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Mesozoic intracontinental underthrust in the SE margin of the North China Block: Insights from the Xu-Huai thrust-and-fold belt

Liangshu Shu , Hongwei Yin, Michel Faure, Yan Chen

Highlights

•The fault-related folds and step-type thrust faults are predominant features of the Xu-Huai thrust-and-fold belt.

•Two geological cross-sections were used for structural balancing and restoration.

•A shortening rate of 43–46% was obtained from the restoration of two balanced cross-sections.

•The Xu-Huai belt was derived from th

Abstract

The Xu-Huai thrust-and-fold belt, located in the southeastern margin of the North China Block, consists mainly of thrust and folded pre-Mesozoic strata. Its geodynamic evolution and tectonic setting are topics of long debate. This paper provides new evidence from geological mapping, structural analysis, and making balance cross-sections, with restoration of cross-sections. Results suggest that this belt was subjected to two-phase deformation, including an early-phase regional-scale NW-ward thrust and fold, and a late-phase extension followed by the emplacement of dioritic, monzodioritic porphyrites dated at 131–135 Ma and locally strike-slip shearing. According to the mapping, field observations and drill-hole data, three structural units were distinguished, namely, (1) the pre-Neoproterozoic crystalline basement in the eastern segment, (2) the nappe unit or the thrust-and-fold zone in the central segment, which is composed of Neoproterozoic to Ordovician carbonate rocks and Carboniferous-Permian coal-bearing rocks, about 2600 m thick, and (3) the western frontal zone. A major decollement fault has also been identified in the base of the nappe unit, on which dozen-meter to km-scale thrust-and-fold bodies were commonly developed. All pre-Mesozoic depositional sequences were involved into a widespread thrust and fold event. Six uncompetent-rock layers with biostratigraphic ages (Nanjing University, 1996) have been recognized, and each uncompetent-rock layer occurred mainly in the top of the footwall, playing an important role in the development of the Xu-Huai thrust-and-fold belt. Geometry of the major decollement fault suggests that the nappe unit of this belt was rooted in its eastern side, near the Tan-Lu Fault Zone. Two geological cross-sections were chosen for structural balancing and restoration. From the balanced cross-sections, ramp-flat and imbricated faults as well as fault-related folds were identified. A shortening of 20.6–29.6 km was obtained from restoration of balanced sections, corresponding to a shortening rate of 43.6–46.4%. This shortening deformation was likely related to the SE-ward intracontinental underthrust of the North China Block beneath the South China Block during the Mesozoic.

Keywords : Thrust; Fault-related fold; Intracontinental underthrust; Mesozoic; Xu-Huai belt; North China Block

1. Introduction

The Qinling-Dabie Orogen, also referred to as the Central China Orogen, is an important tectonic unit, separating the North China Block to the north from the South China Block to the south (Wang and Mo, 1995). To its western segment, an early Paleozoic Ocean subducted northwards beneath the North China Block, followed by the collision of North China and South China blocks in Silurian, building the Qinling Orogen (Zhang et al., 1989). To its eastern segment (Dabie area), no rock record related to the early Paleozoic subduction and collision was preserved because of likely late erosion (Faure et al., 1999), as an early Mesozoic continental subduction of the South China Block beneath the North China Blocks took place, which is proven by the development of coeval UHP coesite-bearing eclogite and HP blue-schist (Faure et al., 1998 and Faure et al., 2003), building the Dabie and the Su-Lu orogens (Gilder et al., 1999, Schmid et al., 1999 and Faure et al., 2003). At the same time, widespread intracontinental deformation took place within the South China Block (Song et al., 2015, Shu et al., 2008 and Shu et al., 2015). Despite that the SE-ward continental crust underthrust of the North China Block beneath the Su-Lu Orogen has rarely been studied, numerous syn-orogenic and post-orogenic rocks and structural records related to early Mesozoic tectonic events are widely exposed in the SE margin of the North China Block near the Su-Lu Orogen, including the thrust and fold structures and strike-slip ductile shear zones (Faure et al., 1998, Lin et al., 2005 and Zhu et al., 2010), UHP metamorphic rocks (Li et al., 2009) and two-stage extrusion of UHP-HP metamorphic rocks (Li et al., 2009 and Li et al., 2010), foreland basin (Zhu et al., 1998) and post-orogenic extension followed by emplacement of dioritic-granitic magma (Lin et al., 2005; Xu et al., 2006, 2009). Tectonic evolution was related to regional-scale thrust, fault-related fold, and strike-slip shearing. The arcuate Xuzhou-Huainan thrust-and-fold belt (the Xu-Huai belt in short) was formed under this geodynamic setting (Xu et al., 1987; Shu et al., 1994).

The Xu-Huai belt is located in the SE margin of the North China Block and to the western side of the Su-Lu Orogen, near the Tan-Lu Fault Zone (Fig. 1). Structurally, it appears as a NW-ward convex thrust-and-fold belt, which was intruded by early Cretaceous granitoids. Several large-scale coal mines are distributed in the late Paleozoic strata and were covered by thrust slices near the western boundary of this belt. Thus this arcuated belt is a suitable place to investigate the geological setting and tectonic evolution of the SE margin of the North China Block.

Despite its importance, the geodynamic mechanism and tectonic evolution of the Xu-Huai belt are poorly studied and were debated in the last decades. Several models have been proposed, such as the syn-tectonic thrust (Xu et al., 1987; Shu et al., 1994, 1996; Wang et al., 1998), a result from the clockwise-rotated South China Block suturing with the North China Block (Zhao and Coe, 1987; Zhang, 1997; Gilder et al., 1999), an effect from syn-tectonic transformation (Zhu et al., 2005, 2009; Zhao et al., 2016), and the post-orogeny gravity collapse (Ma, 1991). All previous studies mainly focus on the Dabie Orogen, however, rarely on the Su-Lu Orogen and the Xu-Huai belt, little attention has been paid to the structural analysis and geodynamic mechanism forming the Xu-Huai belt.

In the 1980s, the balancing cross-section technique was used firstly for study of thrust deformation and deep-seated structure in foreland and piedmont basins of orogenic belt, such as the North Sea (England) and the Rocky Mountains (North American) (Gibbs, 1983; Mitra and Boyer, 1986; Cooper and Trayner, 1986), and then was quickly accepted by geologists all around the world. The balancing of structural section and the restoration of balanced cross-section were mainly used to interpret brittle deformation (Suppe, 1983, 1986; Ramsay and Huber, 1987; Fossen, 2010). Numerous buried thrust faults and folds (Suppe and Medwedeff,

