Polyorogenic evolution of the Paleoproterozoic Trans-North China Belt

—New insights from the Lüliangshan-Hengshan-Wutaishan and Fuping massifs

The Trans-North China Belt (TNCB) is a Paleoproterozoic collisional orogen (ca. 1.9–1.8 Ga) responsible for the amalgamation of the North China Craton. Detailed field works in Lüliangshan, Hengshan, Wutaishan and Fuping massifs where the belt is well exposed, allow us to draw a new tectonic map and crustal-scale cross sections. The available petrologic, radiometric, geochronologic data are integrated in a geodynamic evolution scheme for this orogen. The Low Grade Mafic Unit (LGMU) is interpreted as an ophiolitic nappe rooted in a suture zone located in the western part of the Lüliangshan. This ophiolitic nappe overthrusts to the SE upon the Orthogneiss-Volcanites Unit (OVU) that consists of a bimodal volcanic-sedimentary series metamorphosed under amphibolite facies conditions intruded by calc-alkaline orthogneiss. The OVU is a composite Neoarchean-Paleoproterozoic magmatic arc developed during two stages (ca. 2500 and 2100 Ma) upon a continental basement corresponding to the western extension of the Neoarchean Fuping massif. The OVU overthrusts to the SE the Fuping massif along the Longquanguan shear zone. This stack of nappes, coeval with an amphibolite facies metamorphism, is dated at ca. 1880 Ma. Subsequently, the metamorphic series experienced a widespread migmatization at 1850 Ma and was intruded by post-orogenic plutons dated at 1800 Ma. The weakly to unmetamorphosed Hutuo Supergroup unconformably overlies the metamorphosed and ductilely deformed units (OVU and LGMU), but it is also involved in a second tectonic phase developed in subsurface conditions. These structural features lead us to question the ca. 2090 Ma age attributed to the Hutuo supergroup. Moreover, in the Fuping massif, several structural and magmatic lines of evidence argue for an earlier orogenic event at ca. 2100 Ma that we relate to an older west-directed subduction below the Fuping Block. The Taihangshan Fault might be the location of a possible suture zone between the Fuping Block and an eastern one. A geodynamic model, at variance with previous ones, is proposed to account for the formation of the TNCB. In this scheme, three Archean continents, namely from west to east, the Ordos, Fuping and Eastern Blocks are separated by the Lüliang and Taihang Oceans. The closure of the Taihang Ocean at ca. 2100 Ma by westward subduction below the Fuping Block accounts for the arc magmatism and the 2100 Ma orogeny. The second collision at 1900–1880 Ma between the Fuping and Ordos blocks is responsible for the main structural, metamorphic and magmatic features of the Trans-North China Belt.

Introduction

Since a decade, an increasing amount of information through all Precambrian cratons in the world provided evidence for plate tectonics activity with geodynamic features close to those of the present times since Mesoarchean (ca. 3100 Ma) times (e.g. Smithies et al., 2006; Cawood et al., 2006 and enclosed references). When dealing with Paleoproterozoic geodynamics (ca. 2000 Ma), ophiolites, calc-alkaline magmatic rocks or nappe tectonics are also documented in many places. For instance, subduction-related magmatism and arc collage are described in the Trans-Hudson orogen of Canada (e.g. Hollings and Andell, 2002, Maxeiner et al., 2005), Paleoproterozoic eclogitized oceanic crust is reported in the Usagaran Belt of Tanzania (Möller et al., 1995), ophiolites are identified in several Paleoproterozoic belts (Helmstaedt and Scott, 1992). These geological features agree with a modern-style plate tectonics.

The North China Craton (NCC) contains some of the oldest rocks of Asia: gneiss with 3800 Ma old zircons (Liu et al., 1992) and, although disputed, 2500 Ma old ophiolites (Kusky et al., 2001; Zhai et al., 2005; Zhao et al., 2005). Most of authors agree that the formation of the NCC results of subduction, arc magmatism, accretion and collision processes, similar to those of modern-style plate tectonics, its formation remains controversial in the definition of the involved continental masses, timing and modalities of collision. The N-S trending Trans-North China Belt (TNCB), also called Central Orogenic Belt has been identified as the main place where a western cra-
ton (or Ordos Block) and an eastern one collided (Zhao et al., 2000, 2001). According to some authors (e.g. Wang et al., 1996; Li et al., 2002; Kusky and Li, 2003; Zhai et al., 2005; Polat et al., 2005), the NCC was consolidated in Neorheean times by the welding of Mesaoarchean or older blocks along the TNCB. Conversely, other authors propose that the TNCB is a Paleoproterozoic collisional belt (Li et al., 1990; Wu and Zhong, 1998; Zhao et al., 2000, 2001, 2005; Kröner et al., 2005 and enclosed references, Figure 1). Furthermore, those western and eastern blocks are likely composed of several pieces. In the eastern and western blocks, the E-W and SW-NE trending Paleoproterozoic Liao-Ji and Khondalite Belts have been identified (e.g.Faure et al., 2004; Zhao et al., 2005; Lu et al., 2006, Figure 1).

