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A Late Archean foreland fold and thrust belt in the North China Craton: Implications for early collisional tectonics

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Abstract

The Archean North China craton is divided into the Western and Eastern blocks along the Central Orogenic belt. A 1600 km long Archean foreland basin and thrust belt fringes the eastern side of the Central Orogenic belt. Rocks in the orogen form tectonically-stacked east-vergent fold and thrust sheets including foreland basin sediments, 2.50 Ga ophiolitic mélange, and an island arc complex. Foreland basin sediments overlie a passive margin sequence, and include a 2.50 Ga deep-water turbidite sequence that grades upward and westward into shallow-water molasse, now disposed in structurally imbricated east-verging thrusts and asymmetric folds that gradually migrated craton-ward with deformation, uplift, and erosion of the orogen. There is a strong linked relationship of the formation of the foreland basin to collision of the east and west blocks of the North China craton along the Central Orogenic belt at 2.50 Ga. The Qinglong foreland basin and Central Orogenic belt of the North China craton represents one of the best-preserved Archean orogen-to-craton transitions in the world. Its classic internal to external zonation, and flexural response to loading, demonstrate that convergent tectonics in the Archean were broadly similar to Phanerozoic convergent margin processes.
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Keywords: Fold and thrust belt; Foreland basin; Molasse; Flysch; China; Archean

1. Introduction

Determining the timing of the start of modern-style plate tectonic processes and how tectonic style may or may not have differed between modern and Precambrian times is a hotly debated issue of current geological research, badly in need of new field constraints. In order to constrain models and speculations, it is very important to decipher the geological record of possible Precambrian plate boundaries such as collisional belts (e.g., Burke et al., 1986; De Wit, 1998; Kusky and Polat, 1999). In the last ten years, many geological records supporting the operation of plate tectonic process in the Archean of North China have been documented. For instance, well-preserved ophiolites and ophiolitic mélanges (Kusky et al., 2001, 2004), high-pressure granulites (Kröner et al., 2002; O'Brien et al., 2005), accreted island arcs (Polat et al., 2005a, 2006), remnants of back arc basins, and forearc-accretionary prisms have been widely identified in the North China Craton (Tian et al., 1996; Wang et al., 1996, 1997; Li et al., 1997, 2000; Wang et al., 2001; Li et al., 2002; Kusky and Li, 2003). In addition, some large thrust-sense shear zones that formed at deep levels have been documented, suggesting thin-skinned crustal stacking in the Neoarchean (Li and Qian, 1991; Bai et al., 1992; Wang et al., 1997; Kusky et al., 2001; Li et al., 2002). These events culminated with the emplacement of circa 2.50 Ga tonalite–trondhjemite–granodiorite (TTG) and granite, as dated by U–Pb (zircon) methods (Kröner et al., 1998, 2002; Zhao, 2005, 2006). Based on these relationships, a large orogen, named the Central Orogenic belt (Li et al., 2000, 2002) was suggested to cut across the North China craton (Figs. 1–3).

The Central Orogenic belt is now deeply eroded and not well preserved, its geological units vary considerably along strike, and it is difficult to decipher its tectonics and structural framework, which have rarely been discussed. In contrast, the petrology, geochemistry and geochronology within the Central Orogenic belt have been the subject of extensive research (e.g., Zhao et al.,

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2002; Kröner et al., 2002; Liu et al., 2002, 2004; Zhao et al., 2005, 2006, and references therein). In order to document the geometry and kinematics of the orogenic belt and its relationships to surrounding cratonic blocks, we take a classical approach and first investigate the regional structure, stratigraphy, and age relationships between the orogen, its foreland thrust belt and what we will argue is its foredeep. We suggest that these relationships hold the key to reconstructing the orogenic evolution (Castle, 2001) and interpreting the metamorphic and geochemical data. Studies of the sedimentary record and sequence of crustal stacking provide a history of the final convergence of continental blocks at the end of the Archean. This paper presents a synthesis of the stratigraphic and tectonic evolution of the foreland area of the Central Orogenic belt based upon our field work over the last eight years, and reviews of many new geological data. We focus in particular in this paper on the relation between basin filling and the growth of the adjacent Central Orogenic belt.

2. Regional setting of the Neoarchean Qinglong basin

The Qinglong basin forms an elongate belt parallel to and on the eastern side of the Central Orogenic belt of the North China craton (Fig. 1). The basin is 1600 km long, up to 200 km wide, and contains a several kilometer thick sequence of clastic sedimentary rocks. Regional and local geological studies have revealed many distinct features about this circa 2.5–2.4 Ga basin, largely disposed in east-vergent folds and thrusts (e.g., Xu, 1984; Wu et al., 1986; Li et al., 1990; Tian, 1991b; Bai et al., 1992; Tian et al., 1996; Wu et al., 1998; Li et al., 1998; Miao et al., 1999; Li et al., 2002; Kusky and Li, 2003). The belt mainly consists of weakly metamorphosed Archean–Paleoproterozoic sediments deformed into east-directed thrusts, asymmetric folds, and is cut by ductile shear zones (Fig. 2). These same rocks are incorporated into major thrusts and fold nappes in the internal zones of the orogenic complex in the Wutai–Taihang Mountains to the west (Fig. 1). To the east, Qinglong basin strata onlap shallow water platform sediments deposited on the Eastern block of the North China craton. Based on the geographic distribution of rock types, deformation styles, and exposure, we divide the basin into three sectors along strike: Qinglong (northern sector), Taihang–Wutai (middle sector) and Songshan (southern sector) (Figs. 1 and 2). We colloquially refer to the entire basin as the Qinglong basin, after excellent exposures in that sector.

2.1. Shallow water platform sediments on the western margin of the eastern Block

The Qinglong basin, largely preserved in a fold-thrust belt, locally overlies and is flanked on the east by a shallow water shelf sedimentary succession deposited on the western margin

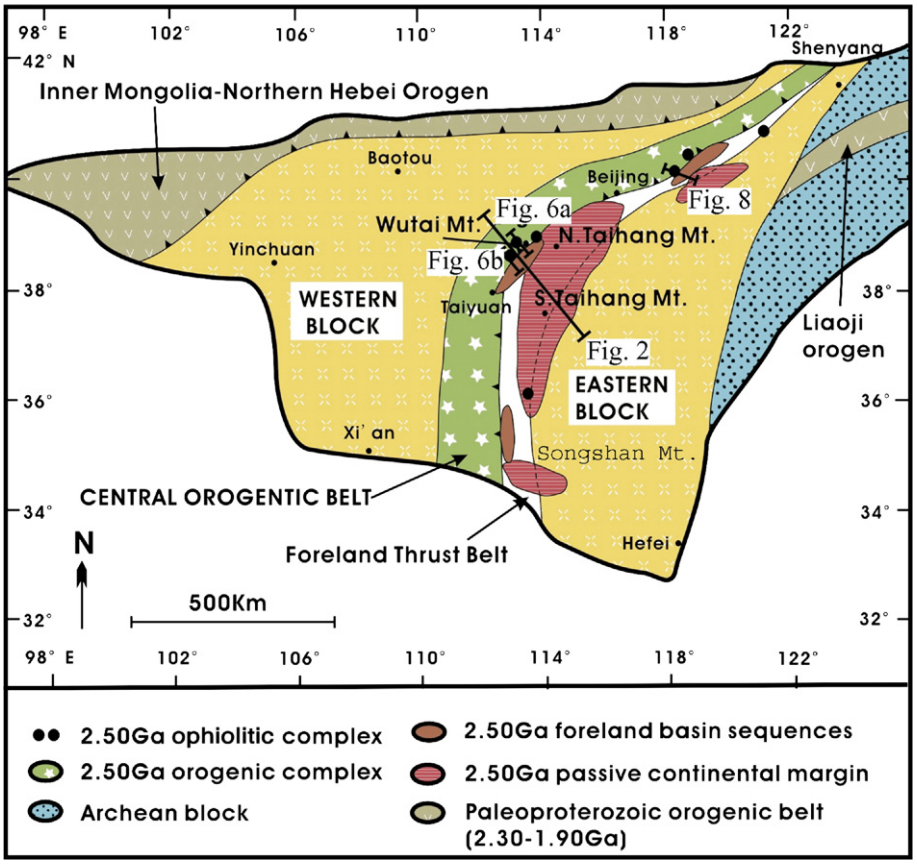


Fig. 1. Generalized geological map showing the tectonic framework and distribution of the 2.50 Ga Qinglong foreland basin of North China. Lines indicate traces of the cross-sections of Figs. 2 6 and 8). In the text, the northern sector refers to the outcrop belt NE of Beijing, the central sector is near Wutai–Taihang mountains, and the southern sector is east of Xi'an.

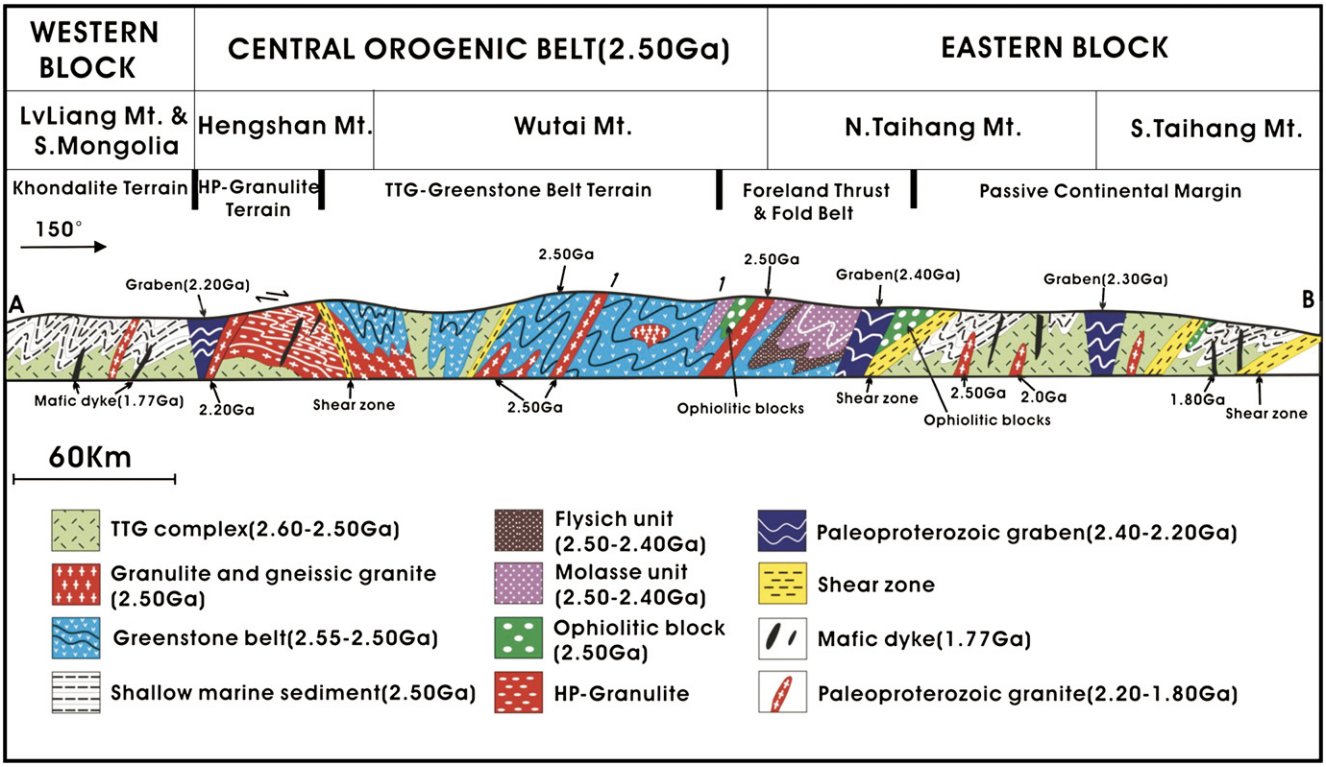


Fig. 2. Schematic geological section across the Central Orogenic Belt of North China, see Fig. 1 for line of section. It shows a nappe stack overlying an asymmetric foreland basin, and the inner zone with complex geometry and deformation. A shallow-water passive margin sequence underlies the foreland basin sequence on the 2.6–2.5 Ga TTG complex of the Eastern Block.