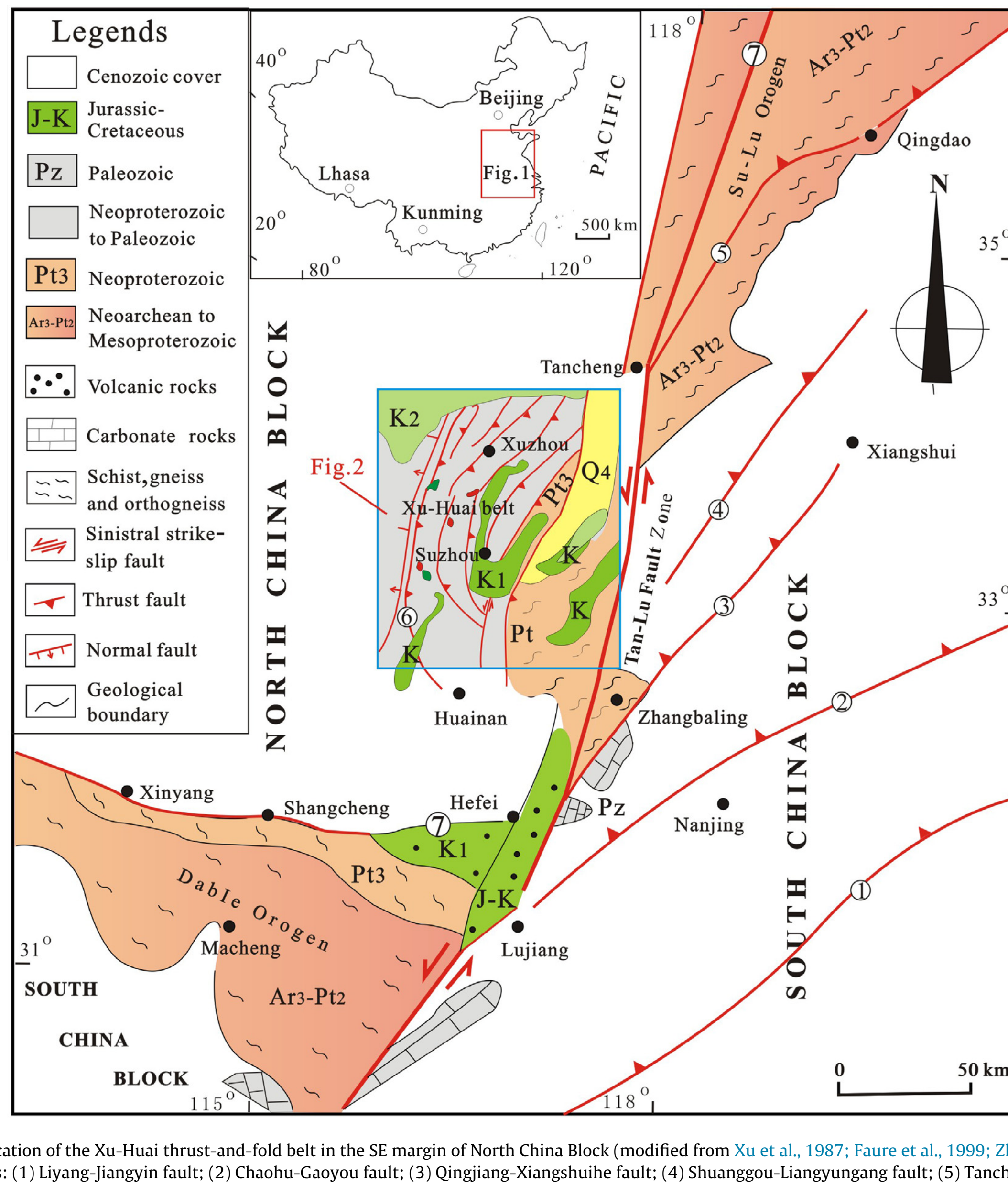


Fig. 1. Tectonic location of the Xu-Huai thrust-and-fold belt in the SE margin of North China Block (modified from Xu et al., 1987; Faure et al., 1999; Zhu et al., 2009; Li et al., 2009). Fault names: (1) Liyang-Jiangyin fault; (2) Chaohu-Gaoyou fault; (3) Qingjiang-Xiangshuihe fault; (4) Shuanggou-Liangyungang fault; (5) Tancheng-Qingdao fault; (6) the western boundary fault of Xu-Huai belt; (7) Tan-Lu Fault Zone.

1990; Wilkerson et al., 1991; Epard and Groshong, 1993) and some coal-trapping and oil-gas-trapping structures (Chamberlin, 1970; Brewer and Groshong, 1993; Groshong, 1994; Yin and Groshong, 2006) were well prognosticated by interpretation of balancing cross-sections and restoration of their initial geometry.

In order to understand the forming process of the Xu-Huai belt, based on first-hand data from geological mapping, field observations and drilling, we have carried out a structural analysis and balancing and restoration of structural profiles throughout the outcrop areas of the Xu-Huai belt. Combined with published geochronological and geochemical data, a tectonic evolution forming the Xu-Huai belt was reconstructed in this study.

2. Geological setting

2.1. Tectonic framework

The Xu-Huai thrust-and-fold belt in the SE margin of the North China Block is developed upon the pre-Neoproterozoic crystalline basement. The North China Block consists mainly of Archean TTG to Proterozoic marine facies carbonate rocks, sandy-muddy rocks intercalated with various volcanic rocks (SDBGMR, 1988; Li et al., 2009), which were metamorphosed into marble, mica schist, amphibolite or amphibole-schist, para-gneiss and orthogneiss. The oldest rock outcrop of this block, called Taishan Group, was dated at 2800 Ma (Jahn et al., 1988, 2008).

The Dabie Orogen is located to the south of the Xu-Huai belt. The eastern boundary of the Xu-Huai belt is the NNE-trending Tan-Lu Fault Zone that directly contacts with the Su-Lu Orogen (Fig. 1) (Zhao et al., 2016). The area between the Dabie and the Xu-Huai belts is mostly covered by Quaternary deposits. The Tan-Lu Fault Zone was generated from a NW-ward oblique convergence of the South China Block beneath the North China Block in early Mesozoic (Zhao et al., 2016). The crustal thickness of the North China Block (32–35 km) in the west to the Tan-Lu Fault Zone is larger than one of the South China Block (30–31 km) that is located in the east to the Tan-Lu Fault Zone (Sun et al., 1992; Zhu et al., 2002), and the lithospheric thickness of the North China Block (110 km) is obviously larger than one of the South China Block (85–88 km) (Sun et al., 1992; Zhu et al., 2002). A three-stage deformation was identified (Zhu et al., 2010), i.e., a late Triassic thrust dated at 220–210 Ma ($^{40}Ar/^{39}Ar$ on phengite of mylonite), an early Cretaceous sinistral shearing with the age of 135–125 Ma ($^{40}Ar/^{39}Ar$ on mica) (Zhu et al., 2005) and an extension in late Cretaceous - Paleogene (Zhu et al., 2009).

The Neoproterozoic Zhangbaling Group is widely distributed along the Tan-Lu Fault Zone (Lin et al., 2005), which consists of meta-volcanic and meta-volcanoclastic rocks dated at 750 Ma (Zhao et al., 2016). Some UHP-HP metamorphic rocks and mylonitic schists dated at 240–235 Ma ($^{40}Ar/^{39}Ar$ on mica) (Xu et al., 2003; Zhang et al., 2007) are exposed in the Zhangbaling belt of the Su-Lu Orogen (Fig. 1). In the northern segment of the Zhangbaling belt, the rocks of ductile deformation with foliation and stretching lineation show a top-to the southeast sense of shearing, and its southern segment is a sinistral shear zone (Zhang et al., 2007; Zhao et al., 2016). The Zhangbaling group shows a geochemical affinity with the Yangtze Block (Lin et al., 2005; Zhang et al., 2007).

2.2. Stratigraphic sequences

The neighboring areas of the Xu-Hai belt are widely covered by Quaternary alluvial deposits, the exposed rocks are mostly non-metamorphosed Neoproterozoic to middle Ordovician marine facies limestone, dolomite and sandy-muddy rocks (Fig. 2). The metamorphosed Mesoproterozoic rocks are distributed on the eastern side of this belt, near the Tan-Lu Fault Zone.

2.2.1. Neoproterozoic strata

It is called the Qingbaikou system ("Pt_3", in Fig. 2) with a thickness of 750 m and consists of limestone, dolomite and stromatolite limestone intercalated with sandstone, siltstone and mudstone. This system is widely distributed in the eastern part of the Xu-Huai belt and is divided into seven formations, namely, the Niuyuan, Jiudingshan, Zhangqu, Weiji, Shijia, Jinshanzai and Wangshan formations (Fig. 3) (Nanjing University, 1996). The Niuyuan Formation, as the base of the Xu-Huai belt, overlies unconformably the metamorphosed Mesoproterozoic basement whereas on the top, the Wangshan Formation contacts disconformably with the Cambrian sequence (Fig. 3).

2.2.2. Cambrian to middle Ordovician strata

The strata of this age are widely distributed in the Xu-Huai belt (Fig. 2). The Cambrian system with a thickness of 964 m consists of various limestone, dolomite, bioclastic limestone and intercalations of sandstone, siltstone and shale. It is divided into five formations, namely, the Houjiashan, Mantou, Zhangxia, Gushan and Chaomidian formations (Fig. 3). Various stromatolite fossils are preserved well in this system. The evident negative C and O isotopic anomalies (δC^{13} and δO^{18}) in the boundary of Cambrian and Ordovician sequences indicate an important event of biomass extinction (Fang et al., 1993). The Ordovician system is composed of dolomite, limestone, wormtalk, bioclastic limestone and intercalations of shale, and is divided into three formations (Sanshanzi, Jiawang and Majiagou), totally thick 610 m. The gypsum beds are widely developed in the top of the Majiagou Formation (Fig. 3). The depositional sequence from middle Ordovician to early Carboniferous is regionally absent due to a long-time uplift and erosion (Fang et al., 1993; Shu et al., 1994).