Due to the Neogene tectonics related to the Indian collision, the TNCB is well exposed in the Fuping, Wutaishan, Hengshan and Lüliangshan of Shanxi and Hebei Provinces, from east to west (Figure 1). These massifs are presently isolated one from another and thus often analyzed separately. However, since similar lithologies and structures are observed in all the massifs, they obviously experienced the same tectonic and metamorphic evolution. Moreover, these massifs are famous places for Precambrian studies of the North China Craton since they are the type localities for the 3.0–2.5 Ga Fuping cycle, the 2.5–2.4 Ga Wutai cycle, and the 2.4–1.8 Lüliang cycle (Huang, 1977; Yang et al., 1986; Ma et al., 1987; Wang and Mo, 1995).

It is well acknowledged that modern collisional belts can be recognized by various criteria, such as: i) arc magmatism indicating lithospheric subduction, ii) subduction complexes formed during plate convergence, iii) ophiolites representing the intervening basin between the two continental blocks, iv) precise definition of the involved continents, v) HP metamorphism developed within the subducted continental crust of the underlying block, vi) nappe structures and associated ductile deformation such as flat-lying foliation and stretching lineation developed non-coaxial strain, vii) post-collisional crustal melting, responsible for migmatic and granitoids, formed immediately after the collision, in response to the exhumation of deeply subducted continental crust. In spite of the timing problem, the collisional model proposed for the TNCB sounds very attractive but still remains weakly documented. Recently, great advances have been made on the petrological, geochemical and geochronological knowledge of the TNCB (Zhao et al., 2000; 2001; 2002; Guan et al., 2002; Liu et al., 2002; 2005; 2006; Wang et al., 2004; Wilde et al., 2004a; 2005; Kröner et al., 2005, 2006; O’Brien et al., 2005; Polat et al., 2005). Nevertheless, the tectonic aspects such as the recognition of the litho-tectonic units, the bulk architecture of the chain, the kinematics of the ductile and synmetamorphic deformation and the deformation-metamorphism relationships remain poorly documented since pioneer studies of Bai (1986) and Tian (1991). Therefore, even if petrological and geochemical data provide evidence for arc magmatism and HP granulitic or even eclogitic metamorphism that support a collisional model, most of the above listed features characteristic of continental collision are not convincingly documented yet.

This paper aims to present the first comprehensive tectonic map and representative cross-sections through the TNCB, from Lüliangshan to Fuping based on our own field survey completed by petrological and geochronological works, and using available geological information. The bulk architecture and timing of the belt are described. A lithosphere scale cross-section and a geodynamic model that emphasizes a polyorogenic evolution of the Trans-North China Belt are proposed as working hypotheses for forthcoming works.

**Tectonic zonation of the Trans-North China Belt**

From west to east, the TNCB consists of several lithological, metamorphic and structural units identified in the Lüliangshan, Hengshan, Wutaishan and Fuping massifs (Figures 2, 3). This section introduces the dominant lithological features for each unit, whereas the structural relationships between the different units will be discussed in the next section.

**The western (Ordos) TTG basement**

This unit is restricted to the northwestern part of Lüliangshan. Gneissic tonalite and granodiorite form the dominant lithology. These rocks exhibit a well-defined foliation. Mylonites with a NW-SE stretching lineation and top-to-the-SE sense of shear form meter-thick shear zones.

**The Khondalite Unit**

To the east of the TTG gneiss, biotite-garnet sillimanite gneiss and micaschists of Paleoproterozoic age, called the Jiehekou Group develop (SBGMR, 1989; Wan et al., 2000). These rocks are derived from terrigeneous sediments such as mudstone, feldspathic sandstone or grauwacke. The Khondalite Unit extends further north of the study area, up to the Jining area where they are intercalated with volcanic rocks (e.g. Condie et al., 1992; Xia et al., 2005). The Khondalite Unit is interpreted as the terrigeneous cover deposited upon the Ordos continental basement.

**The Terrigeneous-Mafic Unit**

Southeast of the previous units, sedimentary and mafic metamorphic rocks crop out. Although placed together with the Khondalite Unit in the Jiehekou Group (e.g. Geng et al., 2000; Wan et al., 2000; Liu et al., 2006 and enclosed references), this rock assemblage exhibits quite distinct lithological features and it is considered here as a separate unit. The metasedimentary rocks consist of centimeter to meter-size sandstone-mudstone alternations derived from a turbidite series (Figure 4C). Mafic and ultramafic rocks represent the second main lithology in this unit. Coarse-grained amphibolites with preserved gabbric textures and fine-grained metabasites derived from basalt or diabase support a magmatic origin of the mafic rocks. Some of those mafic rocks crop out as lenses intercalated within sandstone. Due to the intense ductile deformation, the primary relationships between the two lithologies are not settled. The meter-size of the mafic blocks and their scattering in the terrigeneous rocks suggest that they might be olistoliths, alternatively, the mafic rocks could represent intrusions subsequently sheared during the forma-
tion of the TNCB. However, the first interpretation is preferred here since in some outcrops amphibolite forms centimeter to plurimeter sized isolated blocks and their terrigeneous host rocks do not exhibit any evidence for thermal annealing such as it would be expected in the case of intrusion. In the following, the Terrigeneous-Mafic unit will be interpreted as a subduction complex, associated to the Low Grade Mafic Unit (defined below) exposed in Lüliangshan and Wutaishan.

