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Analysis of structural deformation in the North Dabashan thrust belt, South Qinling, central China

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The North Dabashan thrust belt, which is located in South Qinling, is bounded by the Ankang fault on the north and the Chengkou–Fangxian fault on the south. The North Dabashan thrust belt experienced multiple stages of structural deformation that were controlled by three palaeostress fields. The first structural event (Middle Triassic) involved NW–SSE shortening and resulted in the formation of numerous dextral strike-slip structures along the entire Chengkou–Fangxian fault zone and within the North Dabashan thrust belt, which suggests that the South China Block moved to the NW and was obliquely subducted under the North China Block. The second structural event (Late Triassic–Early Jurassic) involved NE–SW shortening that formed NW–SE-trending structures in the North Dabashan thrust belt. The third structural event (Late Jurassic–Early Cretaceous) involved ENE–WSW or nearly E–W shortening and resulted in additional thrusting of the North Dabashan thrust belt to the WSW and formation of the WSW-convex Chengkou–Fangxian fault zone, which has an orocline shape. Owing to the pinning of the Hannan massif and Shennongjia massif culminations, numerous sinistral strike-slip structures developed along the eastern Chengkou–Fangxian fault zone and were superimposed over the early dextral strike-slip structures.

**Keywords:** Dabashan belt; collisional orogeny; intra-continental orogeny; strike-slip structure; palaeostress fields

1. **Introduction**

The Qinling–Dabie orogen is a complex orogenic belt in central China (Zhang et al. 1996, 2001; Meng and Zhang 1999). Previous studies have demonstrated that the Qinling–Dabie orogen was generated by the northward subduction of the Shandian oceanic crust and the subsequent collision between the North China Block (NC) and the South China Block (SC) along the Shandian suture (Enkin et al. 1992; Li et al. 1993; Okay et al. 1993; Nie et al. 1994; Ames et al. 1996; Hacker et al. 1998; Zhai et al. 1998; Liu and Zhang 1999; Zhang et al. 2001, 2003). However, the Mianlue suture, which is located between the SC and Qinling–Dabie micro-block (QD), has been recognized based on geological, geochemical, geophysical, and geochronological studies (Zhang et al. 1995a, 2001, 2003; Liu and Zhang 1999; Liu et al. 2001). Later, a model including ‘three blocks (NC, QD, and SC) with two sutures (Shandian suture and Mianlue suture)’ was proposed; this model represents the regional tectonic framework of the Qinling–Dabie orogen (Zhang et al. 1995a, 1996, 2001, 2003).

The Dabashan thrust belt, which is a typical SW-convex arcuate structural belt, is located at the edges of the collision zone (Mianlue suture zone) between the QD and SC and is divided into the North Dabashan thrust belt and South Dabashan arcuate belt by the Chengkou–Fangxian fault (Figure 1; Zhang et al. 2001; Dong et al. 2008). The belt’s typical arc-shaped geometry and formation mechanism make this area a natural laboratory to investigate tectonic deformation related to a continental collision. The style of structural deformation, formation mechanism, and tectonic evolution of the South Dabashan arcuate belt have been investigated extensively in recent years (He et al. 1997; Liu et al. 2003, 2006, 2010; Dong et al. 2005, 2006, 2008; Wang et al. 2006; Shen et al. 2007; Shi et al. 2007, 2012; Cheng and Yang, 2009; Hu et al. 2009; Zhang et al. 2009, 2011; Zhang and Dong 2009; Wu et al. 2010; Liu and Zhang 2013). However, insufficient research has been performed on the North Dabashan thrust belt (He et al. 1999; Li et al. 2012, 2013; Shi et al. 2012). In addition, the debate about the mode of the collision between the NC and SC is ongoing and has been highlighted in several tectonic models. Okay and Celal Şengör (1992) proposed a face-to-face collision model between NC and SC. An indentation model was subsequently proposed by Yin and Nie (1993) and Zhang (2002). The former believed that the collision between NC and SC began with the indentation of the northeastern SC into the eastern NC, whereas the latter proposed that the collision occurred by the indentation of the southeastern NC...
into the SC. Eide (1993) proposed that the SC rotated clockwise relative to the NC and first made contact with the eastern part of the NC and later with the western part. Several researchers have accepted the rotation collision model based on palaeomagnetic and sedimentologic studies (Gilder and Courtillot 1997; Yokoyama et al. 2001; Wang et al. 2003; Meng et al. 2005; Zhang et al. 2007).

However, another group of researchers proposed that the SC moved to the NW and was obliquely subducted under the NC based on tectonic and sedimentologic studies of the Dabie orogen and Tanlu fault (Gilder et al. 1999; Liu et al. 2005a; Zhu et al. 2009). The initial formation of the North Dabashan thrust belt is generally considered to have been related to the Middle–Late Triassic collision of the QD and SC (He et al. 1997; Sun 2002; Wang et al. 2004), whereas the South Dabashan arcuate belt was derived mainly from the intra-continental thrusting of the North Dabashan thrust belt (Dong et al. 2006, 2008, 2010; Liu et al. 2006; Hu et al. 2009, 2012). The North Dabashan thrust belt underwent a different tectonic evolution from that of the South Dabashan arcuate belt, which resulted in the syn-collisional structures between the NC and SC being retained in the North Dabashan thrust belt and the collision zone in addition to the structures related to the intra-continental deformation. The deformational structures of the North Dabashan thrust belt are significant for understanding the tectonic evolution of the Dabashan belt and the collision processes between NC and SC. They may also represent an opportunity to examine a continental collision and intra-continental deformation.