2.2.3. Carboniferous and Permian strata

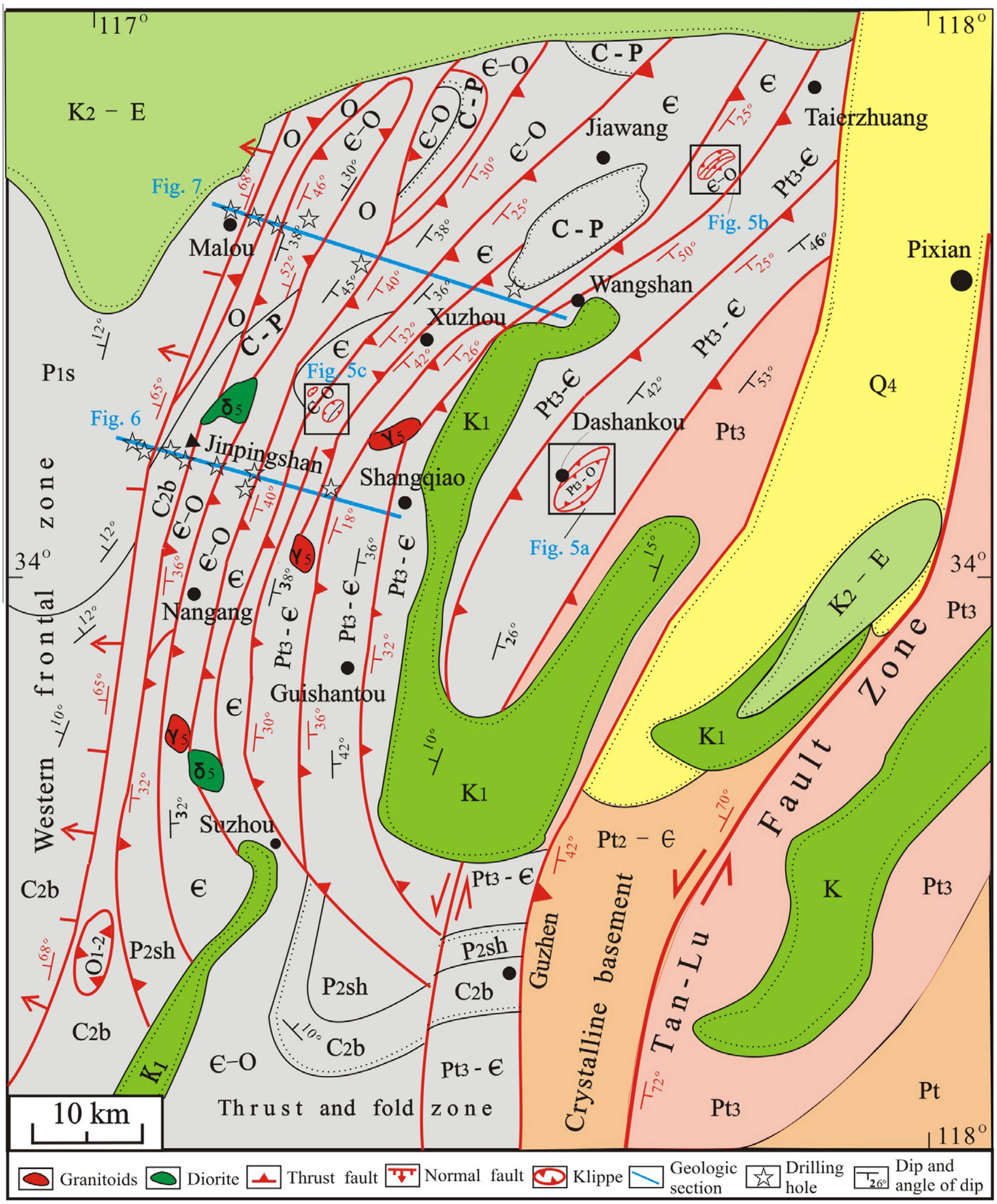
In the studied area, only the upper Carboniferous Benxi and Taiyuan formations and the lower Permian Shanxi Formation are locally exposed in the western segment. They are composed of coal-bearing sandy and muddy rocks, thick 230 m (Fig. 3), and are mostly covered by allochthonous thrust slices or Quaternary alluvial depositions.

2.2.4. Mesozoic depositional sequence

They are not exposed in the studied area; the youngest stratum exposed in the western part of the Xu-Huai belt is the early Permian Shanxi Formation (coal-bearing mudstone). According to 1:50,000 geological map of the Jiagou-Heifengshan region (The 325 Geological Brigade of Anhui Bureau, 1992; Xu et al., 1993), the early Cretaceous rhyolitic, volcanoclastic and sandy-muddy rocks (K_1) were deposited in the areas to the south and southeast of Xuzhou City, and the late Cretaceous-Paleogene red colored sandy-muddy rocks (K_2-E) were exposed in the areas to the northwest and the southeast of Xuzhou City (see Fig. 2). The late Cretaceous-Paleogene red beds were disconformably deposited on the early Cretaceous strata (Fig. 2) (Xu et al., 1993). Previous authors reported that the middle Triassic thin-bedded carbonate rocks intercalated with muddy-sandy rocks are sparsely exposed in the Mengcheng area to the south of the studied area (Wang et al., 1998).

2.3. Magmatic intrusion

Within the Xu-Huai belt, the pre-Mesozoic carbonate strata were intruded by small-scale granite, diorite and monzodioritic porphyrite, these intrusions were dated at 135 ± 4 Ma (U-Pb on

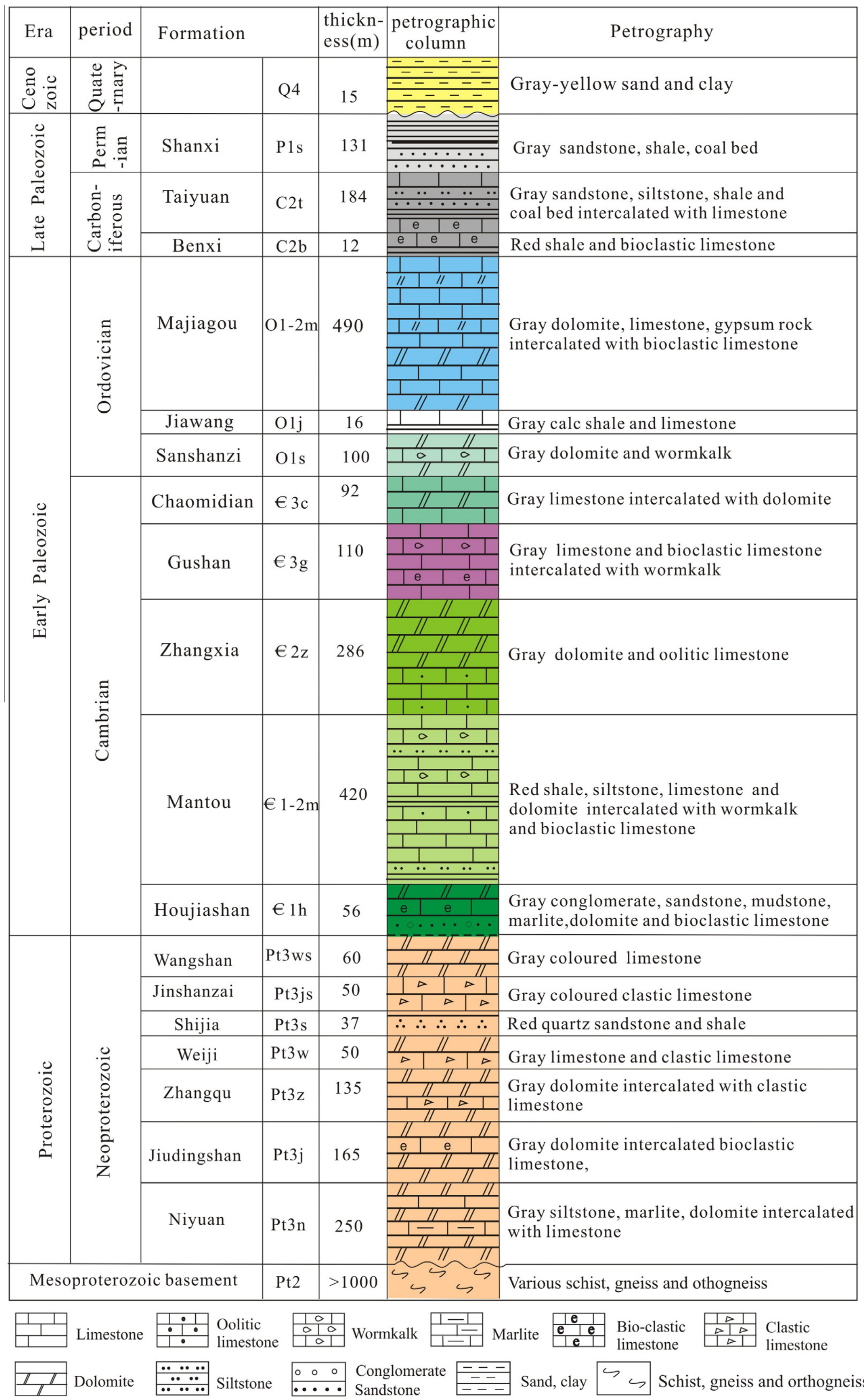


zircon) (Wang et al., 1998) and 131–132 Ma (SHRIMP U–Pb) (Xu et al., 2006). The diorite and monzodioritic porphyrite contain the xenoliths of eclogite, garnet-clinopyroxenite and garnet amphibolite, these intrusions were originally emplaced in the late Mesozoic extensional setting (Xu et al., 2009, 2010).