The Orthogneiss-Volcanites Unit (OVU)

This litho-tectonic unit is widely developed in Wutaishan, Lüliangshan and to a lesser extent in Hengshan (Figures 2, 4F). The typical rock-type consists of centimeter- to meter-scale alternations of light-colored gneiss and amphibolite. The protoliths of the amphibolites are mafic magmatic rocks (i.e. lava flows, dykes or sills) or volcanic-sedimentary rocks. The acidic gneisses are derived from felsic lavas: rhyolite, dacite, and andesite or volcani-clastic rocks. The OVU contains numerous plutons analyzed samples do not belong to the same tectonic unit. Indeed, the calc-alkaline plutons present also geochemical evidence indicating that they are derived from partial melting of the Archean basement which complies with the occurrence of 2700 Ma inherited zircons. In agreement with most of the previous authors (e.g. Zhao et al., 2001; Wilde et al., 2005; Kröner et al., 2005), we interpret the OVU as aductily deformed magmatic arc. Since both pluton generations are converted into ortho-gneiss, the tectonic events responsible for the main deformation in the OVU must be younger than 2120 Ma, i.e. the TNCB belongs to a Paleoproterozoic orogen rather than a Neoarchean one.

The Low Grade Mafic Unit (LGMU)

This unit is recognized in two areas: SW of Lanxian in Lüliangshan and the central part of Wutaishan (Figures 2, 4D). The most common rock-types are greenschist facies sedimentary and magmatic rocks. Metasedimentary rocks such as pelite, silt, grauwacke and quartzite and volcano-sedimentary rocks such as tuffs or pyroclastites are widespread. Basalt, sometimes with pillow structures, dolerite, gabbro, and variously serpentinitized harzburgite and dunite are also widespread. The LGMU corresponds to the Middle and Upper parts of the Wutai Group (Tian, 1991) in Wutaishan and to the Lüliang Group in Lüliangshan, respectively. On the contrary, the LGMU is not recognized in Hengshan. Several geochemical studies dealt with the Wutaishan magmatic rocks (Bai, 1986; Tian, 1991; Wang et al., 2004; Polat et al., 2005). These works emphasize the duality of the geodynamic settings inferred from the chemical signatures. The ultramafics correspond to the depleted oceanic mantle associated with mafic rocks that present a MORB-like affinity. Conversely, the rhyolites, dacites, andesites and some basalts have a calc-alkaline signature showing that these rocks formed in a subduction zone setting developed upon a continental active margin (Wang et al., 2004). These two signatures are interpreted to reflect an interaction between Mid-Oceanic ridge and subduction processes (Polat et al., 2005). However, this conclusion must be considered with caution since the analyzed samples do not belong to the same tectonic unit. Indeed, the calc-alkaline and tholeiitic volcanic rocks correspond to the OVU and LGMU Units, respectively.

In Wutaishan, the LGMU greenstones yield U/Pb zircon and Sm-Nd whole rock ages around 2515–2535 Ma (Wilde et al., 2004a) and 2471–2535 Ma (Zhang et al., 1998). In Lüliangshan, radiometric ages are still rare and quite scattered. The metavolcanites are dated by Sm-Nd method on whole rock at 2360±95 Ma and by U-Pb method on zircon at 2051±68 Ma and 2099±41 Ma (Yu et al., 1997;
Geng et al., 2004a). It is worth to note that the age of the volcanic rocks from the LGMU is similar to that of the OVU early plutons but significantly older than the second plutonic generation. The present geometry that exposes the “old” LGMU rocks above the “young” OVU rocks complies well with a tectonic superposition (cf. below).

The Fuping Complex

High-grade metamorphic rocks and granitoids forming the easternmost domain of the study area are called the Fuping Complex. In agreement with previous works, we recognize three main lithological rock types, namely: i) TTG basement, ii) supracrustal series, iii) 2077–2050 Ma meta- to peraluminous granodiorite and monogranite collectively called the “Nanying granites” (HBGMR, 1989; Guan et al., 2002; Liu et al., 2002, 2005; Zhao et al., 2002). The western margin of the Fuping Complex is a tectonic boundary called the Longquanguan Shear Zone (Li and Qian, 1991, see below). The highly mylonitized Longquanguan augen gneiss is often placed in the Fuping Complex. However, these rocks are petrologically, chronologically (ca. 2500 Ma) and structurally similar to the metagranites that intrude the bimodal magmatic series of the OVU, and thus we place these orthogneiss into the OVU. The TTG basement of the Fuping Complex consists of banded gneiss, foliated tonalite and granodiorite. SHRIMP U/Pb zircon ages range from 2530 to 2480 Ma (Zhao et al., 2002). The supracrustal series contains paragneiss, micaschist, quartzite, marble and amphibolite, and ca. 2500 Ma old detrital zircons were found in the metapelites (Zhao et al., 2002). Thus the Fuping basement rocks are globally coeval with the OVU but formed in an easternly location. Although rarely mentioned in the available literature, both TTG and supracrustal rocks of the Fuping Complex are extensively migmatized.

