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Early Mesozoic tectonics of the South China block: Insights from the Xuefengshan intracontinental orogen

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A B S T R A C T

Intracontinental orogens remain less understood than accretionary or collisional orogens that are related to plate margin interactions. In the center of the South China block, the Xuefengshan Belt provides a well-exposed example of such an intracontinental orogen of Early Mesozoic age. Detailed field tectonic observations indicate that the Xuefengshan Belt can be divided into a Western Outer Zone characterized by km-scale box-fold structures, and an Eastern Zone, separated from the Western Outer Zone by the SE-dipping Main Xuefengshan Thrust. In the Eastern Zone, NW verging folds coeval with a pervasive slaty cleavage and a NW–SE trending lineation are the dominant structures. From west to east, the dip of the cleavage surface exhibits a fan-like pattern. The bulk architecture of the Xuefengshan Belt results from polyphase deformation: D_1 is characterized by a top-to-the-NW ductile shearing; D_2 corresponds to SE-directed back thrusting and folding; D_3 consists of upright folds with vertical cleavage and lineation. At depth, a high strain zone characterized by greenschist facies metamorphic rocks and a top-to-the-NW ductile shearing corresponds to a ductile décollement zone that accommodated the deformation of the Neoproterozoic to Early Triassic sedimentary series. Kinematic compatibility suggests that the syn-metamorphic ductile shearing was coeval with the D_1 event in the sedimentary cover. The Xuefengshan Belt is interpreted as an Early Mesozoic intracontinental orogen, which possibly originated from the SE-directed continental subduction of a piece of the South China block in response to northwestwards subduction of the Pacific plate.

1. Introduction

The mechanisms of intracontinental orogeny have long been discussed, since intraplate mountain belts cannot be ascribed to the plate margin interaction paradigm that assumes that the interiors of a continent are rigid and hard to deform. However, it is now well accepted that the deformation of continental crust can be a far-field consequence of collision, as exemplified by the Miocene tectonics of Asia (e.g. Tapponnier and Molnar, 1979; Avouac et al., 1993). Compared to collisional or accretionary orogens, evidence for oceanic subduction, ophiolites, accretionary complexes, mélange, and arc-related magmatism is lacking. Conversely, fold-and-thrust belts, large-scale décollement, limited crustal melting, and even high temperature metamorphism are well developed tectonic elements in intracontinental orogens. These features are illustrated by the Cenozoic Tianshan Belt in Central Asia (Tapponnier and Molnar, 1979; Hendrix et al., 1992; Avouac et al., 1993; Allen et al., 1999), the Cenozoic Pyrenees in Europe (Roure et al., 1989; Choukroune, 1992), the Late Mesozoic to Cenozoic Laramide orogen in North America (Dickinson and Snyder, 1978; English and Johnston, 2004), the Paleozoic Alice Springs orogen in Central Australia (Hand and Sandiford, 1999; Sandiford et al., 2001), and the Early Paleozoic intracontinental belt of SE China (Faure et al., 2009; Charvet et al., 2010). At the lithospheric plate scale, far-field consequence of continental collision or a flat-slab subduction are often the two main driving forces advocated to account for the origin of intracontinental orogens (Dickinson and Snyder, 1978; Hendrix et al., 1992).

The Xuefengshan Belt is an Early Mesozoic intracontinental orogen in the South China block (SCB) (e.g. Qiu et al., 1998, 1999; Wang et al., 2005b; Fig. 1). When dealing with the Triassic tectonics of the SCB, the Xuefengshan Belt presents a unique example of intracontinental orogens with folds and thrusts post-dated by Late Triassic undeformed post-orogenic plutons. However, the structural style, tectonic evolution, and geodynamic significance of the Xuefengshan Belt are still debated. The proposed tectonic interpretations are still at variance (Hsu et al., 1988, 1990; Gupta, 1989; Rodgers, 1989; Rowley et al., 1989). For some authors, this belt was formed by a large-scale, multi-layer over-thrust system

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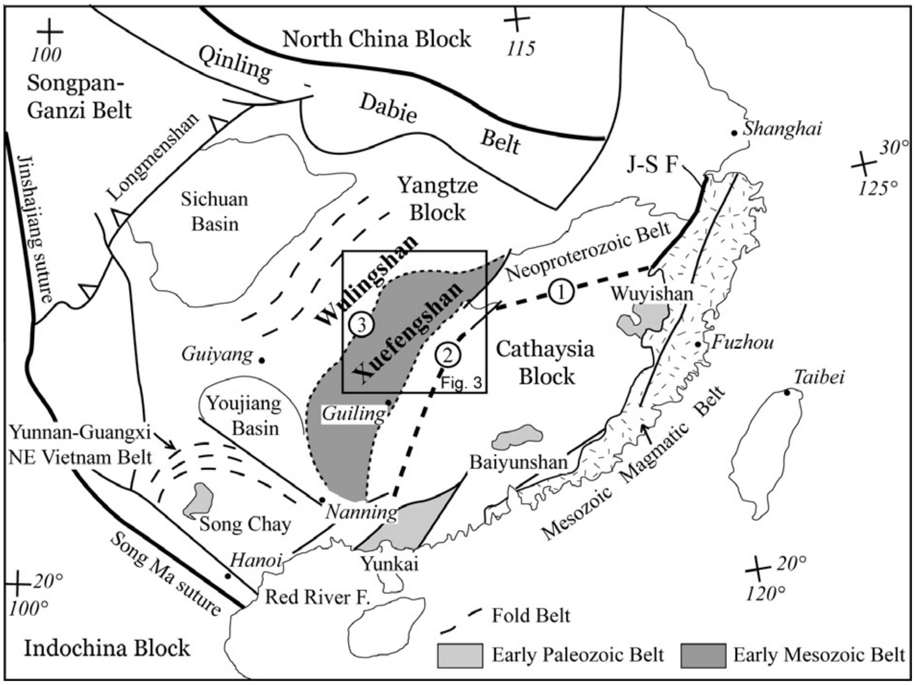

Fig. 1. Tectonic map of the South China block with the location of the intracontinental Xuefengshan Belt (Modified after Faure et al., 2009). J–S F: Jiangshan–Shaoxing Fault. (1) Predicted boundary between the Yangtze Block and the Cathaysia Block. (2) Chenzhou–Linwu Fault. (3) The Main Xuefengshan Thrust.

developed in the Late Mesozoic from the Xuefengshan Belt to the northeastern Sichuan Basin (Fig. 1) (Yan et al., 2003). Another interpretation emphasizes Triassic strike-slip faults leading to transpressional tectonics (Wang et al., 2005b). More recently, a NW-directed, flat slab subduction of the Pacific plate producing a propagating retroarc fold-and-thrust belt accompanied by NW-propagating magmatism during the 250–190 Ma interval has been suggested (Li and Li, 2007). Although, as argued below, in Section 4, this interpretation seems the most likely, structural analyses supporting this model are, up to now, not available.

Here, we present new detailed structural data from the Xuefengshan that aim to improve our understanding of the tectonic evolution of the central part of the SCB, and may provide general insights into the development of intracontinental belts.

2. Geological outline of the Xuefengshan belt in the South China block

2.1. The South China block

The South China block (SCB) formed in the Early Neoproterozoic (ca 900 Ma) by collision of the Yangtze block and the Cathaysia block to the northwest and southeast, respectively (Fig. 1; Shu et al., 1994; Charvet et al., 1996; Li, 1999; Li et al., 2009; Wang et al., 2012, and references therein). The Jiangshan–Shaoxing Fault represents the eastern part of the Neoproterozoic ophiolitic suture between these two blocks (Fig. 1). Farther west, and southwest, this suture is covered by the Paleozoic or Mesozoic sedimentary rocks. From Late Neoproterozoic to the end of Early Paleozoic, the SCB underwent continuous sedimentation, partly controlled by the Neoproterozoic rifting, and marine environment lasted until the Late Ordovician (Wang and Li, 2003). This rift occupies a large part of the western Cathaysia Block and eastern Yangtze Block, approximately in the area from the Neoproterozic Belt to the Xuefengshan Belt (Fig. 1). An Early Paleozoic orogeny occurred around 460–400 Ma which is shown by a Middle Devonian regional unconformity and emplacement of post-orogenic plutons at ca. 420 Ma (Li, 1994; Zhou, 2007). The Early Paleozoic orogen of SE China is well exposed to the south of the Jiangshan–Shaoxing Fault (Wang et al., 2007b; Faure et al., 2009; Li et al., 2010; Charvet et al., 2010). In the Xuefengshan Belt, this event is weakly developed as argued in Section 2.3. The main orogenic episode of the SCB took place in the Early Mesozoic, as demonstrated by a Late Triassic unconformity widespread across the entire SCB. In terms of time, this Middle Triassic event is referred to as the "Indosinian Orogeny" (Chen, 1999; Wang et al., 2005b, 2007c; Li and Li, 2007; Lin et al., 2008; Roger et al., 2008, 2010), but at the scale of the entire SCB, two main Triassic belts are exposed along the SCB margins. Namely, to the north, the Qinling–Dabie Belt is related to the northward subduction of the SCB below the North China block (Hacker and Wang, 1995; Faure et al., 1999, 2008). To the southwest and south, the Jinshajiang and Song Ma sutures are associated with the collision of the SCB with the Indochina block (Lepvrier et al., 2004, 2008; Carter et al., 2001; Wallis et al., 2003; Harrowfield and Wilson, 2005; Carter and Clift, 2008; Roger et al., 2008, 2010).

Another intraplate compression is indicated by fold-and-thrust belt to the southeast of the Sichuan Basin, whereas the geodynamics is still unknown (Yan et al., 2003). Contemporaneously, in the SE margin of the South China block, significant contraction is also characterized by thrusting (Chen, 1999). However, these structures are mostly brittle without ductile deformational fabrics, recognized up to now.

During the Late Jurassic and Cretaceous, the tectonic activity in the SCB was characterized by NE–SW striking normal or strike-slip faults, synkinematic plutons, and syntectonic terrigeneous sedimentation (Xu et al., 1987; Gilder et al., 1991; Faure et al., 1996; Lin et al., 2000; Zhou and Li, 2000, Zhou et al., 2006; Shu et al., 2009). In the Xuefengshan area, strike-slip faults parallel to the belt are rare. These brittle faults bound intramontane half-graben basins or offset the Triassic plutons.

2.2. Regional geology of the Xuefengshan Belt

The Xuefengshan Belt, located in the central area of the SCB, is a NNE–SSW trending range about 100 km wide and more than

300 km long, which is larger than the geographic Xuefengshan Mountain (Fig. 1). The Meso-Neoproterozoic Lengjiaxi group, formed by conglomerates, sandstones, siltstones, phyllites and slates, represents the oldest strata cropping out in the Xuefengshan Belt. The Lengjiaxi group is overlain by more than 3 km of turbidites and volcanic rocks assigned to the Neoproterozoic Banxi group, which underwent a prehnite–pumpellyite to low-greenschist facies metamorphism (BGMRHN, 1988). The Late Neoproterozoic (Sinian) strata include tillite, sandstone, chert and limestone. Until Early Silurian, and locally Middle Silurian, there is no obvious sedimentation gap in the stratigraphic sequence. However, the Cambrian and Ordovician lithology changes this uniform sedimentary pattern in the Xuefengshan Belt, with limestones and black shales to the north, and sandstones, silts, and slates to the south (BGMRGX, 1985; BGMRHN, 1988). In the study area, Silurian deposits are turbidites that can be interpreted as the molasses derived from erosion of the Early Paleozoic orogen (Qiu et al., 1998, 1999; Faure et al., 2009).

Upper Silurian to lower Devonian deposits are missing in the Xuefengshan area, and lower Paleozoic rocks are covered directly by Middle Devonian conglomerates. The upper Devonian–Carboniferous–Permian and lower Triassic series consists of shallow-marine to littoral facies limestones, dolomites, and clastic rocks. All the rocks mentioned above are strongly deformed and unconformably overlain by Upper Triassic or Lower Jurassic sandstones and conglomerates that are distributed limitedly in intramontane basins. This unconformity is interpreted as a response to an Early Mesozoic intracontinental orogeny (Chen, 1999; Wang et al., 2005b; Li and Li, 2007; Shu et al., 2009). From Middle Jurassic to Cretaceous, the sedimentary series consists of red terrestrial clastic rocks interbedded with volcanic rocks.