3. Geological features of the Xu-Huai thrust-and-fold belt

3.1. Petrological and structural units

According to field observations, 1:50,000 geological mapping (Nanjing University, 1996), drill-hole data (Yin, 1994) and geophysical data (Zhang, 1997), petrologically, three units were identified from the bottom to top: (1) the Pre-Neoproterozoic crystalline basement unit consisting of sandstone, mudstone, basalt, greywacke and granitic rock that were metamorphosed into mica schist, amphibole schist, para-gneiss, meta-basalt and orthogneiss; (2) the Neoproterozoic to early Permian rock unit, consisting of un-metamorphosed Neoproterozoic, Cambrian and Ordovician carbonate rocks as well as Carboniferous-Permian coal-bearing terrigenous clastic sequence, 2600 m thick in total. Various stromatolith carbonate rocks developed in the Neoproterozoic to middle Ordovician strata show a typical character of the North China biostratigraphic province. This depositional sequence was involved in an intensive thrusting and folding event; and (3) the Cretaceous-Paleogene rock unit, composed of the sub-horizontal early Cretaceous coarse-grained terrigenous clastic rocks (conglomerate and sandstone), volcanic and volcanoclastic rocks and late Cretaceous-Paleogene red beds (Xu et al., 1993).



Structurally, the Xu-Huai belt can be subdivided into three zones from the east to west (Fig. 2): (1) the pre-Neoproterozoic crystalline basement at the depth and near the Tan-Lu Fault Zone (Shu et al., 1994). It contacts with the overlying thrust slice by a large-scale decollement fault; (2) the thrust and fold zone, being the principal part of the Xu-Huai belt is composed of allochthonous thrust slices with ramp-flat structure, imbricated slices, klippes and fault-related folds; and (3) the western frontal zone, composed of sandy-muddy and carbonate rocks and numerous coal measures.

3.2. The major decollement fault and six decollement layers

A NE-SW-trending major decollement fault occurs between the Neoproterozoic - Permian thrust-and-fold zone and the pre-Neoproterozoic crystalline basement. It has a listric thrust plane dipping to the southeast and disappears near the Tan-Lu Fault Zone (Fig. 2). The Xu-Huai belt is limited in the area between the Taierzhuang-Guzhen fault (eastern boundary) and the Molou-Nangang fault (western boundary). Numerous second-order thrust faults and fault-related folds are developed upon this major decollement fault (Xu et al., 1993; Shu et al., 1994).

Our investigation suggests that each second-order decollement fault occurs between competent-rock (roof) and uncompetent-rock (floor) layers, leading to variable-scale thrusting. The second-order decollement fault and its roof rock slice constitute a thrust body. In the Xu-Huai belt, uncompetent-rock layers are composed of shale, muddy rock, siltstone, gypsum-bearing dolomite and coal-bearing rocks, however, the competent-rock layers consist mainly of sandstone and massive limestone beds.

According to our field observation and structural analysis, six uncompetent-rock layers have been identified, namely, (1) the siltstone and marlite beds of the upper Proterozoic Niyuan formation (Pt_3n), (2) the shale and marlite beds of the lower Cambrian Houjiashan formation ($\in_1h$), (3) the shale and muddy siltstone beds of the lower Cambrian Mantou formation ($\in_{1-2}m$), (4) the shale bed of the lower Ordovician Jiawang formation (O_1j), (5) the gypsum bed of the lower-middle Ordovician Majiagou formation ($O_{1-2}m$), and (6) the shale and coal beds of the Carboniferous-Permian (C-P). The thickness of each uncompetent-rock layer varies from meters to hundreds of meters. The scale of thrust is positively correlated with the thickness of uncompetent-rock layers.

3.3. Structural patterns

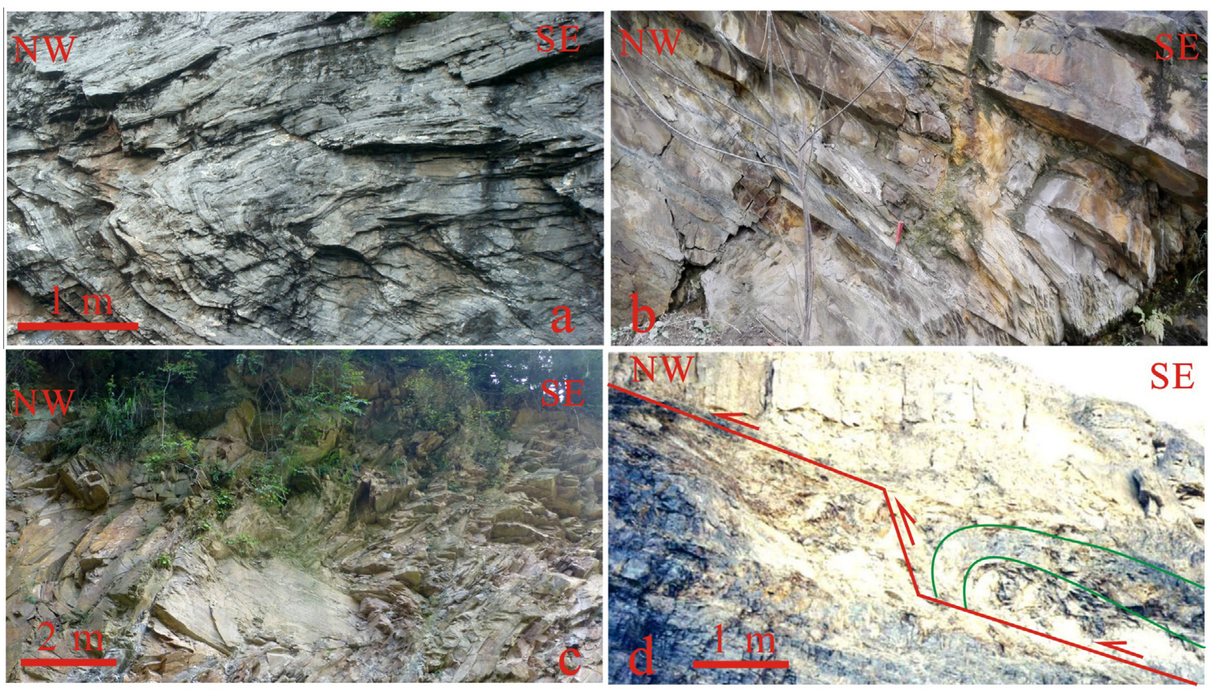
3.3.1. Two-phase folding

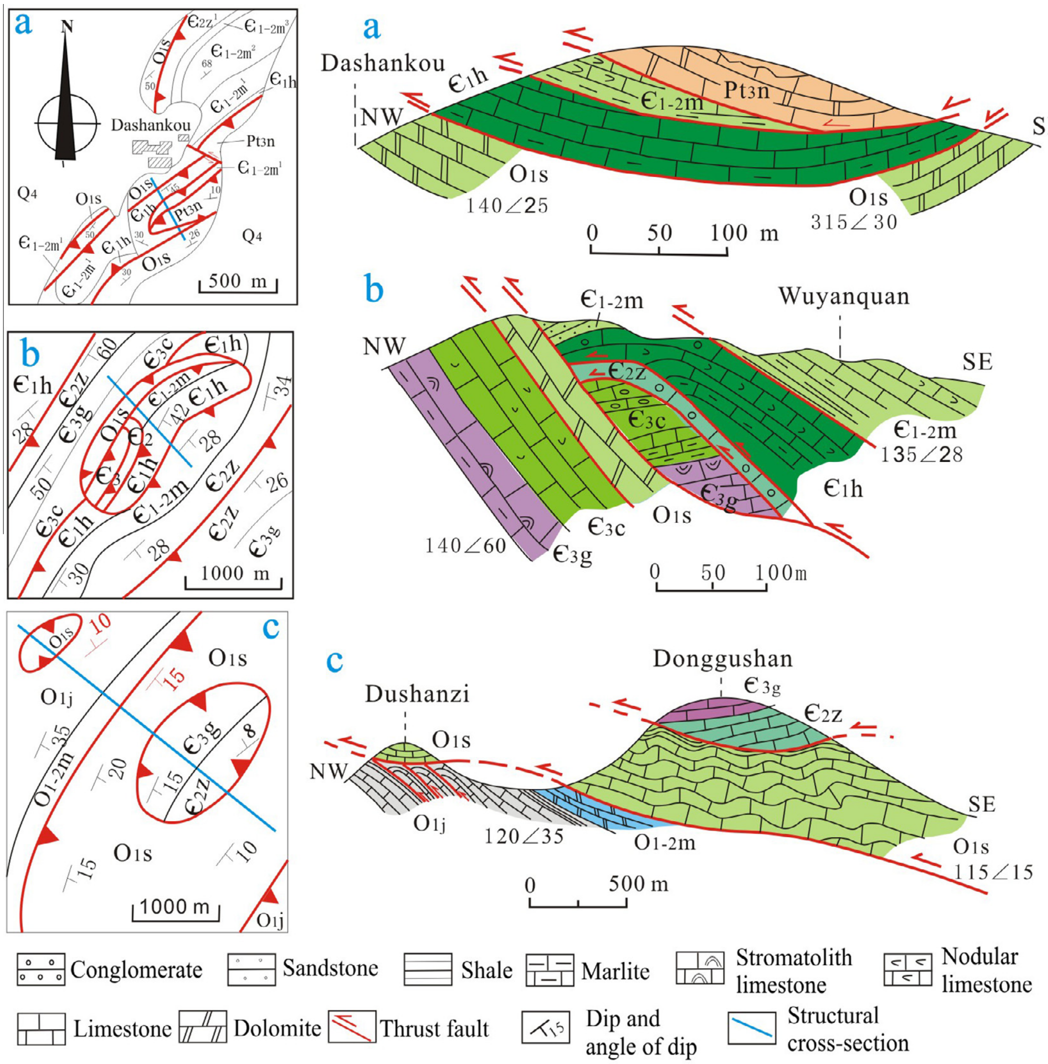
Folding is widely recorded in the pre-Mesozoic carbonate and clastic rocks. The first-phase deformation (D_1) is characterized by recumbent fold (F_1) with NE-striking axial-plane (S_1) dipping 8–15° toward to the southeast (Fig. 4a). The meter- to dozen meter-scale fault-bend fold, fault-propagation fold, asymmetric fold and isoclinal fold are widely developed, indicating a NW-ward motion direction.