of the Eastern block of the North China craton (Fig. 1). Shelf and platform sedimentary units of Neoarchean age have been recognized from many sites in the region, which occupies a large area on the eastern side of the Central Orogenic belt, including Eastern Hebei, Taihang Mountain, and Songshan Mountain. Clastic rocks in the shelf succession have an inferred source area from the Eastern block (Wu et al., 1989). The shelf sediments in many places were onlapped by or were overlain by clastic rocks of the Qinglong basin (Fig. 1). Locally, the basement complex was structurally reactivated and interleaved with the sedimentary sequences (Fig. 3). The main lithologies in the platformal sequence include marble, calc-silicates, banded iron formation (BIF), quartzite, and metapelite, mostly now at amphibolite–facies metamorphic grade (Figs. 3 and 4). We interpret the depositional setting of this Neoarchean rock sequence to be a shallow-marine shelf setting that preserves a general depositional stratigraphic sequence from quartzites through carbonates to pelites. These rocks underwent intense deformation, with the formation of recumbent folds, flat-dipping ductile shear zones, and NNE- to NE-trending overturned folds with west dipping axial surfaces (Fig. 4F). To the east, deformation becomes weaker, and is characterized by dome-like structures, and supracrustal sequences overlying the TTG basement complex (Figs. 1 and 2).

In Taihang Mt., the Wutai Group includes representative shallow-water shelf units of the Banyukou Formation (BYF), and the Wanzi Group (WG), both of which are overthrust by foreland basin molasse and ophiolitic mélange (Figs. 5 and 6).

The Banyukou Formation consists of quartzite, quartzofeldspathic sandstone, pelite, and marble, and is presently more than 650 m thick (thicknesses quoted here and throughout the manuscript are present-day structural thicknesses). It is deformed into several overturned composite synclines wedged between ophiolitic mélange and the Longquanguan (Dragon Spring) thrust-sense shear zone, which can be traced for more than 100 km along strike (Figs. 5 and 6). To the west it is intercalated with ophiolitic blocks by thrusts and recumbent folds (Li and Qian, 1991; Wang et al., 1996). Tubular and sheath-type folds with northwestward plunging hinges and mineral stretching lineations are very common within the Banyukou Formation. Thus, it is clear that shelf-type sediments of the Banyukou Formation were structurally incorporated into the foreland thrust belt. Evaporites in the Banyukou Formation (Tian, 1991a) record a closed and quiescent lacustrine sedimentary setting, associated with the early closed-basin stages of the platformal or shelf succession. Some soft-sediment deformation structures, such as slump folds and olistoliths within the sediments reflect syn-depositional gravitational instabilities probably related to slumping from the edges of the basin.

To the east of the Banyukou Formation, the west-dipping Longquanguan (Dragon Spring) thrust-sense shear zone is characterized by mylonitic gneiss and augen-gniess (Figs. 3, 5, and 6). Rocks in the footwall include the Wanzi Group, composed of fine-grained quartzofeldspathic sandstone, pelitic schist, aluminous paragneiss, BIF and marble. The Wanzi

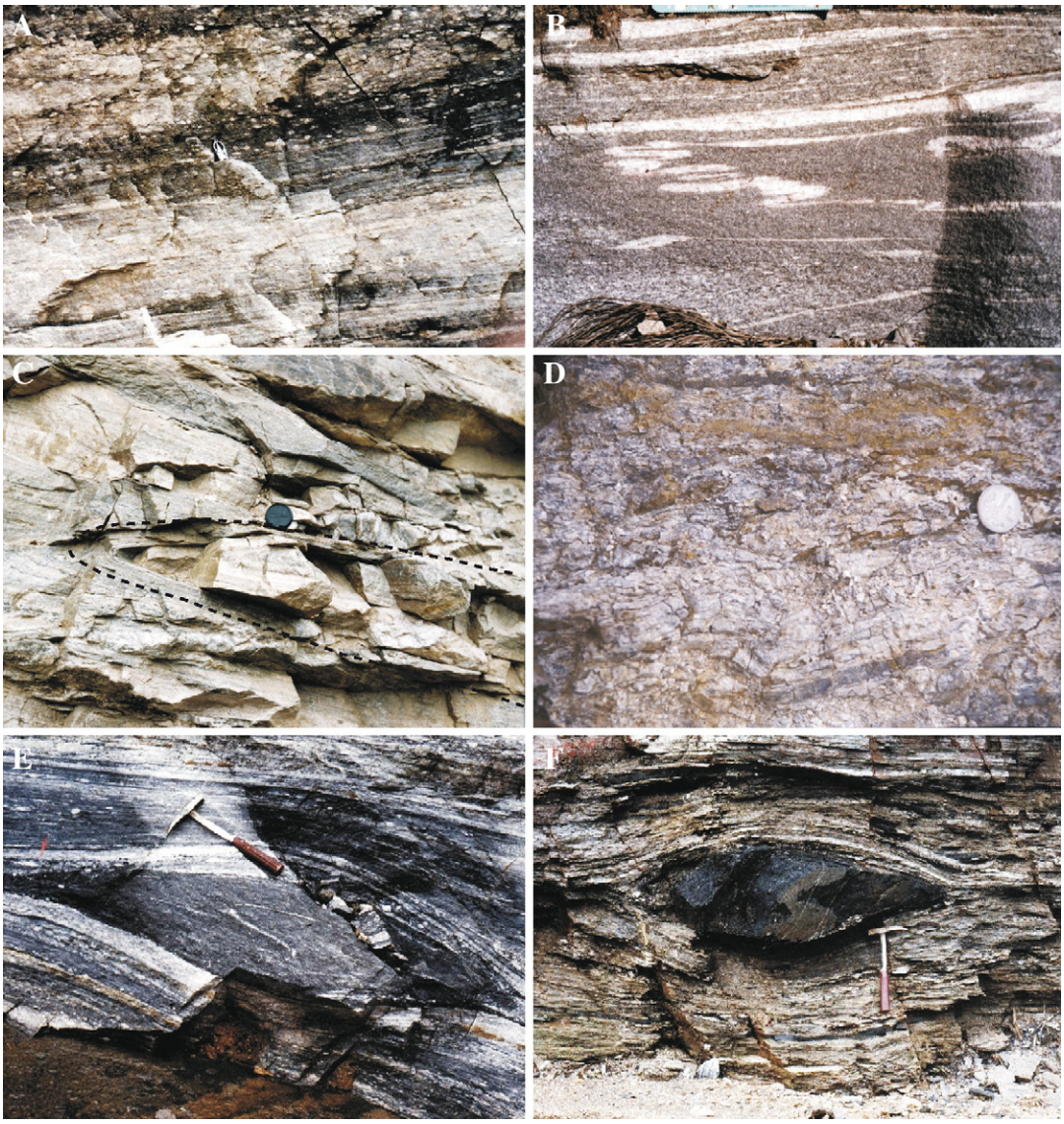


Fig. 3. Shallow-dipping shear zones in the foreland. A, lens and asymmetric folds within the Dragon Spring (Longquanguan) shear zone. B. recumbent folds of Banyukou Formation. Recumbently folded sandstone interleaved with augen gneiss of Dragon Spring shear zone. C. flat-lying thrust within Neoarchean metasediments at South Taihang mountain. D. Metacarbonate (marble) of the Jianping Complex, which is a strongly metamorphosed part of the shelf sequence underlying the foreland basin sequence. E. asymmetric mafic boudin within Neoarchean metasediments at South Taihang mountain. F. mafic boudin within Neoarchean metasediments at South Taihang mountain.

Group is deformed into composite synclines overlying and locally interleaved with the Fuping TTG complex (FTC). Near the Longquanguan shear zone in the west, both the Wanzi Group and Fuping TTG complex were strongly reworked with transposition of the foliation by thrust-sense shearing. Further to the east and in the southern parts of Taihang Mountain, the Fuping TTG complex is exposed within a structural dome, and the Wanzi Group is deformed into NE-trending linear folds. Many recumbent folds, nappe stacks and zones of subhorizontal foliation are recognized within the Wanzi Group in the southern part of Taihang Mountain. Recumbent folding of the sequence was accompanied by thrust-stacking of the TTG thrust sheet (Figs. 4 and 6), implying substantial tectonic transport and considerable crustal shortening in deep levels of the orogen.

Both the Banyukou Formation and Longquanguan shear zone yield U-Pb zircon ages in the range of 2510±8–2715±25 Ma (Cheng et al., 2000; Guan et al., 2001; Wang et al., 2001), supporting the explanation of its Archean ages and being derived from the ancient cratonic provenance.

The southern part of the North China Craton is widely covered by Paleozoic sedimentary sequences. Drilling west of Anhui suggests that Archean basement is mainly composed of paragneiss, with a north–south structural grain and west-dipping foliations. The paragneiss forms composite overturned synclines with west-dipping axial surfaces. The protoliths of the paragneisses are quartzofeldspathic sandstone, siltstone, pelite, BIF and marble with rhythmic layering, deposited in a shallow marine setting (Sun et al., 1985). Thus, it is suggested that the shallow shelf sequence can be also traced to the southern part of