The pre-Late Triassic lithological succession contains several pelitic or shaly layers, some of them with coal measures, which could play a major role in shaping the tectonics of the Xuefengshan Belt. Due to their low yield stress, these soft layers act as décollement levels that accommodate the regional shortening. The Sinian pelite and graphitic layers, and the Cambrian black shales are the main décollement levels, but Devonian, Carboniferous, and Permian pelitic layers may also represent second order décollements (Fig. 2) (Yan et al., 2003).

Plutonic rocks are widespread in the Xuefengshan Belt (Fig. 3). Undeformed Mesozoic peraluminous granites intrude the already deformed pre-Mesozoic series. These Mesozoic granites were generated between 245 and 200 Ma and postdate the Early Mesozoic orogeny (Chen et al., 2006, 2007a, 2007b; Wang et al., 2007a). Furthermore, as described in Section 3.4, Early Paleozoic plutons underwent a pervasive ductile deformation during the Early Mesozoic tectonics.

2.3. Pre-Devonian events in the Xuefengshan Belt

Due to the widespread occurrence of a Devonian unconformity, some geologists interpreted the Xuefengshan Belt as the product of an Early Paleozoic orogeny (e.g. Qiu et al., 1998, 1999). However, according to our survey, the importance of the Early Paleozoic orogeny appears to be overestimated. In the southern part of the study area, Neoproterozoic, Cambrian, and Ordovician pelite-sandstone series are involved in E–W trending, south-verging folds (Fig. 4). These early folds are unconformably covered by Devonian conglomerate and sandstone, followed by a continuous series of limestone and subordinate shale and mudstone. The entire sedimentary pile, from Neoproterozoic to Early Triassic, is deformed by N–S trending folds. This superimposed folding gives rise to a type 2 fold-interference pattern (Ramsay and Huber, 1987).

In fact, the angle of the Devonian unconformity decreases from east to west and even in the northern and northwestern parts of the Xuefengshan Belt, only a disconformity between Silurian and

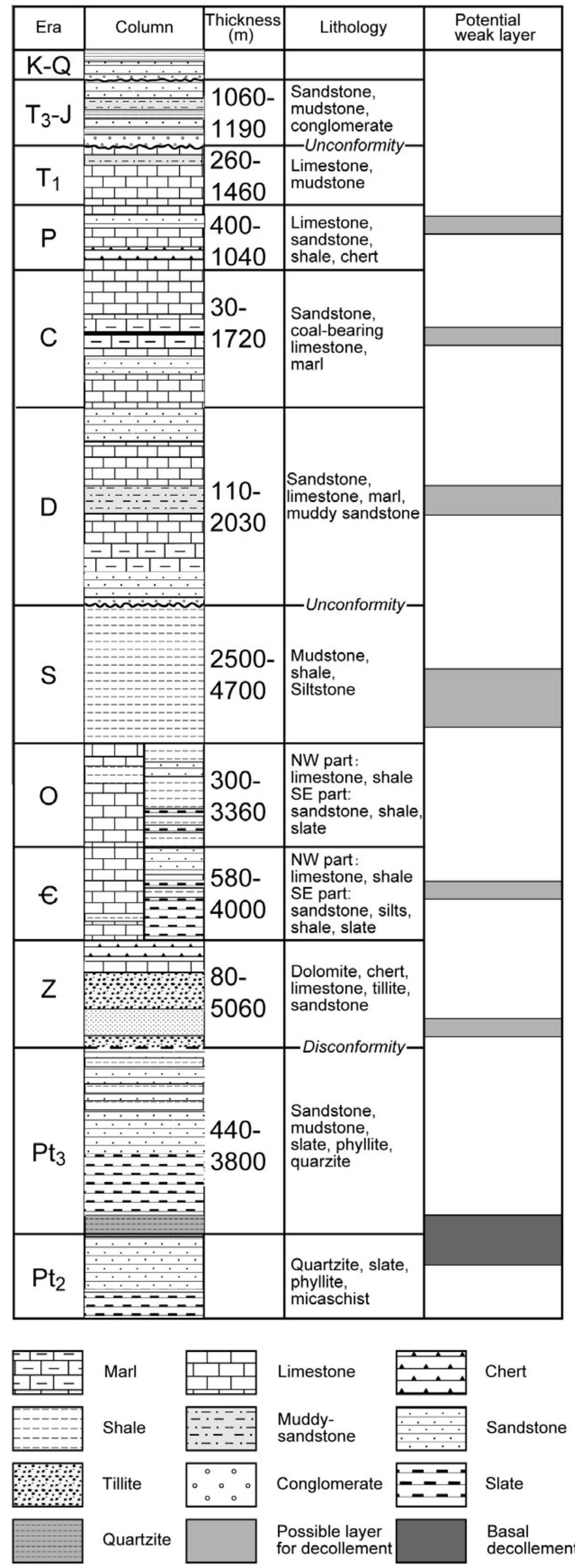

Fig. 2. Stratigraphic column of the Xuefengshan Belt with location of potential décollement zones (BGMRHN, 1988).

Devonian rocks is exposed. Although the Early Paleozoic tectonics have been argued continuously, detailed structural data for deformation related to this event remains poor. Works by Yan et al.

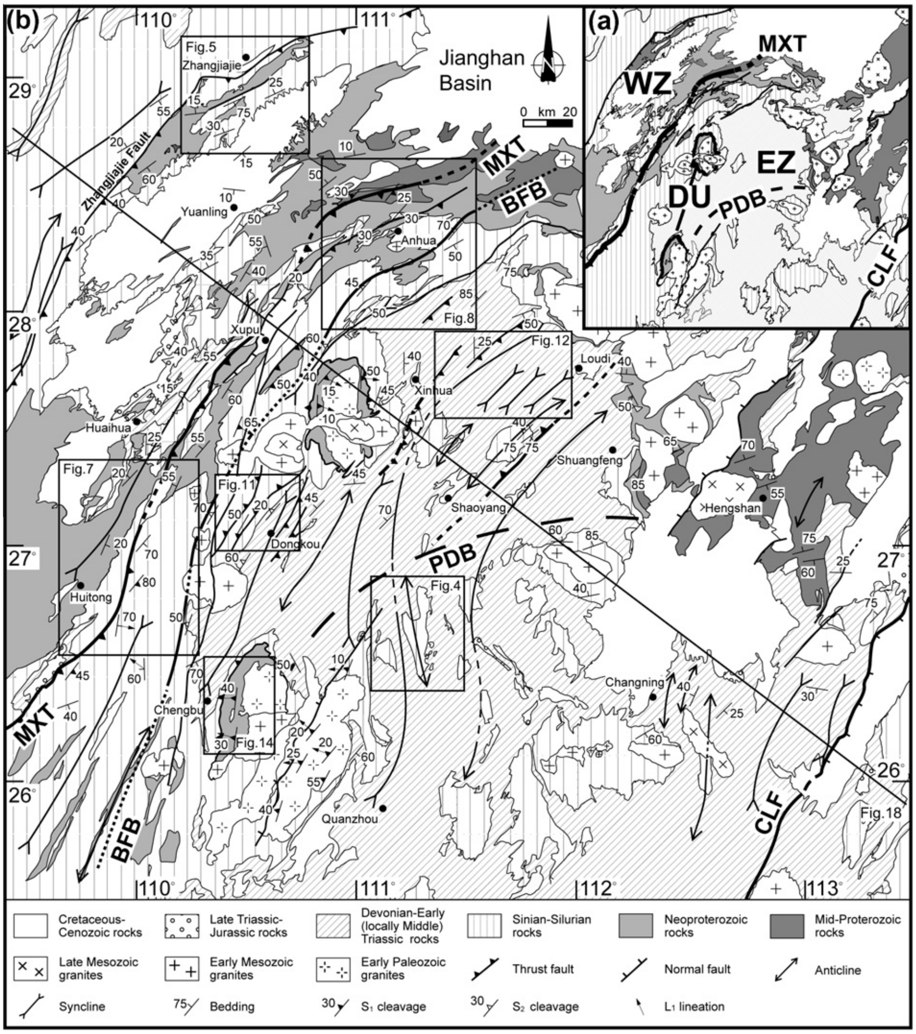

Fig. 3. (a) Sketch map of the Xuefengshan Belt with tectonic division. (b) Structural map of the Xuefengshan Belt (Modified after 1:500,000 Geological map of Hunan, BGMRHN, 1988). WZ: Western Outer Zone. EZ: Eastern Zone. MXT: Main Xuefengshan Thrust. BFB: Back Folding Boundary. DU: Deep Metamorphic Unit. PDB: Pre-Devonian Boundary. North of this limit, pre-Devonian deformation is negligible. CLF: Chenzhou–Linwu Fault.

(2003) and Wang et al. (2005) show that the Mesozoic deformation is dominant, and structural evidence of the Early Paleozoic event was not depicted. The entire pile of sedimentary rocks demonstrates a consistent deformational pattern which will be addressed in the Section 3. The Early Paleozoic folds are open, characterized by kilometer-scale gentle undulations without any axial planar cleavage. Furthermore, in the entire Xuefengshan area, when a slaty cleavage is observed in the Neoproterozoic to Silurian series, this cleavage is also developed in the unconformably overlying Devonian rocks. Conversely, syn-schistose folds restricted to pre-Devonian series is hardly observed but in the southwestern area as described above (Fig. 4). The northern boundary of the Pre-Devonian structures is outlined as the Pre-Devonian Boundary (PDB in Fig. 3b). Additional microtectonic arguments for an Early Mesozoic deformation will be given in the following section. Therefore, the Early Paleozoic event is poorly developed in most parts of the Xuefengshan Belt, and thus we shall focus on the structural analysis of the Early Mesozoic orogeny, which is responsible for the bulk architecture of the belt.

3. Structural pattern of the Xuefengshan Belt

The Xuefengshan Belt can be subdivided into two tectonic zones (Fig. 3a): the Western Outer Zone and the Eastern Zone. The Eastern Zone comprises the Xuefeng Mountain and a lowland area, to the west and to the east, respectively. The Xuefeng Mountain is an area with high elevation, where the intensity of the deformation and metamorphism is the greatest. In the lowland area, Devonian to Early Triassic rocks are poorly exposed. The Western Outer Zone, exposed in the Wuling Mountain, is characterized by box-fold structures. The Main Xuefengshan Thrust (MXT, Fig. 3) separates the Western Outer Zone and the Eastern Zone. It also corresponds to the cleavage front, as cleavage (described in Section 3.2) is absent in the Western Outer Zone but is widely developed in the Eastern Zone. In this zone, NE–SW trending folds with an axial planar cleavage, NW or W-directed thrust faults, and E–W to WNW–ESE trending mineral and stretching lineation are the dominant structures.

Except in a few places around some plutons (e.g. near Chengbu. Fig. 3), highly metamorphosed rocks are not exposed in the study area. Another important structural boundary is the Back-Folding Boundary (BFB, Fig. 3b), defined by the appearance of back-folds and back-thrusts (cf. Section 3.3 for detailed descriptions). East of the BFB, east-verging folds, sometimes with inverted limbs are widespread in the Eastern Zone. Devonian to Triassic formations occupy a large area in the eastern part of the Eastern Zone, whereas pre-Devonian rocks are dominant in the west Eastern Zone. Nevertheless, except the décollement zones, there is not sharp

