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Deformation history of the Hengshan Complex: Implications for the tectonic evolution of the Trans-North China Orogen

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Abstract

Structural analysis indicates that the Hengshan Complex underwent five distinct episodes of deformation (D_1–D_5). The D_1 episode formed small isoclinal folds (F_1), penetrative axial planar foliations (S_1) and mineral stretching lineations (L_1). D_1 fabrics were reworked by following D_2 deformation. Associated with D_2 was the development of NW-verging asymmetric folds and accompanying thrust faults. Both D_1 and D_2 resulted from crustal thickening and coherent with prograde and peak metamorphism. D_2 deformation was followed by transpressional dextral shearing (D_3), including top-to-NW oblique-slip shearing and NNE–SSW dextral strike-slip shearing. Ongoing collision led to development of the Zhujiafang ductile shear zone (D_4), a near E–W trending high strain belt across the Hengshan Complex. D_5 deformation is characterized by F_5 open folds and associated normal faults, probably related to exhumation of the complex. Structural patterns of the Hengshan Complex can place important insights into a recently proposed tectonic model suggesting that an ocean between the Eastern and Western Blocks underwent eastward-directed subduction beneath the western margin of the Eastern Block, and closure of this ocean finally led to collision between the two blocks to form the coherent North China Craton.

Keywords: North China Craton; Trans-North China Orogen; Archaean; Palaeoproterozoic; Hengshan Complex; Deformation

1. Introduction

Recent progress in understanding the basement architecture of the North China Craton has resulted in recognition of the Trans-North China Orogen, which separates the craton into two continental blocks, named the Eastern and Western Blocks (Fig. 1; Zhao et al., 1998, 1999, 2000a, 2001a; Wilde et al., 2002). There is now a broad consensus that the final assembly of the North China Craton was completed by the amalgamation of the Eastern and Western Blocks along the Trans-North China Orogen (Wu and Zhong, 1998; Zhao et al., 1998, 2001a, 2005; Li et al., 2000; Wilde et al., 2002; Guo et al., 2002, 2005; Kusky and Li, 2003; Kröner et al., 2005a,b, 2006; Polat et al., 2005, 2006; Liu et al., 2006). However, there is some debate on the timing and tectonic processes involved in the amalgamation of the two blocks. One school of thought proposed westward-directed subduction of an ocean between the two blocks, with collision at ~2.5 Ga (Kusky and Li, 2003; Polat et al., 2005, 2006), whereas others suggested eastward-directed subduction, with collision at ~1.85 Ga (Wu and Zhong, 1998; Zhao, 2001; Zhao et al., 1998, 1999, 2000a, 2001a; Wilde et al., 2002). To resolve this controversy, several groups have recently carried out extensive investigations on the basement rocks of the Trans-North China Orogen,

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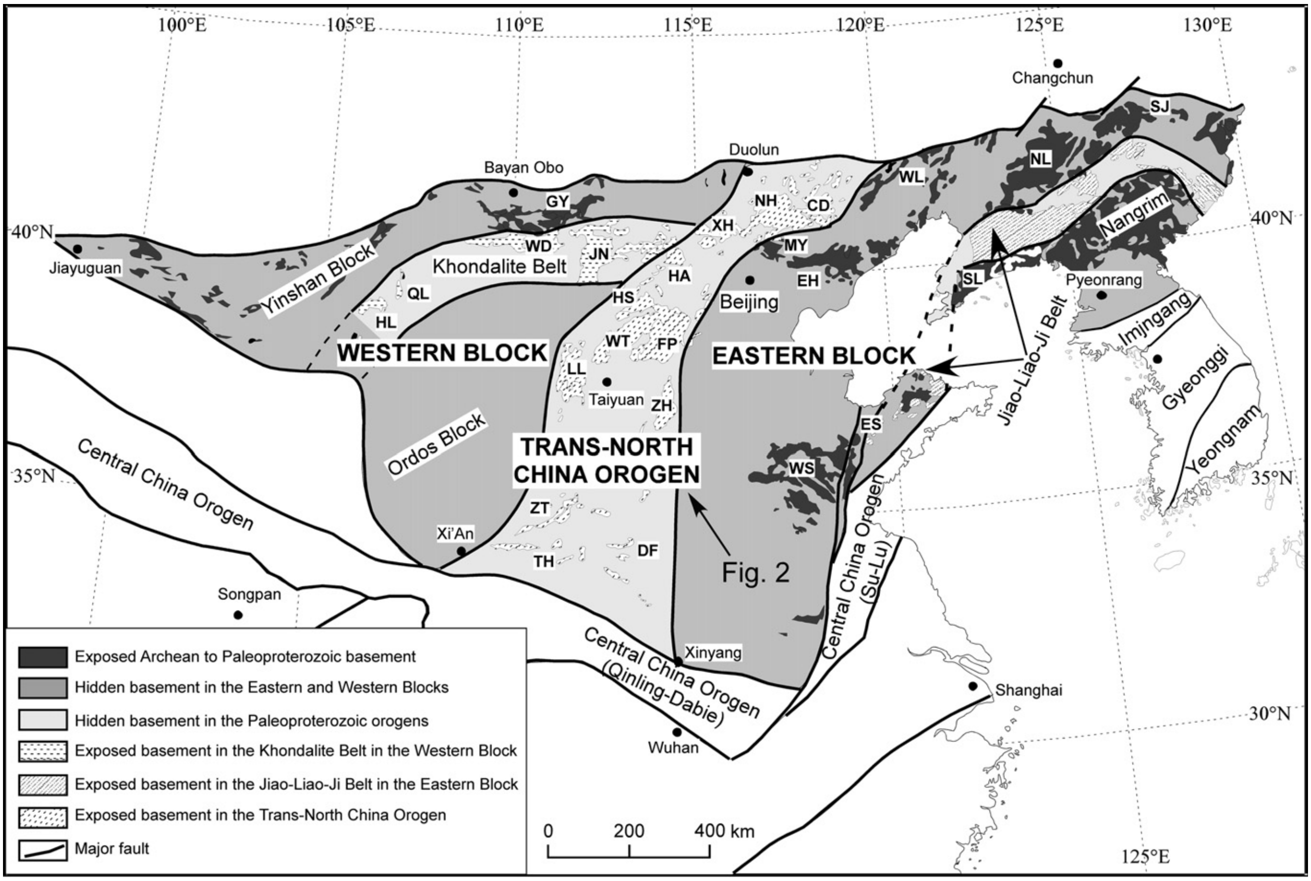

Fig. 1. Tectonic subdivision of the North China Craton (after Zhao et al., 1998, 2001a, 2005), showing the spatial distribution of the basement rocks. Abbreviations for metamorphic complexes: CD — Chengde; DF — Dengfeng; EH — Eastern Hebei; ES — Eastern Shandong; GY — Guyang; HA — Huai'an; HL — Helanshan; 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.

including magmatic and geochemical studies (Liu et al., 2002, 2004, 2005; Wang et al., 2004; Zhang et al., 2004), petrological and metamorphic studies (Zhao et al., 2001a,b; Guo et al., 2002; O'Brien et al., 2005;), geochronological and isotopic studies (Halls et al., 2000; Kusky et al., 2001; Zhao et al., 2002; Wang et al., 2003; Wilde et al, 2004, 2005; Guo et al., 2005; Wu et al., 2005; Kröner et al., 2005a,b, 2006; Wan et al., 2006), and geological interpretations (Passchier and Walte, 2002; Kusky and Li, 2003; Zhai and Liu, 2003; Zhai et al., 2003, 2005; Wilde and Zhao, 2005; Zhao et al., 2005; Zhang et al., 2006). Several conclusions from these investigations can be summarized as follows: (1) the basement of the Trans-North China Orogen is dominated by late Archaean to Palaeoproterozoic (2.55–1.90 Ga) juvenile, arc-related crust with minor remnants of older (2.6–2.8 Ga) reworked basement; (2) high-pressure granulites and retrograded eclogites in the orogen are strongly deformed gabbroic dykes that were emplaced at ~1.92 Ga and experienced high-pressure metamorphism at ~1.85 Ga; (3) the widespread presence of ductilely deformed late Archaean to Palaeoproterozoic granitoid gneisses in the orogen indicates that the main deformation occurred in the Palaeoproterozoic; (4) the basement rocks in the orogen, regardless of their protolith age, composition and metamorphic grade, record similar clockwise metamorphic P–T paths involving near-isothermal decompression and reflecting a continental collisional setting; and (5) metamorphic zircons are present in both the Archaean and Palaeoproterozoic rocks of the orogen and yield consistent metamorphic ages around 1.85 Ga. These data support a model of collision between the Eastern and Western Blocks at ~1.85 Ga and not in the late Archaean.

The above conclusions are mainly derived from metamorphic, geochemical and geochronological studies, and few investigations have been carried out on the structural geology of the Trans-North China Orogen, and the lack of structural data has hampered further understanding of the orogen. Here we report structural data for the Hengshan Complex, a key area in the Trans-North China Orogen, where high-pressure granulites and retrograded eclogites have been reported (Wang et al., 1991; Zhao et al., 2001b; O'Brien et al., 2005).

2. Geological setting

Lithological, geochemical, structural, metamorphic and geochronological differences between the Eastern and Western Blocks and the Trans-North China Orogen have been summarized by Zhao et al. (2001b and references therein) and are not repeated here. This threefold subdivision of the North China

Craton has been further refined and modified by new geological data suggesting that the Western Block formed by amalgamation of the Ordos Block in the south and the Yinshan Block in the north along the E–W trending Khondalite Belt at 1.90–1.95 Ga, earlier than the collision of the Western and Eastern Blocks (Fig. 1; Zhao et al., 2005; Xia et al., 2006a,b). These data also suggest that the Eastern Block underwent a Palaeoproterozoic rifting event along its eastern margin in the period 2.2–1.9 Ga, forming the Jiao-Liao-Ji rift zone (Fig. 1; Hao et al., 2004; Luo et al., 2004; Li et al., 2006 and references therein; Lu et al., 2006).