This paper presents our detailed field investigations, microscopic observations, and structural analysis of the North Dabashan thrust belt and provides a synthesis of the structural framework of the region, including the
structural geometry, deformatonal sequence, and stress fields. Additionally, a new model is proposed to explain the tectonic evolution of the Dabashan thrust belt.

2. Geological background

The Qinling–Dabie orogen underwent a multistage orogenic evolution, including: (1) extension of the Shangdan ocean between the NC and SC during the Neoproterozoic–Early Ordovician, (2) northward subduction of the Shangdan ocean during the Early Ordovician–Silurian, (3) closure of the Shangdan suture accompanied by the extension of the Mianlue ocean during the Devonian–Middle Triassic, and (4) closure of the Mianlue ocean and a collisional orogeny during the Middle–Late Triassic (Zhang et al. 1996, 2001; Liu and Zhang 2008). The South Qinling, which includes the North Dabashan thrust belt, is located south of the Shangdan suture and was a passive continental margin during the early Palaeozoic that contained Meso–Neoproterozoic metamorphic volcanic-sedimentary basement rocks (Wudang Group and Yaolingle Group) and Neoproterozoic to Middle Triassic sedimentary layers. In contrast, most of the Yangtze area does not contain Meso–Neoproterozoic volcanic sequences, and the Upper Yangtze contains no Devonian–Carboniferous units, which are extensive in the South Qinling. The QD separated from the northern margin of the SC with the extension of the Mianlue ocean during the late Palaeozoic (Zhang et al. 1996, 2001). Therefore, the QD and South Qinling were situated between the Shangdan suture to the north and the Mianlue suture to the south. The QD collided with the NC along the Shangdan suture in the north, and the SC collided with the NC along the Mianlue suture in the south, resulting in a complete orogeny during the early Mesozoic (Zhang et al. 1996, 2001). Numerous geochemical and geochronological studies have shown that the Mianlue suture formed due to the closure of the Mianlue ocean, and this suture was subsequently overprinted by the SW-vergent overthrusting of the Chengkou–Fangxian fault in the Dabashan area (Zhang et al. 2001, 2003; Dong et al. 2011a, 2011b). The eastward extension of the Mianlue suture was tectonically buried by the North Dabashan thrust belt (Zhang et al. 1995b; Hu et al. 2012; Liu and Zhang 2013). The Chengkou–Fangxian fault is regarded as the surface outcrop of the Mianlue suture, along which the North Dabashan thrust belt was superimposed on the South Dabashan arcuate belt and Mianlue suture (Zhang et al. 1995b, 2001; Dong et al. 2011a, 2011b; Hu et al. 2012).

The North Dabashan thrust belt is bounded by the NW-trending Ankang fault to the north and the SW-convex Chengkou–Fangxian fault to the south (Figure 1). The Gaochuan terrane is located west of the North Dabashan thrust belt and lies between the North and South Dabashan belts (Figure 1); it has a distinct stratigraphy and structure, including a Devonian–Carboniferous marine sedimentary sequence, N–S-trending high angle dextral strike-slip faults, and sheath folds that are different from those in the North and South Dabashan belts (Zhang et al. 2001; Li et al. 2007; Hu et al. 2008, 2012). The Wudang nappe, which was thrust southward onto Cambrian units, is located east of the North Dabashan thrust belt (Zhang et al. 2001; Shi et al. 2012). The North Dabashan thrust belt consists of Meso–Neoproterozoic metamorphic rocks and early Palaeozoic strata (Zhang et al. 2001; Dong et al. 2008; Hu et al. 2012). The Neoproterozoic strata include dolomite, sandstone, mudstone, and tuff, and the Cambrian sequence is composed mainly of biocalcarenite, dolomitic limestone, argillaceous limestone, sandy slate, and siliceous rocks. The Ordovician sediments are composed primarily of sandy slate, siliceous slate, dololithite, and limestone, and the Silurian rocks are dominated by feldspathic quartz sandstone, silty slate, carbonaceous slate, and trachyte. Studies of sedimentation, the geochemical characteristics of the volcanic rocks and their isotope chronology, and the thrust tectonic deformation have shown that the North Dabashan thrust belt has undergone three stages of tectonic evolution since the late Proterozoic: extension (D1–D2), tectonic inversion (T2), and thrusting (T2–T1) (He et al. 1999).

3. Deformational structures

3.1. Main thrust faults

Series of NW-trending thrust faults and thrust sheets are present in the North Dabashan thrust belt and terminate against the Chengkou–Fangxian fault. From north to south, these faults include the Ankang thrust fault, Hongchunba thrust fault, Gaoqiao thrust fault, Gaotan thrust fault, Lujiaping thrust fault, and Chengkou–Fangxian fault (Figure 2A–B and C–D; Zhang et al. 2001).

3.1.1. Ankang thrust fault

The NW–SE-trending Ankang fault is located at the northern boundary of the North Dabashan thrust belt and separates the Ankang–Wudang nappe to the north from the Pingli–Ziyang nappe to the south (Figure 1). The western Ankang fault curves near Shiquan County, where it trends NNW and merges with the Mianlue suture. A 15 to 30 m-wide, NE- to NEE-dipping zone of intense deformation is located west of Shiquan County. Numerous striations and drag folds resulting from ductile shearing developed in the deformation zone and indicate the dextral strike-slip character of the Ankang fault. Li et al. (2013) recognized two ductile shear zones that are characterized by dextral strike-slip shearing in the metamorphic rocks along the Ankang fault. The eastern segment of the Ankang fault, which is the
main slip plane of the Wudang nappe, links with the Chengkou–Fangxian fault near Fangxian County (Figure 1). Along the thrust front, the Neoproterozoic Wudang Group rocks (Ling et al. 2002) are thrust onto the Cambrian rocks (Zhang et al. 2001; Dong et al. 2008) along a detachment layer within the greenschist facies volcanic and sedimentary rocks of the Wudang Group (Shi et al. 2012).