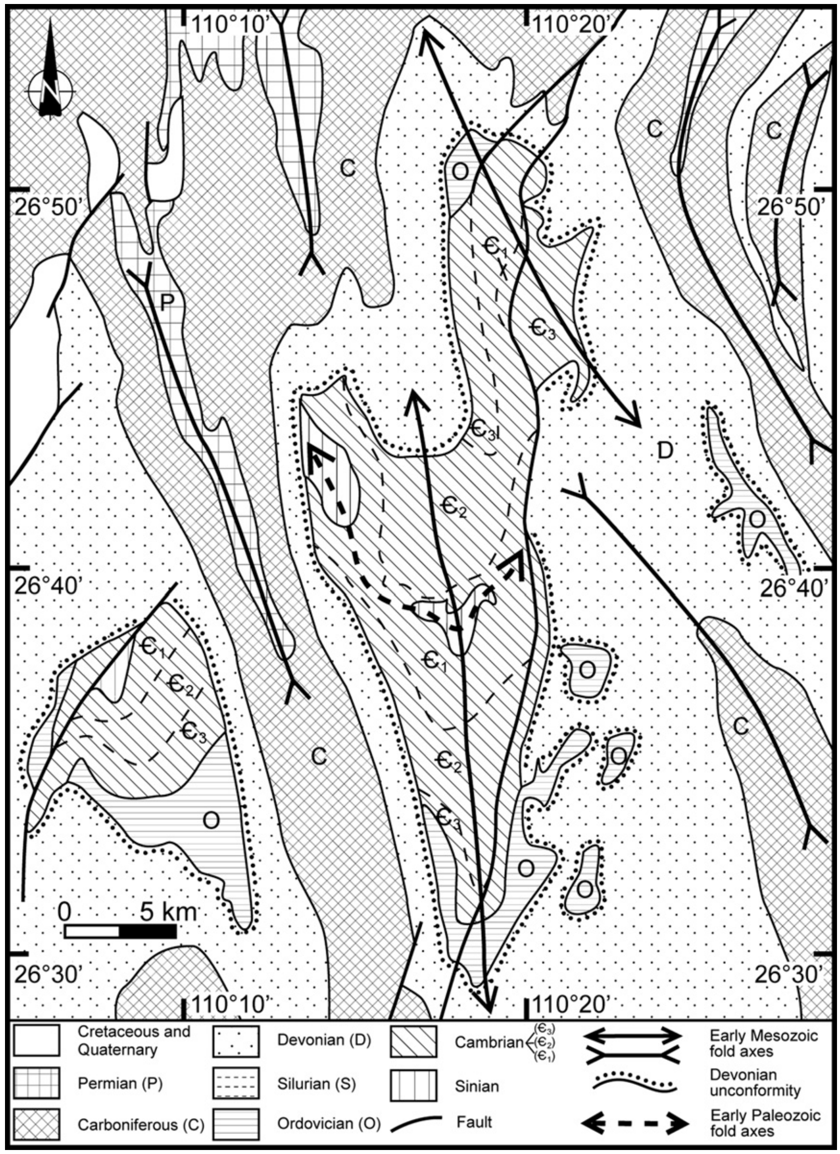

Fig. 4. Geologic map of the southern part of the Xuefengshan Belt showing relics of pre-Triassic E–W trending fold axes, developed only in pre-Devonian rocks and refolded by Triassic N–S trending folds.

discontinuity within the sedimentary series of the Eastern Zone. One of the main structural features is the northwestward progressive weakening, and even disappearance of the cleavage plane.

The whole belt experienced complex polyphase deformation. On the basis of cleavage plane geometry, fold-vergence, and overprinting relationship, we separate three deformation events in the Eastern Zone. The first one, D_1, is characterized by a top to the NW ductile shearing. The second one, D_2, corresponds to a back-folding and back-thrusting stage with SE-verging folds. The last phase, D_3, is represented by upright folds with vertical axial planar cleavage and vertical stretching lineation. For each zone, the typical deformation style relevant to the three events is described in selected areas (Fig. 3b).

3.1. The Western Outer Zone

The Western Outer Zone, bounded to the east by the MXT, shows moderate deformation compared with the Eastern Zone which is strongly deformed. This zone has been investigated in the Wuling Mountain, South of Zhangjiajie (Figs. 3 and 5a–d). There, the Neoproterozoic to Silurian series is deformed by NE–SW trending, kilometer-sized box-folds. In the core of anticlines and synclines, the bedding is flat without any macroscopically observable deformation, whereas highly dipping strata can be observed in the fold limbs (Figs. 5b and 6a and b). Due to their weak rheology, the pelitic layers, namely Cambrian black shale, or Sinian pelite and coal measure are more intensely deformed than the limestone or sandstone beds. Where strata are tilted to dip angles of 70–90°, along these soft-layers, the deformation is accommodated by intense meter to centimeter-scale north-vergent disharmonic folding and layer-parallel slip (Fig. 5b). In the Western Outer Zone, the rocks rarely record metamorphism, even in the core of the anticlines where the deepest Meso-Neoproterozoic sandstone-pelite series crops out. In summary, the Western Outer Zone represents the structurally higher part of the Xuefengshan Belt which is deformed under brittle conditions accommodated by layer-parallel slip, box-folding, and brittle deformation concentrated in the fold hinges, and except along limited soft layers, acting as secondary décollement levels, cleavages are poorly developed in the whole sedimentary series.

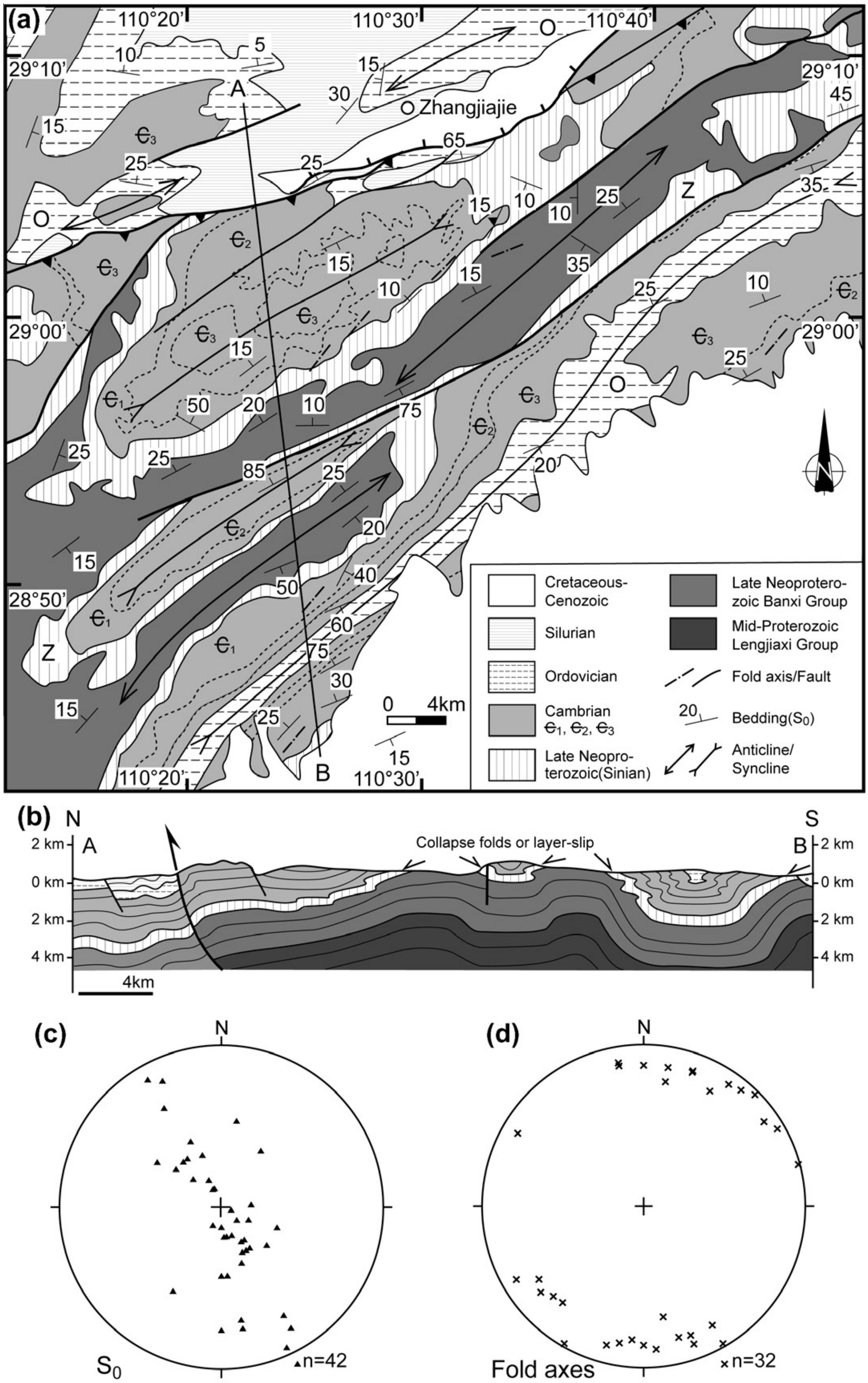

Fig. 5

Fig. 5. (a) Detailed geologic map of the Western Outer Zone in the Wuling Mountain (Modified after 1:500,000 Geological map of Hunan, BGMRHN, 1988). (b) Cross section showing the box-fold structure characteristic of this zone. Stereographic plots (Schmidt lower hemisphere projection) of the structural elements. (c) Bedding. (d) Fold axes.

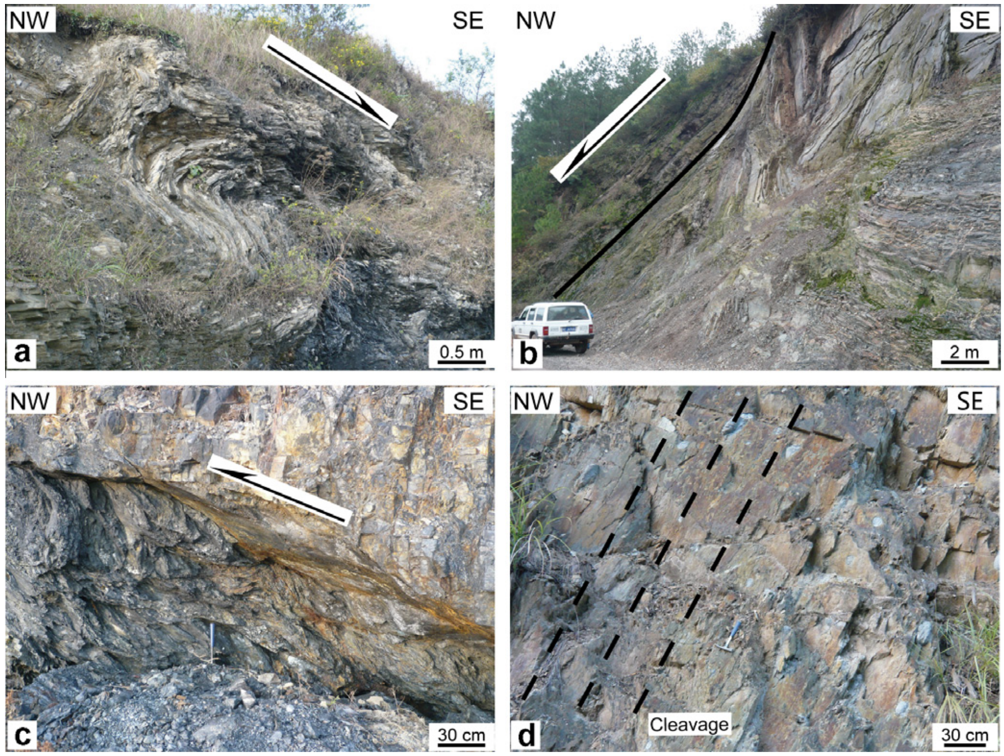

Fig. 6. Photographs of representative structures observed in the Western Outer Zone and the Main Xuefengshan Thrust. (a) Gravitational collapse folds in Cambrian shale, south of Zhangjiajie (N29°00.406′/E110°28.804′). (b) Gravitational collapse structure in Neoproterozoic shale, northeast of Yuanling (N28°25.873′/E110°29.335′). (c) Shear zone in coal-bearing Cambrian black shale with sigmoidal shearing structure, east of Huitong (N26°56.422′/E109°56.097′). (d) Oriented pebbles in Sinian tillite with a NW-dipping cleavage, east of Huitong (N26°56.529′/E109°55.672′).

3.2. The Main Xuefengshan Thrust (MXT)

The MXT is a northwest-directed, gently east-dipping reverse fault that corresponds also to the appearance of the main slaty cleavage (S_1 hereafter). This major structure is over 200 km long and extends farther south in the Youjiang Paleozoic-Early Mesozoic Basin (Fig. 1). Locally, this thrust fault is reactivated as a normal fault that controls the opening of a Cretaceous half-graben. The northern part of the MXT, southwest to the Jianghan Basin (Fig. 3b), has not been directly observed in the field, due to outcrop conditions, but the sharp change between open folds devoid of axial planar cleavage to the NW, and well expressed overturned folds and slaty cleavage to the SE, argues for the existence of such a thrust. To the northeast, it is buried below the Cretaceous-Cenozoic Jianghan Basin (Fig. 3b).

In the southern part of the study area, east of Huitong (Fig. 3b and Fig. 7a), a ca. 10 m thick, moderately east dipping, high strain shear zone is developed in the Cambrian black shale, slate, and schist, separating weakly metamorphosed Sinian sandstone and tillite of the Eastern Zone in the hanging wall from undeformed and unmetamorphosed sub-horizontal Neoproterozoic–Cambrian rocks in the footwall (Fig. 7a–c). In the vicinity of the shear zone, rocks are strongly deformed, whereas 2 km away from the contact, the top-to-the-NW thrusting fabrics disappear. Along the thrust plane, NW–SE trending striations, and kinematic indicators such as sigmoidal shaped lenses developed within Cambrian black shale show a top-to-the-NW displacement (Fig. 6c).