The migmatites

Although little emphasized in previous works, migmatites are conspicuously developed in Lüliangshan and Hengshan massifs. Depending on the degree of partial melting, the protoliths are sometimes difficult to identify, but the bimodal magmatic series and orthogneiss belonging to the Orthogneiss-Volcanite Unit and also the TTG gneiss and amphibolites corresponding to an underlying, but not exposed, basement are found as meter-sized unmetamelted relics in the migmatites (Figure 4E, G; Trap et al., in press). In Hengshan, meter-size blocks of high-pressure mafic granulites or even retrograded eclogites with P and T conditions of 15–20 kb and 750–850°C, respectively, are also found (Zhao et al., 2001; O’Brien et al., 2005; Zhang et al., 2006). Preserved gabbroic textures show that these HP rocks derived from a magmatic protolith (O’Brien et al., 2005; Kröner et al., 2006). The rounded shape of the blocks led some authors to assume that the mafic granulites were boudinaged dykes intruding TTG gneiss (Kröner et al., 2005; 2006). Although possible, such an interpretation is not demonstrated yet, since in the field, the observed boudins are post-migmatitic. The primary relationships between the mafic granulites and the country rocks are erased by the migmatization. Presently, the mafic gneiss and amphibolites appear as residues enclosed within metatexites (Figure 4G). Recent SHRIMP and evaporation methods on magmatic and metamorphic zircons extracted from the granulitic mafic rocks yield ca. 1915 Ma and 1880–1850 Ma ages interpreted as those of the magmatism and metamorphism, respectively (Kröner et al., 2006).

Similar HP granulites crop out also northeast of Hengshan, in the Sanggan area (Figure 1). There, SHRIMP U/Pb zircon dating of the HP granulites gives ages of 1817±12 Ma and 1872±16 Ma (Guo et al., 2002, 2005) that correspond to the recrystallization times of zircon rims. The 1870 Ma age which is close to our U-Th/Pb chemical age get on synmetamorphic monazite in the OVU (cf. below) can be interpreted as the age of the main metamorphic event (Guo et al., 2005).
2005), and the ca. 1820 Ma age is close to the thermal phase that we shall relate to a late orogenic magmatic event (cf. below). It has also been proposed that these HP granulites were formed by continental subduction and fast exhumation around 2500 Ma (Kusky and Li, 2005). This tectonic mechanism might be possible, but the Neoarchean age of the high-pressure event is not demonstrated yet. Moreover, on the basis of the available radiometric ages (e.g. Kröner et al., 2006 and enclosed references), a Paleoproterozoic age, as discussed below, would be in better agreement with other chronological and structural constraints. Our geodynamic model considers that the TNCB developed during the Paleoproterozoic.

In the southern part of Lüliangshan, the magmatic rocks crop out in the Chijianling and Guandishan gneissic granites (Liu et al., 2006). These rocks would be better described as a migmatitic dome developed at the expense of the OVU and underlying TTG basement, the fragments of which are recovered as restites in anatexites or as xenoliths in late granitoids (Figures 2, 4H). It is also worth noting that a high-temperature (HT) metamorphism, characterized by the crystallization of biotite, garnet, and sillimanite develops concentrically around the Guandishan migmatitic dome. This HT metamorphism overprints the primary foliation and coeval greenschist facies metamorphic parageneses of the Low Grade Mafic Unit (Yu et al., 2004). The high angle between the E–W trending isogrades related to the HT event and the submeridian trend of the regional foliation demonstrates that the HT metamorphism is a secondary phenomenon with respect to the regional tectono-metamorphic event responsible for the main structure of the TNCB.

The post-orogenic magmatism

The above presented lithologic, metamorphic and tectonic units are intruded by several generations of undeformed granitoids. The largest plutons form the granodioritic and monzogranitic Guandishan massif and the enderbitic-monzonitic Lüyashan massif in the southern and northern parts of Lüliangshan, respectively. These plutons yield U-Pb ages around 1820–1800 Ma (Geng et al., 2000, 2004b, Yu et al., 2004) that provide the upper time limit for the tectono-thermal events in the Trans-North China Belt. The Cretaceous plutonism that can be found sporadically in Hengshan, Wutaishan and Fuping massifs, for instance around Linqiu, (Figure 2, SBGMR, 1989) is not considered here.

The unmetamorphosed Paleoproterozoic series (Hutuo Supergroup s. l.)

In Lüliangshan, Wutaishan and Fuping massifs, the metamorphic rocks of the OVU, LGMU and Terrigeneous-Mafic Units are unconformably covered by unmetamorphosed or weakly metamorphosed but locally highly deformed sedimentary series of conglomerate, sandstone, mudstone, and carbonates with subordinate intercalations of volcanic rocks. These rocks are widely developed north of Wutai where they are called the Hutuo Supergroup (SBGMR, 1989; Tian, 1991). In the southeastern termination of the Fuping massif, terrigeneous rocks of the Gantaohe Group (HBGMR, 1989) overlie unconformably the TTG gneiss (Figure 2). In Lüliangshan, the Yejishan Group (SBGMR, 1989) consists of turbiditic sandstone and metavolcanites at its base. Due to the lack of any biostratigraphic constraints and direct continuity between the Gantaohe, Hutuo and Yejishan Groups, the relative timing between these series is impossible to assess. According to the geological maps of Hebei and Shanxi Provinces (HBGMR, 1989; SBGMR, 1989) and to synthetic works (Yang et al., 1989), all these terrigeneous series are correlated and called the Hutuo Supergroup. In Wutaishan, zircons from an acidic