The Trans-North China Orogen is a nearly S–N trending zone up to 100–300 km wide and ~1200 km long (Fig. 2) and is separated from the Eastern and Western Blocks by the Xingyang–Kaifeng–Shijiazhuang–Jianping Fault and the Huashan–Lishi–Datong–Duolun Fault, respectively (Zhao et al., 2001a). The orogen can be further divided into high-grade areas and low-grade granite–greenstone terrains. The former includes the Taihua, Fuping, Hengshan, Huaian, and Xuanhua Complexes, and the latter includes the Dengfeng, Zhongtiao, Zanhuang, Lüliang and Wutai Complexes (Fig. 2; Zhao et al., 1999, 2000a). Of these, the Hengshan, Wutai and Fuping Complexes generally collectively named the Hengshan–Wutai–Fuping belt, constitutes a lithologically representative transect across the middle segment of the Trans-North China Craton (Fig. 2). Of particular significance in this belt is the presence of a low- to medium-grade granite–greenstone terrain (Wutai Complex) intervening between two high-grade gneiss terrains (Hengshan and Fuping Complexes). The Hengshan Complex is separated from the Wutai Complex by a broad valley of the Hutuo River and bounded in the NW by the Sanggan River. The Fuping Complex was previously considered to be unconformably overlain by the Wutai Complex along the ‘‘Tiebao unconformity’’ (Bai, 1986; Wu et al., 1989), but this structure is

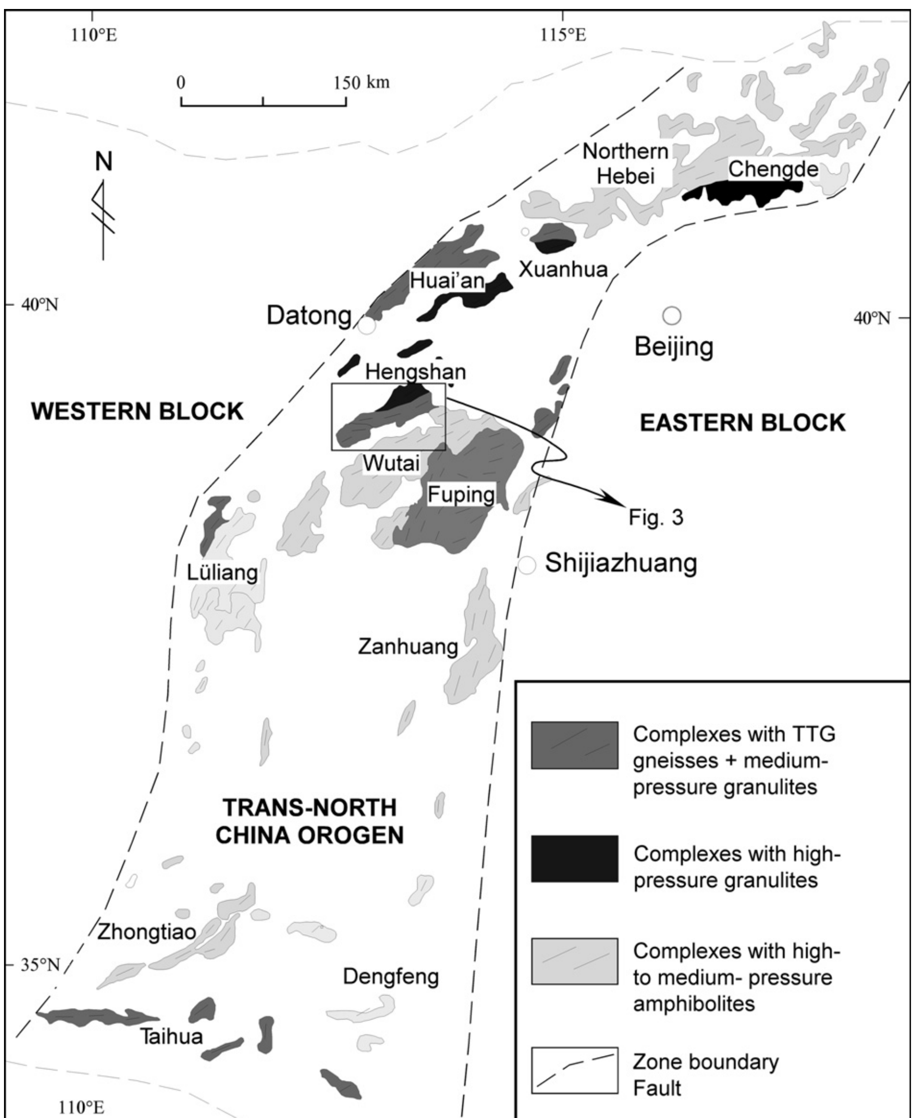

Fig. 2. Spatial distribution of rocks in the Trans-North China Orogen of the North China Craton, showing location of the Hengshan–Wutai–Fuping belt (Zhao et al., 2001b).

a regional-scale ductile shear zone, named the Longquanguan Ductile Shear Zone (Li and Qian, 1991), and the boundary between the Fuping and Wutai Complexes is therefore a tectonic feature.

The Hengshan Complex is a typical high-grade gneiss terrain with complexly deformed and partly migmatized orthogneisses and minor paragneisses (Li and Qian, 1994). It is composed of four lithotectonic units (Fig. 3): (1) Hengshan Tonalite–trondhjemite–granodiorite (TTG) gneisses with high-pressure granulites; (2) Hengshan TTG gneisses with medium granulites; (3) Zhujiafang supracrustal assemblage; and (4) Yixingzhai granitic gneiss (Tian, 1991; Li and Qian, 1994). The Hengshan TTG gneisses are layered orthogneisses of tonalitic–trondhjemitic–granodioritic–granitic compostion and cover more than 80% of the complex. These rocks underwent high-grade metamorphism and extensive migmatization at late Palaeoproterozoic (Wilde et al., 2002; Kröner et al., 2005a,b, 2006). Within the gneisses are discontinuous lenses or blocks of medium- and high-pressure mafic granulites, 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., 2005a, 2006). Regionally, the high-pressure granulites only occur north to the E–W trending Zhujiafang ductile shear zone, whereas the medium-pressure granulites and amphibolites crop out south to the shear zone (Fig. 3; O'Brien et al., 2005). The Zhujiafang supracrustal assemblage consists predominantly of amphibolite, felsic gneiss, mica schist, banded iron formation (BIF) and quartzite, and occurs largely along two nearly E–W trending belts that cut across the regional layering of the Hengshan TTG genisses and Yixingzhai gneisses. Some workers consider the Zhujiafang supracrustal assemblge to be the equivalent of the Wutai greenstones in the Hengshan area (Li and Qian, 1994; Tian et al., 1996), whereas others interpret at least part of these rocks as mylonitized orthogneisses and gabbroic dykes defining major ductile shear zones (Kröner et al., 2006). The Yixingzhai granitic gneisses are chemically similar to the Hengshan granitoid gneisses, but are characterized by strong ductile deformation and ubiquitous mylonitic fabrics, and are metamorphosed in lower amphibolite-facies (Tian, 1991). In addition to these four major lithologies, Kröner et al. (2005b) recognized minor Palaeoproterozoic granitoid gneisses in the Hengshan Complex, but these gneisses have not been mapped in detail and are intimately interlayered with the Archaean TTG gneisses.

The metamorphic evolution of the Hengshan Complex has been well studied (Zhao et al., 2001b; O'Brien et al., 2005). Petrological evidence indicates four distinct metamorphic assemblages in these granulites (Zhao et al., 2001b). The early prograde assemblage (M_1) is only preserved in high-pressure granulites and is represented by quartz and rutile inclusions within the cores of garnet porphyroblasts and omphacite