In the thrust hanging wall, the Sinian sandstone exhibits a high angle East-dipping or subvertical cleavage. In the footwall, tens-of-meters-wavelength folds, overturned to the west, are developed, and several meter-scale shear zones with layer-slip structures are conspicuous. In the Sinian tillite, 10–50 cm-sized pebbles are flattened, forming west-dipping cleavage planes (Fig. 6d). This feature is related to a SE verging fold, analogous to those widely developed to the east (described in the Section 3.3.2). However, this area is the only place where east-vergent structures have been observed in the Western Outer Zone. Thus, we tend to interpret it as a local reverse thrust, corresponding to a pop-up generated during D_1 rather than a true D_2 back-thrust.

At the regional scale, the deformation in the entire Proterozoic series that crops out to the west of the MXT is weak or almost absent (Fig. 7a). The bedding remains sub-horizontal over a large distance, and only joints, and kilometer-scale gentle upright folds represent the macroscopic deformation structures. Conversely, to the east of the MXT, folds coeval with a pervasive axial planar cleavage deform the sedimentary rocks (Fig. 7b–f).

3.3. The Eastern Zone

Due to the high elevation and good exposure, the western part of the Eastern Zone provides important information to explore the geometry and kinematics of this zone. From west to east, different structural features are recognized. In the west, top-to-the-NW folding and shearing dominate, whereas in the east the opposite (i.e. eastward) vergence is predominant. These two contrasted vergences are not synchronous but successive, as demonstrated below (Sections 3.3.1, 3.3.2 and 3.3.3), the eastward shearing overprints the westward one. These key areas are described as examples of the representative structure and of the superimposed deformation of the Eastern Zone. The timing question will be addressed in Section 4.

3.3.1. Anhua section

In the northern part of the orogen, Meso-Neoproterozoic sandstone and argillite with a well-developed slaty cleavage occupy a large domain (Fig. 8a and b). Northeast of Anhua, the N70–90E

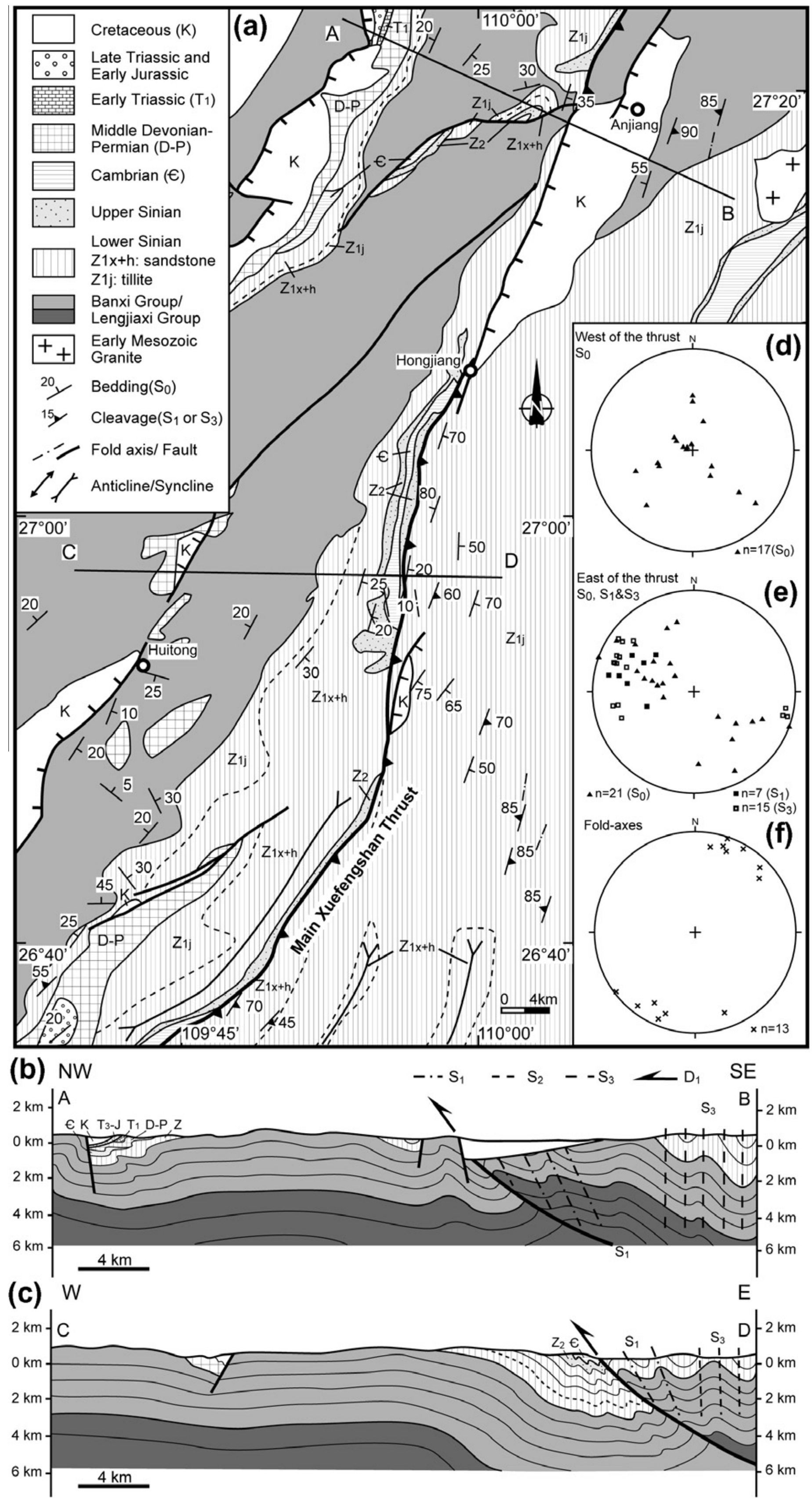

Fig. 7. (a) Detailed geologic map of the Main Xuefengshan Thrust or Cleavage Front (Modified after 1:500,000 Geological map of Hunan, BGMRHN, 1988). (b) and (c) Cross sections showing the structure of the area close to the MXT. Stereographic plots (Schmidt lower hemisphere projection) of the structural elements. (d) bedding west of the thrust. (e) Bedding (S_0), S_1 and S_3 cleavage, east of the thrust. (f) Fold axes.

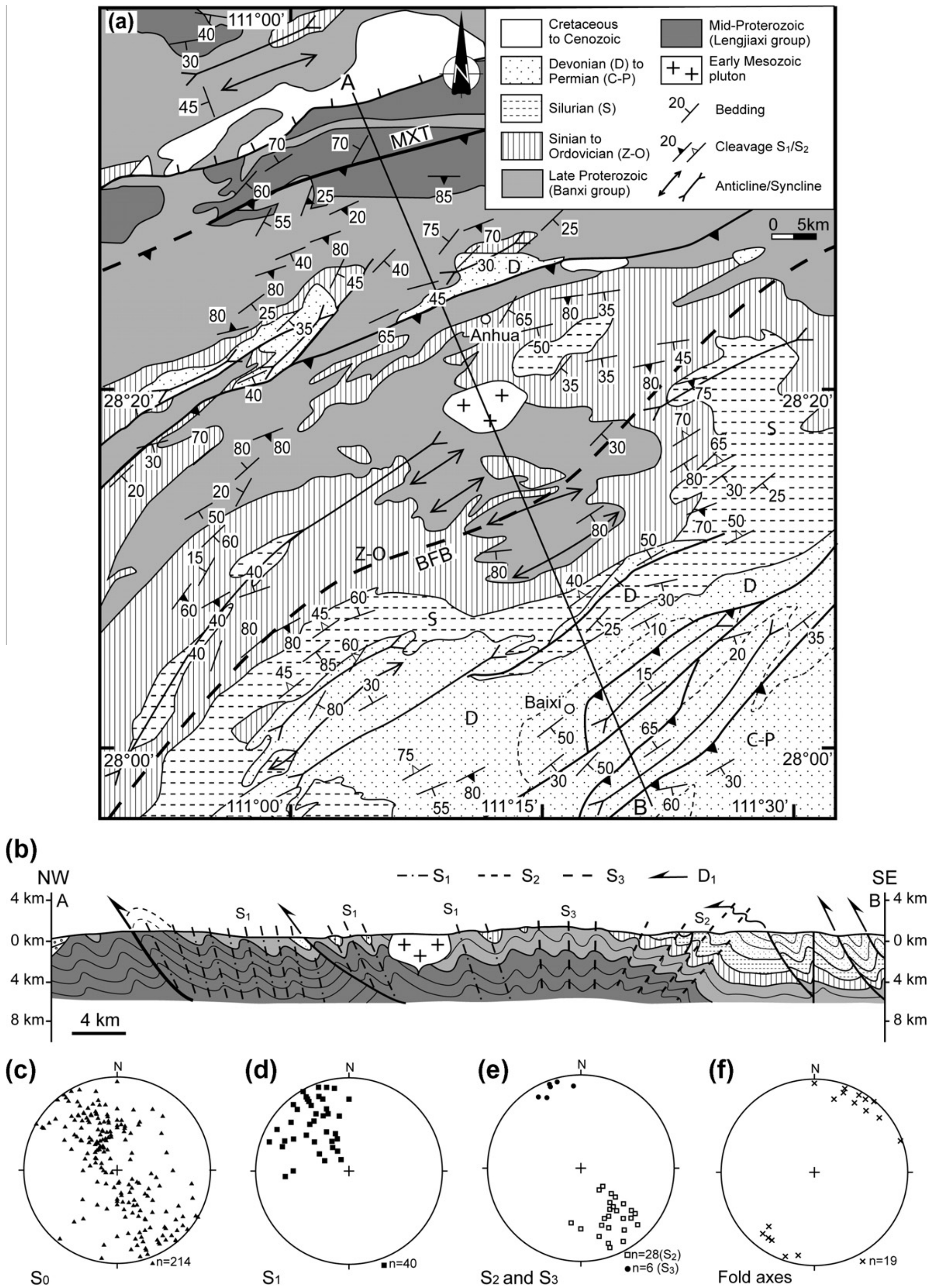

Fig. 8. (a) Detailed geologic map of the Eastern Zone near Anhua (Modified after 1:500,000 Geological map of Hunan, BGMRHN, 1988). (b) Cross section showing the structure of the Anhua section. Stereographic plots (Schmidt lower hemisphere projection) of the structural elements. (c) Bedding (S_0), (d): S_1 cleavage. (e) S_2 and S_3 cleavages. (f) Fold axes.

striking cleavage is steeply dipping to the SE, and from N to S, becomes more and more penetrative. S_1 gradually replaces the original S_0 bedding (Fig. 9a), but the dip angle of S_1 changes slightly from place to place in different parts of the folds (Fig. 8d). Nevertheless, the fold vergence determined by the S_0/S_1 relationships, is consistently to the NNW, even if cleavage refraction due to alternation of pelite and sandstone layers is locally well developed.