Fault-bend fold is a fold formed in the hanging wall or above a fault ramp in response to a bend in the fault surface; and fault-propagation fold means a fold formed ahead of a propagating thrust fault tip (Suppe, 1983, 1986). These two kinds of folds are dominant structures in the studied area. The decollement layers are widely developed in the thrust slices with SE-dipping planes. The fault-bend (Fig. 4d) and fault-propagation folds with an axial plane dipping 30° to the southeast are mainly outcropped in the Lihuashan area (Fig. 6). Kinematic indicators such as drag fold, intrafolial fold, crenulation, boudinage, slickensides on the fault plane, and the relationship between fracture cleavage and fault plane (Fig. 4b) indicate a top-to-the NW thrusting.

The second-phase deformation (D_2) is locally developed in the western frontal zone and is characterized by intrafolial fold and "S-shape" asymmetric fold (F_2) with axial-plane (S_2) dipping to the NW. Associated sharp faults dipping 70° to the NW were observed, cutting the D_1 structural trace. Kinematic indicators, such as the NW-ward intrafolial fold (Fig. 4c), the asymmetric boudinage and the relationship between fracture cleavage and fault plane suggest a normal fault nature with a top-to-the NW dip-slip movement. This second-phase deformation was likely related with late Mesozoic collapse and extensional tectonics (no dating data).

The Xu-Huai belt was affected by the emplacement of late Mesozoic diorite and granite plutons (131–135 Ma) with high MgO and low Epsilon Nd (t) values (Xu et al., 2006) in an





extensional setting. Both the late Mesozoic intrusions and the above-mentioned basaltic xenoliths were considered to be related with the delamination of the sub-continental lithospheric mantle (Lin et al., 2005; Xu et al., 2009, 2010).

The strike-slip shear structures are exposed locally in the west of Guzhen, and cut the early thrusting structures (Fig. 2). Sinistral sense of shear is demonstrated by sub-vertical fault and displacement of strata along both sides of the fault (Fig. 5a, left).

3.3.2. Three kinds of fault

Many faults in the Xu-Huai belt display a composite pattern including imbricated, ramp-flat and listric ones, which closely relate to the formation of fault-related folds and imbricate thrust slices (Figs. 6 and 7).

The imbricated fault displays a parallelism of thrust fault and the related fold axial plane. The ramp-flat fault is composed of two parts, one part cross-cuts strata (ramp) and another is parallel to strata (flat). These two parts are spatially connected with each other (Fig. 4d). Generally, folds were generated when the ramp-flat fault moved forward. The ramp part was developed within the competent-rock layers (sandstone and massive limestone), while the flat part occurs between the competent- and uncompetent-rock layers. This composite fault is mainly distributed in the thrust and fold zone of the Xu-Huai belt. The listric fault displays distinct geometry, including a high-angle dip in the upper part and a low-angle dip in the lower part parallel or sub-parallel to the major decollement fault; this kind of fault is widely developed in both the thrust and fold zone and the western frontal zone of the Xu-Huai belt.

Regionally, the listric-shape major decollement fault dipping to the southeast reveals a NW-ward raising of the buried basement, implying that the original place of the Xu-Huai belt is likely seated in the eastern segment, near the Tan-Lu Fault Zone.

3.3.3. Four kinds of thrust pattern

Four kinds of thrust were identified from field investigations, including ramp-flat, imbricated (Figs. 6 and 7), klippe (Fig. 5) and duplex (Fig. 5b) thrust. As aforementioned, the ramp-flat and imbricated thrust structures are the most developed structure in the Xu-Huai belt. The rootless structural block was often thrust on other slice by a thrust fault. A later erosion can make the structural block to be appeared as isolated allochthonous body, forming a klippe. The klippe structures are distributed in the thrust and fold zone of the Xu-Huai belt, such as Jiawang, Jingpinshan (Fig. 2), Dashankou (Figs. 2 and 5a), Donggushan and Dushanzi (Fig. 5c) areas.

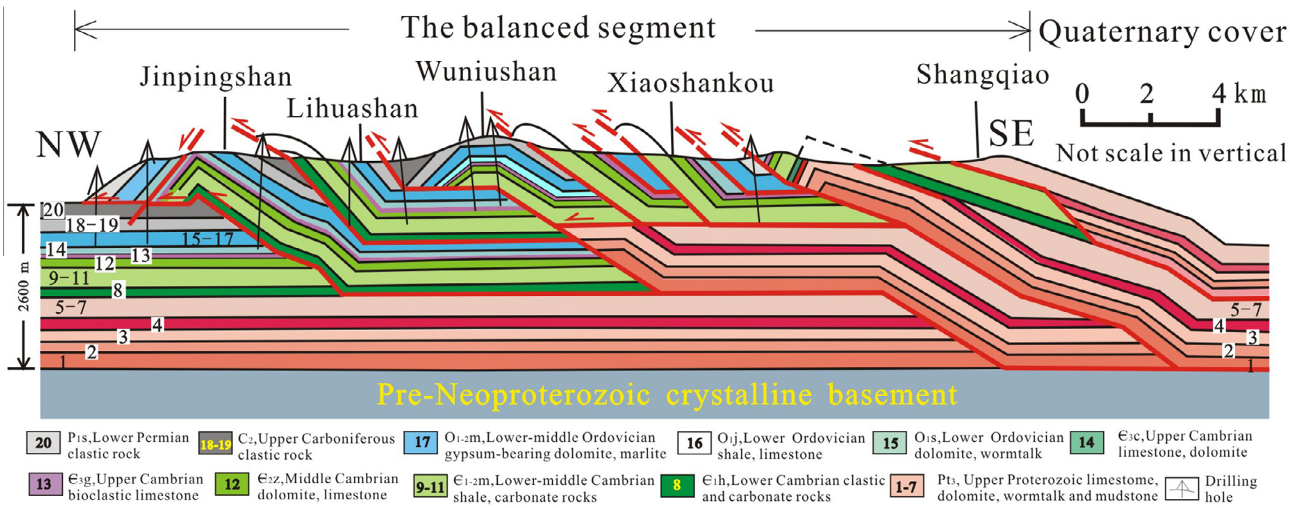
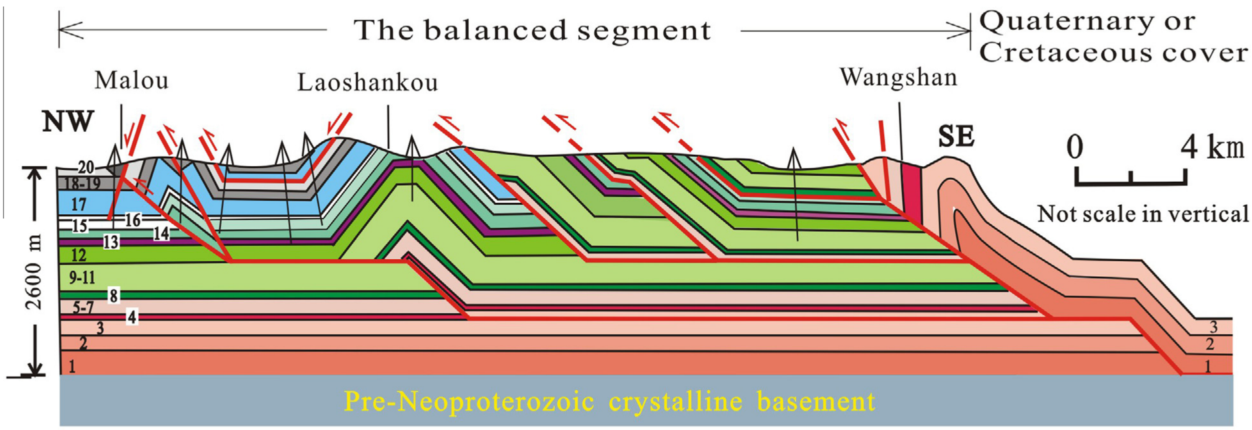


Fig. 6. The Shangqiao to Jinpingshan balanced cross-section in the Xu-Huai belt.