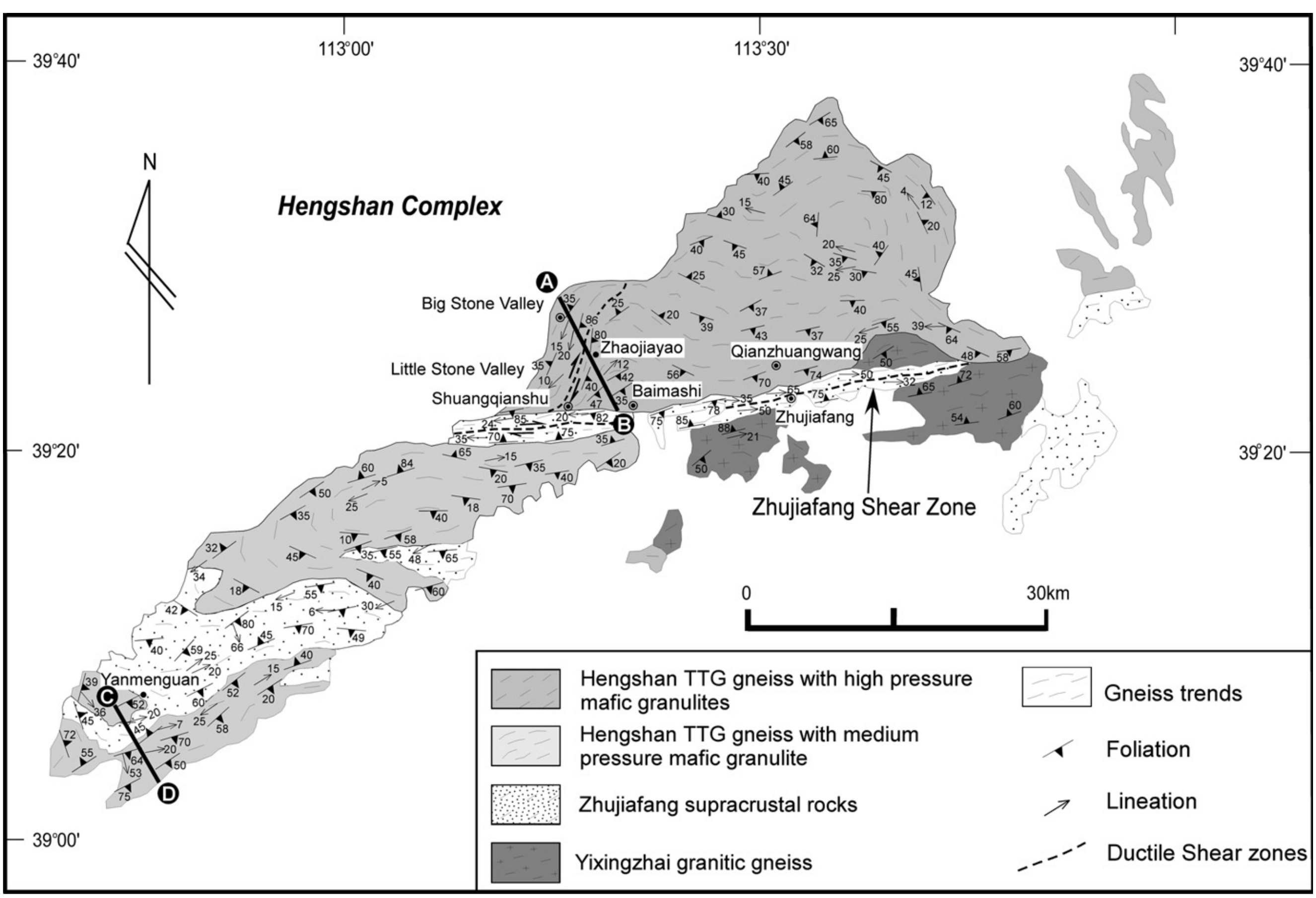

Fig. 3. Simplified geological map of the Hengshan Complex, showing the major lithological units and structural elements (after Tian, 1991; Miao, 2003 and this study).

pseudomorphs indicated by clinopyroxene + sodic plagioclase symplectic intergrowths. The P–T conditions cannot be quantitatively estimated because of the absence of representative high-pressure minerals (e.g. omphacite and garnet). The peak metamorphic phase (M_2) is characterized by the assemblage clinopyroxene + garnet + plagioclase + quartz ± hornblende in the high-pressure granulites, with P–T conditions of 13.4–15.5 kbar and 770–840 °C; and othropyroxene + clinopyroxene + garnet + plagioclase + quartz in the medium-pressure granulites, with P–T conditions of 9–11 kbar and 820–870 °C. Peak metamorphism was followed by near-isothermal decompression (M_3), which resulted in the development of orthopyroxene + clinopyroxene + plagioclase symplectites and coronas surrounding the embayed garnet grains, at P–T conditions of 8.0–6.5 kbar and 830–750 °C. Finally, these granulites experienced retrograde metamorphism, forming hornblende + plagioclase symplectites (M_4) on garnet (Zhao et al., 2001b). These mineral assemblages and their P–T estimates define clockwise P–T paths (Fig. 4), suggesting that the Hengshan Complex underwent initial crustal thickening and subsequent exhumation, which is considered to record a major phase of collision between the Eastern and Western Blocks to form the North China Craton (Zhao et al., 2001b).

Kröner et al. (2005a,b) have shown from zircon geochronology that the majority of the Hengshan TTG gneisses were emplaced between 2520 and 2475 Ma. They dated two high-pressure granulite-facies mafic dykes that contain magmatic zircons with clear oscillatory zoning and yielded mean $^{207}Pb/^{206}Pb$ ages of 1915 ± 4 Ma and 1914 ± 2 Ma. These ages were interpreted to reflect the time of emplacement of the mafic granulite precursors (Kröner et al., 2006). In addition, Kröner et al. (2005a,b) recognized minor 2360–2045 Ma granitoid gneisses within the Hengshan gneiss assemblage. It is important to note that the granitoids emplaced at 2360–2330 Ma display the same structural features as the older gneisses and thus unambiguously demonstrate that the main deformational event is not Archaean but Proterozoic in age. Metamorphic zircons from two high-pressure granulite-facies mafic dykes (with peak metamorphic P–T conditions of 13–15.5 kbar and 780–840 °C; Zhao et al., 2001b) yielded SHRIMP $^{207}Pb/^{206}Pb$ ages of 1850 ± 3 Ma and 1867 ± 23 Ma (Kröner et al., 2006). Metamorphic zircons from another two high-pressure granulite-facies mafic dykes were evaporated and produced mean $^{207}Pb/^{206}Pb$ ages of 1859.7 ± 0.5 Ma and 1881.3 ± 0.4 Ma (Kröner et al., 2006). These data show that the granulite-facies metamorphic event in the Hengshan Complex occurred at ~1.85 Ga. A later, cross-cutting and unmetamorphosed mafic dyke in the Hengshan Complex was dated at 1769 ± 2.5 Ma (Halls et al., 2000), suggesting that a post-collisional extensional event led to intrusion of a mafic dyke swarm shortly after the *c*. 1.85 Ga collisional event (Zhao et al., 2001a).

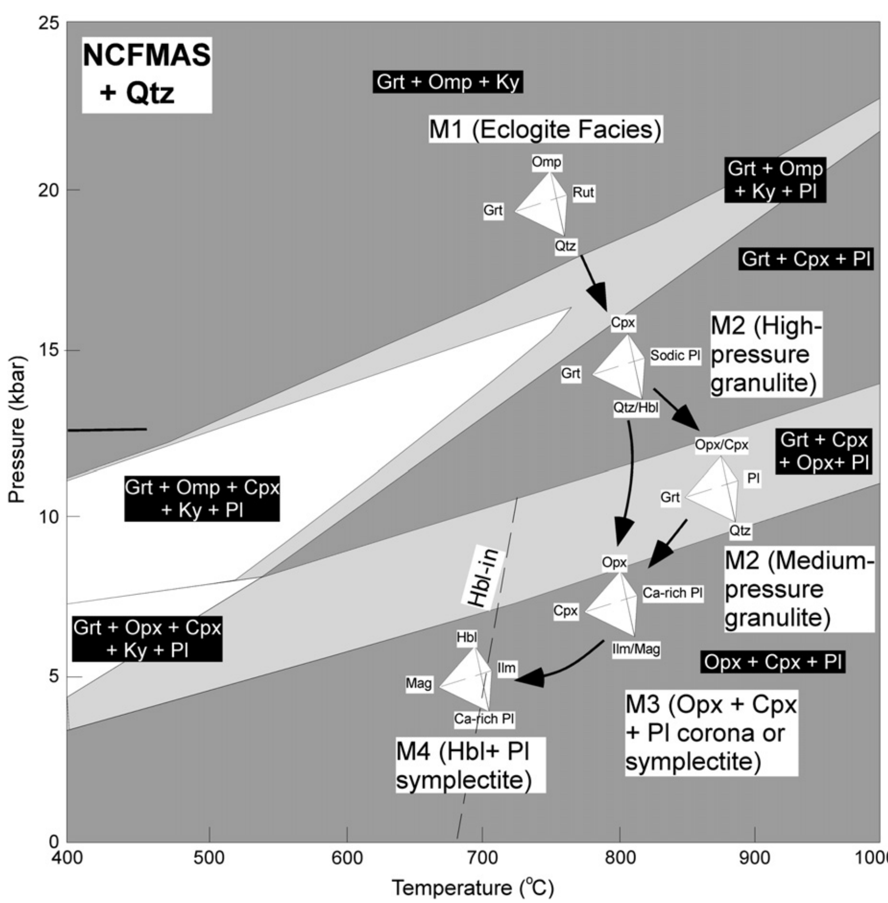

Fig. 4. P–T evolution of the mafic granulites of the Hengshan Complex showing different metamorphic stages (Zhao et al., 2001b).

3. Structural geology

Structurally, the Hengshan Complex can be subdivided into the northern and southern domains, separated by the Zhujiafang ductile shear zone. The northern domain is interpreted to represent a lower crustal segment which underwent high-pressure granulite-facies metamorphism and ductile deformation, whereas the southern domain represents a middle crustal segment that underwent medium-pressure granulite-facies metamorphism and intensive deformation (Kröner et al., 2005a and references therein).

The Hengshan gneisses display folds interference patterns and shear zones (Fig. 3) that can be resolved into five principal episodes of deformation (D_1−D_5). The D_1 deformation generated a compositional fabric and a sub-parallel foliation (S_1). S_1 was then transposed by the subsequent D_2 deformation. Top-to-the-NW thrusting characterizes the D_2 deformation and produced the dominant fabrics in the Hengshan Complex. Associated with the D_2 deformation is the development of the transpressional Zhaojiayao ductile shear zone (D_3). Subsequent near the E−W trending Zhujiafang ductile shear zone (D_4) crosscuts the earlier D_3 shear zone and is considered to represent a major tectonic boundary between the northern and southern domains. The latest extensional deformation (D_5) was associated with the exhumation of the Hengshan Complex and reworked the early fabrics. These episodes of folding and shearing and the resulting major structural features are described as follows.