Figure 4  Representative field pictures. A—Late Paleoproterozoic sandstone-pelite of the Hutuo Supergroup (Yejishan Group) folded with a vertical slaty cleavage (NW of Lanxian). B—Ductilely deformed conglomerate in the basal part of the Hutuo Supergroup (N. of Wutai). C—Metasandstone-metapelitite alternations in the Terrigeneous-Mafic Unit (western part of Lüliangshan). D—Gabbro block in greenschist metapelite in the Low Grade Mafic Unit (Lüliang group, S. of Lanxian). E—Partly migmatized metadiorite (Yixingzhai pluton) belonging to the Orthogneiss-Volcanites Unit (SE of Linqiu). F—typical amphibolite-acidic gneiss alternations of the Orthogneiss-Volcanites Unit (N. of Fanxi). G—Migmatites enclosing mafic restites (NE part of Hengshan). H—Xenolith of banded TTG gneiss into the ca. 1800 Ma post-orogenic granite of Guandishan.
tuff yield a SHRIMP U/Pb age of 2087+/-9 Ma (Wilde et al., 2004b). In the Yejishan Group, zircons from an acidic tuff yield 2124+/-38 Ma (Geng et al., 2000). The significance of these dates in the tectonic framework of the Trans-North China Belt is discussed below.

**Structure and age constraints of the Trans-North China Belt**

The bulk architecture of the above-presented units is a stack of nappes cross cut by migmatites and granitic plutons. The metamorphic units of the TNCB are characterized by a flat-lying foliation between coevally with ductile shearing. Several tectonic-metamorphic units of the TNCB are characterized by a nappes cross cut by migmatites and granitic plutons. The metamorphic and structural features, the Terrigenous-Mafic Unit of Lüliangshan is correlated with the LGMU. The occurrence of MORB-type mafic rocks, ultramafites, cherts and turbidites comply with the interpretation of the LGMU as an ophiolitic nappe.

In agreement with previous works (e.g. Li et al., 1990; Wilde et al., 2004, 2005; Kröner et al., 2005; Polat et al., 2005; Zhao et al., 2005), we interpret the calc-alkaline bimodal magmatic assemblage of the amphibolite-acidic gneiss series and the plutons that compose the OVU as a magmatic are installed upon a continental basement as shown by the TTG xenoliths found in the post-tectonic granitoids or in the migmatites (Figure 4H). The rocks of the OVU are extensively deformed with a flat-lying foliation and a NW–SE stretching lineation (Figure 3). The top-to-the-SE sense of shear deduced from field and microstructural analyses is coeval with an amphibolite facies metamorphism. In Lüliangshan, Wutaishan and Hengshan, the present erosion level does not expose the contact between the Terrigenous-Volcanic Unit and its TTG basement. For simplicity, a depositional contact is assumed in the cross-sections (Figure 3). However, a layer-parallel decollement cannot be ruled out.

In western Lüliangshan, the TTG and the Khondalite Unit correspond to basement and cover of the Western Block, respectively. The vertical fault that separates the Terrigenous-Mafic Unit from the Western Block appears as a major tectonic boundary that we call here the Trans-North China Suture (Figure 2). In previous works (e.g. Zhao et al., 2005 and enclosed references), the boundary between the TNCB and the Western Block is always located to the west of Lüliangshan. Moreover, in spite of their quite distinct lithological, metamorphic and structural features, the Terrigenous-Mafic Unit and the OVU are not distinguished but both units are placed in the Jiahekou group (Liu et al., 2006). Lastly, the tectonic contact between the overlying Terrigenous-Mafic Unit and underlying OVU is post-dated by unmetamorphosed terrigenous rocks of the Yejishan group. Due to late tectonics, the unconformable contact between the Yejishan Group and the underlying metamorphic rocks is sheared. The terrigenous rocks of the Yejishan group are deformed by upright folds with an axial planar cleavage (Figure 4A). More to the East, the mafic and sedimentary rocks of the LGMU (i.e. the former Lüliang Unit) are separated from the OVU by a decameter- thick mylonitic shear zone. Thus, tectonically, the rocks of the Lüliang Group must be considered as a klippe transported to the SE above the OVU and rooted in the Trans-North China Suture. Consequently, the continental basement that underlies the Wutaishan, Hengshan and Lüliangshan masses up to the Trans-North China suture, can be structurally correlated to the Fuping gneiss. In the following, we shall call this basement the Fuping Block (Figure 3).

Along the SE margin of the Fuping Complex, near Pingshan, the terrigenous rocks of the Gantaohao Group, correlated to the Hutoo supergroup that unconformably cover the Fuping gneisses, are deformed by a ductile low-angle detachment fault with NW–SE stretching lineation and a down-dip movement (Figure 3). In a previous work (Zhao et al., 2002), this ductile shear zone, called the Ciyu-Xinzhuang Shear Zone, was correlated to the Longquanguan Shear Zone, but neither the geometry nor the kinematics of the migmatites was provided. In our opinion, such a correlation is unlikely due to the quite different metamorphic conditions, amphibolite facies and greenschist facies in the Longquanguan and Ciyu-Xinzhuang Shear Zones, respectively.

The Hutoo Supergroup is well exposed between Wutai and Yuanping (Figure 2). As indicated on the geological maps (SBGMR, 1989; HBGMR, 1989) and confirmed by our own survey, but never clearly pointed out previously, the doming and crustal melting of the Fuping Block is older than the activity along the Longquanguan Shear Zone since in the footwall of the shear zone, the Fuping migmatites and the Nanying granites are foliated and lineated under post-solidus rheological conditions. Thus, in our interpretation, the Longquanguan Shear Zone is an intracontinental flat-lying structure developed within the Fuping Complex. Consequently, the continental basement that underlies the Wutaishan, Hengshan and Lüliangshan masses up to the Trans-North China suture, can be structurally correlated to the Fuping gneiss. In the following, we shall call this basement the Fuping Block (Figure 3).