The Shiquan–Ankang segment of the Ankang fault divided a single dome into the Manpoling dome to the north and the Fenghuangshan dome to the south (Figure 1). The Manpoling dome was thrust onto the Fenghuangshan dome, which transposed the layers of the Yaolinghe and Yunxi Groups into cleavages (Figure 3A). The NE-dipping cleavage indicates that the Ankang fault was thrust to the SW. Additionally, NE-dipping axial-plane cleavages are common in the Palaeozoic strata throughout the entire North Dabashan thrust belt and are coeval with the NW–SE-trending folds. They structurally transposed the bedding of the strata in many locations within the North Dabashan thrust belt (Li et al. 2013).

3.1.2. Hongchunba thrust fault

The NW-trending Hongchunba fault is located in the central North Dabashan thrust belt in the eastern part of Langao County. The western end of this fault was cut by the Chengkou–Fangxian fault at a high angle north of the town of Lianghekou, and the east end terminates against the Chengkou–Fangxian fault east of the town of Fengxi (Figure 1).

A 150 m-wide ductile shear zone is present in the calcic slate of the Ordovician Erdaoqiao Formation north of the town of Xiangyang in Ziyang County. This shear zone is characterized by S-C fabrics (Figure 3B) and asymmetric sub-vertical folds with hinges that plunge steeply SE (e.g. 110° ∠ 50°, 114° ∠ 56°, 125° ∠ 48°), indicating SW-trending shear and dextral strike-slip on the Hongchunba fault (Figure 4E). Furthermore, microscopic structures within the mylonitic rocks sampled from a fracture zone near the town of Xiangyang also contain dextral strike-slip features (Figure 2D). Therefore, the Hongchunba fault experienced dextral strike-slip and...
thrust displacements. The Gaotan and Lujiaaping faults contain similar structural features.

3.1.3. Gaoqiao thrust fault

The Gaoqiao fault developed within the Palaeozoic strata (Figures 1 and 2A–B). The main part of this fault strikes NW–SE, parallel to the regional structure, but its west end curves to strike nearly N–S. Both its west end (west of the town of Lianghekou in Xixiang County) and east end (southern Zhenping County) were cut or terminated against the Chengkou–Fangxian fault. Previous studies proposed that similar to most thrust faults in the North Dabashan thrust belt, the Gaoqiao fault had SW displacements on a NE-dipping fault plane (Zhang et al. 2001; Dong et al. 2008, 2010, 2011a, 2011b; Hu et al. 2009).
However, detailed field investigations have indicated that the Gaoqiao fault was a backthrust with a SW-dipping fault plane (Li et al. 2012).

In the western part of the Gaoqiao fault, an approximately 70 m-wide fractured zone in the sandy slate of the Ordovician Gaoqiao Formation is located north of the town of Gaotan (Figure 2A and B) and is marked by a series of asymmetric folds, whose southern limbs have lower dip angles and are longer than the northern limbs. Numerous SW-dipping cleavages (e.g. $196^\circ \angle 68^\circ$, $205^\circ \angle 63^\circ$) formed in the footwall (Figure 2B). These structures indicate that the Gaoqiao fault thrust to the NE, which is opposite to the propagation direction of the North Dabashan thrust belt, and is a backthrust. Numerous tight asymmetric folds developed adjacent to the fault plane; both of their limbs dip to the SW, and their hinges plunge steeply NW, indicating the dextral strike-slip thrust displacement of this fault (Figures 2A and 4D). The microscopic structures within the mylonitic rocks of the fracture zone also demonstrate the fault has a component of dextral strike-slip (Figure 2F). The older folds were truncated by the Gaoqiao fault and other associated faults in this fracture zone; this type of relationship is found in many other locations throughout the North Dabashan thrust belt (Li et al. 2013). The striations on fault planes generally plunge steeply and overprint the ductile lineations ($L_1$) within the North Dabashan thrust belt (Shi et al. 2012), which suggests that thrusting on the brittle faults occurred after the ductile deformation.

Similarly, the eastern part of the Gaoqiao fault (south of the town of Taohe in Langao County) is a 60 m-wide SW-dipping zone of ductile deformation. Several distinct shear planes with similar dips (e.g. $232^\circ \angle 65^\circ$, $226^\circ \angle 60^\circ$, $218^\circ \angle 57^\circ$) are well exposed in this zone and indicate NE thrusting. The kinematic features of the folds with steeply NW-plunging hinges in the footwall also indicate a component of dextral strike-slip (Figure 4H).

3.2. Strike-slip zone along the Chengkou–Fangxian thrust fault

The Chengkou–Fangxian fault, which is located along the northern margin of the SC, is an arcuate fault zone (Zhang et al. 2001). This fault zone is generally considered to be the boundary fault between the North and South Dabashan belts, and between the QD and SC. The Pingba thrust fault is part of the Chengkou–Fangxian fault zone and represents its southwestern margin (Figures 1 and 2A–B). The Chengkou–Fangxian fault can be divided into three segments based on its strike direction and deformation style: the western segment, which strikes N–S with the undulating curve in the northern part; the middle segment, which
strikes NW–SE, parallel to the thrust faults in the North Dabashan thrust belt; and the eastern segment, which strikes nearly E–W (Figure 1).