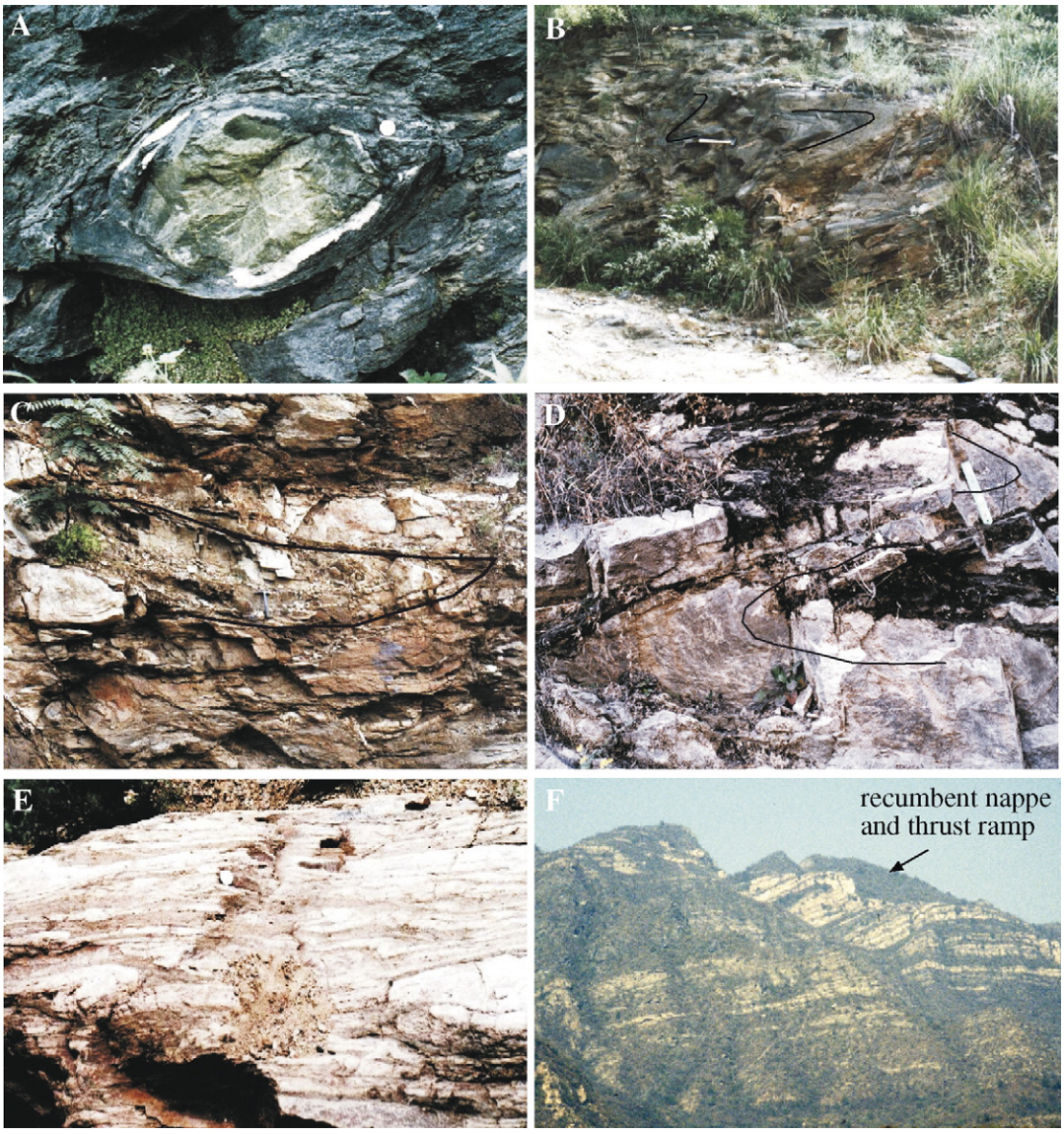


Fig. 4. Structural deformation of Neoarchean sediment along the passive continental margin. A. epidosite lens within mafic Neoarchean volcanics, that was thrust over Neoarchean metasediments at South Taihang mountain. B. asymmetric recumbent fold of Neoarchean metasediments at South Taihang mountain. C and D. recumbent folds of marble in Neoarchean metasediments at South Taihang mountain. E. asymmetric folds with Banyukou Formation, Neoarchean passive continental margin metasediments at north Taihang mountain. F. Mountain scale recumbent fold overlying a thrust ramp in Archean foreland basin sediments on Taihang mountain.

the North China Craton, showing that it is extensive across a region comparable in size to younger passive continental margins.

Current age constraints on the shelf sequence are quite poor. The rocks overlie unconformably circa 2.8–2.7 Ga gneiss of the Eastern Block and are younger than the circa 2.7 Ga Taishan komatiites that are interpreted to have erupted from a plume source associated with the break up of a continent that the Eastern block was part of prior to 2.7 Ga (Polat et al., 2005a; Cheng and Kusky, 2007). Break-up of this (super) continent led to the formation of passive margins at 2.7 Ga, including the western margin of the Eastern block. High-grade rocks of the Jianping Complex of Liaoning include magnetite quartzite, marble, and other metasedimentary rocks that are probably correlative with the shallow water platform sediments in lower part of the Qinglong basin, and have been dated (U–Pb) by Kröner et al. (1998) to be 2.551–2.522 Ga old. Thus, the best age constraints on the shallow water shelf are between 2.7 and 2.52 Ga. Passive margin sedimentation was terminated by the deposition of flysch-type rocks of the Qinglong basin at circa 2.5 Ga (see below).

3. Sedimentary sequences of the Qinglong basin, their ages and deformation styles

The Qinglong basin sedimentary sequences are mainly situated between the Central Orogenic belt and passive continental margin (Fig. 1). On the western side of the basin, basinal strata are widely overridden by the encroaching orogenic complex, separated by ophiolitic mélange from the Central Orogenic belt (Fig. 2). Relatively intact stratigraphic sections of the basin are preserved in the higher mountains, such

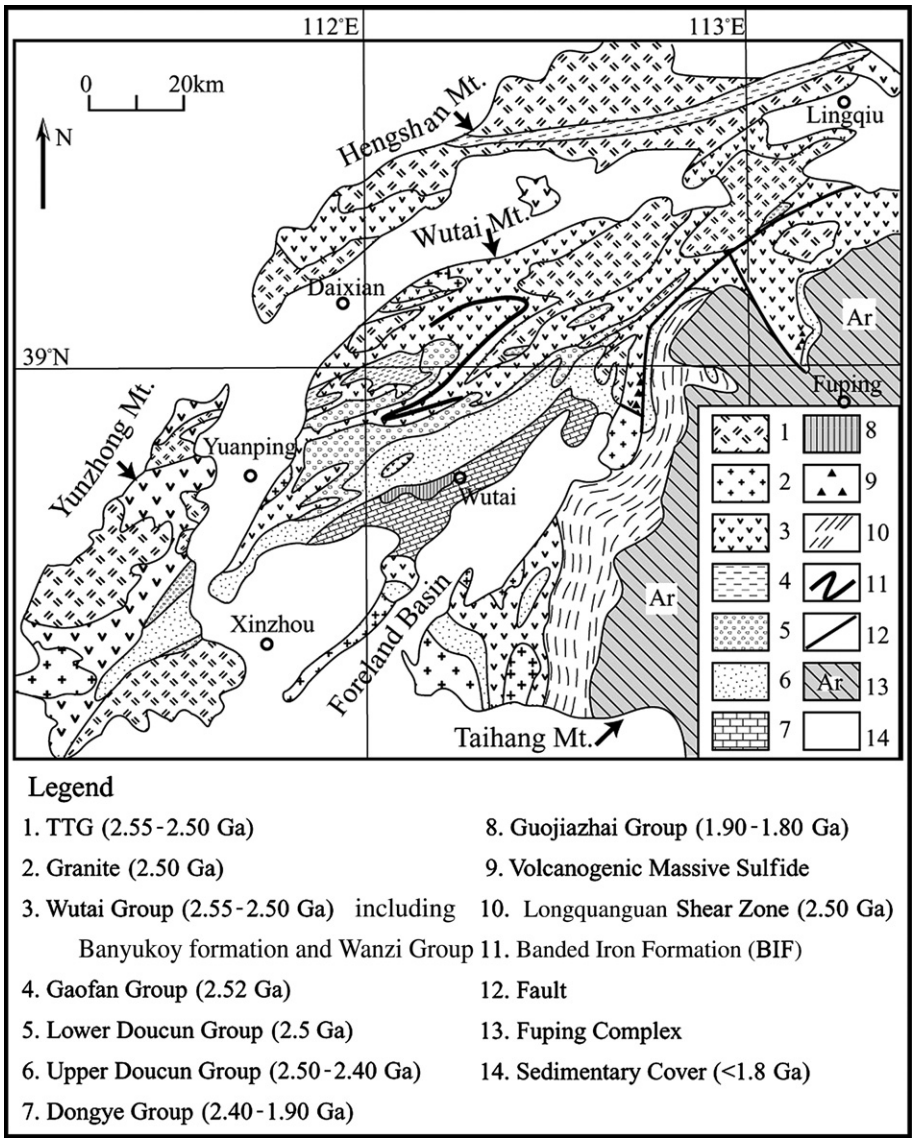


Fig. 5. Map of Wutai and Taihang Mountains showing the relationships between the Central Orogenic belt, foreland basin sediments (Gaofan, Doucun and Dongye Groups), and underlying passive margin (Wutai Group) and older gneiss. Lines of section "A" and "B" refer to profiles shown as Fig. 6.

as the junction area of Wutai and Taihang Mountains. The basinal strata also onlap the passive continental margin sediments, as shown in Wutai and Songshan Mountains. Their deposition was clearly synchronous with orogenic uplift of the internal zone of the orogen.

The Qinglong basin is filled with similar sedimentary sequences along the length of the orogen, generally including a 2.50 Ga lower turbidite unit, and overlying 2.50–2.40 Ga conglomerates and sandstones. Age constraints on the sedimentary fill of the basin are currently not very precise. The basement underlying the sedimentary succession generally ranges in age from 3.5–2.7 Ga, and the best estimates for the age of the underlying shallow water shelf are 2.7–2.52 Ga (see above, Kröner et al., 1998; Polat et al., 2005a, and reviews by Kusky and Li, 2003, 2004; Kusky et al., 2007). There are no direct dates on sedimentary rocks of the Qinglong basin, and no volcanic or tuffaceous horizons have yet been identified that are suitable for dating. The basin is cut by several late Archean plutons, including granites dated at 2.54 Ga (Wu et al., 1998), 2501±60 Ma (Qi et al., 1999), and a dioritic intrusion gave Rb–Sr whole-rock ages of 2452±18 Ma, 2432±41 Ma, and 2446±82 Ma (Wang, 1986). Several gabbroic–granitoid plutons have reported Rb–Sr ages of 2.40+/−.015 Ga (Wu et al., 1998). From these generally poor age constraints, it is clear that the Qinglong Group was deposited and deformed between 2.56 and 2.40 Ga.

The ages of metamorphism in the Qinglong basin are likewise poorly constrained, but it appears that the sedimentary sequence has experienced two phases of regional metamorphism. The first is indicated by higher-grade assemblages indicated by metamorphic cores on zircons of the Jianping Complex that have been dated by Kröner et al. (1998) to be 2490–2485 Ma old. These rocks are intruded by post-tectonic circa 2472 Ma granitoids (Kröner et al., 1998). All Archean and Paleoproterozoic rocks of

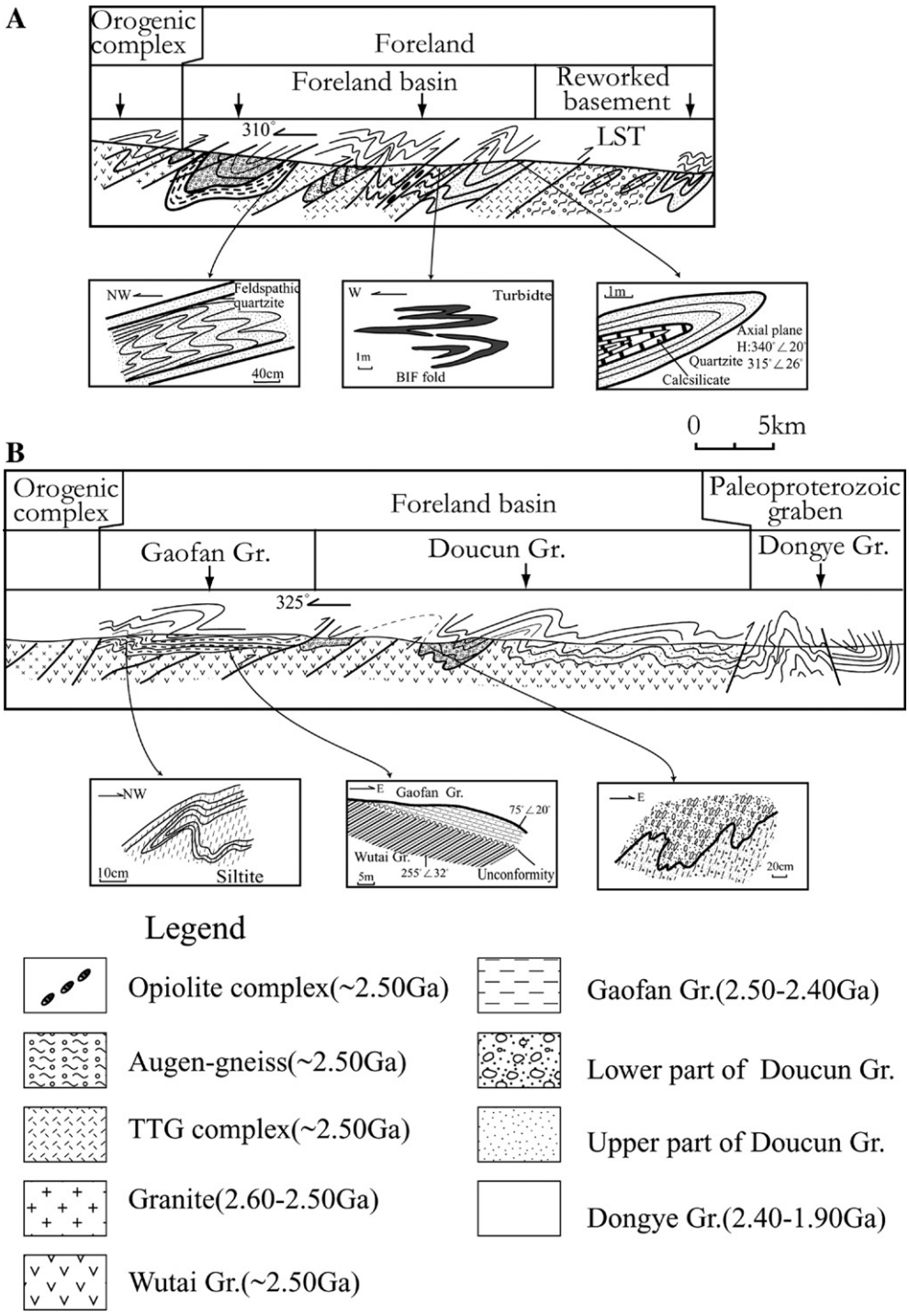


Fig. 6. Structural cross-sections of foreland fold-thrust belt, Wutai–North Taihang Mountains, see Figs. 1 and 5 for traces and the text for explanations.