3.1. Deformation D_1

Structures designated as D_1 include micro- to mesoscopic folds (F_1) and associated penetrative axial plane foliation (S_1) and a mineral stretching lineation (L_1). The D_1 fabrics are pervasive in the Hengshan Complex and show different characteristics in different metamorphic grade rocks. They include small-scale, tight isoclinal, rootless intrafolial folds, here designated F_1, which are rarely preserved and limited to several decimetre-scale folds (Fig. 5a). F_1 is reworked by the subsequent D_2 to D_5 deformation, and thus it is hard to restore its original orientation. Parallel to the F_1 fold axial plane is S_1 that is usually a transposing and intrafolial foliation. The S_1 foliations mostly show a preferred orientation, although random and irregular S_1 foliations are dominant in the northern domain of the Hengshan Complex due to reworking by the later deformational events (e.g. D_2 and/or D_5). As shown in the stereonet

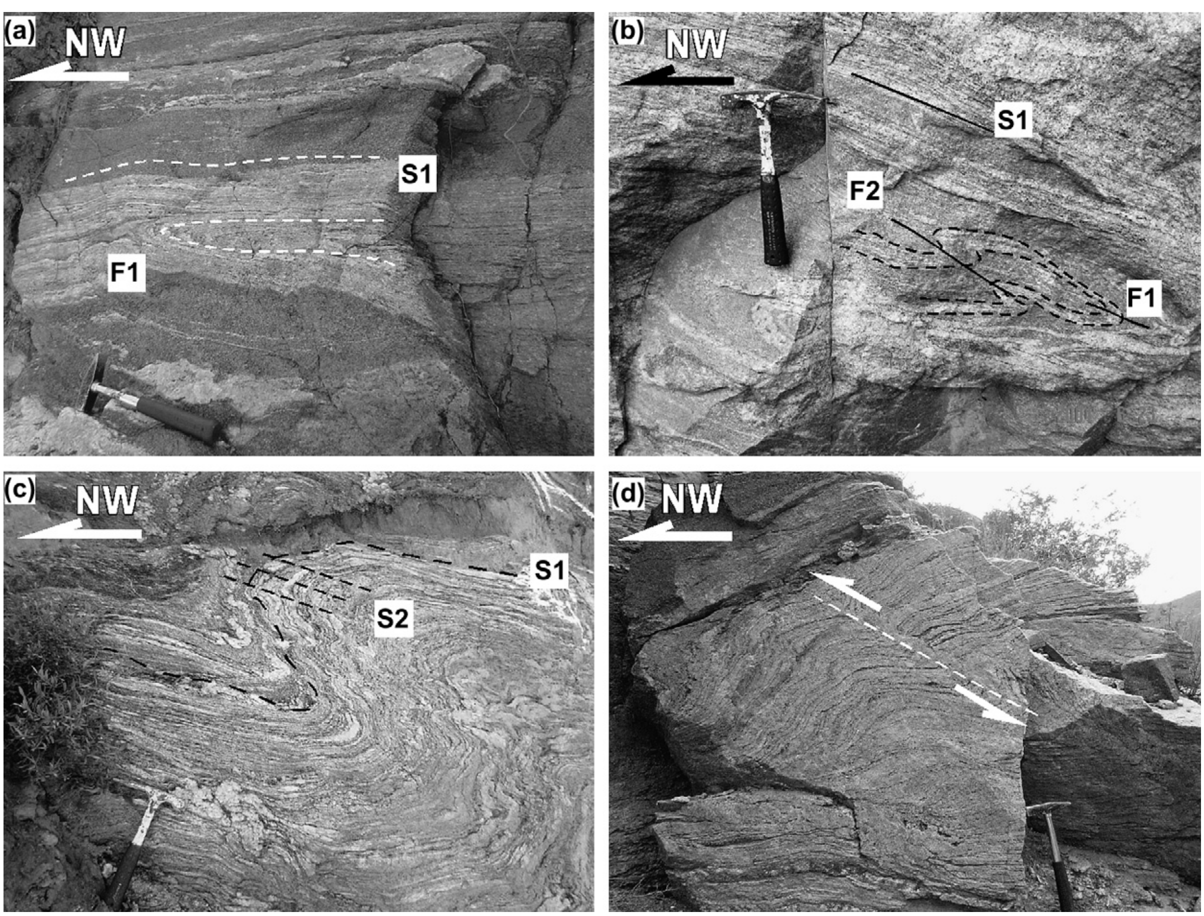

Fig. 5. Field photographs of typical structures associated with D_1 and D_2 deformation in the Hengshan Complex. (a) F_1 tight isoclinal folds preserved in TTG gneiss, with F_1 fold axial plane (S_1) preserved in mafic rocks. (b) superimposition of F_2 and F_1, F_2 fold axial plane (S_2) is sub-parallel with the S_1 foliation. (c) S_2 crenulation cleavage preserved in the hinge zone of F_2 folds in the high-grade gneisses of the Hengshan Complex. S_2 is parallel to S_1 at the limbs and intersects S_1 in the hinges. (d) Small ductile shear zone (D_3) formed during D_2 deformation, indicating top-to-the-NW shearing.

projections that represent a cross-section through the northern part of the area (Fig. 6), the S_1 foliations are pervasive throughout the region, mostly dipping SE except for the north area. Where amphibole and granulite boudins are present, the S_1 foliations occur as asymmetrical and irregular folds around these boudins. At the lower crustal level where high-pressure granulites formed, ductile deformation and migmatization are pervasive and different parts of a rock body are deformed (folded) to different degrees.

3.2. Deformation D_2

The D_2 deformation is marked by tight to open, asymmetric folds (F_2), axial plane foliations (S_2), and crenulation and mineral stretching lineations (L_2). F_2 refolds earlier D_1 fabrics, and in most cases shows successive deformation from D_1 to D_2 (Fig. 5b). Also associated with D_2 is the development of transpressional shearing in many areas of the complex.

A detailed structural investigation has been carried out along the Big Stone Valley section (Fig. 3). The F_2 folds occur at different scales, varying from a few metres to several kilometres (Fig. 6), though the centimetre-scale F_2 folds are ubiquitous and easy to recognize in the field. Regionally, most of the F_2 asymmetric fold axes are nearly horizontal and plunge NE or SW. Some F_2 fold axes plunge NNE or SSW, which may have resulted from later reworking by the D_3 and/or D_5 deformation (Fig. 6). Although classical overprinting criteria such as crenulation foliations and small-scale refolded folds are less commonly present in high-grade gneiss terrains than in medium- to low-grade areas (Passchier et al., 1990), the existence of refolded S_1/S_2 patterns can be important structural evidence for structural superimposition. The D_2 fabrics consist

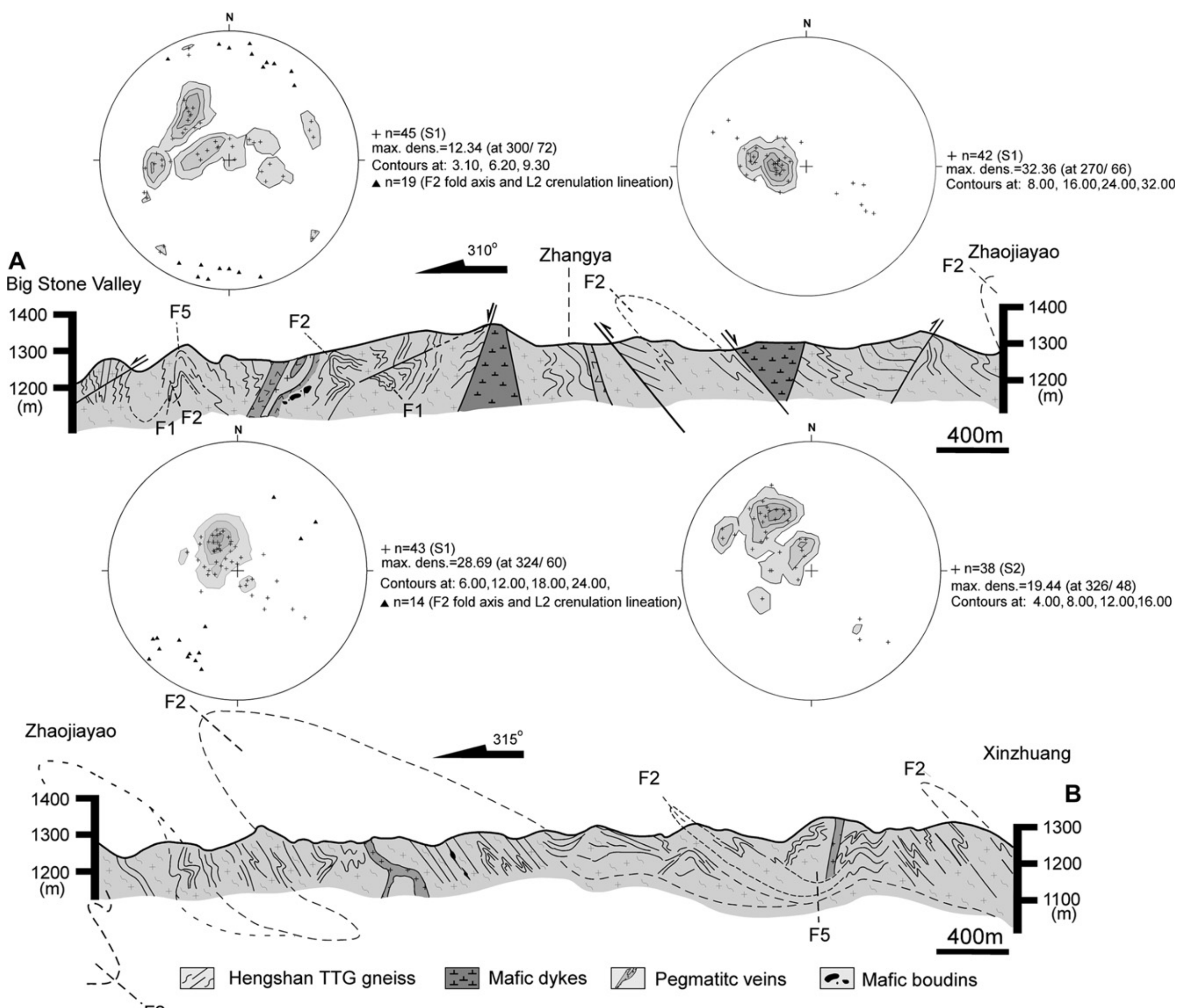

Fig. 6. Geological cross-section of the northern domain of the Hengshan Complex (locality of cross-section 'A–B' in Fig. 3). NW-verging folding and shearing (D_2) is responsible for the main structural pattern, although D_1 fabrics in the northern part display complicated orientations and show domiform patterns in the stereonet projection (most likely affected by later deformations). The structural elements indicate a preferred orientation dipping to the SE. Variable scales of the F_2 asymmetric folds overprint D_1 fabrics, indicating top-to-the-NW thrusting. The S_2 foliation dips similar to S_1, but commonly steeper.

of well developed, continuous S_2 foliation. The S_2 foliation is either parallel to the axial planes of F_2, deforming an earlier S_1 foliation, or represents a composite surface resulting from transposition of S_1. In the former case, S_2 is sub-parallel to the S_1 foliation in the limbs of F_2 folds and intersects at a high angle with S_1 in the hinge zones (Fig. 5c). The major D_2 fabrics are represented by a series of large-scale folds (F_2) and associated foliation (S_2) which are parallel to southeast-dipping S_1 foliations, indicating that the F_2 folds formed as a result of refolding of the earlier S_1 foliation. Most of the small-scale, tight to isoclinal, asymmetric F_2 folds in the Big Stone Valley show top-to-the-NW thrusting in the hanging wall.