3.2.1. Western segment of the Chengkou–Fangxian thrust fault

The fault plane of the western segment of the Chengkou–Fangxian fault dips steeply to the E. The deformed strata in the hanging wall include the Neoproterozoic Yaolinge Group and Nantuo Groups and the early Palaeozoic Donghe Group; the footwall consists of the Devonian Panlongshan Formation, Permian Guojianay Formation, and Triassic Daye and Jialingjiang formations. The shear zone that cuts through the Nantuo Formation contains numerous rotated gravels of granite and limestone (Figure 3C). The statistics of the measured rotation axes of the rotated gravels indicate that the dominant directions of the rotation axes plunge steeply to the SE–SSE (Figure 4Z). A series of asymmetric sub-vertical folds (near the town of Guanyin) with hinges that plunge steeply SE or SSE are well exposed adjacent to the shear zone (Figure 4Y). These geological features indicate that the western Chengkou–Fangxian fault was thrust to the west with a component of dextral strike-slip (Figure 4Y and Z). This type of dextral strike-slip thrust displacement was also demonstrated by the N–S-trending high-angle dextral strike-slip faults and shear folds in the Gaochuan terrane bounded by the western Chengkou–Fangxian fault on the east (Hu et al. 2008, 2012).

3.2.2. Middle segment of the Chengkou–Fangxian thrust fault

The middle segment of the Chengkou–Fangxian fault zone is located between the towns of Maliu (Ziyang County) in the NW and Dongan (Chengkou County) in the SE. The fault strikes NW–SE, parallel to the thrust faults in the North Dabashan thrust belt, and the boundary fault planes dip to the NE (Figure 1). The shear belt within the fault zone, which dips steeply to the NE and SW, is well developed in the till conglomerate of the Neoproterozoic Nantuo Formation in the hanging wall. Abundant rotated granite gravels within the shear zone, which have rotation axes that plunge at high angles to the SE and NW, indicate dextral strike-slip thrusting on the fault (Figure 4R and T).

Thrusts with directions that are opposite to the kinematic direction in the Dabashan area are confined to the middle segment of the Chengkou–Fangxian fault and are well developed between Maliu and Dazhu. In this region, the deformation zone of the Chengkou–Fangxian fault is characterized by approximately 3 km-wide penetrative and distributed asymmetric sub-vertical folds. The axial planes of the folds and the fault planes mainly dip steeply to the SW, and the boundary thrust dips to the NE, forming a positive flower structure (Figure 2A–B). The hinges of the folds plunge steeply to the NW–NNW (Figure 3D), and the SW limbs of the largely asymmetric folds have lower dip angles and are longer than the NE limbs, which have higher dip angles (Figure 3E). Domino structures (Figure 2E) and similar microscopic structures that indicate dextral strike-slip motion are present in the mylonitic rocks north of the town of Maliu. These geological features indicate that the Chengkou–Fangxian fault underwent dextral strike-slip thrusting in the Maliu–Dazhu area (Figure 4V and W).

The Zhongting segment of the Chengkou–Fangxian fault in Wanyuan County contains an imbricate thrust that consists of several parallel faults with SW displacement. Northwest of the town of Zhongting, the till conglomerates of the Neoproterozoic Nantuo Formation in the hanging wall are thrust onto the siliceous rocks of the Cambrian Lujiaping Formation in the footwall on a steeply NE-dipping fault plane (e.g. 51°∠72°). A 40 m-wide zone of ductile deformation along the thrust fault in the siliceous rocks of the Cambrian Lujiaping Formation is characterized by numerous rotated calcite lenticles and asymmetric sub-vertical folds with NEE-plunging hinges (Figure 3F), which also indicate dextral strike-slip thrusting (Figure 4S). The NE-dipping thrust faults exhibit SW displacements, and several ductile deformation zones that indicate dextral strike-slip thrusting are also well exposed adjacent to the thrust faults in the Chengkou, Xiuqi, and Gaoguan segments.

3.2.3. Eastern segment of the Chengkou–Fangxian thrust fault

Near the town of Dongan, the strike of the Chengkou–Fangxian fault changes from NW–SE in the middle segment into nearly E–W in the eastern segment. The east ends of several parallel faults in the North Dabashan thrust belt were cut or terminated by the eastern Chengkou–Fangxian fault (Figure 1). The deformed strata in the hanging wall include the Neoproterozoic and the Early Palaeozoic (Cambrian and Silurian) units, whereas the strata in the footwall consist mainly of Cambrian, Ordovician, and Silurian rocks.

The town of Dongan is located at the intersection of the middle and eastern segments of the Chengkou–Fangxian fault. To the north, an approximately 25 m-wide fracture zone crops out in the tuff slate of the Neoproterozoic Yaolinghe Group. Rotated gravels with rotation axes that plunge steeply to the SE are distributed throughout this ductile shear zone and indicate that it is a dextral strike-slip thrust (Figure 4O). To the south, asymmetric overturned folds with N-dipping axial planes are well exposed in the Cambrian limestone and indicate southward thrusting of the Chengkou–Fangxian fault.
The detailed field investigations indicated that in contrast to the western and middle segments, both dextral and sinistral strike-slip indicators are present throughout the eastern segment of the Chengkou–Fangxian fault, and the latter are superposed on the former. The sinistral strike-slip indicators are largely located from west of the town of Zhongbao in Zhenping County to Fangxian County. For example, to the south of Zhongbao, two types of asymmetric sub-vertical folds with hinges that plunge in different directions were recognized in the dolomite of the Neoproterozoic Dengying Formation. Sub-vertical folds with ENE–SE-plunging hinges (Figure 4N) were folded and superposed by folds with NW-plunging hinges (Figure 5B), which indicate dextral and sinistral strike-slip features, respectively. The dextral strike-slip indicators formed prior to the sinistral strike-slip structures.