the northern part of the craton, and most in the south seem to have experienced a major metamorphic event at around 1.85 Ga (Wilde et al., 1998; Zhao et al., 2001, 2002; Kröner et al., 2002; O'Brien et al., 2005; Kröner et al., 2005; Zhao et al., 2006). We relate this major tectonothermal event to crustal thickening and heating in response to collisional orogenesis on the north margin of the craton at circa 1.85 Ga (Kusky and Li, 2003; Kusky et al., 2007). The Qinglong basin sequence is also intruded by circa 2.4 Ga mafic dikes and overlain by circa 2.4 Ga mafic lava flows that Kusky and Li (2003) interpreted as Paleoproterozoic flood basalts.

The conglomerate layers in the upper sections vary in thickness from tens of meters to more than 2000 m, reflecting the active tectonics in the depositional basin. The widespread distribution of the 2.50–2.40 Ga conglomerates along the western side of the basin demonstrates that the main convergent orogenic episode with the Central Orogenic belt occurred in the Neoarchean.

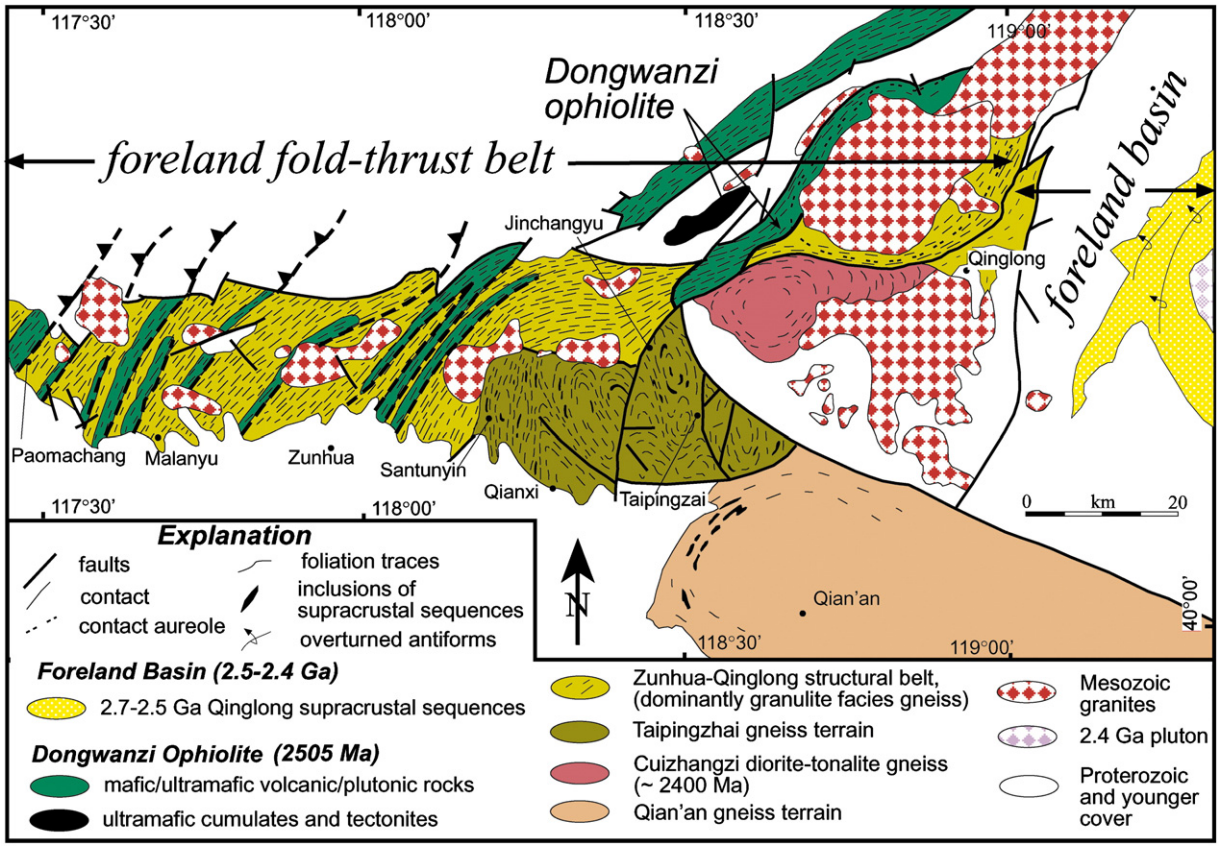


Fig. 7. Simplified map of the foreland fold-thrust belt (Central Orogenic Belt) to foreland basin transition in eastern Hebei.

The Qinglong basin and fold-thrust belt is characterized by intense folding and thrusting of sedimentary strata along the western margin of Eastern block, and it is overridden by the orogenic belt to the west. The boundary between the foreland and orogenic belt is marked by ophiolitic mélange, within which relict ophiolitic blocks are distributed, suggesting regional horizontal shortening of at least hundreds of kilometers. The composite synclines commonly have asymmetric geometry with east-directed vergence. The relevant thrusts, ductile shear zones, and closed to overturned folds uniformly show east-or southeast-directed movement toward the foreland. One of the other important features shown on cross-sections of the orogen and basin is the basement involvement with 2.50 Ga orogenic wedges in the foreland area (Figs. 3 5 6 and 8).

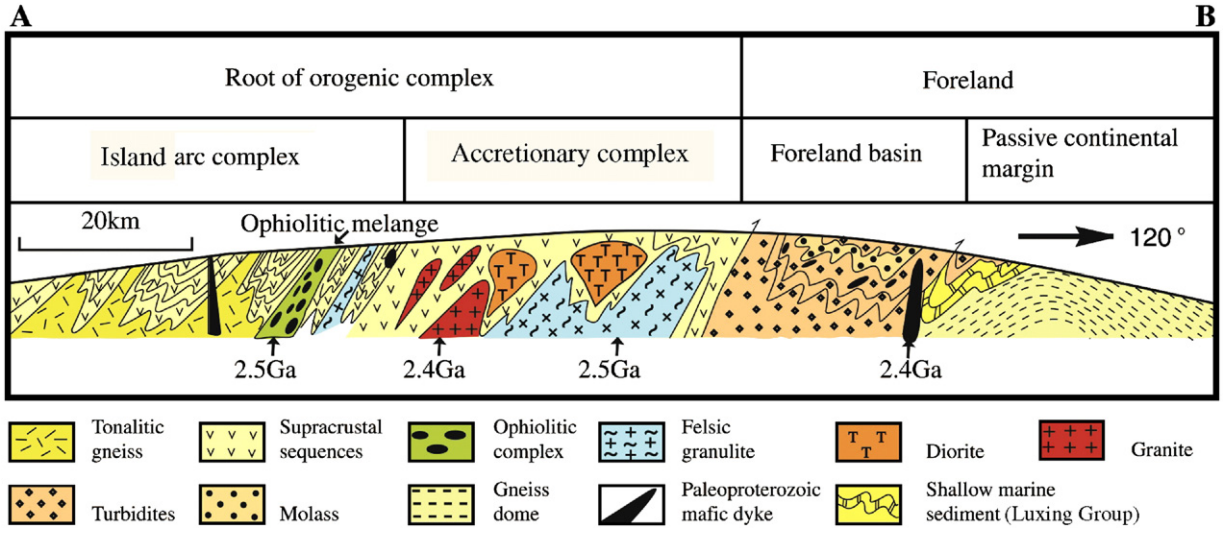


Fig. 8. Structural cross-sections of the foreland fold-thrust belt, Eastern Hebei, see Fig. 1 for line of section and the text for explanations.

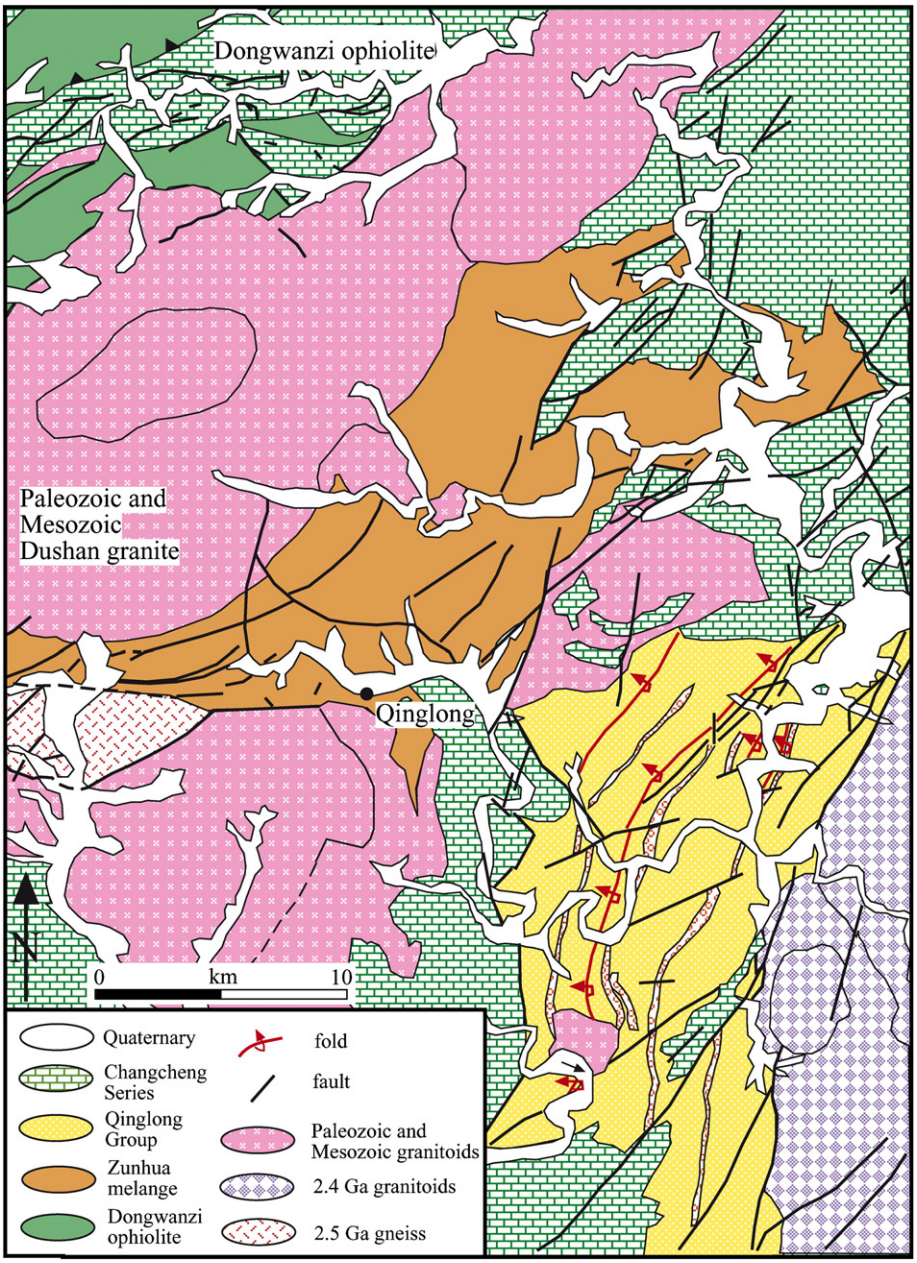


Fig. 9. Map of Qinglong foreland near Qinglong. Note asymmetric overturned folds and conglomerate beds in the foreland basin.