Duplex structure is a compressive zone confined between two decollement faults, with the interbedded fault slice. This pattern is well developed in the thrust and fold zone and formed when the flat and ramp move. At Wuyanquan, the interbedded fault slices of carbonate rocks ($\in_2$ to $\in_3$) are trapped well between two thrust faults (Fig. 5b). To the western side of Wuniushan, a dozens-meter-scale duplex structure, consisting of coal-bearing Carboniferous and Permian clastic rocks, is developed between floor and roof thrust faults (Fig. 6).

3.4. Inferring formation time of the Xu-Huai thrust-and-fold belt

Field observations suggest that a thrust and fold event took place in the interval of Permian and early Cretaceous. This was confirmed by the following evidence: (1) the Permian depositional sequence has been involved in a thrust and fold unit (Figs. 6 and 7): (2) the drill-hole data with a depth of 400–900 m suggest that the sub-horizontal early Cretaceous volcanic and clastic rocks unconformably overlie the folded late Paleozoic strata (Shu et al., 1994; Wang et al., 1998) although no Cretaceous rock is exposed in the Xu-Huai belt. Thus, we suggest that the thrust and fold event took place in the period between the Permian and early Cretaceous, likely in the middle Triassic, corresponding to the time of continental subduction and exhumation of UHP-HP rocks in the Dabie and Su-Lu orogens.

4. Balancing and restoration of geological cross-section

4.1. General principles

Balancing of structural cross-section is a method to construct or interpret a geological profile that can be reconstructed by means of geologically realistic processes to a geologically un-deformed state. Balancing adjusts a geological interpretation so that it is not only reasonable in its present state, but also restorable to its pre-deformational state according to some assumptions about the deformation (Suppe, 2005; Fossen, 2010). The "balance" occurs when bed-lengths or cross-section areas are equal in both deformed and un-deformed states. If not, a section is not balanced. A balanced cross-section does not mean that it is correct. However, if it is not balanced, it cannot be correct, assuming plane strain and no area or volume change. In the metamorphosed areas with penetrative foliations, the balancing of cross-section is difficult (Lisle et al., 2011).

According to Fossen (2010), five conditions must be followed for balancing of cross-sections: (1) sound geologic interpretations; (2) plane strain deformation; (3) the section should be parallel to the motion direction of the geological body, and ramp cuts upward strata; (4) the choice of deformation (vertical shear and rigid rotation, etc.) must be reasonable and based on the general knowledge of deformation in a given tectonic setting; and (5) the results must be reasonable and admissible based on the geological observations and experience. Two methods can be adopted for balancing cross-sections, namely, equal-length and equal-area. In practice, these two methods are often combined to obtain a better result.

If the deformed section is presented without a restored section, it may be not balance. The so-called "restoration section" is an expression used for the reconstruction of a geological section to its pre-deformed state.

4.2. Making procedures of cross-section balance

4.2.1. Choosing suitable cross-section

In order to understand deformation features of the Xu-Huai belt, we carried out a study of balancing and restoration of two measured cross-sections (the Shangqiao to Jinpingshan and the Wangshan to Malou sections) (Figs. 6 and 7) with the deformed length ranges from 26.6–34.1 km, respectively. To get the best results, we also collected data from more than 80 drill-holes, the depth of each drill-hole ranges from 404 to 885 m. In these two measured sections with detailed structural observations, the Neoproterozoic to late Paleozoic strata outcrop successively together with the deformed structures, and their geological settings are clear. Minor penetrative fabrics occur in rocks, with neither loss of area or volume nor formation of neo-formed mineral and texture, which belong to brittle deformation at a shallow crustal level. Thus, these two sections can satisfy the making conditions of cross-section balance.

4.2.2. Working procedures

Balancing of cross-section is a complex work, consisting of 18 working steps. The most critical steps could be summarized as follows (Woodward et al., 1989; Fossen, 2010).

(1) To collect drill-holes and structural data as well as seismic reflection profiles, if possible.
(2) To check and verify the location and orientation of profile line, to precisely project and mark the buried structures in the cross-section.
(3) To confirm all pre-deformation strata with thickness that were late involved in a thrust and fold event.
(4) To determine nail line. Nail line is an important reference element of balancing length and conserving area. It must be vertical to the bedding plane and should be located in places with minimum shearing, also, could be divided in regional and local ones, the former can be settled at the frontal terminal of the thrust zone whereas the latter is placed at the trail terminal of a secondary thrust slice. In this study, the regional nail line followed by 6–7 local nail lines is settled nearby the Huaibei coalfield in the western boundary of Xu-Huai belt that has rarely late structural disturbances.
(5) To make the balancing of cross-sections. From settled parameters like the intersection relation between axial planes, the depth of the deformation zone and fault displacement, the deformed structures can be extended to the underground, making the trail part of each nappe extends to corresponding location of stratum. Meanwhile, the geometrical shapes will be drawn from fold features of footwall and from the ramp and flat of corresponding hanging wall, and then, to fill all lines and areas of strata in the underground according to their structural patterns (imbricated, ramp-flat and duplex).
(6) To make the restoration of balanced cross-section. This step requires to pull backward the frontal and local nail lines, to retract each thrust slice to its original location (horizontal depositional beds). The original main fractures should be appeared in this restoration section.
(7) To check all works, including the ramp and flat structure and area conservation, etc. If this cross-section can pass all inspections, it would be a balanced section. And then, we could estimate the shortened distance and shortening ratio.

4.3. Geological implications from balanced cross-sections

4.3.1. Direction of nappe movement

Field investigations suggested a principal NW-ward thrust polarity for the Xu-Huai belt. All the faults display an upward motion trend. This NW-ward thrust direction has been verified from the Jinpingshan-Shangqiao and the Wangshan-Malou balanced cross-sections, they show a NW-ward young trend of thrust slices from Neoproterozoic in the eastern segment to Cambrian-Ordovician in the major thrust-and-fold zone and then to Carboniferous-Permian coal measure strata in the western segment (frontal zone) (Figs. 6 and 7). Correspondingly, the structural level of major decollement fault is gradually raised westward. In the Malou-Nangang area (Fig. 2), Carboniferous and Permian coal measure strata were thrust to the surface, revealing that the frontal zone is located to the west.

4.3.2. Decollement layers

Six uncompetent-rock layers, as decollement ones, were identified in the Xu-Huai belt as mentioned above. These six layers occur mainly in the footwall top of nappe, which can be checked and verified from the two balanced cross-sections. The larger-scale nappes are well developed in the four places close to uncompetent-rock layers, namely, the Niyuan, Mantou, Jiawang formations and Carboniferous-Permian coal measure; the first one occurs between the pre-Neoproterozoic crystalline basement and Neoproterozoic strata, while the second one is located in the boundary of Neoproterozoic and Cambrian strata, the third one is observed in the area between Cambrian and Ordovician strata, and the fourth one is developed in the contact between the Majiagou dolomite and Carboniferous-Permian coal-bearing mudstone. The decollement layers often form duplex structures intercalated with the Cambrian and Ordovician fault blocks (Fig. 5b).