To the east of the town of Fengxi in Zhuxi County, a typical sinistral strike-slip zone with a width of approximately 100 m is well exposed in the limestone, siliceous rocks, and mudstone of the Cambrian Shuijintuo Formation. The fault zone contains penetrative and distributed tightly asymmetric sub-vertical folds. The folded strata generally dip to the NNW–N, and the shearing fracture planes within the zone dip to the N–NNE. The

Figure 5. Stereographic plots of the structural elements indicating the sinistral strike-slip feature along the eastern segment of the Chengkou–Fangxian fault zone. Based on the analysis of the occurrence of strata, fault, and kinematics direction in the corresponding location, the slip plane in stereonet is a comprehensive inference.
kinematic indicators of the chevron folds and tightly sub-vertical folds, including hinges that mainly plunge steeply to the NW–NNW (Figure 5C and K) and microscopic structures (Figure 2G) along the narrow shear fractures, demonstrate sinistral strike-slip thrusting on the Chengkou–Fangxian fault. Kinematic indicators that indicate dextral and sinistral strike-slip motion, such as rotated gravels (Figure 2H), S-C fabrics (Figure 3G), and rotational clasts (Figure 3H), are also present in other parts of the eastern segment of the Chengkou–Fangxian fault.

The folds with high plunge angles could have formed by two processes. One is the superposition of two phases of folding; in this case, an earlier horizontal fold was subsequently deformed by a vertical lateral fold. The other process is strike-slip shear. Based on our observations, objective screening, and elimination of the influence of superposition, the steeply plunging to sub-vertical folds identified in our fieldwork are interpreted to be strike-slip features. In addition, the distributions of the high-angle folds and other indicators that indicate strike-slip motion have typical zonations and universality. No field evidence for the superposition of folds with nearly vertical hinges has been recorded in the Dabashan area; thus, the formation of the folds was attributed to strike-slip shear. Therefore, based on a series of detailed field investigations and structural analysis, we recognized kinematic features along the Chengkou–Fangxian fault zone that indicate two types of deformation (Figure 1): dextral strike-slip thrust deformation and thrust deformation of the entire fault zone (Figure 4) and sinistral strike-slip deformation mostly in the eastern segment (Figure 5). The dextral strike-slip shear zone, including the shear zone in the Gaochuan terrane (Hu et al. 2008, 2012; Liu et al. 2011), is wider in the west than in the east and extends eastward to Fangxian County. The sinistral strike-slip shear zone, which begins west of the town of Zhongbao and extends eastward to Fangxian County, modified and overprinted the previous dextral strike-slip kinematic indicators to the east of Zhongbao. The sinistral strike-slip zone along the eastern segment of the Chengkou–Fangxian fault zone becomes wider toward the east.

The northern sub-zone trends NW–SE and mainly consists of Meso–Neoproterozoic and early Palaeozoic units. It includes the Fenghuangshan (described above) and Pingli domes, which contain outcrops of the basement rocks, namely, the Yunxi and Yaolinghe Groups. The Pingli dome was thrust southward onto the Gaotan nappe, which bent the eastern segment of the Hongchunba fault.

The southern sub-zone, which is mainly composed of the Neoproterozoic and early Palaeozoic rocks, is bounded by the Hongchunba fault on the north and the concave Chengkou–Fangxian fault on the south and is composed of SW-vergent imbricate stacked thrusts (Shi et al. 2012; Li et al. 2013) and a few NE-vergent backthrusts. Numerous overturned folds indicate SW-directed movement. For example, a large-scale asymmetric overturned fold is well exposed to the south of the town of Gaotan (Figure 6A). Upright folds gradually become more common as the distance from the collision front increases in the southern sub-zone. During propagation of the southward thrusting, a series of backthrusts and folds formed because of the obstruction from the frontier of the North Dabashan thrust belt (Li et al. 2012) and the continuously deep subduction of the SC under the NC (Dong et al. 2013). The Malili–Dazhu area of the collision front contains SW-vergent thrusts with clear backthrust structures and asymmetric sub-vertical folds. The strata in this area are the most deformed in the study region. This area represents the top of the Dabashan arcuate tectonic belt.

4. Structural evolution

4.1. Deformational sequence

The timing of the convergence between the NC and SC and deforming sequence of the North Dabashan thrust belt is controversial (Dong et al. 2011a; Shi et al. 2012). Many studies have shown that the SC began colliding with the NC in the Middle Triassic (Lin et al. 1985; Zhao and Coe 1987; Huang and Opdyke 1991; Enkin et al. 1992; Yang et al. 1992; Gilder and Courtillot 1997; Yokoyama et al. 2001; Meng et al. 2005; Tan et al. 2007). The tilted Upper Triassic conglomerates and sandstone unconformably overlie the Lower Triassic limestone in the town of Pingba in Chengkou County (Figure 7A, D, and E). The Lower Triassic limestone below the angular unconformity was folded to steep dips (Figure 7A and E), and most of the axial planes of the folds dip to the NNW. A similar angular unconformity also crops out in the town of Dazhu in Wanyuan County (Figure 7B, F, and G); the underlying limestone was tightly folded with fold hinges that plunge steeply to the NE or ENE (Figure 7G), which indicates that it is a dextral strike-slip thrust feature. Therefore, we interpret that the dextral strike-slip folds and thrusts that
developed along the Chengkou–Fangxian fault zone (Figure 4) were related to the continental collision in the late Middle Triassic and were syn-collisional structures. The ENE–WSW-trending folds that are widely exposed in the North Dabashan thrust belt are interpreted to be the first episode of deformation (D1).