3.1. Northern sector: Qinglong area

In the Eastern Hebei Province, several NE-striking shear zones and elongate folds with west-dipping axial surfaces were superimposed on the western side of the Qian'an dome (Zhao, 1993), forming an east-vergent imbricated structural belt west of a belt of ophiolitic mélange (Figs. 7 and 8). These young-generation folds correlate with the continuation of the Qinglong thrust belt in the northeast, interpreted to be the result of reactivation in response to the east-vergent thrusting and crustal shortening. Moreover, shallow-marine sediments (quartz–schist, marble, sandstone, and BIF) and underlying rift-related volcanics (metabasalt and tuff) are recognized within the Luanxiang Group (Wu et al., 1998), which forms a north to south-trending fold belt. The Luanxiang Group structurally underlies the Qinglong thrust belt, and we interpret it as a sedimentary sequence deposited on a passive continental margin.

The sedimentary basin fill in the Qinglong area is called the Qinglong Group (QLG), which crops out along the eastern side of Zunhua ophiolitic melange in Qinglong County (Figs. 7–9). The Qinglong Group was intruded by a circa 2510±8–2715± 25 Ma diorite in the eastern part of its outcrop area (Fig. 9). On its western side, it is overthrust by the orogenic complex and the 2.54–2.64 Ga Shuangshanzi Group (volcanics yield zircon ages of 2546±40 and 2641±30 Ma; Bai, 1986), correlative with the Zunhua ophiolitic melange (Li et al., 2002). To the south, these rocks are cut by Mesozoic faults.

The Qinglong Group is divided into a lower part consisting of turbidites and an upper part consisting of molasse-style

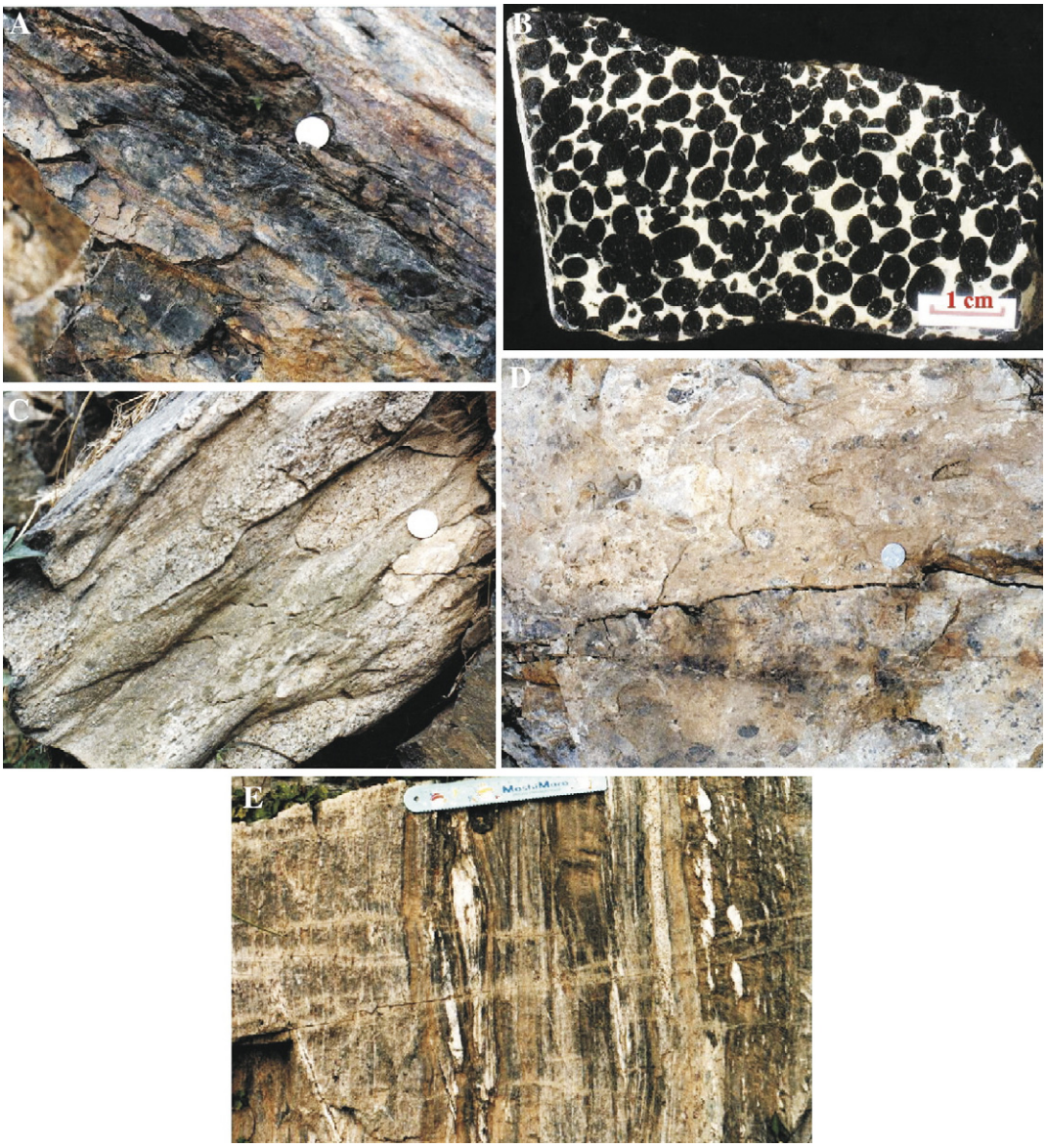


Fig. 10. Foreland sequences in the Qinglong area. A. pillow lava thrust over molasse in the Qinglong area. B. Podiform chromite showing nodular texture, from Zunhua ophiolitic mélange zone. C. Deformed conglomerate. D. Conglomerate in molasse E. Sheared molasse conglomerate.

deposits, all of which underwent greenschist–facies metamorphism. It mainly consists of conglomerate, graywacke and sandstone turbidite, siltsone, and pelite with interbeds of BIF (Figs. 9 and 10).

Pebbles in the molassic conglomerate of the Qinglong Group include mafic volcanics, granodiorite, quartz veins, siltstone, tuff, siliceous rock, granite, andesite, quartz–diorite, metasediments, and other minor components. The conglomerate ranges in thickness from several meters to 400 m. The pebbles are generally well rounded and clast supported, but not well sorted (Li et al., 1996; Zhao and Li, 1996; Qi et al., 1999). Sedimentary analysis of the components of the conglomerate, including the size of the pebbles, which show regular variation from coarsest in the west to finest in the east across the basin, are consistent with the hypothesis that the basin was thrust-controlled, and deepened to the west (Bai et al., 1996). Pebbles are widely flattened along the foliation by shearing (Fig. 10).

On aeromagnetic maps the northern sector of the Qinglong basin and fold-thrust belt forms a negative anomaly interpreted as a west-dipping boundary. Structurally, the belt forms a NNE-striking composite fold belt (Figs. 7–9), in which at least four large folds with penetrative foliations have been recognized. They consist of asymmetric tight to isoclinal east-vergent folds with west-dipping axial planes. Two major thrust-sense shear zones have west-dipping foliations (Qi et al., 1999). The stretching and mineral and pebble elongation lineations plunge to the west, whereas bed/cleavage intersection lineations and fold hinges plunge gently SSW. To the west, the basin sequences were overthrust by the orogenic complex and the Zunhua ophiolitic mélange (Figs. 7–9). Their boundary is delineated by a NNE-striking shear zone that is tens of kilometers long, and dips west. In addition, fold hinges plunge 20° to the SSW, which may suggest late tilting to the south along the northern margin of North China craton.

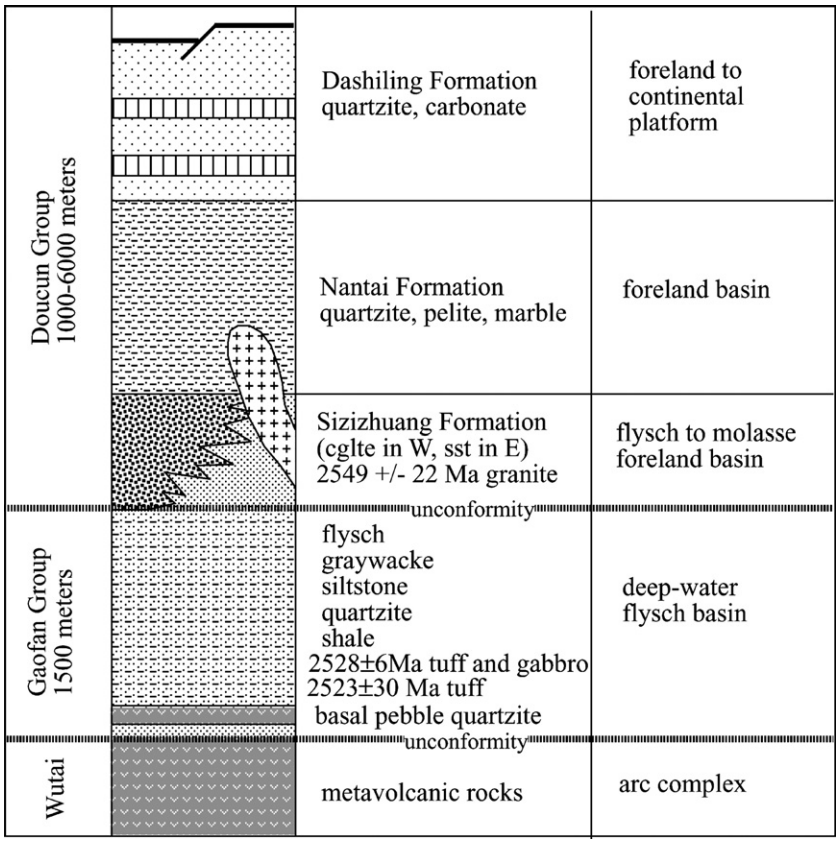


Fig. 11. Stratigraphic column of foreland basin and related sequences, Wutai–Taihang Mountians area. Note the U–Pb ages that constrain the age of the flysch and molasse to be older than 2.5 Ga.