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The Hutoo Supergroup is well exposed between Wutai and Yuanping (Figure 2). As indicated on the geological maps (SBGMR, 1989), the Hutoo unconformity upon both LGMU and OVU has been observed in several places during our field survey. However, the primary unconformable relationship is often more recognized, since the conglomerate and sandstone of the Hutoo Supergroup frequently exhibit a vertical or even upside-down attitude. The lower part of the Hutoo Supergroup experienced a ductile deformation coeval with a greenschist facies metamorphism. A NW–SE trending stretching lineation marked by elongated or boudinaged pebbles in conglomerates and quartz-chlorite pressure shadows is associated with a top-to-the-SE shearing (Figure 4B) that complies with the SE-verging recumbent folds and the bedding-cleavage relationships. This ductile deformation overprints similar geometric and kinematic features to that observed in the LGMU and OVU, but differs from the latter on the basis of the grade of the syntectonic metamorphism. The unconformable relationships between the Hutoo Supergroup

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and the underlying rocks argue for the reality of two tectono-meta-
morphic phases responsible for the formation of the TNCB in Lüliangshan, Hengshan and Wutaisha. An early one coeval with an amphibolite facies metamorphism is responsible for the formation of the main foliation and nappe stacking. After the unconformable deposition of the Hutuo terrigenous rocks upon the metamorphic rocks, a second tectonic and metamorphic event is responsible for the first deformation of the Hutuo rocks whereas in the same time, the underlying units experienced a moderate structural reworking and a metamorphic retrogression. Since both deformation phases develop with the same top-to-the-SE kinematics, they likely repre-
sent two stages of the same orogenic event.

Moreover, the 2070–2050 Ma Nanying magmatism of the Fup-
ing Complex argues for an older Paleoproterozoic event.

The timing of the tectono-metamorphic events

As presented above, numerous radiometric data are available to con-
strain the age of the various protoliths involved in the TNCB (Grau et al., 2002; Zhao et al., 2002; Wilde et al., 2004a, 2005; Kröner et al., 2005). However, the timing of the ductile deformation and migmatization was still poorly established since important data were released only recently (Kröner et al., 2006; Liu et al., 2006). In order to implement our understanding, zircon LA-ICP-MS U/Pb and EPMA chemical U-Th/Pb datings have been undertaken. Due to restricted space, only outlines of the methods and the most signifi-
cant results are given here.

U-Pb analyses

For LA-ICP-MS U-Pb analyses, zircon grains were mounted in epoxy resin with chips of a standard material (G91500; Wiedenbeck et al., 1995). Analyses were performed at the University of Montpel-
lier II using a VG Plasmaquad II turbo ICP-MS coupled to a Geolas (Microlas) automated platform housing a 193 nm Complex 102 laser from LambdaPhysik. Analyses were conducted in a He atmosphere, which enhances sensitivity and reduces inter-element fractionation (Günter and Heinrich, 1999). Data were acquired in the peak jump-
ing mode using one point per peak and measuring the $^{204}$Hg, $^{206}$Pb + Hg, $^{206}$Pb, $^{207}$Pb and $^{208}$Pb isotope ratios similarly to the proce-
dure described in Bruguer et al., 2001. The laser was fired using an energy density of 15 J cm$^{-2}$ at a frequency of 4 Hz and a spot size of 26 µm. This resulted in a sensitivity of ca. 1000 cps/ppm for Pb based on measurements on the G91500 reference material. The Pb/Pb and U/Pb isotopic ratios of unknown grains were calibrated against the G91500 crystal as an external standard.
The contribution of $^{204}$Hg on $^{206}$Pb was estimated by measuring the $^{202}$Hg and analy-
ses yielding $^{204}$Pb close to, or above, the limit of detection were rejected. Errors measured on the standard were added in quadrature to those measured on the unknown grains. This resulted in a 2 to 4% precision (1σ RSD%) after all corrections have been made. Age cal-
culations were done using the Isoplot program (Ludwig, 2000) and are quoted at the 2σ level.

All zircons from the migmatitic leucosome extracted from a migmatitic leucosome of the Hengshan Massif (sample FP 52, located in Figure 2, N39°27.225' E113°28.202'). The upper intercept at 2686±7 Ma corresponds to the core of inherited grains and the 1850±5 Ma is that of the zircon rims formed during the leucosome crystallization. The number of analyzed grains, data-point error ellipses are 1σ but age errors are 2σ.

Figure 5  Concordia graph for ICP-MS U-Pb dates from zircons 
extracted from a migmatitic leucosome of the Hengshan Massif.

U-Pb/Th chemical dating

Due to its negligible common Pb and high Th and U contents (Parish, 1990), monazite is a suitable chronometer for both mag-
matic and metamorphic rocks. Moreover, in monazite, U, Th, and radiogenic Pb are not significantly affected by diffusion (Crowley and Ghent, 1999; Zhu and O'Nions, 1999; Cocherie et al., 1998), thus the isotopic system remains undisturbed with respect to these elements. U, Th, Pb contents in monazite were measured with a camcera SX50 EPMA cooperated by BRGM, CNRS and Orléans University with a detection limit of 150 ppm. Details of the analyti-
cal procedure are given (Cocherie et al., 1998, 2005). The results are represented in a Th/Pb vs. U/Pb isochron diagram using an ISO-
PLOT program (Ludwig, 2000) according to Cocherie and Albarède, 2001. In such a plot, the slope of the regression line drawn using the experimental data can be compared with the theoretical isochron to ensure that a single age has been recorded. The EPMA dating pro-
gram (Pommier et al., 2002) simplifies age calculations on monazite. All reported uncertainties are two-sigma.