The NW–SE-trending folds and SW-vergent thrust faults have been confirmed by several geologists (Dong et al. 2008, 2010; Zhang et al. 2010; Hu et al. 2012; Shi et al. 2012). The superposition of two stages of folds is well exposed in the Silurian Wuxiahe Formation to the south of the town of Xiangyang in Ziyang County.
Figure 6B). Based on the field observations and the axial plane of the fold restoration, the early ENE–WSW-trending folds (D1) were deformed by the NW–SE-trending folds. The former, which has steeply SW–WSW-plunging hinges, indicates dextral strike-slip deformation, and the latter was formed by NE–SW-oriented shortening. To the north of Xiangyang, a series of asymmetric folds, the north limbs of which have shallower dip angles and are longer than the south limbs, are present in the Ordovician Erdaoqiao Formation (Figure 2C). These folds, which
have NNW-dipping axial planes and ENE-plunging hinges, and the microscopic structures within these folded rocks also indicate dextral strike-slip deformation (Figure 2D). In addition, these folds were overprinted by a penetrative NE-dipping cleavage that was clearly not related to the folding and formed during a different stage of deformation (Figure 2C). Therefore, we suggest that the ENE–WSW-trending structures (D1) formed earlier than the NW–SE-trending structures. The NW–SE-trending structures developed widely throughout the North Dabashan thrust belt and represent the second episode of deformation (D2). The Lower–Middle Jurassic conglomerates unconformably overlie the Silurian units in the Hongchunba area (Figure 7C, H, and I) and are overthrusted by the Hongchunba fault (Figure 7H; Geological Survey of Sichuan Province 1973). Based on these observations, we infer that the SW-vergent thrusting of the North Dabashan thrust belt might have occurred during the latest Triassic, and another deformational event occurred after the Middle Jurassic. Although we could not clearly differentiate these two structural events, we suggest that the D2 structures formed in the latest Triassic.

The North Dabashan thrust belt has been considered to be a single SW-vergent thrust sequence in the past (Zhang et al. 2001; Dong et al. 2008, 2010; Hu et al. 2009, 2012; Shi et al. 2012); however, our fieldwork indicates that NNW–SSE-trending folds (nearly E–W shortening) also developed throughout the North Dabashan thrust belt. These folds, which represent the third episode of deformation (D3), formed after the NW–SE-trending deformation. In addition, the folds (D3) with NNW-plunging hinges that developed along the eastern segment of the Chengkou–Fangxian fault indicate sinistral strike-slip deformation. For example, an approximately 40 m-wide shear zone is present in the limestone of the Cambrian Lujiaping Formation to the north of the town of Bashan in Chengkou County. The superposition of two stages of folds is well exposed in this shear zone (Figure 6C). The vertically plunging folds (D3) formed by sinistral strike-slip deformation were superimposed on the folds (D2) with moderately SE-plunging hinges. The NNW–SSE-trending folds within the North Dabashan thrust belt and along the eastern segment of the Chengkou–Fangxian fault zone should represent the D3 folds, and the latter indicates the sinistral strike-slip thrusts (Figure 5). The deformation of the remaining Lower–Middle Jurassic conglomerates (Figure 7C) and the additional thrusting (Figure 7H) in the North Dabashan thrust belt indicate that the D3 structural event initiated after the Middle Jurassic and caused the additional thrusting. The Upper Cretaceous–Paleogene conglomerates and sandstone unconformably overlie the lower units along the Ankang fault in the Ankang, Zhushan, and Fangxian areas (Figure 1; Shi et al. 2012), which indicates that the D3 phase might have continued into the Early Cretaceous. Thus, we suggest that D3 might have occurred in the Late Jurassic–Early Cretaceous.

4.2. Palaeostress fields

The palaeostress fields in the South Dabashan foreland belt have been investigated extensively (Sun and Lu, 1993; Liu et al. 2005b; Li et al. 2005, 2009, 2013; Dong et al. 2006, 2010; Shi et al. 2007; Zhang et al. 2010; Hu et al. 2012) and experimentally simulated (Wu et al. 2009; Zhang et al. 2010; Wang et al. 2011). However, the palaeostressess in the North Dabashan thrust belt have not been studied systematically (Dong et al. 2006, 2010; Zhang et al. 2010; Li et al. 2013). Here, we present a regional dataset that includes measured axial planes, cleavages, and fault-slip data from the entire North Dabashan thrust belt. Using the inversion techniques of Angelier (1984), we identified three regional palaeostress fields that were associated with the formation of the North Dabashan thrust belt.

At the exposures of angular unconformities in Pingba (Figure 7A and D) and Dazhu (Figure 7B, F, and G), the folds with NNW-dipping axial planes and ENE-plunging hinges were located in the strata below the unconformities but were not present in the overlying strata. Detailed field observations revealed that numerous folds with NNW-dipping axial planes are present throughout the North Dabashan thrust belt and indicate NNW–SSE shortening (Figure 8). Additionally, most of the dextral strike-slip thrusts and shear zones (Figure 4) were also formed by the NNW–SSE compressive stress field, and penetrative cleavages that dip to the NNW can also be recognized in the field outcrops (Figure 6D). This shortening event was related to the continental collision between the NC and SC in the Middle Triassic.