To understand the major deformational features in the southern domain of the Hengshan Complex, we measured a detailed structural section along the Yanmenguan Valley (“C-D” on Fig. 3 and Fig. 7). Like those in the northern domain, the structural elements of the D_2 deformation are also pervasive. F_2 folds are ubiquitous, and some metamorphosed mafic dykes have also been deformed into asymmetric folds indicating a top-to-NW thrusting. Here, S_2 is a penetrative foliation almost parallel to the S_1 foliation, dipping towards the southeast. Associated with the NW-verging F_2 asymmetric folds and axial planar S_2 foliations are thrusts (Fig. 7). In most cases, the F_2 axes plunge NE or W, whereas their axial planes dip SE. Like those in the northern domain, the F_2 axes in the southern domain have been slightly re-orientated by later D_5 deformation (Fig. 7). Two distinct groups of L_2 lineations have been recognized. The first group, here defined as L_{2b} is a b-type lineation orientated parallel to F_2 fold axis and perpendicular to the relative sense of motion. The L_{2b} lineation is characterized by crenulation lineation, sub-horizontally plunging NE or SW (Fig. 7). The second group, here defined as L_{2a} is a SE-plunging mineral stretching lineation, marked by elongated hornblende grains and small grains of stretched quartz, which is an

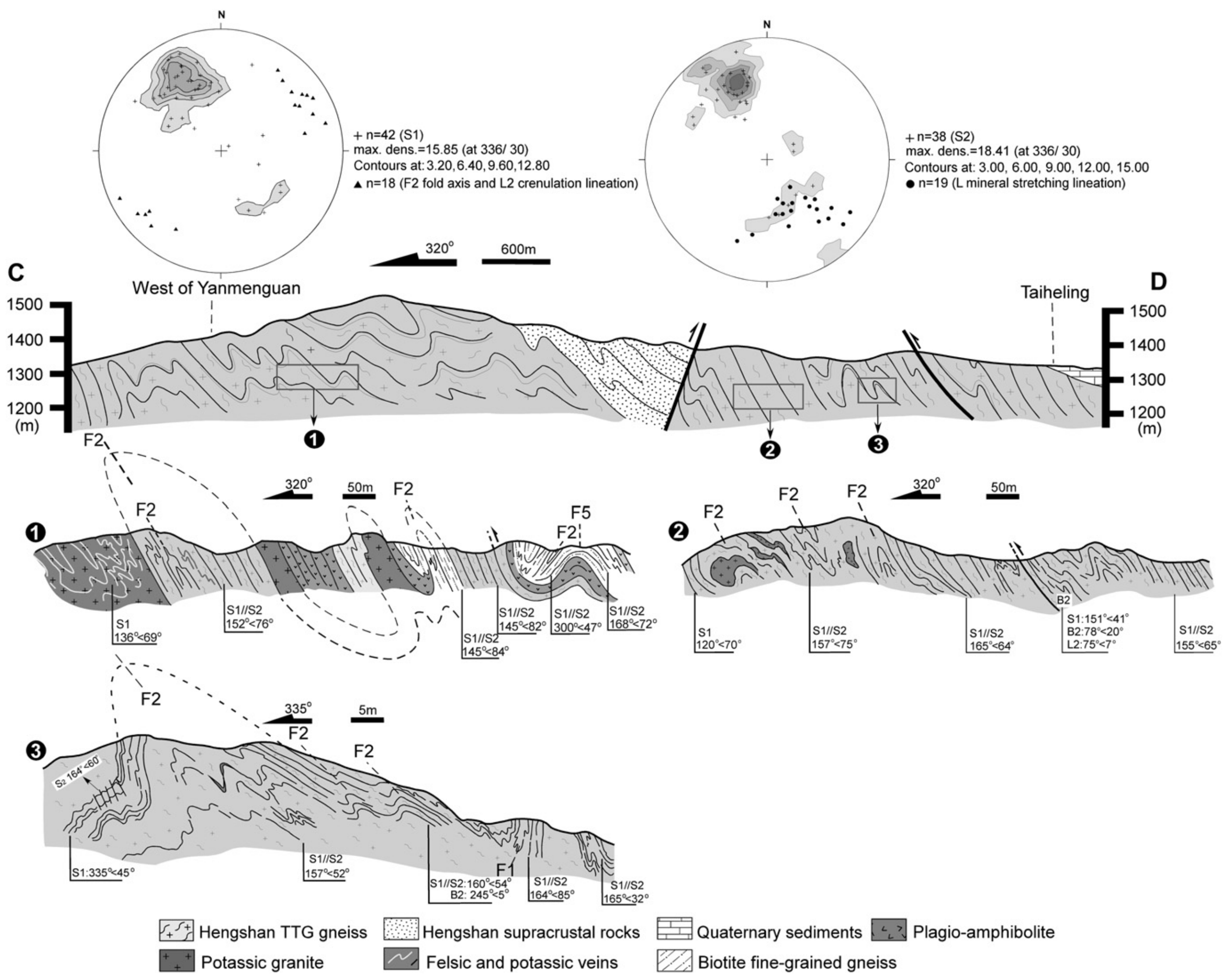

Fig. 7. Geologcial cross-section in the southern domain of the Hengshan Complex (locality of cross-section ‘C-D’ in Fig. 4). Sections 1–3 display the detailed structures of different parts, respectively. (1) Section 1: Major D_2 fabrics are superimposed by subsequent deformations. S_1 foliation underwent intensive folding and completely reworked by S_2 foliation. (2) Section 2 is characterized by a series of the F_2 asymmetric folds and thrust faults, indicating a top-to-the-NW thrust. F_2 fold axis (B_2 axis) and L_2 crenulation lineations (b-type lineation) plunge to the NEE–SWW. (3) Section 3 displays a medium-scale antiform forming during the D_2 deformation. SE limb of antiform is represented by small-scale F_2 asymmetric folds, suggesting an intense shortening during D_2 deformation, whereas the lack of these folds in the NW limb suggests only a passive rotation of the S_1 foliation during D_2 deformation.

a-type lineation parallel to the relative movement direction. The stereonet projection of the L_{2a} lineations on the S_2 plane indicates a NW-directed movement in the hanging wall. Regionally, the D_2 deformation is characterized by NW–SE shortening.

3.3. Zhaojiayao ductile shear zone (D_3)

High strain concentration during D_2 deformation led to the development of a series of transpressional ductile dextral shear zones (D_3) of varying scales, of which the most representative is the Zhaojiayao ductile shear zone. We interpret these shear zones as a result of transpressional deformation in association with the D_2 structures. In the field, two diagnostic types of shearing can be recognized, namely oblique-slip shearing along the F_2 fold axial planes, and strike-slip shearing along the F_2 fold hinges.

3.3.1. Oblique-slip shearing

The NNE–SSW trending oblique-slip ductile shear zones are parallel to the hinges of most small-scale F_2 folds. It is manifested by SE-dipping mylonitic foliations as seen in metre-scale outcrops. Regionally, the mylonitic foliations within oblique-slip shear zones are invariably parallel to the S_2 foliation, suggesting that they developed simultaneously with, or immediately following, the D_2 deformation. A successive relationship between this type of oblique-slip shearing and F_2 can be observed in some outcrops (Fig. 5d). Both the F_2 asymmetric folds and the asymmetric fabrics of small-scale shear zones indicate top-to-the-NW shearing and thrusting, which suggests that D_2 deformation occurred in a compressive environment.

3.3.2. Strike-slip shearing

The strike-slip shearing is represented by a series of NNE–SSW trending ductile shear zones, successively following the D_2 deformation. They are observed in the field as a series of asymmetrical F_2 fold limbs that are offset by shears along the fold axial planes. At some localities, the Hengshan grey gneisses are refoliated by strong NNE–SSW strike-slip shearing that cuts across earlier foliations. In the areas northwest of the Zhaojiayao Village (Fig. 3), some fine-grained felsic gneisses are locally interlayered with the coarse-grained TTG gneisses, and have all been intensively deformed into fine banded, upper amphibolite-facies gneisses that have structural features similar to those in the ductile shear zones in the Little Stone Valley as described by Kröner et al. (2005a). The shear zone outcropped at Zhaojiayao Village is about 100 m in width and is characterized by steep mylonitic fabrics and numerous kinematic indicators, such as sheath folds, ‘δ’/‘σ’-type augen and asymmetric folds, all indicating NNE–SSW dextral movement. Sheath folds to the north of the Zhaojiayao Village indicate top-to-the-SSW shearing (Fig. 8a, b). On a YOZ section, a plane perpendicular to long axis *X*, the fold is a circle type (Fig. 8a, b) or a ‘Ω’ type (Fig. 8c), and on a XOZ section the fold is an asymmetric ‘Z’ type with the hinge tip to the shearing direction. Measurement of the mineral lineations, which are parallel to the hinges of ‘Ω’ type folds, indicates that the *X*-axes point to the SSW (205°), also representing the shearing direction (Fig. 8c). The mylonitic foliation varies from horizontal to steep, and the mineral stretching lineations plunge NNE with a shallow angle (Fig. 9a). Some high-pressure granulite boudins were deformed to σ-type augen, indicating a dextral (NNE–SSW) sense of shearing (Fig. 8d). Earlier fabrics (e.g. S_1) are well preserved in some boudins where they are crosscut by the strongly deformed anatectic veins that have been refoliated to asymmetric isoclinal folds with a similar NNE–SSW dextral sense of shearing (Fig. 8d). These anatectic veins are probably derived from partial melting of TTG gneisses under high temperature conditions, and thus the Zhaojiayao ductile shear zone could have developed at a relative deep crustal level. Regionally the D_3 structures extend across the northern domain of the Hengshan Complex, where they have variably re-orientated F_2 fold axes to NNE–SSW (Fig. 6), whereas in the south they are crosscut by the later E–W trending Zhujiafang ductile shear zone (D4).