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Monazite grains were identified within a thin section using SEM images in back scattered mode obtained in Orléans University. Such an in situ approach preserves the primary microstructural relationships between monazite and other metamorphic phases (Foster et al., 2002; Williams and Jercinovic, 2002). Sample FP 35 is a biotite-garnet-kyanite-staurolite gneiss from the Orthogneiss-Volcanites Unit sampled in the Hengshan massif (located in Figure 2, N39° 23.743/ E113° 35.831). Textural observation of this micaschist shows that biotite grains forms the macroscopic foliation. The close association of monazite with biotite, either as inclusion or along the grain boundaries, indicates that crystallization of monazite occurred during the development of the amphibolite facies metamorphism coevally with the first ductile shearing. SEM images do not reveal any chemical zoning of the monazite grains, suggesting that relict cores are absent. In the Th/Pb vs. U/Pb diagram (Figure 6), the analytical data points obtained from 9 grains plot along a well-delineated regression line (MSWD = 0.78) that fits well with the theoretical isochron at 1883±11 Ma. The mean age, calculated at the centroid of the population, corresponds to the amphibolite facies metamorphism developed during the formation of the TNCB. It is also interpreted as that of the emplacement of the LGMU above the OVU. Our LA-ICP-MS U/Pb and chemical U-Th/Pb ages comply with previous SHRIMP U/Pb zircon ages ranging from 1880 to 1850 Ma (Wilde et al., 2004a, 2005; Kröner et al., 2005, 2006; Liu et al., 2006), indicating that primary magmatic grains experienced a recrystallization around 1900 Ma during the amphibolite facies metamorphism.

The problem of the age of Hutuo Supergroup

The radiometric ages inferred for the amphibolite facies metamorphism and subsequent migmatization indicate that the Hutuo unconformity must be at least younger than 1850 Ma and older than 1800 Ma. However, on the basis of a SHRIMP U/Pb date from zircons extracted in a felsic tuff near Wutai, a 2087±9 Ma age is suggested for the Hutuo Supergroup (Wilde et al., 2004b). According to the field description of the sampling site (Wilde et al., 2004b), the dated tuff is in primary sedimentary contact with marbles, garnet micaschists and amphibolites, but according to our own field survey, the Hutuo sedimentary rocks experienced only a single low-grade metamorphism. In the sampling place of this tuff, the structure is quite complex; and a tectonic imbrication of several thrust sheets resulting in ductile and brittle deformations can be recognized there. The discrepancy between the two sets of age can be solved if one considers either that the dated felsic tuff belongs to the underlying Low Grade Mafic Unit rather than to the Hutuo Supergroup, or alternatively that the analyzed zircons are inherited grains. The available radiometric constraints, including the two generations of arc magmatism, the Fuping migmatization, the 1880–1850 Ma main tectono-metamorphic event are summarized in Figure 7, that emphasizes also the age problem of the Hutuo Supergroup.

Discussion

The lithosphere scale structure

Our observations document a collision model for the TNCB that agrees with previous works (e.g. Zhao et al., 2005 and enclosed references). Arc magmatism, ophiolites and turbidites, HP metamorphism, symmetamorphic nappes, post-collisional migmatites recognized in Lülüiangshan, Hengshan, Wutaishan and Fuping massif, which are among the most significant criteria for collision belt, are fulfilled in the TNCB.

However, a simple collision involving the two continental masses of Western (Ordos) and Eastern Blocks does not account well for the bulk architecture and the chronological constraints available for the belt. Thus, we propose here to consider an intermediate continent, called here the “Fuping Block”. The existence of an Archean Fuping Block has already been invoked by earlier workers (e.g. Yang et al., 1986; Ma et al., 1987; Tian, 1991), but as stated above, in this paper, we use “Fuping Block” to describe a large continental mass that includes not only the Fuping Massif but also the TTG gneiss that underlie the Orthogneiss-Volcanites Unit (Figure...
3). The Low Grade Mafic Unit represents the intervening ocean that up to now was neither clearly identified in the previous models. Moreover, the consistent top-to-the SE sense of shear coeval with a synmetamorphic nappe displacement does not agree satisfactorily with the east directed subduction proposed for the formation of the Orthogneiss-Volcanites magmatic arc (Zhao et al., 2001; Kröner et al., 2005). A westward dipping subduction would better explain the bulk architecture of the belt and the kinematic features described in this paper.

Our study also suggests that the Fuping Block underwent an older event responsible for crustal melting, doming and emplacement of the Nanying granites at ca. 2050 Ma, i.e. 200 Ma before the tectono-metamorphic events observed in Lüliangshan, Hengshan and Wutaishan. In order to account for the 2150–2050 Ma tectonic, metamorphic and magmatic events observed in the Fuping Complex, another orogenic episode must be considered. Unfortunately, Precambrian rocks are not exposed east of the Fuping Complex, thus the following interpretation remains hypothetical based on indirect geophysical evidence.