The structural analysis of numerous outcrop-scale folds indicates that their hinges trend NW or SE and that their axial planes dip NE or SW, which indicates NE–SW-vergent shortening (Figure 9). Besides the folds, other measured kinematic indicators include cleavages, shear structures, and faults that developed throughout the North Dabashan thrust belt. For example, cleavage replacement structures are exposed in the Fenghuangshan (Figure 3A) and Pingli domes and in some deformed strata. These cleavages generally dip to the NE, which indicates NE–SW shortening. S-C fabrics (Figure 3B) and other shear structures (Figure 6E) typically indicate shearng toward the SW. The brittle faults (Figure 6F) trend NW–SE and dip moderately to steeply to the NE or SW. All of these structural indicators were formed by the NE–SW compressive stress field (Figure 9). Analysis of the superposition relationship (Figures 2C and 6B) suggests that NE–SW shortening (Figure 9) began in the latest Late Triassic after the episode of NNW–SSE shortening (Figure 8).
Furthermore, the numerous folds with ENE-dipping axial planes in the North Dabashan thrust belt indicate ENE–WSW (nearly E–W) shortening (Figure 10). For example, to the north of Taohe (Langao County), a series of overturned folds with ENE-dipping axial planes are well exposed in the limestone of the Cambrian Heishuihe Formation (Figure 6G) and indicate SWW-vergent thrusting and ENE–WSW shortening. Gentle folds with NNW–SSE-trending axial planes (Figure 6H) are also common in the North Dabashan thrust belt and indicate ENE–WSW shortening. Superposition relationships (Figure 6C) indicate that the ENE–WSW shortening (Figure 10) began in the Late Jurassic–Early Cretaceous after the episode of NE–SW shortening (Figure 9). This stress field also induced deformation of the sinistral strike-slip thrust along the eastern segment of the Chengkou–Fangxian fault zone (Figure 5).

In summary, three stages of superposed folding and thrusting have been recognized within the North Dabashan thrust belt. The D1 folds, which have ENE–WSW-trending axial traces, were formed by the Middle Triassic continental collision and were controlled by the NNW–SSE compressive stress field. The NW–SE-trending folds and thrusts in D2 were deformed in the latest Late Triassic and earliest Early Jurassic and were controlled by the NE–SW shortening. The D3 NNW–SSE-trending folds formed in the Late Jurassic–Early Cretaceous and were controlled by the ENE–WSW (nearly E–W) compressive stress field. Both the D2 and D3 folds and thrusts were responses to the intra-continental deformation in the South Qinling.

4.3. Structural deformation mechanism and evolutionary model

Numerous NW–SE-trending intermediate-basic and alkali dikes are present in the North Dabashan thrust belt and terminate against the Chengkou–Fangxian fault zone. These dikes record early Palaeozoic rifting in the northern margin of the SC and indicate that the North Dabashan region experienced a stage of tectonic extension during the early Palaeozoic (Luo and Duan 2001; Wang et al. 2009; Zou et al. 2011). The Middle Triassic continental collision between the NC and SC drastically changed the dynamics of the North Dabashan area (He et al. 1999; Zhang et al. 2001). New seismic data indicate that eclogitization of the dominantly mafic crust on the northern margin of the SC might have facilitated the prolonged continental convergence (Dong et al. 2013). After the closure of the Mianlue ocean, the continued continent–continent convergence resulted in the formation of the North Dabashan thrust.
Figure 9. NE–SW compressive stress field in the North Dabashan thrust belt is revealed by the analysis of structural deformation. The stereonets (lower hemisphere) on the map give foliation (P) and lineation (L) data of specific outcrops, foliations (P) display the limbs of folds excluding the foliations in station number C that display the cleavage, and lineations (L) display the hinges of folds (B-type lineation). Opposing arrows are trends of the maximum principal stress (σ1).

Figure 10. ENE–WSW (nearly E–W) compressive stress field in the North Dabashan thrust belt is revealed by the analysis of structural deformation. The stereonets (lower hemisphere) on the map give foliation (P) and lineation (L) data of specific outcrops, foliations (P) display the limbs of folds, and lineations (L) display the hinges of folds (B-type lineation). Opposing arrows are trends of the maximum principal stress (σ1).
belt. Based on the lithology and mechanical properties of the stratigraphy, four major detachment layers were identified in the North Dabashan thrust belt: the Proterozoic metamorphic basement, lower Neoproterozoic, lower Cambrian, and lower Silurian (Bureau of Geology and Mineral Resources of Sichuan 1991; Bureau of Geology and Mineral Resources of Shaanxi 1991; Dong et al. 2013). The nappes in the North Dabashan area were thrust to the SW along the detachment layers; for instance, the North Dabashan thrust belt was thrust to the SW along the Chengkou–Fangxian fault onto the north margin of the South Dabashan arcuate belt along the lower Neoproterozoic detachment layer. The North Dabashan region is characterized by SW-vergent imbricate thrust sheets with several backthrusts within the soft layers of the Cambrian and Ordovician units; the backthrusts dip to the NE and form positive flower structures. For example, the Gaoqiao fault dips to the SW and forms a positive flower structure with the NE-dipping thrusts to the south. In the Chengkou–Fangxian fault zone (Figure 2A–B), only the Malu–Dazhu area exhibits a small-scale positive flower structure with SW-dipping backthrusts (Geological Survey of Shaanxi Province 1966). Therefore, the Malu–Dazhu area should represent top of the thrust front of the North Dabashan thrust belt.

Based on a collisional orogenic model, if the boundary fault is arcuate, the internal tectonic structures should also be bent (Macedo and Marshak 1999). In contrast, the thrust faults in the North Dabashan thrust belt generally strike NW and terminate against the arcuate Chengkou–Fangxian fault zone; however, the thrust faults in the South Dabashan arcuate belt are parallel to the Chengkou–Fangxian fault zone and form an arc (Figure 1). Therefore, the geological features indicate that the thrust faults within the North Dabashan thrust belt and Chengkou–Fangxian fault zone underwent different kinematic histories, and the former may be the result of reactivation of earlier normal faults (He et al. 1999, Zhang et al. 2010 and Wang et al. 2011) used sandbox models with varying boundary conditions to demonstrate that the thrust faults were originally extensional faults that formed during the early Palaeozoic and were reactivated as thrust faults in the early Mesozoic.

