI, J. H. & ZHOU, S. P. 1997. Neoarchaean mafic–ultramafic rocks from the Wuatishan, Shanxi Province: a possible ophiolite melange. *Acta Petrologica Sinica* **13**, 139–51.

WANG, K. Y., LI, J. L. & LIU, L. Q. 1991. Petrogenesis of the Fuping grey gneisses. *Acta Geologica Scientia* **11**, 254–67.

WANG, K. Y., WANG, Z., YU, L., FAN, H., WILDE, S. A. & CAWOOD, P. A. 2001. Evolution of Archaean greenstone belt in the Wutaishan region, North China: constraints from SHRIMP zircon U–Pb and other geochronological and isotope information. In *4th International Archaean Symposium* 2001, *Extended Abstracts* (ed. K. F.

Cassidy), pp. 104–5. AGSO, Geoscience Australia, Record 37.

WANG, Y. J., FAN, W. M., ZHANG, Y. & GUO, F. 2003. Structural evolution and ^{40}Ar–^{39}Ar dating of the Zanhuang metamorphic domain in the North China Craton: constraints on Palaeoproterozoic tectonothermal overprinting. *Precambrian Research* **122**, 159–82.

WANG, Y. J., FAN, W. M., ZHANG, Y. H., GUO, F., ZHANG, H. & PENG, P. 2004*a*. Geochemical Ar–40/Ar–39 geochronological and Sr–Nd isotopic constraints on the origin of Palaeoproterozoic mafic dikes from the southern Taihang Mountains and implications for the ca. 1800 Ma event of the North China Craton. *Precambrian Research* **135**, 55–77.

WANG, Z. H., WILDE, S. A., WANG, K. Y. & YU, L. J. 2004*b*. A MORB-arc basalt–adakite association in the 2.5 Ga Wutai greenstone belt: Neoarchaean magmatism and crustal growth in the North China Craton. *Precambrian Research* **131**, 323–43.

WILDE, S. 2002. SHRIMP U–Pb zircon ages of the Wutai Complex. In *A Neoarchaean to Palaeoproterozoic Lower to Upper Crustal Section in the Hengshan–Wutaishan Area of North China* (eds A. Kröner, G. C. Zhao, S. A. Wilde, M. G. Zhai, C. W. Passchier, M. Sun, J. H. Guo, P. J. O'Brien & N. Walte). Guidebook for Penrose Conference Field Trip, September 2002, pp. 32–4. Beijing: Chinese Academy of Sciences.

WILDE, S. A., CAWOOD, P. & WANG, K. Y. 1997. The relationship and timing of granitoid evolution with respect to felsic volcanism in the Wutai Complex, North China Craton. Proceedings of the 30th IGC. *Precambrian Geology and Metamorphic Petrology* **17**, 75–88.

WILDE, S. A., CAWOOD, P. A. & WANG, K. Y. 1998. SHRIMP U–Pb data of granites and gneisses in the Taihangshan–Wutaishan area: Implications for the timing of crustal growth in the North China Craton. *Chinese Science Bulletin* **43**, 144.

WILDE, S. A., CAWOOD, P. A., WANG, K. Y. & NEMCHIN, A. A. 2005. Granitoid evolution in the Late Archaean Wutai Complex, North China Craton. *Journal of Asian Earth Sciences* **24**, 597–613.

WILDE, S. A., CAWOOD, P. A., WANG, K. Y., NEMCHIN, A. & ZHAO, G. C. 2004*a*. Determining Precambrian crustal evolution in China: a case-study from Wutaishan, Shanxi Province, demonstrating the application of precise SHRIMP U–Pb geochronology. In *Aspects of the Tectonic Evolution of China* (eds J. Malpas, C. J. N. Fletcher, J. R. Ali & J. C. Aitchison), pp. 5–26. Geological Society of London, Special Publication no. 226.

WILDE, S. A., ZHAO, G. C. & SUN, M. 2002. Development of the North China Craton during the Neoarchaean and its final amalgamation at 1.8 Ga; some speculations on its position within a global Palaeoproterozoic Supercontinent. *Gondwana Research* **5**, 85–94.