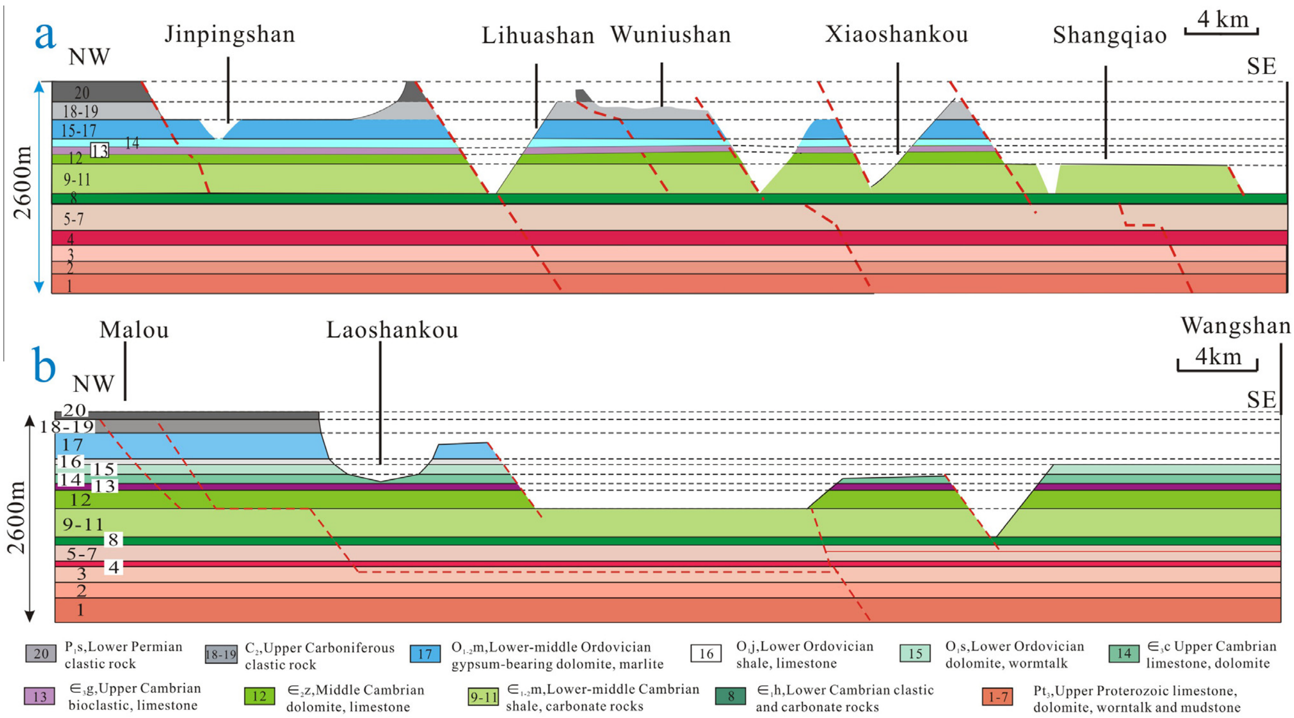
4.3.3. Ramp-flat fault

Ramp-flat shape thrust faults appeared gently on each balanced cross-section (Figs. 6 and 7). Due to late structural disturbances, the ramp-flat fault is less observed than imbricate fault on the surface. Actually, the geometry of thrust structure from balanced cross-section is more reasonable and more admissible. In Fig. 6, the footwall ramp structure outcrops to the west of the Lihuashann whereas hanging wall ramp is exposed in areas to the east of the Lihuashan. Similar structures also occur in Fig. 7. The ramp-flat fault, therefore, is a major structural pattern in the Xu-Huai belt.

Break through fault, as a decollement structure resulted from fracture propagation gradually as slip accumulates (Suppe and Medwedeff, 1990), was distinguished from balanced cross-sections. This kind of fault is related to the propagation fold and took place along the fold axial plane, leading to upward displacement of the roofwall block. The break through fault is mainly observed in the western Wuniushan (Fig. 6).

4.3.4. Fault-related folds

Fault-related folds are widely distributed in the two balanced cross-sections. Five fault-related folds with asymmetric geometry are developed in the Jinpingshan-Shangqiao balanced cross-section (Fig. 6). Generally, the axial plane of fold dips to the SE, the SE-limb of fold extends a larger length with lower dip-angle, while the NW-limb shows a less length with high dip-angle and terminates directly on the fault plane (Figs. 6 and 7). The hanging wall ramp of fault-related fold is mostly thrust to the surface and



then eroded (Fig. 8a and b). In the restored sections, the eroded parts are shown by dotted lines.

Geological information from dozen drill-holes (several ones are up to 900 m in depth) has been partly marked in the two measured cross-sections (Fig. 2) and used for balancing and restoration of the cross-sections. Results verify the existence of duplex structures, revealing that the thrust slices composed of Cambrian and Ordovician carbonate rocks structurally overlie the coal-bearing strata in the western frontal zone. From this we estimated that Carboniferous-Permian coal measure strata may occur below thrust slices of Cambrian and Ordovician strata, which has been verified by late practical drillings (Nanjing University, 1996). Duplex structures are developed in the Jinpingshan, Lihuashan and Xiaoshankou areas (Fig. 6); in the Lihuashan, the fault blocks of lower Permian coal-bearing rocks occur between the roof wall of the Ordovician gypsum-bearing dolomite and the floor wall of Cambrian limestone.

4.3.5. Shortening amount and rate

The two balanced cross-sections have been restored in order to estimate the shortening rate of nappe structure. Restoration was carried out according to strict requirements as mentioned above, and each step has been carefully checked. Results are reasonable and admissible and thus the two restored sections can be used for an estimation of shortening rate. On this basis, lengths of cross-section in the pre- and post-deformation were measured and then shortening rate was estimated.

The Jinpingshan-Shangqiao restored section has a pre-deformation length of 47.16 km (Fig. 8a) and was shortened to 26.6 km in the balanced cross-section (Fig. 6) due to thrust and fold, yielding a shortening length of 20.56 km and a shortening rate of 43.6%. Similarly, the restoration of the Wangshan-Malou balanced cross-section indicates a pre-deformation length of 63.68 km (Fig. 8b), whereas the balanced cross-section is a length of 34.1 km (Fig. 7), suggesting a length of 29.58 km was shortened, corresponding to a shortening rate of 46.4%.

Therefore, in the Xu-Huai belt, thrust caused an upper crust shortening of 43.6–46.4%, indicating an extensively compressive setting, which was likely related to the intracontinental underthrust.

5. Discussion

5.1. Quality evaluation of the balanced cross-sections

Profile lines of two structural sections in this study are parallel to the regional motion direction. Along the two cross-sections, no metamorphism has been observed. Each section shows complete strata sequence, abundant structures and successive outcrops. The geological attitudes are obtained from 1:50,000 geological mapping and more than 80 drill-holes. The basement is composed of pre-Neoproterozoic metamorphic rocks. The oldest stratum involved into thrust and fold is of the upper Proterozoic Niyuan Formation and the youngest one is of the lower Permian Shanxi Formation. The thickness of the pre-deformed strata is about 2600 m, which represents the minimum burial depth of the pre-Neoproterozoic crystalline basement.

All working steps for making the two balance cross-sections have been carefully checked, suggesting that their lengths and areas are conserved, and other factors, such as upward movement of thrust faults and invariable thickness of strata along the strike direction as well as same fault displacement distance, are up to standard. Thus, they can be considered as balanced sections.

5.2. Mechanism of NW-ward thrusting

In the Su-Lu Orogen, kinematic analysis yielded a top-to-the SE sense of shearing for the crustal slabs, implying a NW-ward continental subduction of the South China Block beneath the North China Block (Faure et al., 2003; Lin et al., 2005). However, different from the SE-directed thrust in the Su-Lu Orogen, almost all the kinematic fabrics from the deformed rocks and thrust fault zones within the Xu-Huai belt show a top-the NW thrusting. This NW-ward thrusting was not dated, although the neighboring Tan-Lu Fault Zone recorded an early Mesozoic thrusting event around 205–190 Ma ($^{40}Ar/^{39}Ar$ on phengite) (Zhu et al., 2005, 2009), which was considered as a response to the intracontinental subduction (Lin et al., 2005).

Previous studies suggest that the continental subduction in the Dabie and Su-Lu areas occurred during 240–230 Ma and subsequently the UHP-HP metamorphic rocks were rapidly exhumed from late Triassic to early Jurassic time (Hacker et al., 2000; Liu and Xu, 2004; Li et al., 2011). Shu et al. (1994) introduced an SE-ward continental subduction of the North China Block beneath the South China Block to interpret the mechanism of the Xu-Huai belt. Zhu et al. (2005, 2009) noted a curved boundary along the Dabie and Su-Lu orogens and obtained kinematic evidence of sinistral strike-slip with a thrust component, suggesting that a syn-tectonic transform displacement (Zhao et al., 2016) took place among the Su-Lu, Dabie and North China. They proposed that the Su-Lu Orogen moved rapidly northwards followed by a shearing and rotation, and the transform displacement was initiated by differential rates of continental subduction in different places along the Dabie and Su-Lu orogens, resulting in the sinistral offset of the Tan-Lu Fault Zone.