The N-S trending Taihangshan Fault separates the Precambrian rocks and the North China Plain sedimentary rocks (Figure 1). The important gravimetric and magnetic anomalies suggest that the Taihangshan Fault is a major lithospheric boundary along which dense and magnetic rocks such as mafic and ultramafic rocks might occur. Obviously, like most of the large-scale continental faults, the Taihangshan Fault probably moved several times during the geological history of the North China Block (Griffin et al., 1998; Huang and Zhao, 2004 and enclosed references). Along the fault, Cretaceous gabbroic plutons exhibit geochemical features indicating that the magma originates from an ultramafic source metasomatized by subduction related melts (Wang et al., 2006). The central part of the North China Block did not experience any Phanerozoic subduction since this area is quite remote from the Mesozoic Pacific subduction zone. Thus, in agreement with Wang et al. (2006), we suggest that the Taihangshan fault might be interpreted as a Paleoproterozoic suture resulting from the closure of an oceanic basin, called here the Taihang Ocean. The Eastern Block that collided with the Fuping Block corresponds to the area that extends eastwards of the Taihangshan Fault, probably up to the Tan-Lu Fault (Figure 1). A 2D lithosphere-scale cross-section is proposed in Figure 8.

A possible geodynamic scenario for the Trans-North China Belt

Although still preliminary, the available data allow us to propose a two-step geodynamic evolution model to account for the formation of the Trans-North China Belt (Figure 9). This model, at variance from previous ones (Zhao et al., 2004; Kröner et al., 2005), emphasizes two diachronous east-directed subductions. Moreover, the model takes also into account the structure of the Lüliangshan, which was never considered in previous ones.

The Wutai Arc installed on the continental Fuping Block records two magmatic episodes. The geodynamic setting of the oldest one, around 2540–2510 Ma, remains poorly constrained. It is nearly 400 to 450 Ma older than the tectonic and metamorphic events observed in the Fuping Block. Such a quite unusual long time
span between subduction and collision has been already pointed out (Kröner et al., 2005; Zhao et al., 2005). Tentatively, the Wutai Arc can be compared to an Andean-type arc where oceanic subduction lasts also since more than 250 Ma. The available radiometric ages for the Low Grade Mafic Unit range between 2535 Ma and 2000 Ma. This suggests that the Lüliang Ocean that separated the Western Ordos Block and the Wutai Magmatic Arc already existed in Neoarchean times. In our interpretation, the Wutai Arc is related to the westward subduction of the Taishang Ocean. However, this Neoarchean evolution is largely speculative.

The youngest Wutai magmatic arc formed around 2170–2120 Ma in response to the westward subduction of the Taishang Ocean before the first continental collision between the Fuping Block and the Eastern Block. This event occurred probably around 2100 Ma since the 2070–2050 Ma magmatics and Nanying granites formed during a post-collisional crustal melting (Guan et al., 2002; Liu et al., 2002, 2005). The suture that might corresponds to the present Taihangshan Fault is not exposed.

Since the tectonics related to the closure of the Lüliang Ocean is dated around 1900–1850 Ma, the Lüliang Ocean lasted more than 500 Ma. Compared to the average lifetime of the present oceanic basins, this duration is quite long. However, the Neoarchean-Paleoproterozoic history (i.e. opening, width, etc.) of the Lüliang Ocean remains presently poorly documented. The large scatter of the radiometric ages of the mafic rocks requires further studies.

Our structural studies suggest that the Lüliang Ocean closed due to the subduction of the Fuping Block below the Ordos Block. The crust and oceanic sediments of the Lüliang Ocean are presently preserved in the Low Grade Mafic Unit. At that time, top-to-the-SE ductile and synmetamorphic shearing deformed the bimodal volcanic-sedimentary series and the calc-alkaline plutons corresponding to the Orthogenesis-Volcanites Unit. The Wutai Arc was sliced to the SE by intracontinental thrusts such as the Longquanguan Shear Zone. The high-pressure granulites and eclogites coeval with the continental subduction of the Fuping Block might also form during this second collisional orogenic event.

Lastly, during its exhumation, the subducted crust of the Fuping Block and the Wutai Arc rocks experienced migmatization and plutonism. In this scheme, the deposition of the Huutuo Supergroup occurred immediately after the closure of the Lüliang Ocean and subsequent collision, but continuing convergence deformed also this sedimentary unit during the second tectonic phase.

Conclusion

The structural, metamorphic and magmatic features of the Trans-North China Belt allow us to conclude that the amalgamation of the North China Craton took place in Paleoproterozoic times through two distinct continental collisions at ca. 2100 Ma and 1900 Ma. The Neoarchean to Paleoproterozoic geodynamic evolution of the TNCB is quite similar to that of the modern-type collisional orogens. The materials involved in the orogen, namely, ophiolites, turbidites and subduction related magmatic rocks do not differ from those that form the present mountain belts. The HP granulitic metamorphism, argues for continental subduction, and the flat-lying foliation developed coevally with an amphibolite facies metamorphism complies with crustal thickening. Alike in many Phanerozoic belts, the migmatization and plutonism can be seen as a late to post-orogenic crustal melting in response to the thermal disturbance due to collision. From the mechanical point of view, this comparison implies that around 2000–1800 Ma, the strength of the continental crust of the North China Craton was already high enough to accommodate horizontal shortening by ductile flat-lying shearing.

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