WILDE, S. A., ZHAO, G. C., WANG, K. Y. & SUN, M. 2004*b*. First precise SHRIMP U–Pb zircon ages for the Hutuo Group, Wutaishan: further evidence for the Palaeoproterozoic amalgamation of the North China Craton. *Chinese Science Bulletin* **49**, 83–90.

WINDLEY, B. F., ALEXEIEV, D., XIAO, W. J., KRÖNER, A. & BADARCH, G. 2007. Tectonic models for accretion of the Central Asian Orogenic Belt. *Journal of the Geological Society, London* **164**, 31–47.

WINDLEY, B. F., KRÖNER, A., GUO, J. H., QU, G. S., LI, Y. Y. & ZHANG, C. 2002. Neoproterozoic to Paleozoic geology of the Altai orogen, NW China: New zircon age data and tectonic evolution. *Journal of Geology* **110**, 719–37.

WU, C. H., LI, H. M., ZHONG, C. T. & ZHUO, Y. C. 2000. TIMS U–Pb single zircon ages for the orthogneisses and paragneisses of Fuping Complex. *Progress in Precambrian Research* **23**, 130–9.

WU, C. H. & ZHONG, C. T. 1998. The Palaeoproterozoic SW–NE collision model for the central North China Craton. *Progress in Precambrian Research* **21**, 28–50 (in Chinese).

WU, F. Y., ZHAO, G. C., WILDE, S. A. & SUN, D. Y. 2005. Nd isotopic constraints on crustal formation in the North China Craton. *Journal of Asian Earth Sciences* **24**, 524–46.

WU, J. S., GENG, Y. S., XU, H. F., JIN, L. G., HE, S. Y. & SUN, S. W. 1989. Metamorphic geology of the Fuping Group. *Tianjin Institute of Geology Bulletin* **19**, 1–213.

XIA, X. P., SUN, M., ZHAO, G. C. & LUO, Y. 2006*a*. LA-ICP-MS U–Pb geochronology of detrital zircons from the Jining Complex, North China Craton and its tectonic significance. *Precambrian Research* **144**, 199–212.

XIA, X. P., SUN, M., ZHAO, G. C., WU, F. Y., XU, P., ZHANG, J. H. & LUO, Y. 2006*b*. U–Pb and Hf isotopic study of detrital zircons from the Wulashan khondalites: Constraints on the evolution of the Ordos Terrane, Western Block of the North China Craton. *Earth and Planetary Science Letters* **241**, 581–93.

XIA, X. P., SUN, M., ZHAO, G. C., WU, F. Y., ZHANG, J., HE, Y. H., XU, P. & ZHANG, J. G. 2006*c*. U–Pb and Hf Isotope Study of Detrital Zircons from the Wanzi Supracrustals: constraints on the tectonic setting and evolution of the Fuping Complex, Trans-North China Orogen. *Acta Geologica Sinica* **80**, 844–63.

XIAO, W. J., WINDLEY, B. F., HAO, J. & ZHAI, M. G. 2003. Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: Termination of the central Asian orogenic belt. *Tectonics* **22**, 1069, doi: 10.1029/2002TC001484.

XIAO, W. J., WINDLEY, B. F., LIU, D. Y., JIAN, P., LIU, C. Z., YUAN, C. & SUN, M. 2005. Accretionary tectonics of the Western Kunlun Orogen, China: A Paleozoic–early Mesozoic, long-lived active continental margin with implications for the growth of southern Eurasia. *Journal of Geology* **113**, 687–705.

XIAO, W. J., ZHANG, L. C., QIN, K. Z., SUN, S. & LI, J. L. 2004. Paleozoic accretionary and collisional tectonics of the Eastern Tianshan (China): Implications for the continental growth of Central Asia. *American Journal of Science* **304**, 370–95.

YU, J. H., WANG, D. Z. & WANG, X. Y. 1997. Ages of the Lüliang Group and its main metamorphism in the Lüliang Mountains, Shanxi: evidence from single-grain zircon U–Pb ages. *Geological Review* **43**, 403–8.

YUAN, G. P. & ZHANG, R. Y. 1993. The structural environment of the paleo-rift in the Wutai greenstone belt. *Shanxi Geology* **8**, 21–8.