3.4. Zhujiafang ductile shear zone (D_4)

The second episode of shearing D_4 is represented by the Zhujiafang ductile shear zone (Fig. 3), which is the largest ductile shear zone in the Hengshan Complex extending E–W and up to ∼60 km long or ∼2 km wide. It is considered to represent an important metamorphic boundary between the northern and southern domains of the Hengshan Complex, where high- and medium-pressure granulites are preserved, respectively (Kröner et al., 2005a; O’Brien et al., 2005). North of the Zhujiafang ductile shear zone, the dips of NE–SW trending foliations are progressively steepened and the strikes change to approximately E–W in areas adjacent to the shear zone (Figs. 8e, 9b, c). At the margin of the shear zone, the grey gneisses have undergone intense deformation to complete refolding (Fig. 8f). An S–L fabric is pervasively developed in this shear zone. On the mylonitic foliation, mineral stretching lineations are characterized by elongated hornblende grains, pyroxene aggregates and stretched quartz grains, plunging to the east and west at moderate to high angles (Figs. 9b, c, d). Many other movement indicators, including intrafolial asymmetric folds and asymmetric porphyroblasts such as “σ-type” augen, provide an unambiguous sense of movement that indicates an E–W orientated dextral sense of shearing. In addition, mafic dykes that intruded into the Zhujiafang supracrustal rocks and the Yixingzhai TTG gneisses (Fig. 3) have the same deformational features. At the margins of the dykes, the mineral stretching lineations are represented by well-elongated hornblende aggregates that plunge shallowly to the east and west, although less deformation is recorded in the interior of the dykes. This suggests that the mafic dykes also underwent shearing deformation. Regionally, the D_4 fabrics show transpressional features involving oblique convergence and strike-slip shearing, similar to D_3. We suggest that this shear zone probably developed through relative movement between the lower (northern domain) and middle (southern domain) crust during the collisional event.

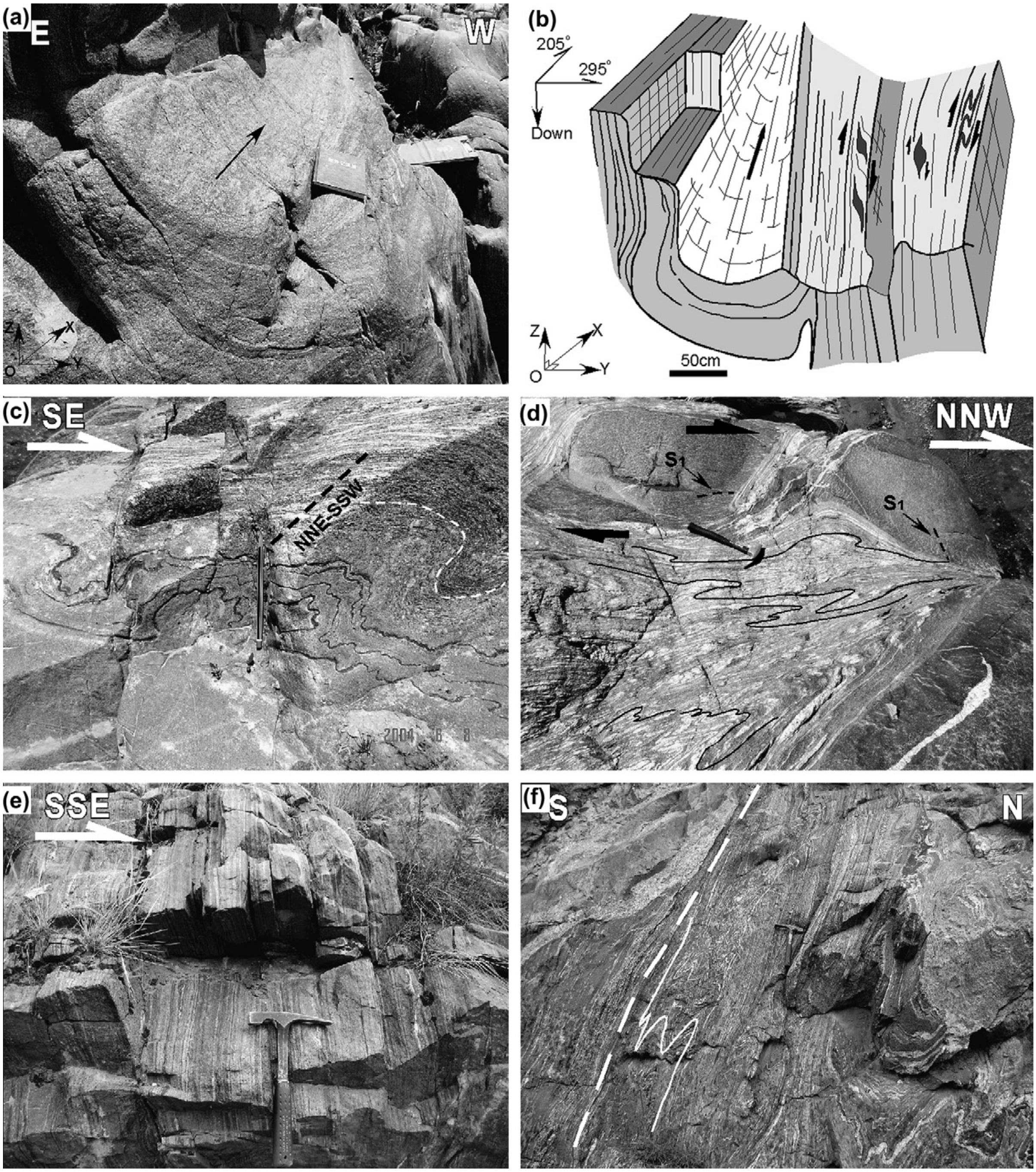

Fig. 8. Field photographs showing ductile shear zones in the Hengshan Complex. (a) A sheath fold in the Zhaojiayao ductile shear zone (D_3), with mineral stretching lineations characterized by elongated hornblende crystals, indicating NNE–SSW sense of shearing. On the YOZ section, it shows a circle-type fold. (b) A sketch diagram outlining the sheath fold in the Zhaojiayao ductile shear zone (D_3) and relative kinetic indicators. Mafic rocks were dragged to 'σ'-type augen, suggesting a dextral strike-slip sense of shearing. (c) Another type of sheath folds observed in the Zhaojiayao ductile shear zone (D_3), representing an 'Ω'-type fold on the YOZ section. Orientation of sheath fold tip is equal to other kinetic indicators, indicating a top-to-the-SSW movement. (d) Anatectic veins folded by ductile shearing, with earlier fabrics (e.g. S_1) preserved in the mafic boudins (HP granulites). (e) Grey gneiss and mafic dykes developed in the Zhujiafang ductile shear zone (D_4). (f) Intensely folded grey gneisses at the margin of the Zhujiafang ductile shear zone (D_4).

3.5. Deformation D_5

The D_5 deformation produced regional-scale open folds, reworking earlier D_1 to D_4 fabrics. The F_5 folds are defined as upright open folds and generally lack an axial plane foliation. The superimposition of D_5 on D_1 and D_2 plays an important role in shaping the general structural outline of the Hengshan Complex, for example, the regional-scale dome-and-basin structure in the Hengshan Complex (Fig. 3). In the southern domain, especially in areas close to Yanmenguan, three phases of folding (F_1, F_2 and F_5) can be observed in a single outcrop (Fig. 10a). Both of the F_1 and F_2 folds were slightly refolded

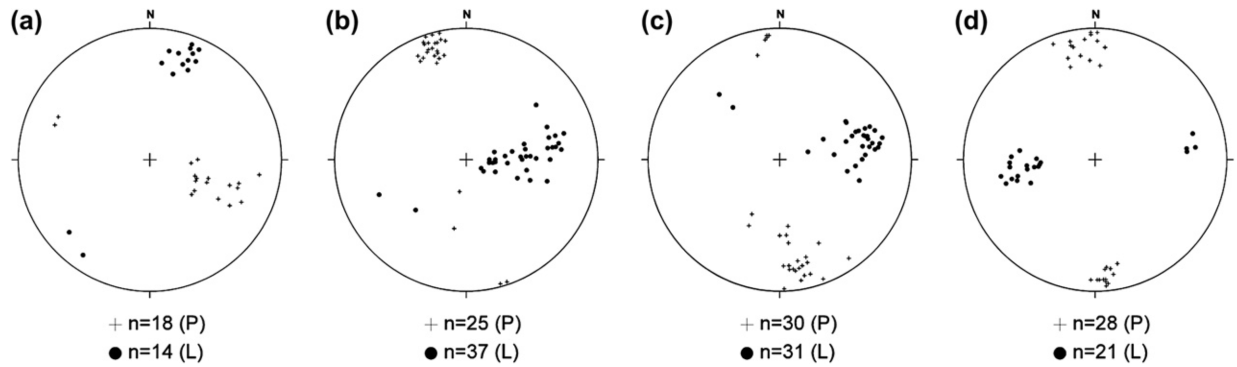

Fig. 9. Stereonet projections (equal area projection, lower hemisphere) showing the poles to mylonitic foliations (cross) and dominant orientations of mineral stretching lineations (dot) in the Zhaojiayao (D_3) and Zhujiafang ductile shear zones (D_4). (a) D_3 structural elements in the northern domain of the Hengshan Complex; (b) D_4 structural elements, Eastern segment of the Zhujiafang ductile shear zone, north of Zhujiafang Village; (c) D_4 structural elements, Eastern segment of the Zhujiafang ductile shear zone, south of Zhujiafang Village; (d) D_4 structural elements, Western segment of the Zhujiafang ductile shear zone, around Shuangqianshu Village.

by F_5, and some earlier fabrics have been transformed to slip bands along the two limbs of F_5, indicating that the D_5 represents an extensional episode after collision (Fig. 10a). D_5 has also reworked the Zhujiafang ductile shear zone (D_4) to be open folds, where a nearly vertical cleavage can be observed along fold axial planes (Fig. 10b). The absence of S_5 foliations in F_5 hinges suggests that D_5 occurred at a lower temperature and brittle condition than D_1 to D_4. Also associated with the D_5 deformation is a series of low angle detachment faults, indicating post-collisional extension after a compressional event (Fig. 10c).