North of Anhua (Fig. 8a), a several meters thick, highly deformed shear zone with top-to-the-north thrusting, separates the Neoproterozoic and Paleozoic rocks. Cataclasites are well

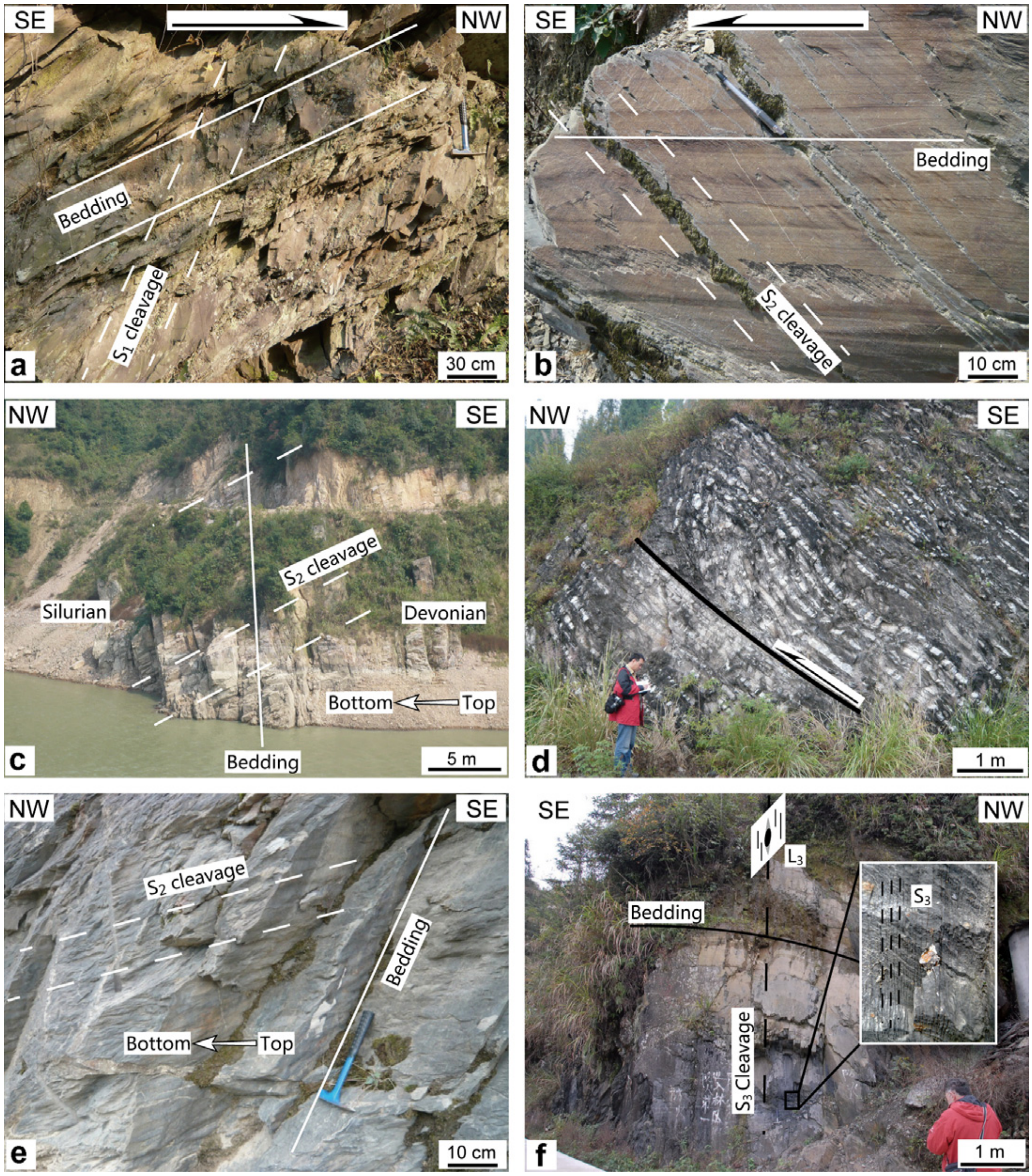

Fig. 9. Photographs illustrating the deformation in Anhua and Dongkou sections. (a) SE dipping cleavage in Neoproterozoic Banxi sandstone, south of Anhua (N28°27.182′/E111°01.374′). (b) S_2 cleavage in Silurian mudstone in a normal limb of a SE-verging fold, south of Anhua (N28°02.531′/E111°02.792′). (c) S_2 cleavage in vertical layers of Devonian sandstone involved in a SE-vergent fold. The same cleavage affects the underlying Silurian strata, south of Anhua (N28°04.012′/E111°02.332′). (d) NW-directed reverse fault and associated fold in Carboniferous limestone, south of Anhua (N27°55.886′/E111°18.307′). (e) NW dipping S_2 cleavage in inverted Cambrian shale with ripple marks on the top surface (N27°04.762′/E110°31.480′). (f) Upright fold in Sinian shale with vertical pressure shadows, north of Dongkou (N27°27.604′/E110°24.581′).

developed along the fault zone. The foliated argillaceous matrix includes sigmoidal-shaped sandstone boudins with a top-to-the-NW sense of shear. In some places, the Neoproterozoic sandstone overthrusts onto the Devonian limestone. In the thrust footwall, the limestone is intensely folded and sheared whereas in the hanging wall, the sandstone is folded with a penetrative, SE-dipping, axial planar cleavage.

South of Anhua (Fig. 8a), the cleavage surface gradually turns to vertical and then dips to the northwest. In the Sinian to Ordovician series, the verticalization of S_0 is coeval with the development of upright folds associated with an axial planar cleavage. Farther south, a NW-dipping slaty cleavage associated with SE verging folds is widely developed. As indicated by ripple marks, load casts and groove casts, the S_0 surface in the southeastern limb of anticlines is overturned in some places. Furthermore, the pelitic layers of the Silurian turbidite often exhibit a SE-dipping cleavage that cannot be related to these SE-verging folds (Fig. 10a and b). There are two possibilities: firstly, the cleavage could be due to the NW vergent layer-slip. However, in the southeastern high-angle limb of the fold, no evidence of gravitational collapse fold or layer-slip has been observed, where in fact these structures should be more intensive. Hence, we turn to a second interpretation that this feature is a relic of the S_1 cleavage, coeval with the early NW-verging folds, which is later involved in SE-verging folds. Thus, these overprinting relationships show that the SE-verging folds can be considered as back-folds formed during a second deformation stage (D_2) (Fig. 8a, e, and f).

North of Baixi (Fig. 8), the Silurian and Devonian bedding dips gently to the SE, striking N20–50E. SE-verging D_2 folds, associated with a northwest dipping cleavage, deform the entire series (Fig. 9b and c). This structural consistency shows that the deformation occurred after the Devonian.

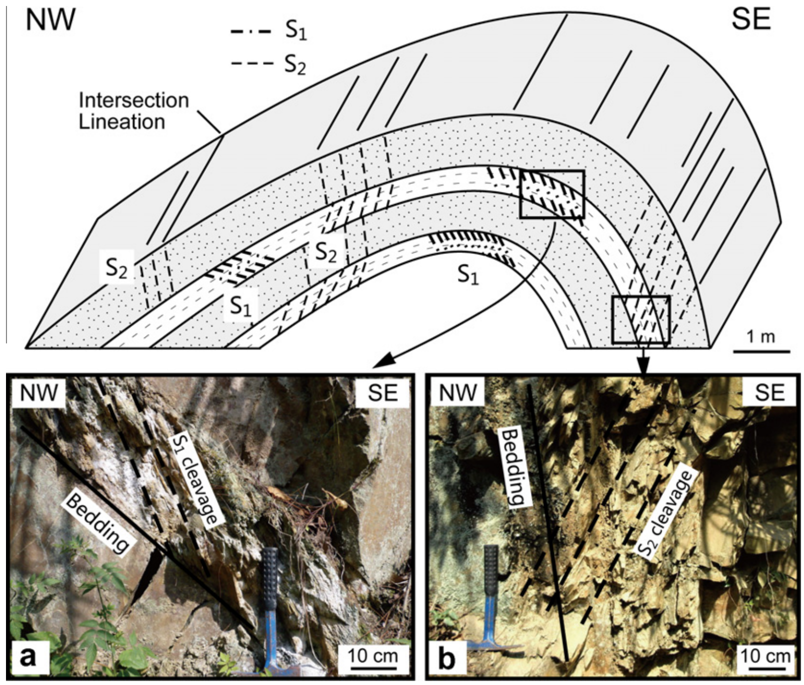

Fig. 10. Field evidence of superimposed deformation. The S_1 cleavage is deformed by a SE-verging F_2 fold associated with a S_2 axial planar cleavage, northwest of Xinhua (N26°25.228′/E110°26.868′). (a) Relict S_1 cleavage in a mudstone layer. (b) Pervasive NW dipping S_2 cleavage.

From Baixi to the south (Fig. 8a), in the Carboniferous and Permian limestone and mudstone, thrust faults associated with NW-verging folds indicate again a northwestward movement (Fig. 9d). In this area, back folding is no longer observed. Nevertheless, the D_2 back-folding development is, to some extent, more intense in the Dongkou area, which will be discussed in the next section.

3.3.2. The Dongkou section

The main structure of this area is represented by large scale overturned bedding involving Upper Neoproterozoic to Lower Devonian rocks (Fig. 11a and b). Northwest of Dongkou, the slightly metamorphosed Cambrian to Silurian black shales and siltstones are deformed by NE–SW trending, SE-verging folds with axial-planar cleavage (Figs. 9 and 11e). These structures are related to the D_2 back-folding event. Around Dongkou, the inverted limbs of the D_2 back-folds are less developed than to the west. The unconformable Devonian sandstone is generally rotated to vertical due to D_2 folding. A pervasive, NW-dipping S_2 cleavage is developed in the Devonian and Silurian strata (Fig. 11b and d). However, evidence for an earlier, D_1 event, can be recognized too. The bedding (S_0) is generally parallel to S_1 cleavage, except in some rare hinges of isoclinal folds that are refolded by SE-vergent F_2 folds. East of Dongkou, top-to-the-NW thrusting dominates again with Devonian sandstone overthrusting onto the Carboniferous to Permian limestone. This structure is consistent with the one described in the Anhua section. Lastly, in this region, Cambrian and Ordovician black shales are deformed by up-right folds with vertical cleavage and vertical lineation (Fig. 9f).

3.3.3. The Lianyuan section

To the east of the Anhua section, the Eastern Zone is mostly represented by Middle Devonian to Early Triassic sedimentary rocks (Figs. 3 and 12). Upper Triassic clastic deposits unconformably overlie the older deformed series. This part of the Eastern Zone exhibits well-developed folds and thrusts but slaty cleavage is generally less penetrative than to the west (Fig. 12a, b, and e). This feature might be due to a higher structural level in this area. North of Lengshuijiang, Late Devonian sandstone overthrusts northwestwards onto Carboniferous limestone that in turn overthrusts onto Permian formations (Fig. 12a and b). SE-dipping cleavage, well developed in mudstone layers interbedded by limestone (Fig. 13a), is related to the D_1 event. In this thrust system, the coal-bearing argillite and shale layers in the Devonian, Carboniferous and Permian series acts as subordinate, locally developed décollement levels during the NW-directed thrusting. In the stronger limestone and sandstone layers, cleavage is generally absent. Hence, the deformation was largely accommodated in these soft layers. In the core of synclines, Early Triassic thin-bedded limestone is strongly folded (Fig. 13b). In addition, SE-verging folds and thrust faults are also observed. For instance, northeast of Lengshuijiang, SE-vergent back-thrusting and back-folding are well developed with subhorizontal or gently SE-dipping cleavage preserved in Carboniferous slaty layers (Fig. 12c). Likewise, in Devonian mudstone interbedded with sandstone, the S_1 cleavage is refolded by an F_2 fold (Fig. 13c). Moreover, north of Shaoyang (Fig. 3b), a NW-dipping cleavage, associated with SE-verging folds, is also widely developed. These structures are interpreted here as the result of the D_2 back-folding, as described above in the other areas of the Eastern Zone.

Locally, several meters of inverted limbs can be observed (Fig. 13d). Moreover, at the scale of a single 10-meter-wavelength fold, gravitational sliding along the anticline limbs is responsible for the development of collapse folds with contrasting kinematics. West- and east-verging folds formed on both sides of the anticline (Fig. 13e). NE of Hengshan city, drilling reports describe a top-to-the-NW thrust of Neoproterozoic sandstone and slate onto Devonian limestone (Bai et al., 2009).

Therefore, to summarize, the bulk geometry of the Eastern Zone is controlled by folding and thrusting with top-to-the-NW shear sense (D_1 event) reworked by SE-verging back folding and back thrusting (D_2 event). Structurally, the eastern part of the Eastern Zone can be considered as the eastern extension of the fold-and-thrust belt that is developed in the west Eastern Zone, but the difference lies in the thermobarometric conditions of the polyphase deformation, which took place in the west under higher metamorphic conditions than in the east.