The Xu-Huai belt with NW-ward verging folds and thrust shows a NW-directed shortening deformation. If considering coeval SE-ward continental underthrust of the SE margin of the North China

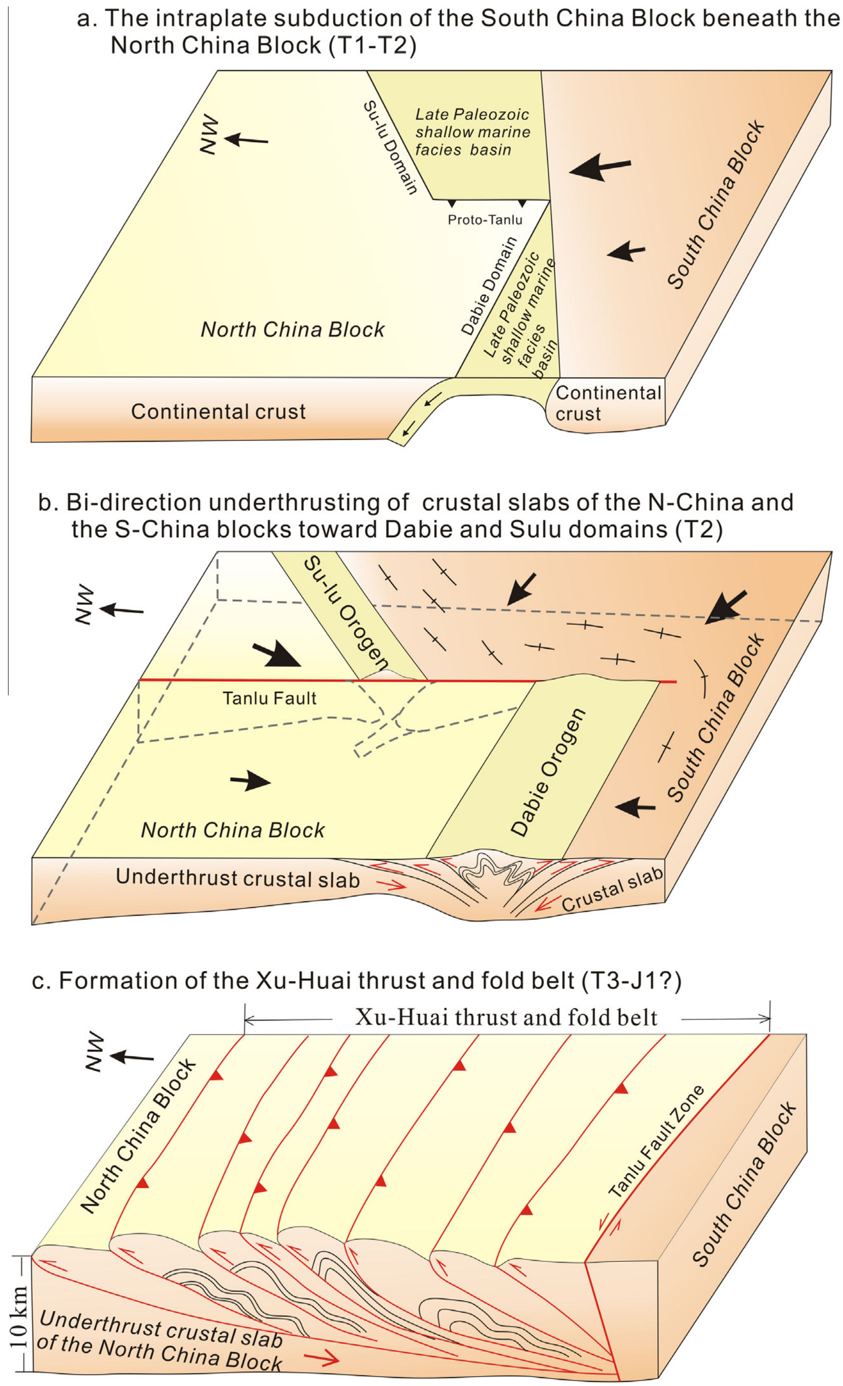


Fig. 9. Tectonic evolutional model of the Xu-Huai thrust-and-fold belt (the crustal features of the North and South China blocks, from Sun et al., 1992; Zhu et al., 2002).

Block beneath the Su-Lu Orogen along the Tan-Lu Fault Zone, the mechanism forming the Xu-Huai thrust-and-fold belt could be supported by kinematic indicators of the top-to the NW as mentioned above. In fact, from our results in this study, the extensive thrusting and folding in the Xu-Huai belt took place in the upper crustal level, less than 10 km in depth. It belongs to "thin-skin tectonics" that was likely related to the underthrust of continental crustal slabs in the SE margin of the N-China Block beneath the Su-Lu Orogen along the Tan-Lu Fault Zone. Unfortunately, the southeastern segment of the studied area is widely covered by Quaternary alluvial deposits whereas available seismic data are absent, leading to rare preservation of the geological records.

5.3. Tectonic evolution

We have not obtained reliable age constraint on the Xu-Huai belt because neither the Mesozoic strata are exposed and nor the newly-formed metamorphic minerals were found. Furthermore, the field observations and drill-hole data demonstrated that the thrusting and folding of the Xu-Huai belt took place after the deposition of early Permian coal-bearing rocks and before the deposition of early Cretaceous volcano-clastic beds, suggesting an early Mesozoic, i.e. Triassic to Jurassic age for the deformation. Thus the following tectonic evolution is only a preliminary discussion considering the available information from regional geology and previously published references.

The early Mesozoic event was coeval with ductilely sheared rocks (Mattauer et al., 1985; Xu et al., 2003), UHP-HP metamorphic rocks dated at 240–220 Ma in the Dabie and Su-Lu areas (Jahn et al., 1999; Hacker et al., 2000; Lin et al., 2005; Li et al., 2011), and Jurassic-Cretaceous foreland basins in the Hefei area (Faure et al., 1999; Zhu et al., 1998) as well as post-orogenic emplacement of granitoids around 130 Ma in the Xu-Huai belt (Xu et al., 2003). From the early Mesozoic geological records of the Dabie and the Su-Lu belts, Li et al. (2009, 2010) proposed a two-stage extrusion model, the first one was an upward extrusion that took place during the middle Triassic, and the second one, an eastward extrusion, occurred during late Triassic to early Jurassic, which can be correlated with the two stages of rapid exhumation of HP-UHP rocks, respectively.

Following the Early Mesozoic continental subduction in the Dabie and Su-Lu areas (Fig. 9a), a bi-direction underthrust of continental crust developed between the South and North China blocks (Fig. 9b). The NW-ward continental subduction of the South China Block formed the NE-trending Su-Lu belt and SE-ward thrust slices within the Su-Lu belt, whereas the SE-ward underthrust of the crustal slabs in the southeastern North China Block generated a top-to the NW nappe tectonics, building the Xu-Huai thrust-and-fold belt (Fig. 9c) (Shu et al., 1994; Faure et al., 2003; Lin et al., 2005). The late Triassic-early Jurassic coarse grained clastic sequence deposited in a foreland setting that overlaid the metamorphosed and deformed pre-Mesozoic rocks in the Zhangbaling segment of the Su-Lu Orogen and the Hefei Jurassic basin of the northern margin of the Dabie Orogen (Zhu et al., 1998), suggesting that the deformation took place in the pre-Jurassic time (Faure et al., 2003). In this process, a tectonic transformation was recorded by deformed structures from the sub-E-W-trending in the Dabie orogenic belt into the NE-striking in the Su-Lu orogen and Xu-Huai belts. Zhu et al. (2009) attributed this change to the synconvergent faulting and continental subduction of the South China and North China blocks, which occurred simultaneously in the Dabie and Su-Lu areas, constructing a curved structure.

After the orogeny, some basins parallel to the orogenic belt were filled by middle-late Jurassic-Cretaceous clastic deposits of more than 1000 m in thickness (Zhu et al., 1998). A SE-ward paleo-current predominates in the Hefei Jurassic terrigenous clastic basin located to the southeast of the Xu-Huai belt (Zhu et al., 1998; Zhao et al., 2016), indicating that the Xu-Huai belt is likely a source of fragments for Hefei Jurassic clastic basin.

6. Concluding remarks

(1) The Xu-Huai belt in the SE margin of the North China Block was subjected to two-phase deformation, the early-phase, a NW-ward thrusting and folding, and the late-phase, an extension followed by the emplacement of dioritic and monzodioritic porphyrites dated at 131–135 Ma.
(2) The Xu-Huai belt can be subdivided into three units, (1) the pre-Neoproterozoic crystalline basement in the eastern segment, (2) the thrust and fold zone composed of Neoproterozoic to middle Ordovician carbonate rocks and Carboniferous-Permian coal-bearing rocks, 2600 m thick in total, and (3) the western frontal zone. A major decollement fault was identified in the base of the thrust and fold zone. All pre-Mesozoic depositional sequences were involved into a tectonic event and then were overlain unconformably by late Mesozoic strata. Six uncompetent-rock layers have been recognized and each occurs in the top of a footwall nappe.
(3) The two geological cross-sections are chosen for structural balancing and restoration, from which ramp-flat faults and fault-related folds were identified. A ca 20–30 km shortening was obtained from the restoration of balanced sections, corresponding to a shortening rate of 43–46%. This shortening deformation was likely related to the SE-ward underthrusting of the crustal slices of the North China Block beneath the South China Block in Mesozoic.

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