4. Summary and discussion

The structural data reported here show that the Hengshan Complex underwent five episodes of deformation (D_1–D_5). The first episode (D_1) resulted in the formation of tight isoclinal folds (F_1) and associated foliations (S_1). Most D_1 fabrics have been overprinted by D_2, although some structural elements are well preserved in the pre-tectonic mafic dykes (Fig. 8d), now preserved as boudins of high- and medium-pressure mafic granulites (Kröner et al., 2006 and references therein). The SE-dipping D_1 fabrics were most probably products of early NW–SE-directed compressive deformation and D_1 may have occurred simultaneously with early prograde metamorphism (M_1), represented by quartz and rutile inclusions in the cores of garnet porphyroblasts and by omphacite pseudomorphs as indicated by the symplectic intergrowths of clinopyroxene and sodic plagioclase in the high-pressure granulites (Zhao et al., 2001b).

D_2 is the major penetrative deformation, leading to the development of ubiquitous open to tight asymmetric folds (F_2) and composite foliations (S_1/S_2). NE–SW-directed L_{2b} lineations (crenulation lineations) and F_2 fold axes and NW–SE-directed mineral L_{2a} stretching lineations (Fig. 7), suggest that the Hengshan Complex underwent strong NW–SE-directed shortening. The NW-verging F_2 asymmetric folds and thrust faults of varying scales indicate top-to-the-NW thrusting, leading to regional-scale crustal thickening and high-pressure granulite-facies metamorphism. The typical high-pressure assemblage in the deformed mafic dykes is clinopyroxene + garnet + plagioclase + quartz, with P–T conditions of 13.4–15.5 kbar and 770–840 °C (Zhao et al., 2001b), suggesting that the crust was thickened up to ~55 km during D_2.

Associated with D_2 was the development of the NNE–SSW-striking transpressional Zhaojiayao ductile shear zone (D_3) at a relative deep crustal level. The shear zone resulted from dextral transpression combined with top-to-the-NW oblique-slip shearing and NNE–SSW dextral strike-slip shearing. An earlier study interpreted this shear zone as a result of strike-slip shearing overprinted by extensional deformation (Huang et al., 2003). This assumption is inconsistent with our observation that the shear zone is characterized by a steep mylonitic foliation and is controlled by transpression that does not seem to be of an extensional nature.

The Zhujiafang ductile shear zone (D_4) is characterized by the development of a steep to sub-vertical mylonitic foliation associated with an E–W directed lineation with shallow to medium plunges. All rocks within the shear zone underwent near E–W oriented dextral shearing along the contact between the northern and southern domains of the Hengshan Complex (Fig. 3). Some workers suggested that the Zhujiafang ductile shear zone is correlated with a major extensional event (Li et al., 2002), whereas others argue that it represents an important boundary between the lower and middle crust, along which the lower crustal components including high-pressure granulites were exhumed to a shallower level or the surface (O'Brien et al., 2005, Kröner et al., 2005a,b, 2006). Field observation such like steep foliations, moderately plunging lineations in the shear zone and transpressional mechanism does not support the viewpoint that it is a major extensional feature. As mentioned earlier, high-pressure granulites only occur north of the Zhujiafang ductile shear zone, whereas rocks to the south were metamorphosed only at amphibolite-facies, consistent with the latter interpretation. In our interpretation, the nearly E–W collision between the Eastern and Western Blocks led to movement of the lower crust thrust/exhumed along the Zhujiafang ductile shear zone, bringing high-pressure granulites up to a shallow level.

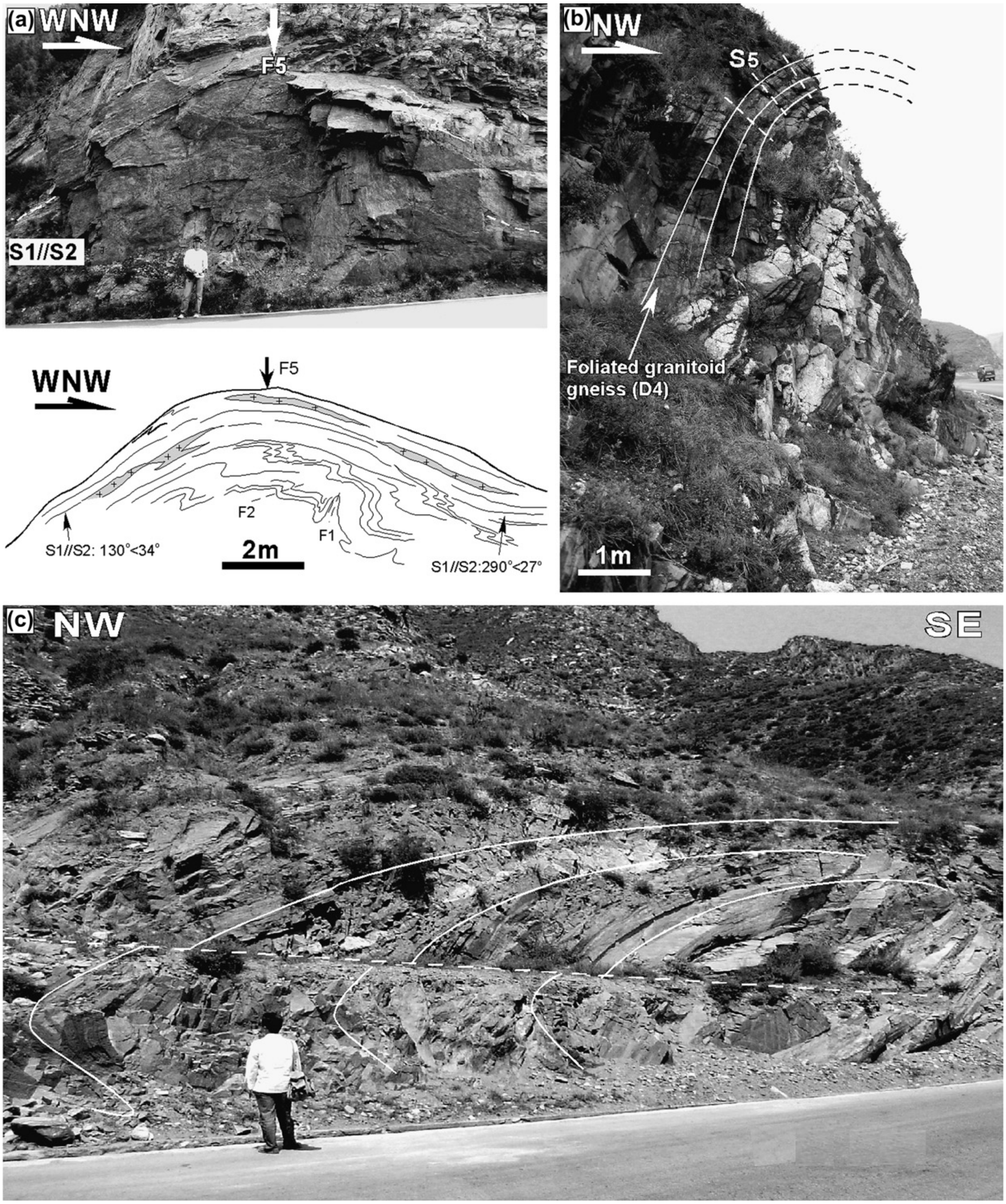

Fig. 10. Field photographs showing the Zhujiafang ductile shear zone (D_4) and D_5 deformation in the Hengshan Complex. (a) NNE–SSE trending upright open F_5 fold, overprinting earlier D_1 and D_2 fabrics. (b) The Zhujiafang ductile shear zone (D_4) is folded by subsequent D_5 deformation. (c) D_5 Low angle detachment fault developed in the supracrustal rock assemblages in the Hengshan Complex.

D_5 deformation may be related to exhumation/uplift of the entire Hengshan Complex, which may have occurred simultaneously with formation of the near-isothermal decompressional assemblage orthopyroxene + clinopyroxene + plagioclase (M_3) symplectites and coronas and a cooling assemblage of hornblende + plagioclase (M_4) symplectites surrounding embayed garnet grains (Zhao et al., 2001b).

Similar structural patterns, high-pressure metamorphism, and exhumation of high-pressure rocks are also well established in young orogens such as the Cenozoic European Alps (Escher and Beaumont, 1997; Ceriani et al, 2001; Ganne et al., 2005; Behrmann and Tanner, 2006). In the European Alps, two earlier tectonic stages are NW vergent and correspond to the subduction of continental margin crust, crustal thickening, fold nappes and high-pressure metamorphism (Escher and Beaumont, 1997; Behrmann and Tanner, 2006). The further descent of continental crust initiated the uplift and exhumation of high- to medium-pressure rocks under compressional conditions and squeezed these rocks to the surface along a certain boundary (Chemenda et al., 1995; Ganne et al., 2005). Meanwhile, collision led to backfolding and thrusting in the hinterland of Alps (Escher and Beaumont, 1997) that can be correlated to the structural patterns of the Fuping Complex in the Trans-North China Orogen (work on-going). Later ductile to brittle deformation represents an extensional stage, probably corresponding to a regional retrogression (Ceriani et al., 2001; Ganne et al., 2005). The whole orogenic process probably lasted for 60–70 million years, consistent with that (1880–1820 Ma) of the Trans-North China Orogen (Zhao et al., in press).