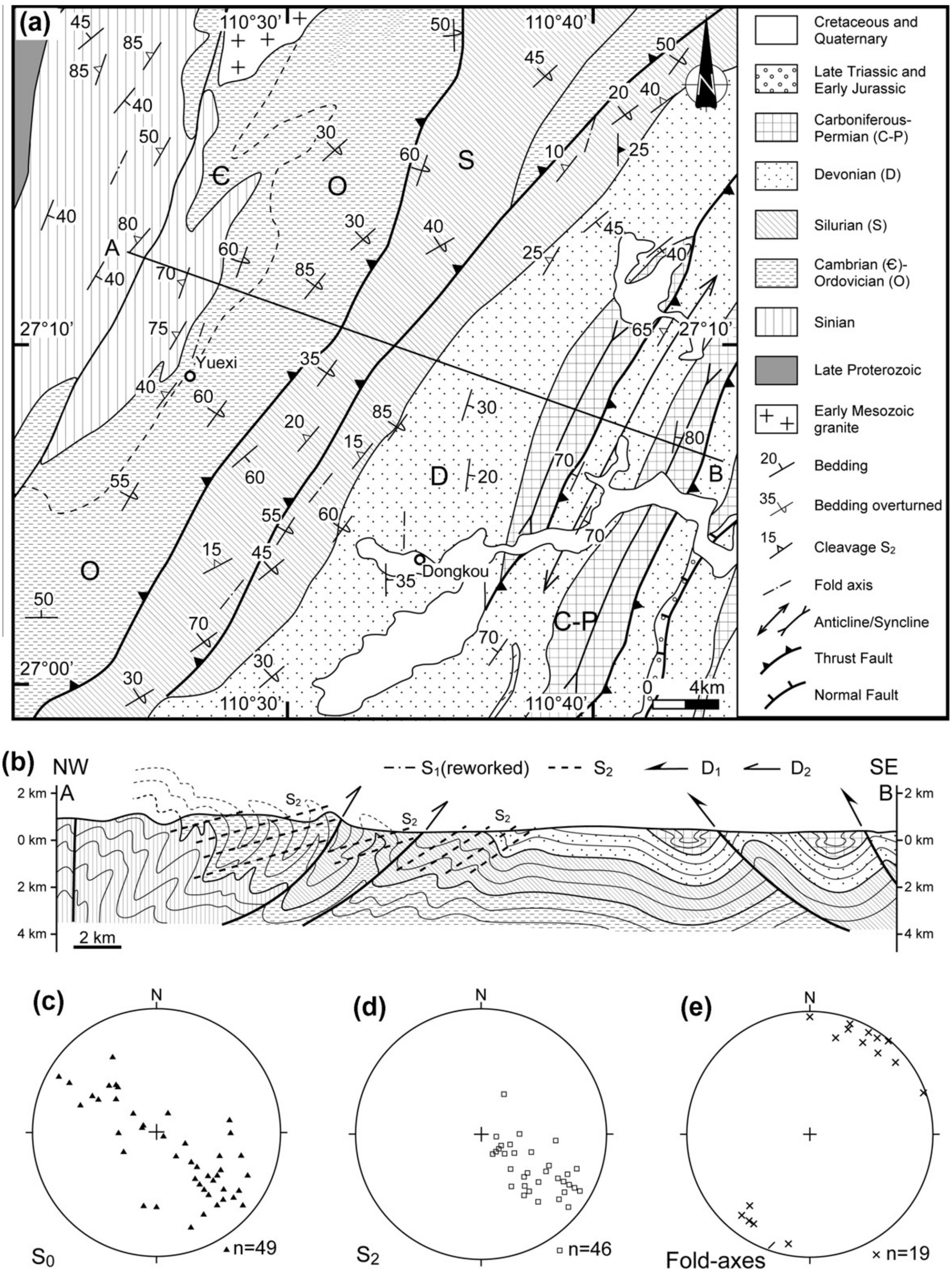

Fig. 11. (a) Detailed geologic map of the Eastern Zone near Dongkou showing back-folding structure (Modified after 1:500,000 Geological map of Hunan, BGMRHN, 1988). (b) Cross section with F_1 folds refolded by F_2 folds. Stereographic plots (Schmidt lower hemisphere projection) of the structural elements. (c) Bedding. (d) S_2 cleavage. (e) F_2 fold axes.

3.4. The Deep Metamorphic Unit and the Décollement

Most of rocks in the areas abovementioned in the Eastern Zone show only a low grade metamorphism coeval with the polyphase deformation, however, around some of the Mesozoic granitic plutons, metamorphic rocks are exposed as the deepest part of the Xuefengshan Belt, (Figs. 3b, 14 a and b).

East of Chengbu (Fig. 3), and around Lanrong (Fig. 14a), the Proterozoic rocks underlying the Late Neoproterozoic (Sinian) to Paleozoic series consists of slate, schistose sandstone, quartzite and garnet-bearing two-mica schist. These rocks show a pervasive foliation, and a mineral and stretching lineation. In some places, the well developed foliation, represented by a 1–5 mm compositional layering marked by alternation of quartz (light) and micaceous

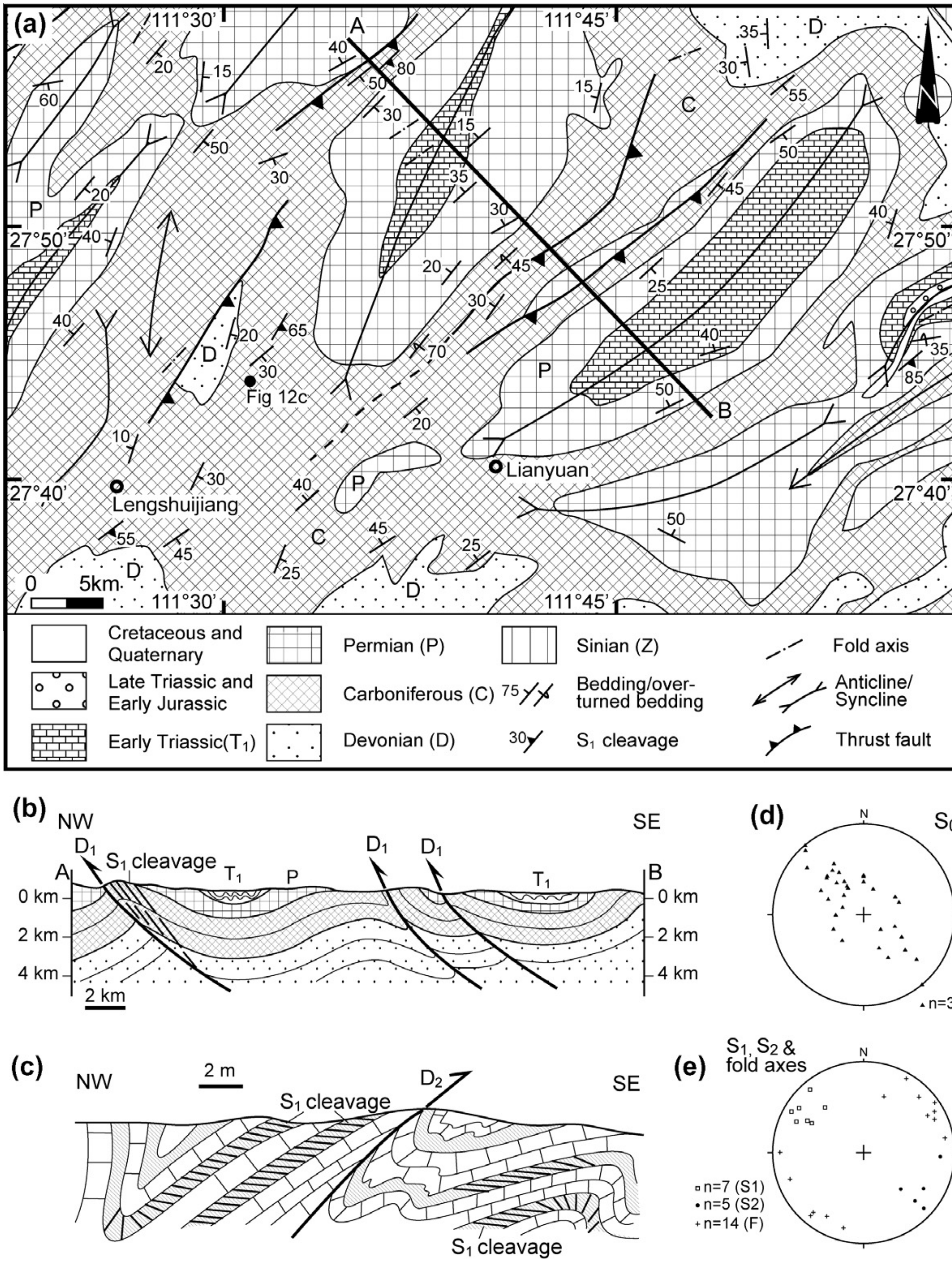

Fig. 12. (a) Detailed geologic map of the Eastern Zone near Lianyuan (Modified after 1:500,000 Geological map of Hunan, BGMRHN, 1988). (b) and (c) Cross sections of the area. Stereographic plots (Schmidt lower hemisphere projection) of the structural elements. (d) Bedding. (e) S_1, S_2 cleavage and fold axes.

(dark) ribbons with a marked grain size reduction, corresponds to a mylonitic fabric (Fig. 15a). In these metamorphic rocks, the sub-horizontal N–S trending foliation contains a WNW–ESE stretching lineation (Fig. 14d and e). The top-to-the-NW shearing is documented by asymmetric pressure shadows surrounding garnet porphyroblasts, sigmoidal quartz clasts and quartz veins. Isoclinal folds with axes parallel to the lineation formed during the ductile shearing are also found (Fig. 15b–d).

In the mica-schist, host rock of the Early Paleozoic Maoershan pluton, the mineral lineation is represented by andalusite grains that were formed by the contact metamorphism related to the granite emplacement, but reoriented during the ductile shearing (Fig. 15e). The granitic intrusions, particularly the small monzo-granitic Lanrong pluton east of the Maoershan pluton (Fig. 14a), are also ductilely deformed. The granitic rocks are deformed and metamorphosed into orthogneiss, the foliation of which dips to

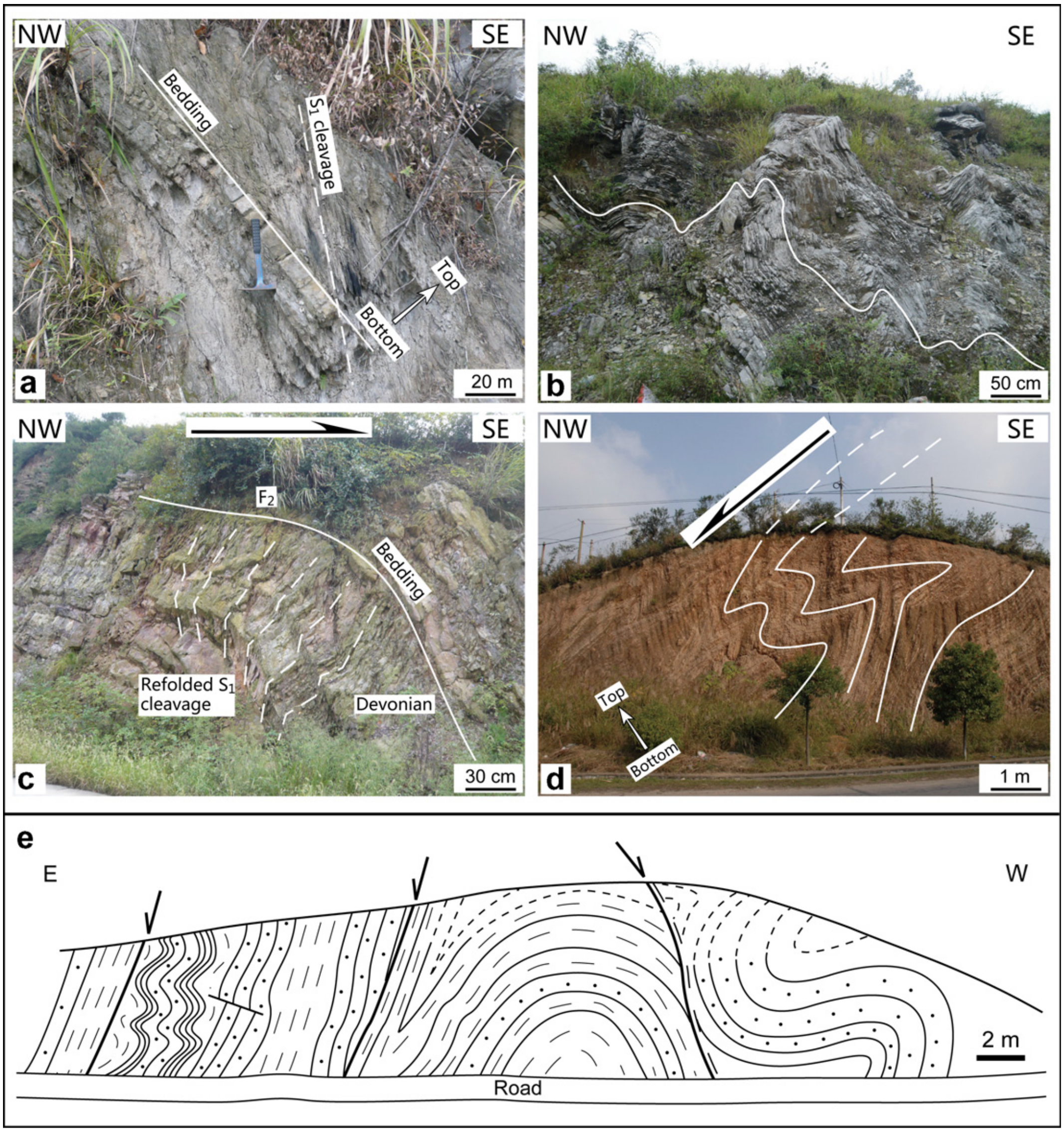

Fig. 13. Examples of structures observed in the Eastern Zone. (a) S_0 bedding-S_1 cleavage relationships in Carboniferous limy-mudstone layers indicating a northwestward F_1 fold vergence, east of Anhua (N27°46.268′/E111°31.012′). (b) Strongly folded thin-layer Triassic limestone (N27°53.639′/E111°37.699′). (c) S_1 cleavage refolded in a SE-vergent fold in Late Devonian rocks, indicating that D_1 and D_2 both occurred in the Early Mesozoic (N28°09.767′/E112°05.173′). (d) Gravitational collapse folds in Triassic sandstone interlayered with mudstone, west of Changning (N26°23.541′/E112°29.062′). (e) Secondary collapse folds developed in both limbs of an upright fold in Permian sandstone and shale series, east of Changning (N26°23.434′/E112°29.882′).