3.2. Central sector: Wutai mountain area

Strata of the Wutai Mountain area that are similar in age, sedimentary succession, and structural style to the Qinglong basin strata include the greenschist facies Gaofan (GFG) and Douchun Groups (DCG), separated by an unconformity (Figs. 5 and 11). The Gaofan Group is dominated by turbidites and siliceous rocks deposited in a deep water setting, whereas the Douchun Group is composed of molasse, clastic rocks, pelite, and carbonates deposited in a fluvial environment. They were overthrust by the orogenic wedge to the west (Li et al., 1990; Li, 1996) and onlap the Wanzi Group deposited in the shallow marine realm to the east. Tuff in the Gaofan Group and a gabbro that intrudes the Gaofan Group yield U–Pb SHRIMP ages of 2528±6 Ma and 2523±30 Ma, respectively (Wang et al., 2001; Kröner et al., 2004).

The Gaofan Group has a thickness of about 1500 meters and consists dominantly of siliciclastic flysch, including greywacke, siltstone, tuff, quartz arenite, and shale. Xu et al. (1991) divide the group into five sedimentary cycles. Its base is marked by a layer of pebble-bearing quartzite, overlain by a volcanic unit that is hundreds of meters thick. It shows well-preserved sedimentary cycles, graded bedding, and convolute bedding, interpreted as slumped marine turbidites. REE patterns of Gaofan Group pelites show a negative Eu anomaly, suggesting that its provenance was rich in plagioclase, such as granitic rocks (Bai et al., 1996).

The Douchun Group is about 1000–6000 m thick, and is divided into three formations including, from base to top, the Sijizhuang, Nantai, and Dashiling Formations. It shows significant lateral changes in facies between the proximal and distal reaches of the basin, which Li (1996) attributed to the tectonic migration of the orogenic belt toward the craton, similar to that observed in other foreland basins (e.g., Bradley and Kusky, 1986). Molasse of the Douchun Group records the rapid unroofing and denudation of the orogenic belt to the west. A granite intruded within the Sijizhuang and Dashiling formations yielded a U–Pb zircon age of 2549±22 Ma (Bai et al., 1992), confirming the Archean age of this sequence.

The Sijizhuang Formation is hundreds to 2000 m thick, and is characterized by thick beds of conglomerate, with well-rounded, poorly sorted, polymictic pebbles. The pebbles from the lower part of the Sijizhuang Formation include quartzite, BIF, greenschist, amphibolite, granite, gneiss, and quartz veins, all in a matrix of pelite and sandstone (Figs. 11 and 12) (Bai et al., 1992; Shen et al., 1994). The pebbles in the lowermost units are mainly schist, greywacke, siltstone, and quartzite, clearly derived from the Gaofan Group. The roundness of conglomerate clasts in the Sijizhuang Formation increases in the upper part of the formation, which is dominated by round pebbles of quartzite.

The coarsest conglomerates are located along the northwest side of the basin where they are overthrust by the Wutai orogenic belt, whereas the conglomerate becomes finer-grained



Fig. 12. The foreland basin sedimentary sequence and its deformation in the Wutai Mountain area. A. Turbidites of the flysch sequence, Gaofan Group. B. turbidite with horizontal (now vertical) and graded beds. C. recumbent fold in molasse, Wutai Mountain. D, E and F. deformed conglomerates and pebble-bearing sandstones from lower part of molasse in the Doucun Group (Sizizhuang Formation).

toward the interior of the basin, grading into pebble-bearing sandstone and sandstone (Miao et al., 1999). The source area of the Sijizhuang Formation was located in the orogenic belt to the northwest. Based on the correlation of interbedded mafic volcanic horizons, we suggest that the Sijizhuang Formation conglomerates were deposited diachronously from the northwest to southeast. The Sijizhuang Formation was originally deposited in NE-striking marine basins that underwent secondary uplift that we interpret as a thrust-propagation anticline developed over piggy-back thrusts (see below).

The molasse shows rapid lateral facies changes and was trapped mainly in foreland synclines (see Fig. 6) developed immediately ahead of the thrusts. Similar structures have been reported in the Taiwan foreland basin (Mouthereau et al., 2001). As the thrusting deformation propagated outward, progressive unconformities and onlap relationships were produced, indicating syntectonic deposition in the frontal zone of the collision belt. The Sijizhuang Formation is overlain unconformably and onlapped by the Nantai Formation (NTF), which consists of quartzite, metapelite, and marble.

The Dashiling Formation (DSF) consists mainly of quartzite and carbonate. A 50-km long NE striking fracture zone characterized by synsedimentary breccias cuts the Dashiling Formation. Clasts from breccias along this fault zone are of various sizes, with angular shapes. The thickness of the dolostone increases abruptly across the fracture zone several times from southeast to northwest (Bai et al., 1996), indicating down-to-the-northwest faulting. We interpret this lithofacies to have been deposited in small graben formed as an accommodation of flexural uplift on a forebulge, similar to fault–breccias and thickened growth fault deposits in the Ordovician Taconic foredeep of eastern North America (e.g., Bradley and Kusky, 1986; Bradley and Kidd, 1991).

In summary, at least three thrusting/erosional unroofing phases are recognized within the foreland basin deposits, each marked by unconformities and conglomerates, associated with

the approach of orogenic thrust wedges, and cratonward migration of the foredeep. Unconformities developed near the thrust front, and foreland basin facies onlap the carbonate platform facies toward the interior of the basin. A coarsening-upward conglomeratic sequence is recognized in the upper part of the sequence in the proximal foreland (including the Sijizhuang Formation), indicating increased erosion of the hinterland (Heller et al., 1988).

3.2.1. Structure and deformation of the central sector of the Qinglong foreland

Fold hinges in the foreland basin strata plunge southwest. The metamorphic grade changes along strike from greenschist to amphibolite-facies in Wutai Mountain, with a corresponding change in structural style from composite synforms to thrust slices. The Central, Wutai Mountain sector of the foreland basin is characterized by several basins separated by thrusts and related anticlines ((Figs. 5 6 and 14)). Further work is needed to determine if these are piggy-back basins deposited on moving thrust sheets, or if they are simply remnants of the foreland basin caught in the thrust belt. The asymmetric tight folds show overturned SE limbs of antiforms with SE-vergence. Along strike to the northeast, thrusts become the dominant structures, and ophiolitic mélange is thrust over the foreland sequences. As indicated by NW-plunging mineral lineations and structural fabrics, the thrusts were SE-directed.

The Gaofan and Doucun Groups record a deformation gradient, with the intensity of deformation decreasing gradually from the Gaofan to the Doucun Group. At least two phases of deformation are documented within the Gaofan Group, which contains refolded and recumbent folds (Figs. 2 6 and 8). However, the Doucun Group records only one major phase of deformation. This records linear, tight folds and SE-directed thrusts, and is correlated with the late phase of deformation in the Gaofan Group.

The Gaofan Group is deformed into a regional-scale recumbent composite synform with a NW-dipping axial plane, and is overridden by orogenic thrust slices from the northwest. It onlapped the Wutai complex to the southeast (Bai et al., 1992, 1996; Tian, 1991b). The Gaofan Group composite synclines are widely overprinted by secondary asymmetric folds with NW-dipping axial surfaces (Xu et al., 1991; Bai, 1986).

The Doucun Group was deposited southeast of and unconformably on the Gaofan Group. It onlapped shallow marine sediments of the passive continental margin in the east, and it clearly migrated southeast with the foredeep, recording the lateral propagation of the orogenic belt. Moreover, the coarse-grained sediments of the Doucun Group were deposited close to the thrust front, and graded rapidly into fine-grained deposits to the interior of basin, which is one of the distinct features of foreland basins (e.g., Heller et al., 1988).

The Doucun Group is also deformed into asymmetric composite synclines and incorporated into thrust slices between ophiolitic mélange and shallow marine sediments overlying the basement complex (Fig. 6). Folds within the Doucun Group are more open than in the Gaofan Group. The secondary folds superimposed upon the Doucun Group are commonly asymmetric, tight or overturned with NW-dipping axial surfaces. SE-directed thrusts typically formed along the overturned limbs of these folds, with the formation of synclines in front of thrusts. The lower parts of the Doucun Group were deposited adjacent to thrusts, and underwent more intense deformation.

From the distribution of foreland molasse and imbricated thrust strata, we infer that the inner part of the Central Orogenic Belt strikes through the northwestern part of Wutai Mountain, and to the southeast is the foreland fold-thrust belt. The foreland fold-thrust belt can be traced further south, to Songshan Mountain. The correlative Songshan Group is characterized by NS-trending, tight to closed asymmetric folds with west-dipping axial surfaces (Sun et al., 1985). The western limbs of composite folds are commonly overturned, with the development of east-directed thrusts.

3.3. Southern sector: Songshan area

The correlative sequences of the foreland basin in the southern sector are represented by part of the Dengfeng Group (Laoyanggou Formation) and the Songshan Group (SSG), which overlies the Archean Dengfeng greenstone belt with a basal conglomerate. The basin formed on the eastern side of the Central Orogenic belt, and is dominated by turbidites with several interbeds of conglomerate (Lao and Wang, 1999), and overlying molasse further east.

3.4. Summary of stratigraphic relationships

In summary, the early deposits of the Qinglong basin include a deep-water turbidite sequence, indicating that the basin was underfilled and the thrust belt was far away from the passive continental margin in the east. With the continued advance of the orogenic wedge, the basin was loaded by the thrust sheets, became deeper, and sediment filling began to outpace the tectonic subsidence as more turbidites were deposited. The depocenter migrated in the early stages of basin evolution to the southeast, as a response to plate convergence then loading and reworking by the thrust sheet in the west, which is well recorded by the foreland sequence in Wutai Mountain. With the final collision, the orogenic wedge overrode the cratonic margin to the east, and the wedge and proximal parts of the basin began to be exposed above sea-level. With the flexural subsidence being accommodated by a broader and shallower basin, voluminous terrigenous sediments accumulated in the foredeep to form molasse, and the basin became overfilled.

At the end of Archean, molasse formed a N–NE striking belt, derived from the Central Orogenic belt to the west. These relationships provide strong evidence for active thrusting associated with orogeny at 2.50 Ga, with the syn-tectonic sediments preserved in the foredeep. Thus, it can also be inferred that the existence of a mountain belt with high relief was caused by collision in the Neoarchean.

The time of the onset of foreland thrusting at any given location can be inferred from the latest strata structurally incorporated in the orogenic wedge, and unconformities developed in synclines in front of thrusts (Boccaletti et al.,

1998). The base of the Gaofan Group unconformably overlies the Central Orogenic belt to the west, recording the initial collision. It was followed by deposition of thick sequences of molasse (2.50 Ga), such as the Sijizhuang Formation conglomerate. The latest deformed strata in the foredeep are in the Dashiling Formation (2.50 Ga). Thus, we suggest that the collision between the Eastern block and the Central Orogenic belt occurred at the end of the Neoarchean.

4. Summary of structural relationship between the foreland basin and orogenic belt

Many relict Archean ophiolitic blocks occur in a structural zone along the western side of the Qinglong basin and fold-thrust belt ((Fig. 1, 2, 5 and 7)). They can be traced for more than 100 km along strike in the Wutai Mountains, and 600 km along strike within the Central Orogenic belt, and are 2–10 km wide in the junction area of the Wutai and Taihang Mountains. The ophiolitic blocks and lenses are fault bounded, are concordant with the foliation in the country rocks, and were thrust over the shallow marine sediments (marble, quartzite etc.) of the Wanzi Group (Bai et al., 1992; Wang et al., 1997). More than 130 ultramafic blocks occur in this belt. The ophiolitic complex consists of peridotite, pyroxenite, dunite, serpentinite, gabbro, sheeted dikes, pillow lava, and chert. These mafic to ultramafic blocks are elongate parallel to the NW-dipping foliation, and the regional structural grain of the ultramafic blocks was intensely sheared along the contact with their country rocks, with formation of marginal schists. Different rock units are interleaved, forming recumbent to tight folds. Some possible piggy-back basins developed over the ophiolitic mélange zone, and some molasse was deposited in active synclines. Eastward, a flat NW-dipping shear zone formed and was intensely reworked and interleaved with shallow marine rocks of the Wanzi Group and its underlying basement complex.