5. Tectonic implications

In earlier studies, the tectonic evolution of the Hengshan Complex was considered to be related to closure of the Wutai rift (Tian, 1991; Yuan and Zhang, 1993) or the collision between the Hengshan and Fuping micro-continental blocks (Bai, 1986; Bai et al., 1992; Li et al., 1990; Li and Qian, 1994; Wang et al., 1996; Wu and Zhong, 1998). However, more recent data suggested that the Hengshan, Wutai and Fuping Complexes were all part of a single late Archaean to Palaeoproterozoic magmatic arc that was incorporated into the Trans-North China Orogen during collision of the Eastern and Western Blocks (Zhang et al., 2004; Zhao et al., 2005; Wilde et al., 2005; Wilde and Zhao, 2005; Kröner et al., 2006). In the past few years, a large amount of geological data have been produced related to this collisional event (e.g. Zhao et al., 2001a,b; Kusky and Li, 2003; O'Brien et al., 2005; Polat et al., 2006; Wu et al., 2005; Zhai et al., 2005; Liu et al., 2006; Kröner et al., 2006). Detailed structural analysis of the Hengshan Complex lead us to provide important constraints to understanding the tectonic processes involved in the subduction and collision of the Western and Eastern Blocks along the Trans-North China Orogen.

As mentioned earlier, Kusky and Li (2003) and Polat et al. (2005, 2006) proposed westward-directed subduction of an old ocean between the two blocks, with final collision at ~2.5 Ga, whereas many other workers have suggested eastward-directed subduction, with final collision at ~1.85 Ga (Wu and Zhong, 1998; Zhao et al., 2000a, 2001a; Zhao, 2001; Wilde et al., 2002). The latter model has been strongly supported by geological and geochronological data obtained in the last few years (Guan et al., 2002; Zhao et al., 2002; Wilde et al., 2004; Guo et al., 2005; Kröner et al., 2005a,b, 2006). Firstly, both SHRIMP U–Pb metamorphic zircon ages and mineral Sm–Nd and Ar/Ar ages produced indicate that metamorphism in the Trans-North China Orogen occurred at ~1.85 Ga (Guo and Zhai, 2001; Guan et al., 2002; Zhao et al., 2002; Wang et al., 2003; Guo et al., 2005; Kröner et al., 2005a,b, 2006; Liu et al., 2006). Secondly, recent geochronological data also reveal the existence of 2.65–2.85 Ga old continental components in the arc-related granitoid gneisses and volcanic rocks of the Trans-North China Orogen (Liu et al., 1997; Wilde et al., 1997, 2004; Guan et al., 2002; Zhao et al., 2002; Kröner et al., 2005a,b). These old crustal components most likely represent the remnants of older continental crust related to the Eastern Block, suggesting that the arc developed as a continental arc (Japan-type island arc or Andean-type continental margin arc). Rocks with reliable ages of 2.65–2.85 Ga were have not been reported from the Western Block, but occur widely in the Eastern Block, especially Shandong, Southern Jilin and Northern Liaoning Provinces (Jahn et al., 1988; Zhao et al., 1998). This strongly suggests that the arc developed on the western margin of the Eastern Block, and thus, that subduction between the Western and Eastern Blocks was eastward-directed (Zhao et al., 2001a, 2005). Structural data presented in this study are also consistent with eastward-directed subduction, since most early structures (e.g. D_1, D_2 and D_3) in the Hengshan Complex indicate top-to-the-NW thrusting.

Based on these new structural data and available lithological, metamorphic and geochronological data, we propose the following brief scenario for the evolution of the Trans-North China Orogen (Fig. 11):

(1) In the period 2560–1880 Ma, the Hengshan Complex and associated Wutai and Fuping Complexes were part of a magmatic arc that developed by the eastward subduction of an old ocean beneath the western margin of the Eastern Block (Fig. 11a). Associated with the development of the arc were the sequential formation of the late Archaean Wutai granitoids, Wutai greenstone-type volcanics, supracrustal rock assemblages, Hengshan and Fuping TTG gneisses, a multiphase of Palaeoproterozoic granitoids (e.g. the Nanying granitoid gneisses in the Fuping Complex and the Dawaliang granite in the Wutai Complex), Palaeoproterozic Hutuo Group, and 1915 Ma Hengshan mafic dykes (now high- to medium-pressure mafic granulites).

(2) At 1880–1850 Ma, the old ocean between the Eastern and Western blocks of the North China Craton was consumed by subduction, and continent-arc-continent collision between the blocks occurred (Fig. 11b). At the initial stage, the collision led to the development of regionally top-to-the-NW thrusting, small-scale tight isoclinal folds (F_1) and associated penetrative foliations (S_1) in the lithologies of the Hengshan Complex, accompanied by early prograde metamorphism (M_1).

(3) Ongoing subduction of the Western Block led to crustal-scale top-to-the-NW thrusting, isoclinal asymmetric folding (F_2) and the development of associated S_2 foliations and a-/b-type lineations (Fig. 11c), resulting in crustal thickening and peak metamorphism (M_2), represented by medium- to high-pressure granulite-facies assemblages in the Hengshan Complex. Accompanying or immediately following D_2 deformation was the development of the NNE–SSW trending transpressional ductile shearing (D_3) at a relative deep crustal level, represented by the Zhaojiayao ductile shear zone, which resulted from a combination of top-to-the-NW oblique-slip shearing and NNE–SSW dextral strike-slip shearing.

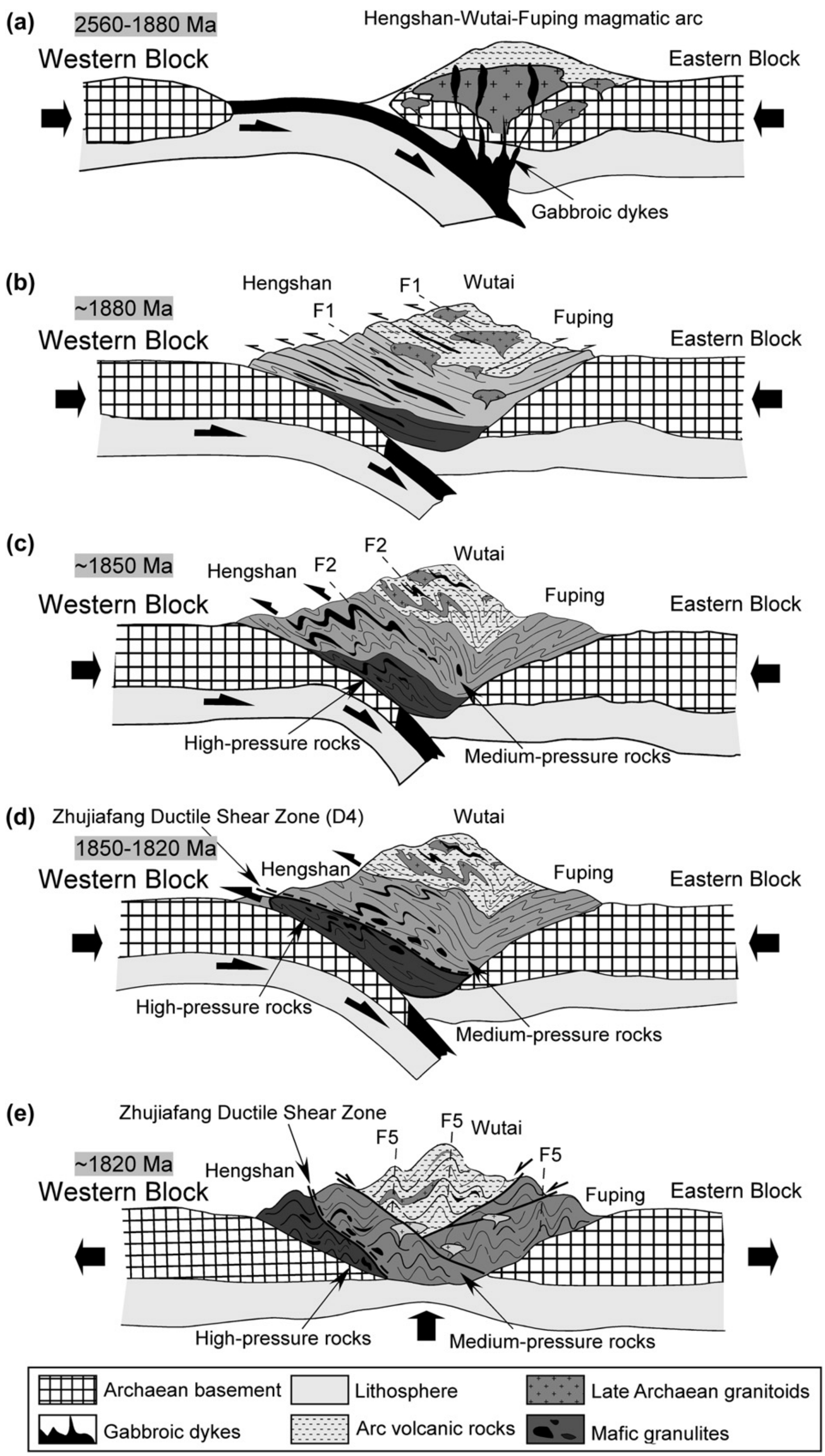

Fig. 11. A tectonic model proposed for the evolution of the Hengshan–Wutai–Fuping belt and the Trans-North China Orogen, based on structural data presented in this study.

(4) Further subduction led the high-pressure rock assemblages (lower crust) to be detached, ledding to development of the Zhujiafang ductile shear zone (D_4), along which high-pressure rocks in the Hengshan Complex were exhumed to the shallow level (Fig. 11d). This led to decompression metamorphism (M_3), as indicated by orthopyroxene + plagioclase symplectites and coronas in the high-pressure granulites in the Hengshan Complex.
(5) Finally, the thickened crust underwent pervasive exhumation/uplift, possibly due to the break-off of the downgoing slab, resulting in the development of regional upright F_5 folds and low angle detachment faults in the upper crustal domain (Fig. 11e). Accompanied with the exhumation/uplift was retrogression and cooling metamorphism (M_4), as indicated by hornblende + plagioclase symplectites in the medium- to high-pressure granulites in the Hengshan Complex.

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