the west or east in the western and eastern margins of the Lanrong body, respectively (Fig. 15f). The mylonitic foliation formed by the alternation of quartz-feldspar layers and biotite-rich parts exhibits a stretching lineation oriented along the NW–SE trend, similar to that observed in the metamorphic aureole and the country rocks of the pluton. Around the orthogneiss massif, granitic dykes intruding into the micaschist and quartzite host rocks, are highly sheared, boudinaged, or folded. These asymmetric lenses show an unambiguous top-to-the-NW sense of shear. All the deformation features indicate that the ductile shearing occurred in a post-solidus stage after granite emplacement.

Upright folds and crenulations rework the synmetamorphic foliation and lineation. Sometimes a subvertical crenulation cleavage pervasively develops parallel to the upright fold axial plane (Fig. 15e). The superimposition of the early fabric by a late one is also indicated by the refolding of isoclinally folded quartz veins in the micaschist (Fig. 16).

In summary, ductile and synmetamorphic fabrics indicate that the observable deepest part of the Xuefengshan Belt was intensely deformed by a top-to-the-NW shearing, leading to the formation of mylonites. We interpret this high strain zone as a ductile décollement along which the horizontal shortening, accommodated by folding and thrusting in the upper sedimentary units, is transferred. The décollement was folded in an antiformal pattern during the D_3 event. The tectonic significance of this décollement will be discussed in the forthcoming sections.

4. Polyphase deformation and timing

4.1. Polyphase deformation

As depicted in the previous section from several examples in the Xuefengshan Belt, the Neoproterozoic to Early Triassic rocks of the SCB experienced several deformation events. In this section the general features of each event are synthesized.

The D_1 event corresponds to the top-to-the-NW thrusting and folding developed in the entire Xuefengshan. Two different

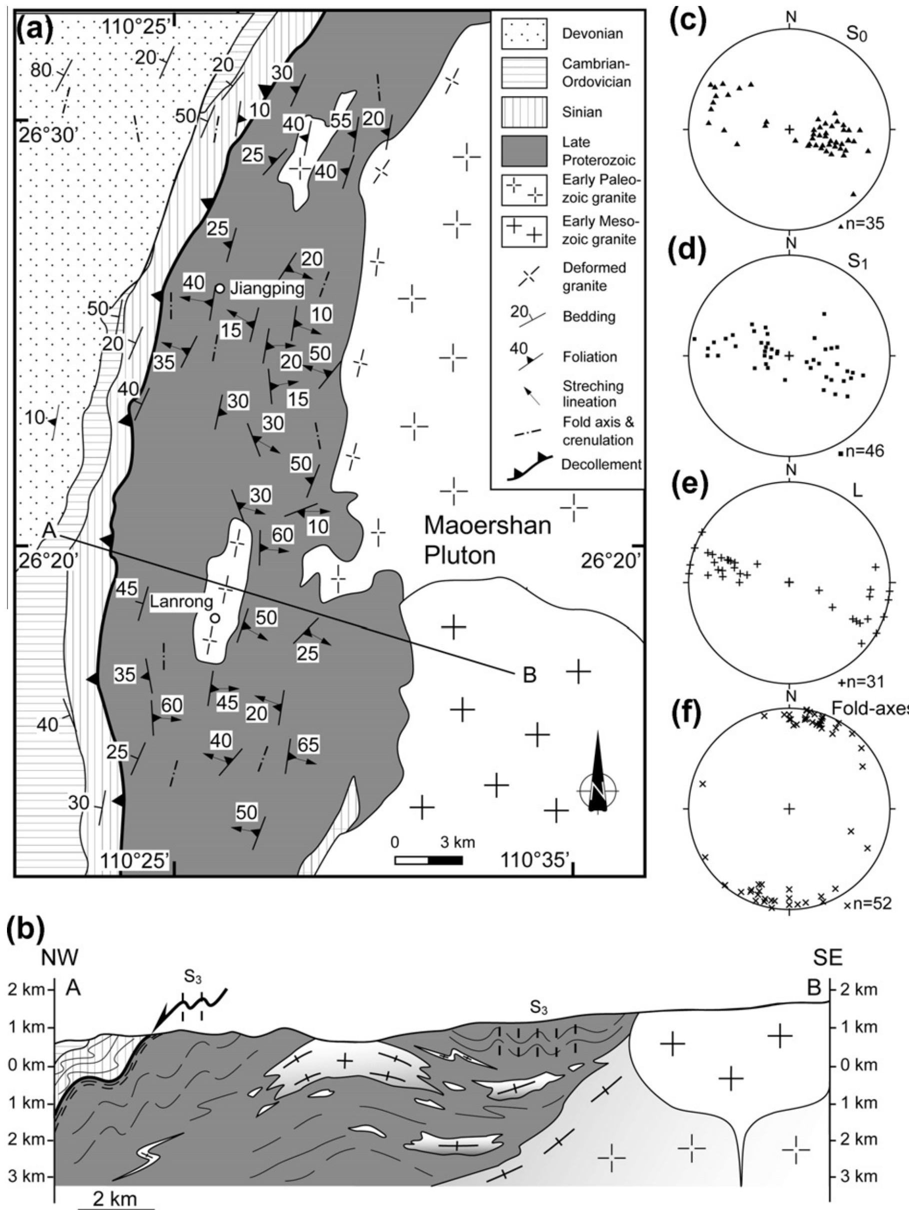

Fig. 14. (a) Detailed geologic map of the décollement, east of Chengbu (Modified after 1:500,000 Geological map of Hunan, BGMRHN, 1988; Zhou, 2007). (b) General cross section of the area. Stereographic plots (Schmidt lower hemisphere projection) of the structural elements. (c) Bedding. (d) S_1 foliation. (e) Stretching lineation. (f) F_3 fold axes and crenulation lineation.

structural styles can be attributed to D_1 deformation (Fig. 17). In the Western Outer Zone, box-fold structures with localized deformation in the fold hinges are the dominant structural element. Brittle to brittle-ductile structures such as layer-parallel slip, and disharmonic folding are the main features that accommodated shortening in the Western Outer Zone. In the Eastern Zone, the D_1 deformation is essentially ductile. The dominant S_1 slaty cleavage is axial planar to NW-vergent recumbent folds (F_1). S_1 contains a NW-SE striking mineral and stretching L_1 lineation. Shear criteria such as asymmetric quartz or calcite pressure shadows, sigmoidal veins and sheared pebbles in Sinian tillite consistently indicate a top-to-the-NW sense of shear, coeval with a greenschist facies metamorphism. Moving eastward, the D_1 event is also recognized in the eastern, and geometrically upper part of the Eastern Zone with similar structural features but without synkinematic metamorphism. The ductile deformation observed at depth in the décollement, which is developed along a NW-SE striking stretching lineation, and exhibits with the top-to-the-NW shearing sense. This deformation is also attributed to the D_1 event.

Wang et al. (2005b) suggested that the top-to-the-WNW thrusting was accompanied by a significant sinistral N–S to NE–SW trending strike-slip component with subhorizontal lineation. However, based on our work, the D_1 deformation is characterized by NW-directed folds and thrusts only with a NW–SE lineation and top to the NW shear sense. Microstructural evidence for a strike-slip component, such as high-angle foliation and subhorizontal stretching lineation, has not been recognized in our study area.

The D_2 event is also widespread in the Eastern Zone. Several observations unambiguously demonstrate that SE verging F_2 folds associated with a S_2 cleavage overprint the D_1 structures. This event is not as intense as the first one since no metamorphism and high strain zones are observed. Due to the top-to-the-SE D_2 shearing, Sinian to Devonian strata, in the eastern part of the

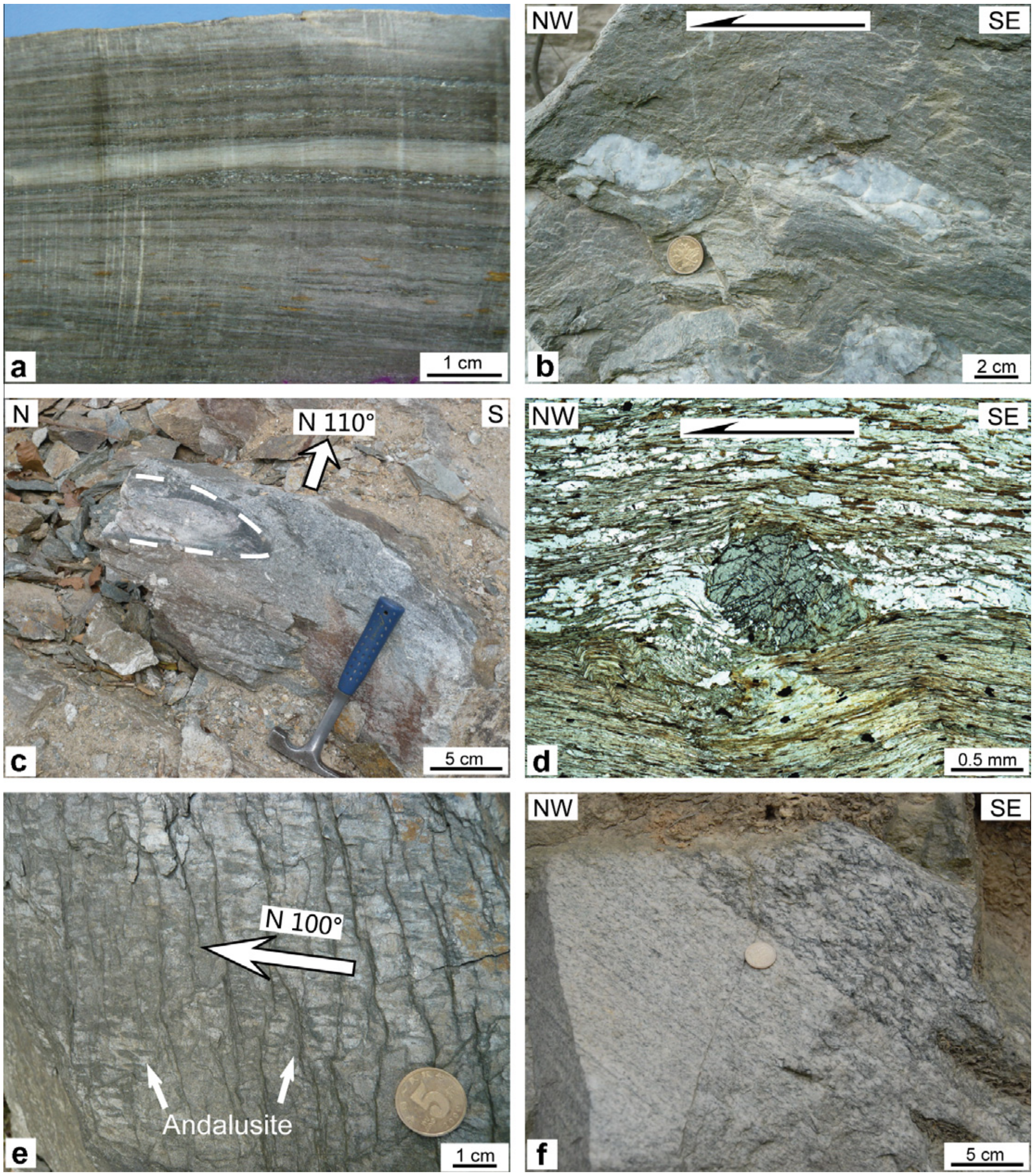

Fig. 15. Deformation features along the décollement. (a) Mylonite showing a well developed banded foliation with alternations of quartz ribbons (light), and mica (dark), southeast of Jiangping (N26°25.228′/E110°26.868′). (b) Sigmoidal quartz veins in the mylonitic Neoproterozoic quartzite, east of Jiangping (N26°10.109′/E110°43.674′). (c) Isoclinal fold with fold axes parallel to the shearing direction, northeast of Lanrong (N26°17.885′/E110°26.868′). (d) Garnet porphyroclast with quartz pressure shadows showing the top-to-the NW sense of shear, southeast of Lanrong (N26°14.688′/E110°25.811′). (e) Crenulated micaschist foliation with folded mineral, and stretching lineation marked by reoriented andalusite grains crystallized during the emplacement of the Paleozoic granite, east of Lanrong (N26°21.002′/E110°26.180′). (f) Mylonitized Paleozoic granite with foliated porphyritic granite (top) and fine grained biotite granite (bottom), east of Lanrong (N26°19.743′/E110°26.519′).