The Wutai ophiolitic mélange can be traced to eastern Hebei, where it is correlated with the Zunhua ophiolitic mélange belt and Dongwanzi ophiolite (Kusky et al., 2001; Li et al., 2002; Kusky and Li, 2003. The Zunhua ophiolitic mélange belt was deeply eroded, where typical ophiolites and related podiform chromite in harzburgite blocks are well-preserved. Although it was reworked by Mesozoic fractures, it can still be demonstrated that the Zunhua ophiolitic melange belt was in structural contact with the Qinglong foreland basin. Some Archean pillow lavas (2641±35 Ma; U–Pb) are tectonically interleaved with turbidite sequences and molasse, and these show MORB-type REE-patterns (Wu et al., 1998; Yang et al., 2000).

5. General geological features of foreland basins and foreland fold-thrust belts

We suggest that the stratigraphic and structural relationships of the Qinglong basin show many similarities to younger foreland basins associated with collisional orogens. The detailed history of many paired foreland fold-thrust belts and foreland basins have been documented around the world, with some classic examples including the Pyrenees, many Alpine–Himalayan basins, the Zagros, North Caucasus, south Urals, and Appalachian foreland thrust belts and foredeeps (Allen and Allen, 1990; Allen et al., 1991; Bradley and Kidd, 1991; Barnolas and Teixell, 1994; Khain, 1996; DeCelles and Giles, 1996; Schlunegger and Jordan, 1997; Brown et al., 1998; Mikhailov et al., 1999; Jiang, 2000; Mouthereau et al., 2001; Castle, 2001). Foreland basins are narrow wedge shaped sedimentary basins that form on the continent-ward side of fold-thrust belts, filling the topographic depression created by loading from the mountain belt. Most foreland basins have asymmetric, broadly wedge-shaped profiles with the deeper side adjacent to the mountain range, and a forebulge developed about 150 km from the deformation front. The Indo-Gangetic plain on the south side of the Himalayan Mountains is an example of an active foreland basin, whereas some ancient examples include the Cretaceous Canadian Rockies Alberta foreland basin, the Cenozoic flysch basins of the Alps, and the Ordovician and Devonian clastic wedges in the Appalachian foreland basins. Foreland basins are characterized by asymmetric subsidence, with greater amounts near the thrust front. Typical amounts of subsidence fall in the range of about one kilometer every 2–5 million years.

Collisional or peripheral foreland basins form where an arc or continental terrane on one plate overrides another plate that is flexed and faulted downwards forming a basin on the under-riding plate. Deformation such as folding, thrust faulting, and repetition of stratigraphic units may affect collisional foreland basins near the orogenic front. These types of foreland basins appear to have formed largely through flexure of the lithosphere by the weight of the mountain range, with the space created by the flexure filled in mostly by sediments eroded from the uplifted mountains (e.g., Jordan, 1981). Sedimentary facies typically grade from fluvial/alluvial systems near the mountains to shallow marine clastic environments (in underfilled foreland basins) farther away from the mountains, with typical deposition of flysch sequences by turbidity currents. These deposits may be succeeded laterally by distal black shales, then shallow water carbonates over a cross-strike distance of several hundred kilometers. There is also often a progressive zonation of structural features across the foreland basin, with contractional deformation (folds and faults) affecting the region near the mountain front, and normal faulting affecting the area on the flexural bulge a few tens to hundreds of kilometers from the deformation front (Bradley and Kidd, 1991). Sedimentary facies and structural zones all may migrate toward the continent in collisional foreland basins in response to plate convergence as the orogenic belt advances toward the continent (e.g., Bradley and Kusky, 1986).

A second variety of foreland basins are found on the continent-ward side of non-collisional mountain belts such as the Andes, and these are sometimes referred to as retroarc foreland basins (e.g., Allen and Allen, 1990). They differ from the collisional foreland basins described above in that the mountain ranges are generally not advancing (or not as rapidly as collisional foreland basins) on the foreland, and the basin subsidence is a response to the weight of the mountains, added either by magmatism or the weight of the adjacent fold/thrust belt. Some retroarc basins are characterized by fold-thrust belts

that have advanced toward the craton (Jordan, 1981; DeCelles and Giles, 1996; DeCelles and Currie, 1996; DeCelles and Horton, 2003).

Foreland basin deposits commonly consist of terrestrial clastic sediments that unconformably overlie early passive continental margin sediments. A typical foreland basin sequence can be further subdivided into lower deep-water turbidite or flysch facies, a shallow-marine molasse and finally terrestrial molasse separated by unconformities (Sinclair, 1997). As the foreland basin is progressively filled by synorogenic deposits, the basin evolves progressively from early submarine to late terrestrial sedimentation associated with upward coarsening sequences, derived from the orogenic belt or forebulge (Mouthereau et al., 2001). The deposition of molasse marks the transition from an underfilled basin to a filled basin, typically many millions of years after the initial collision (Khain, 1996). If the foreland basin is collisional in origin it may show a lateral migration of sedimentary facies, at a rate approximately equal to the convergence rate (e.g., Bradley and Kusky, 1986). As the geometry of the foreland basin is governed by the mechanical response to loading (elastic, elastic–viscous, etc.) by the thrust belt and is most commonly elongate parallel to mountain, foreland basins have similar lengths and orientations as the related mountain belt (DeCelles and Giles, 1996). By virtue of their generally low states of strain and nearly complete records, foreland basins have proven very useful for reconstructing the history of the adjacent eroded orogen.

Foreland basins commonly lie between the orogenic wedge and the adjacent craton. They are separated from the orogenic belt by thrusts, and characterized by the development of unconformities adjacent to the orogen. The sedimentation breaks associated with the unconformities are commonly associated with the lateral thrusting within the orogen, as the structural deformation propagates to the foreland. Depocenters develop near the orogenic belt and migrate toward the cratonic block. The sedimentary units are asymmetric in cross-section, with progressive migration of depocenters. The molasse shows a gradual decrease in the grain size with increasing distance from orogenic front. Foreland basin fill sequences thicken toward the orogenic front, and onlap the distal basin margin (Castle, 2001).

Toward the inner part of the orogen, the intensity of deformation of the basinal sediments typically increases greatly as the sequence becomes incorporated into the thrust belt, with the presence of asymmetric folds and imbricate thrusts in molasse. In addition, shallow-dipping thrusts may also bring crystalline basement rocks over the foreland thrust belt, overriding the molasse and shelf sediments.

5.1. Kinematic interpretation of the Qinglong basin

The general structural features of the Qinglong basin and fold-thrust belt are remarkable like the younger foreland basins described above. The pertinent features of the Qinglong foreland basin can be summarized as following:

1) The sequence within the Qinglong foreland basin consists of lower turbidites and upper molasse, overlying passive continental margin sediments. They underwent progressive greenschist to amphibolite facies metamorphism. The initiation of molasse deposition at the end of the Neoarchean marked rapid uplift and erosion within the Central Orogenic belt and the transition from an underfilled to overfilled foreland, and was associated with the initial exhumation of the Hengshan high-pressure granulites in the inner zone of the orogen (Kusky and Li, 2003).
2) The imbricated thrusts and asymmetric linear folds are associated with the eastward propagation of orogenic deformation and migration of the coupled orogenic belt and foreland basin. In front of the orogenic belt, sequences are intensely sheared by thrusting, with the development of overturned folds.
3) Higher metamorphic facies are preserved in the foreland and orogen in northern sectors of the orogen. This observation suggests that the North China craton underwent differential uplift or some form of tilting toward the south, leading to the preservation of the foreland thrust belt in the central part of North China, with fold hinges commonly plunging to the southwest. The age of this differential uplift and tilting may relate to the important 1.9–1.8 Ga orogenesis along the northern margin of the craton (see Kusky et al., 2007; Wilde et al., 1997, 1998; Zhao et al., 1998, 2000, 2001, 2002, 2003; Kusky and Li, 2003; Zhao et al., 2005, 2006).
4) In front of the orogenic wedge, foreland basin sequences are characterized by asymmetric structures, such as east-directed thrusts and folds with west-dipping axial surfaces. The western limbs of folds are commonly overturned or cut by thrusts, whereas the eastern limbs are relatively flat.
5) Toward the cratonic block, two major sedimentary sequences are distinguished in vertical section, where shallow-marine sediments of passive continental margin origin are overlain by turbidites and molasse of the foreland basin. Shallowly-dipping structures (shear zones, foliations, and recumbent folds) are very common in the lower sequence, and formed through the reactivation of the basement complex, with local examples being well-exposed on Taihang Mountain.

6. Paleoproterozoic rifting and anorogenic magmatism (2.40–2.00 Ga)

The Qinglong foreland basin preserves a record of collision of the orogenic belt preserved in the Central Orogenic belt with the Eastern block of the North China craton at 2.5 Ga. Following continental collision in the Neoarchean, the North China craton underwent widespread extension in the Paleoproterozoic (Fig. 2). The Central Orogenic belt and its foreland were widely overprinted by Paleoproterozoic graben systems from 2.40–2.0 Ga, and intruded by related mafic dyke swarms between 2.50–2.30 Ga, and anorogenic granite (2.40 Ga, 2.20–2.00 Ga) (Peng et al., 2007; Li et al, 2001, 2000, 2002; Li and Kusky, 2002, in review; Kusky and Li, 2003). The 2.50–2.30 Ga dike swarms transect rocks and terrane boundaries, demonstrating that the collision between the Central Orogenic belt and the Eastern block occurred in the Neoarchean or Paleoproterozoic.

The mafic dike and gabbroic intrusions (2.50–2.40 Ga) were reported from Wutai Mountain, Hengshan Mountain, the Northern Granulite-facies province, Taihang Mountain, Songshan Mountain, and the Qinglong areas (Li et al., 2002, 2001). Both Sm–Nd whole-rock and U–Pb (zircon) ages of the dikes are between 2.40–2.50 Ga. The dikes show well-preserved igneous textures in their cores. They were emplaced by 2.40 Ga, and underwent metamorphism between 2.20–1.80 Ga.

Several nearly north–south trending Paleoproterozoic graben developed across the North China Craton (Fig. 2). They are superimposed on or unconformably overlap the underlying foreland-thrust belt and Archean basement (Kusky and Li, 2003; Li and Kusky, in review). Periods of continental extension and platformal sedimentation continued in the craton interior for 600 million years, punctuated by several orogenic events on the craton margins (see Kusky and Li, 2003; Kusky et al., 2007).

Circa 2.40 continental flood basalts are exposed at the base of the Dongye Group in Wutai Mountain (Fig. 13). Comparable sequences include the Gantaohe Group (2.30–1.90 Ga), Lanhe Group (2.20–1.90 Ga), Zhongtiao Group (2.20–1.90 Ga) in other graben, all of which consist of bimodal volcanic and clastic sedimentary rocks, subjected to a lower-greenschist grade metamorphism. They are interpreted to have been deposited in the craton-wide graben system, recording regional extension and orogenic collapse following collision at 2.50 Ga (Kusky and Li, 2003). These flood basalts (Fig. 13) marked the initiation of the Proterozoic evolution of North China (Li et al., 2000).

In addition, many granitic intrusions with ages between 1.80–2.0 Ga within Archean basement in the northwestern part of the North China craton are associated with tectono-thermal reworking in the Proterozoic Inner Mongolian Northern Hebei orogenic belt (Kusky and Li, 2003).