The Early–Middle Triassic Mianlue suture represents the final amalgamation of the NC and SC (Zhang et al. 1996; Meng and Zhang 2000). The unconformity between the Upper Triassic conglomerates and sandstone and the Lower Triassic limestone in the Pingba (Figure 7A, D, and E) and Dazhu areas (Figure 7B, F, and G) along the Chengkou–Fangxian fault zone indicates that the final amalgamation of the NC and SC in the Dabashan area occurred during the Middle Triassic. During this period, the SC moved to the NW and was obliquely subducted under the NC (Figure 11A). Numerous dextral strike-slip syn-collision structures in the North Dabashan thrust belt and Chengkou–Fangxian fault zone were controlled by the NNW–SSE compressive stress field (Figure 11A). The Chengkou–Fangxian fault, which is parallel to the faults to the north, had been a crucial boundary fault before the collision between NC and SC (Figure 11A). After the early oblique collision, the SC rotated clockwise relative to the NC during the Early Jurassic so that the continental collision took place across all of the northern Yangtze and formed the extensive foredeep subsidence belt from east to west along the northern Yangtze Block (Liu et al. 2005a). The sustainability of the continental collision resulted in the large-scale thrusts of the North Dabashan thrust belt. This thrust event occurred in the latest Late Triassic in response to the intra-continental collision orogeny in the Qinling orogen. The SW-vergent thrusting of the North Dabashan area was controlled by the NE–SW compressive stress field, which formed numerous NW–SE-trending structures. During the SW-vergent thrusting, the Chengkou–Fangxian fault zone was not only the primary detachment surface but also the leading edge of the North Dabashan nappe. Owing to the pinning of the Hannan massif (to the west) and the Shennongjia massif (to the east) culminations, the originally linear Chengkou–Fangxian fault zone began bending into an arcuate fault zone (Figure 11B). During the Late Jurassic–Early Cretaceous, the orientation of the stress field in the North Dabashan region changed gradually from NE to ENE during intra-continental orogeny. Additional thrust in the North Dabashan thrust belt was controlled by the ENE–WSW compressive stress field. The deformation of the Dabashan seems to be proceeded by an oblique indentation of the Hannan massif into the Qinling orogenic belt (Li et al. 2013). Due to the synthetical effects of the ENE–WSW compressive stress field and the pinning of the Shennongjia massif culmination, the eastern Chengkou–Fangxian fault was dragged to the WSW, which formed the sinistral strike-slip structures (Figure 11C). The Chengkou–Fangxian fault zone was deformed into a WSW-convex arcuate fault zone due to the pinning of both of its ends and the detachment layer that developed in the Lower Neoproterozoic strata. At the same time, the NW-trending thrust faults within the North Dabashan thrust belt were truncated by the arcuate Chengkou–Fangxian fault zone (Figure 11C). We suggest that the final arcuate Chengkou–Fangxian fault zone formed later than the NW-trending faults to the north, resulting in the truncated relationship between the faults. Finally, the Dabashan thrust belt evolved into a SWW-convex arcuate tectonic belt with a significantly shorter western segment than its eastern segment (Figure 11C).

5. Conclusions

(1) The northern sub-zone of the North Dabashan thrust belt is characterized by two Meso–Neoproterozoic basement units that include the Fenghuangshan and Pingli
domes and contain SW-vergent imbricate thrust sheets. The southern sub-zone consists of SW-vergent thrusts and backthrusts that form positive flower structures.

(2) During the Middle Triassic, the SC moved to the NW and was obliquely subducted under the NC. Numerous dextral strike-slip syn-collision structures in the North Dabashan thrust belt and Chengkou–Fangxian fault zone indicating that the SC moved northward and was obliquely subducted under the NC; (B and C) the Late Triassic–Early Cretaceous during which the intra-continent orogeny of the Dabashan fell into two stages: (i) (B) the Late Triassic–Early Jurassic period during which the North Dabashan thrust belt happened to thrust toward to the SW, and created numerous NW–SE-trending folds within the North Dabashan thrust belt; (ii) (C) the Late Jurassic–Early Cretaceous during which the North Dabashan thrust belt thrust further. Owing to the pinning of the Hannan massif and Shennongjia massif culminations, the deformation of North Dabashan thrust belt is dominated by ENE–WSW orientation stress, which created numerous sinistral strike-slip thrusts developed along the eastern Chengkou–Fangxian fault zone, and nearly S–N-trending folds developed along the western Chengkou–Fangxian fault zone.

(3) Based on detailed field investigations, structural analysis, and microscopic observations, two strike-slip zones with dextral and sinistral strike-slip properties were recognized along the Chengkou–Fangxian fault zone. The dextral strike-slip motion along the entire fault zone was caused by the collision between the NC and SC, and the sinistral strike-slip motion, which occurred only along the eastern part of the fault zone, was related to the intra-continental orogeny. The dextral deformation was superimposed and deformed by the sinistral deformation.

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References


Geological Survey of Shaanxi Province, 1966, Geological map of Ziyang (I-49-31), scale 1:200 000, 1 sheet. [In Chinese.]

Geological Survey of Sichuan Province, 1973, Geological map of Chengkou (I-49-1), scale 1:200 000, 1 sheet. [In Chinese.]


Li, P.Y., Zhang, J.J., Guo, L., and Yang, X.Y., 2012, Structural features and deformational ages of the northern Dabashan...


Lin, J.L., Zhang, W.Y., and Fuller, M., 1985, Preliminary Phanerozoic polar wander paths for the North and South China blocks: Nature, v. 313, p. 444-449. doi:10.1038/313444a0


Sun, Z.C., 2002, Mesozoic-Cenozoic foreland basins and their hydrocarbon prospect in middle and western parts of China,