ZHAI, M. G., BIAN, A. G. & ZHAO, T. P. 2000. The amalgamation of the supercontinent of North China Craton at the end of Neo-Archaean and its breakup during late Palaeoproterozoic and Mesoproterozoic. *Science in China (Series D)* **43**, 219–32.

ZHAI, M. G., GUO, J. H. & YAN, Y. H. 1992. Discovery and preliminary study of the Archaean high-pressure

granulites in the North China. *Science in China* **12B**, 1325–30.
ZHANG, J. S., DIRKS, H. G. M. & PASSCHIER, C. W. 1994. Extensional collapse and uplift in a polymetamorphic granulite terrain in the Archaean and Palaeoproterozoic of North China. *Precambrian Research* **67**, 37–57.
ZHANG, J., ZHAO, G. C., SUN, M., WILDE, S. A., LI, S. Z. & LIU, S. W. 2006. High-pressure mafic granulites in the Trans-North China Orogen: Tectonic significance and age. *Gondwana Research* **9**, 349–62.
ZHAO, G. C. 2001. Palaeoproterozoic assembly of the North China Craton. *Geological Magazine* **138**, 87–91.
ZHAO, G. C., CAO, L., WILDE, S. A., SUN, M. & LI, S. Z. 2006. Implications based on the first SHRIMP U–Pb zircon dating on Precambrian granitoid rocks in North Korea. *Earth and Planetary Science Letters* **251**, 365–79.
ZHAO, G. C., CAWOOD, P. A. & LU, L. Z. 1999. Petrology and P–T history of the Wutai amphibolites: implications for tectonic evolution of the Wutai Complex, China. *Precambrian Research* **93**, 181–99.
ZHAO, G. C., CAWOOD, P. A., WILDE, S. A. & LU, L. Z. 2000*a*. Metamorphism of basement rocks in the Central Zone of the North China Craton: implications for Palaeoproterozoic tectonic evolution. *Precambrian Research* **103**, 55–88.
ZHAO, G. C., CAWOOD, P. A., WILDE, S. A. & LU, L. Z. 2001*a*. High-pressure granulites (retrograded eclogites) from the Hengshan Complex, North China Craton: Petrology and Tectonic implications. *Journal of Petrology* **42**, 1141–70.
ZHAO, G. C., CAWOOD, P. A., WILDE, S. A. & SUN, M. 2002*a*. Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. *Earth-Science Reviews* **59**, 125–62.
ZHAO, G. C., SUN, M., WILDE, S. A. & LI, S. Z. 2004. A Paleo-Mesoproterozoic supercontinent: Assembly, growth and breakup. *Earth-Science Reviews* **67**, 91–123.
ZHAO, G. C., SUN, M., WILDE, S. A. & LI, S. Z. 2005. Neoarchaean to Palaeoproterozoic evolution of the North China Craton: key issues revisited. *Precambrian Research* **136**, 177–202.
ZHAO, G. C., WILDE, S. A., CAWOOD, P. A. & LU, L. Z. 1998. Thermal evolution of the Archaean basement rocks from the eastern part of the North China Craton and its bearing on tectonic setting. *International Geology Review* **40**, 706–21.
ZHAO, G. C., WILDE, S. A., CAWOOD, P. A. & LU, L. Z. 1999. Tectonothermal history of the basement rocks in the western zone of the North China Craton and its tectonic implications. *Tectonophysics* **310**, 37–53.
ZHAO, G. C., WILDE, S. A., CAWOOD, P. A. & LU, L. Z. 2000*b*. Petrology and P–T path of the Fuping mafic granulites: Implications for tectonic evolution of the central zone of the North China Craton. *Journal of Metamorphic Geology* **18**, 375–91.
ZHAO, G. C., WILDE, S. A., CAWOOD, P. A. & SUN, M. 2001*b*. Archaean blocks and their boundaries in the North China Craton: lithological, geochemical, structural and P–T path constraints and tectonic evolution. *Precambrian Research* **107**, 45–73.
ZHAO, G. C., WILDE, S. A., CAWOOD, P. A. & SUN, M. 2002*b*. SHRIMP U–Pb zircon ages of the Fuping Complex: implications for accretion and assembly of the North China Craton. *American Journal of Science* **302**, 191–226.