7. Discussion and conclusions

Although the strata within the Qinglong– Wutai foreland basin are only weakly metamorphosed, dominated by

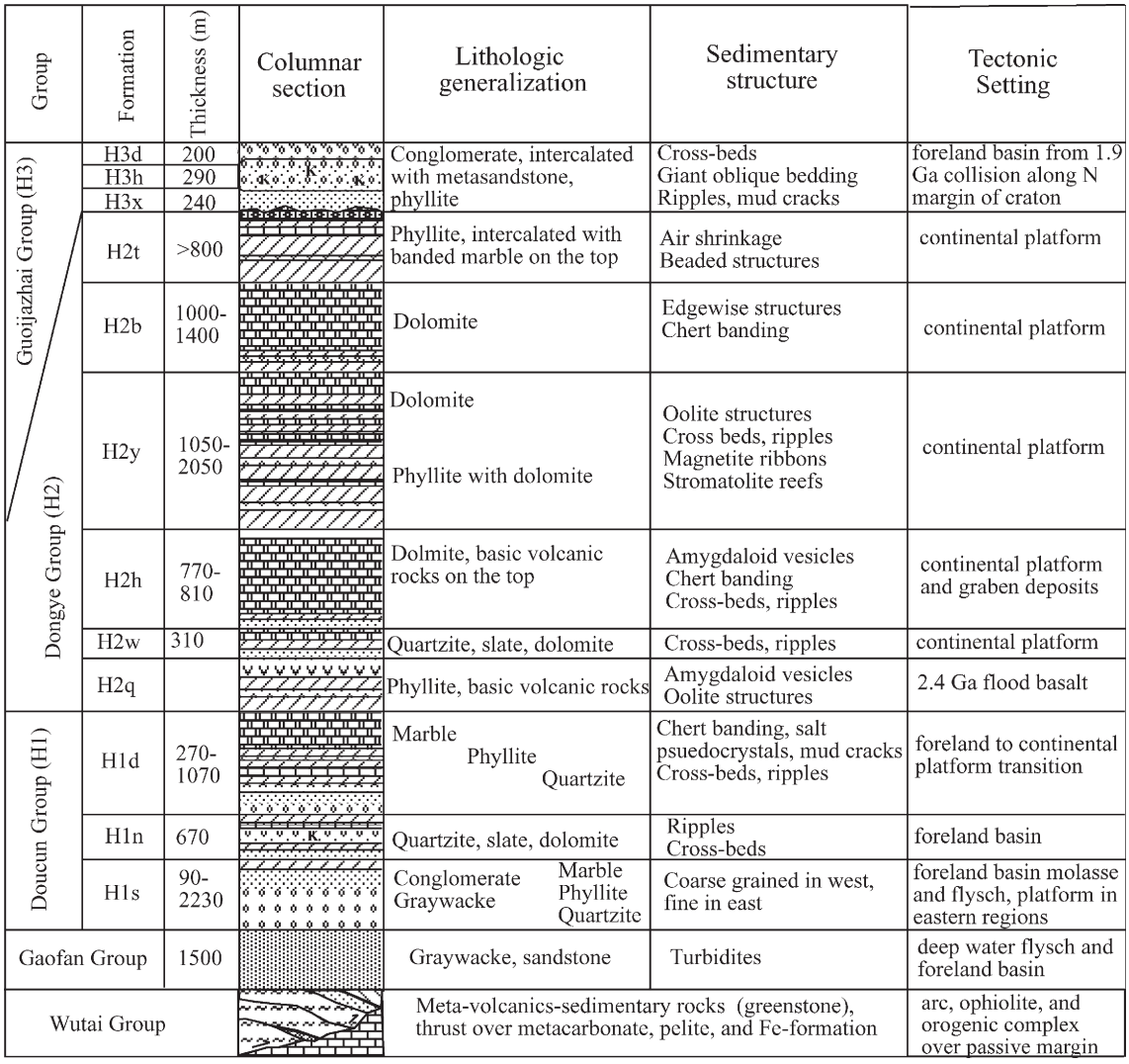


Fig. 13. Stratigraphic column including Paleoproterozoic rift and shelf sequences of the North China craton. The foreland basin is cut by 2.5–2.4 Ga mafic dikes and overlain by 2.4 Ga flood basalts, followed by thick, continental graben and shallow water shelf-type deposits. Formation name abbreviations used in text as follows: Hls, Sijzhuang Formation; Hln, Nantai Formation; Hld, Dashiling Formation.

greenschist-facies parageneses, they underwent intense deformation including the development of thrusts and tight folds, formed during 2.50–2.40 Ga collisional tectonics with the Central Orogenic belt. In contrast, the inner zone of the orogenic belt exposes deep crustal levels and the rocks in the internal zones of the orogen display complex deformational and metamorphic histories.

The Qinglong–Wutai foreland basin provides important constraints for the geometry, kinematics, timing and evolution of the Central Orogenic belt. Syntectonic basinal deposits preserve records of horizontal contraction and unroofing associated with the collision. As outlined by the framework of the preserved foreland thrust belt, we suggest that the original Central Orogenic belt was more than 1600 km long.

To the west, the foreland basin was overthrust by ophiolitic mélange belts of the orogenic complex. Laterally, from west to east, the architecture of the foreland thrust belt is divided into imbricate thrusts with foreland sediments, a fold belt, and a reworked basement complex and overlying shallow marine shelf formation (Fig. 14). The passive continental margin sediments are widely interleaved by thrust-sense shear zones, demonstrating that intense shortening of shallow crustal levels occurred in the foreland area. With the encroaching orogenic wedge, loading of the crust of the Eastern block led to more subsidence in the foreland basin, and sediments onlap older deposits southeastward. In addition, basement involvement is also important in the tectonic evolution of foreland fold-thrust belt.

Several possible piggy-back basins in the foreland-fold-thrust belt formed on the hanging wall of thrust sheets and migrated cratonward. Some coarse clastic sediments were deposited in front of the thrust sheets, and then were overrun by the thrust sheets during continued crustal shortening.

The foreland basin consists of turbidites and molasse, which overlie unconformably the passive continental margin, revealing at least three orogenic episodes and uplift events. Molasse is commonly interpreted to result from loading of a thrust belt on a more rigid continental passive margin (Lihou and Allen, 1996). The basin was filled with shallowing-upward fluvial deposits as the thrust belt advanced eastward. Many thrusts with related syntectonic unconformities are recognized in the molasse basins. Therefore, we suggest that the foreland fold-thrust belt provides convincing evidence for the operation of plate tectonics in the Archean.

7.1. Comparison with Phanerozoic foreland basins: similarities and differences

In comparison with typical foreland basins worldwide, the general geological features of the Qinglong foreland basin can be summarized as follows:

1) The basin is composed of intensely folded and thrust-faulted sedimentary strata, flanking the eastern side of the Central Orogenic belt. To the east, it onlaps shallow-water shelf sediments deposited on the western margin of the Eastern block. Close to the inner part of the Central Orogenic belt in the west, the foredeep sequences were intensely deformed by thrusting and folding. They are separated from a contemporaneous to slightly older (2.5–2.6 Ga) island-arc complex (Polat et al., 2005b, 2006) and fore-arc prism by a major thrust and overridden by thrust sheets from the internal zone of the orogen (Figs. 2 5–8). An ophiolitic melange zone demarcates its western boundary, with ophiolitic blocks of different scales.
2) Imbricate thrusts, ductile shear zones, and tight-overturned folds are widely developed in the Qinglong foreland basin, with mainly west or northwest-dipping structural planes (foliation, axial surfaces) and east-vergent folds and thrusts. Several major flat-lying shear zones, such as the Longquanguan and South Taihang, brought deep metamorphic rocks of the basement complex to the surface, emplacing them over the foreland basin deposits (Figs. 3 5 and 6). Farther east, a structurally reworked passive continental margin sequence overlies the basement complex (Figs. 2 and 6).

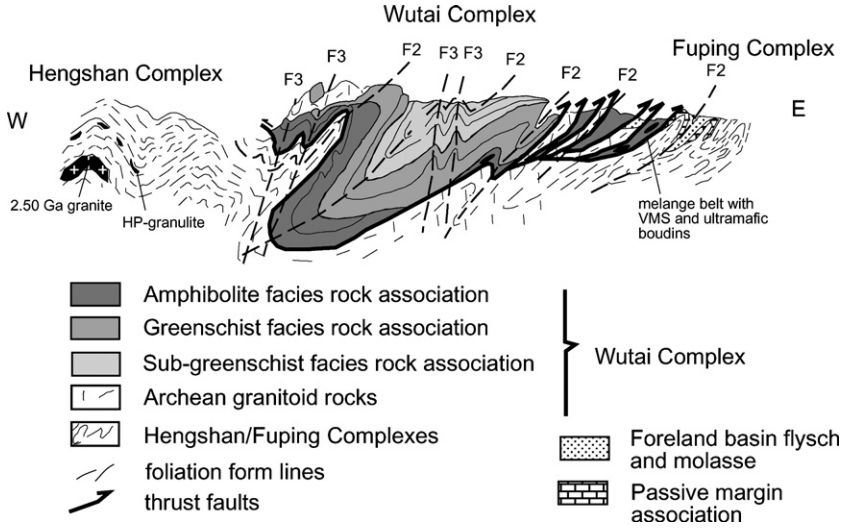


Fig. 14. Schematic cross-section of the orogen–foreland basin and craton margin transition, Wutai Mountain area. Modified after (Tian et al., 1996).

3) The weakly metamorphosed foreland basin deposits reach thicknesses of up to 2 km near the mountain front, where the foreland basin sediments rest on a basal unconformity developed on older greenstone belts. The sequences begin with deep-water turbidites, onlapped by overlying molasse, demonstrating that the foredeep formed rapidly and filled up gradually (Fig. 2). Foreland basin strata locally onlap passive continental margin sediments (marble–pelite–quartzite). With continued shortening, the foreland basin gradually migrated to the east, and was filled with thick molasse sediments (2.50–2.40 Ga). The molasse was involved in thrusting along its northwest side, whereas it is weakly disturbed by the deformation in the interior of the basin.
4) The Qinglong foreland basin is cut by 2.501 granite, 2.54 granite, 2.50–2.40 Ga mafic dikes and 2.30–2.20 Ga anorogenic granite, and overprinted by overlying Paleoproterozoic rift systems (Dongye Group (2.30–1.9 Ga; Gantaohe Group, 2.30 Ga) (Fig. 2), providing crucial constraints for the age of deformation (pre-2.50–2.40 Ga). These data unequivocally demonstrate that the Central Orogenic belt formed by collision tectonics in the Archean. Proterozoic PT–t paths that indicate crustal thickening at circa 1.8 Ga are interpreted to be related to a second collision, along the northern margin of the craton that overprint this early event (see Kusky and Li, 2003; Polat et al., 2006; Kusky et al., 2007).
5) The Qinglong foreland basin is 1600 km long, up to 200 km wide, and contains at least 2 km and locally more than 6 km of sediments. The length, thickness, width, and time interval of formation of the Qinglong foreland basin are all similar to foreland basins that developed in front of Phanerozoic mountain belts on continental crust. Since the geometry and thickness of foreland basins is controlled by the mechanical response of the lithosphere to loading, the similar responses of Archean and Phanerozoic lithospheres to loading suggests that the mechanical behavior of the lithosphere has not changed dramatically over the past 2.5 billion years. Furthermore, since the mechanics of the lithosphere is dependent on continental geothermal gradients and thicknesses, the geometry of the Qinglong basin suggests that the thermal structure and thickness of Archean lithosphere was similar to that of today. Thus, any additional heat loss from the early Earth was not lost through an increase in continental geothermal gradients, but rather through the making and aging of oceanic crust.

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