Eastern Zone, are largely overturned by SE directed folding. These D_2 structures are also recognized by Wang et al. (2005b), but considered as coeval, not successive, with the NW-directed deformation. The overprint on D_1 by D_2, as shown above, is not in agreement with this interpretation.

Lastly, upright D_3 folds with a subvertical S_3 cleavage and down-dip L_3 stretching lineation are developed in the Eastern Zone. In the field, it is sometimes difficult to determine if this vertical cleavage represents S_1 turned to a steeper dip or a newly formed S_3 cleavage. However, since the surface folded by the tight upright folds sometimes exhibits a preferred orientation of platy phyllitic minerals developed during D_1 metamorphism, the upright folds are attributed here to a D_3 event. In the same way, the upright folding of S_2 cleavage can be observed in a few places, for instance north of Chengbu.

The three events can also be understood as three increments of a single compressional event. During the Early-Middle Triassic, the regional NW–SE shortening of the Xuefengshan Belt was accommodated by a NW-directed, flat-lying ductile shearing. Similar to various orogenic belts for instance in the Alps, (e.g. Escher and Beaumont, 1997), Himalaya (Godin et al., 1999) or Taiwan (Malavieille, 2010), a bi-vergent fold system develops in the Xuefengshan Belt. In agreement with analog experiments and numerical modeling, (e.g. Willett et al., 1993; Beaumont et al., 1994; Malavieille, 2010), back-folding will form in the layers that cannot be underthrusted below a frontal thrust, (i.e. the MXT in the case of the Xuefengshan Belt). Geophysical data show that the current crustal thickness does not demonstrate the thickening of the Early Mesozoic (Sun and Toksoz, 2006; Zhang et al., 2011). The continuing convergence, responsible for thickening in the western

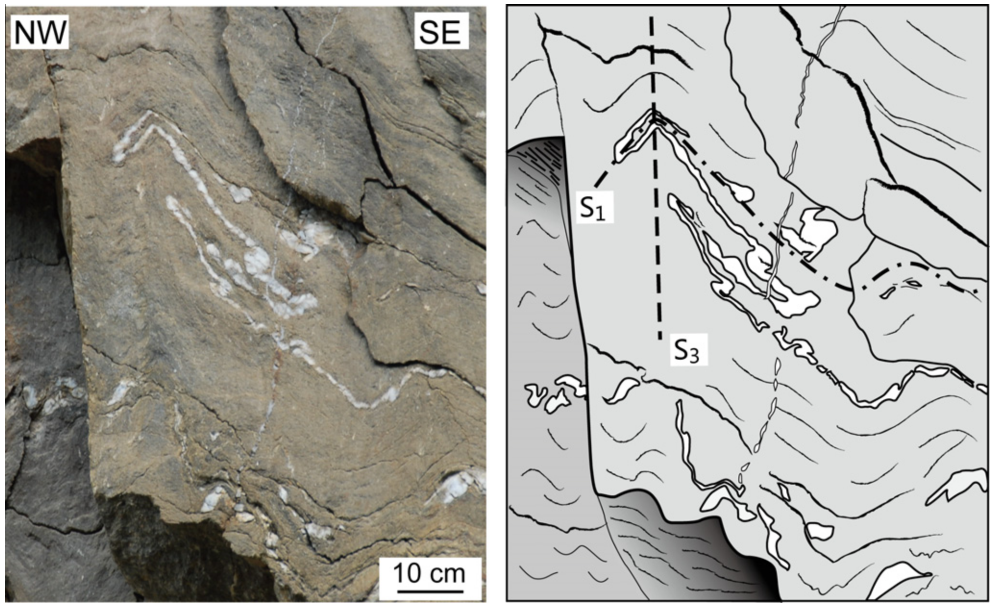

Fig. 16. Field picture and interpretation of D_1 isoclinal folds reworked by D_3 NW–SE trending upright folds and crenulation in biotite-garnet micaschist of the décollement, southeast of Lanrong (N26°14.743′/E110°25.979′).

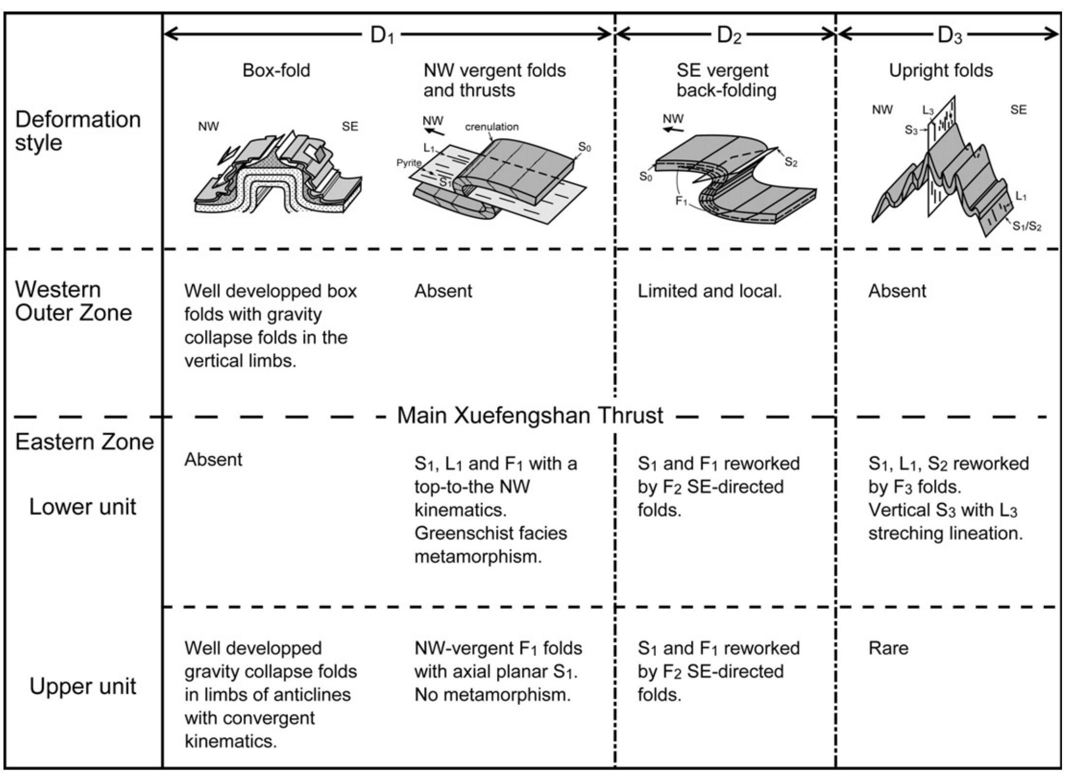

Fig. 17. Summary of the main deformation structures. D_1, D_2 and D_3 events recognized in the Western Outer Zone, the Eastern Zone and the Deep Metamorphic Unit of the Xuefengshan Belt.

Eastern Zone of the Xuefengshan Belt, induces an instability that will be removed by back-folding and back-thrusting as illustrated in the Alps and Himalaya (Escher and Beaumont, 1997; Godin et al., 1999). An alternative interpretation is the widespread Cretaceous extension with upwelling of the mantle that enhanced the readjustment of the thickened crust.

Superimpositions of S_1–S_2, S_2–S_3, and S_1–S_3 cleavages recognized in several areas of the Eastern zone argue for a relative timing of the polyphase deformation. However, the three episodes of deformation are not equally distributed in space. The D_2 and D_3 events are poorly developed in the Western Outer Zone, as illustrated in Fig. 17. As one possible reason, the westward decrease of the deformation intensity may play an important role in the development of deformation pattern. As a whole, the three deformation events correspond to the structural response of a bulk NW–SE shortening. The D_1 event characterized by top-to-the-NW asymmetric structures and a deep-seated ductile décollement zone with similar kinematics suggests that the formation of the Xuefengshan Belt is related to northwest directed crustal scale shearing.

4.2. Timing of the D_1, D_2, and D_3 events

As mentioned in Section 2.3, the Early Paleozoic event is restricted to the southeastern part of the Eastern Zone where the pre-Devonian structures are represented by south-verging folds (Fig. 4). Furthermore, both Early Paleozoic synmetamorphic deformation and crustal partial melting are absent in the Xuefengshan. As already demonstrated to the east of the Xuefengshan (e.g. Faure et al., 2009; Charvet et al., 2010), the Late Silurian-Early Devonian plutons that intrude the Early Paleozoic folded series are undeformed. Middle Devonian or younger rocks directly overlie the granitoids. It is hereby concluded that, in the Xuefengshan Belt, the post-solidus ductile deformation of the granitoids took place after the Early Paleozoic orogeny. Thus, the Xuefengshan Belt shows little evidence of the Early Paleozoic orogeny of SE China.

From Neoproterozoic to Early Triassic, the sedimentary rocks involved in the Xuefengshan Belt were deposited in a shallow sea environment except a short hiatus between Late Silurian and Early Devonian. But Middle Triassic strata are missing in the Xuefengshan Belt. The subsequent Late Triassic to Early Jurassic sedimentary series consists of clastic rocks conglomerate, sandstone and mudstone derived from the erosion of the Xuefengshan Belt. These Mesozoic deposits are post-orogenic products accumulated in small intramontane basins. In contrast to the pre-Middle Triassic strata that are all involved in folding and thrusting, Late Triassic-Early Jurassic strata show only limited brittle deformation (BGMRHN, 1988; Shu et al., 2009). At depth, the ductile deformation related to the décollement described in Section 3.4 involves mylonitized Early Paleozoic granitoids (BGMRHN, 1988; Zhou, 2007), and their Proterozoic country rocks. Thus, the ductile deformation along the D_1 décollement belongs to the Early Mesozoic event. Furthermore, the Triassic aluminous to peraluminous plutons, which intrude already deformed rocks are found widely distributed across the Xuefengshan Belt (Fig. 3b). These magmatic rocks, devoid of any ductile deformation, are dated between in 245–200 Ma (Ding et al., 2005; Chen et al., 2006, 2007a, 2007b; Wang et al., 2007a; Li and Li, 2007; Li et al., 2008). Newly obtained precise SIMS U–Pb dating indicates that the plutonic rocks of the Xuefengshan Belt are emplaced between 225 and 215 Ma (Chu et al., 2012). These lines of evidence indicate that the D_1, D_2 and D_3 events occurred after the Early Triassic, between 245 and 225 Ma. Although radiometric dating of the D_3 folding is not available, it appears rather reasonable to consider that the D_3 event that gave rise to the regional upright folds predated the granite emplacement, because the upright folding was formed due to locally compressional environment and provided room for the granite emplacement.

In the Xuefengshan Belt, the timing of box-folding in the Western Outer Zone is not well constrained. Thus, the eventuality that box-fold developed during the D_2 event cannot be excluded. Lastly, D_3 upright folding and vertical stretching accommodated the last stage of progressive shortening.

5. Discussion

5.1. Bulk architecture of the Xuefengshan Belt

The regional top-to-the-NW ductile shearing with folding and thrusting in the Xuefengshan Belt has been recognized by other geologists in spite of differences, as stated in Section 2, in the structural style, or the timing of the deformation (Qiu et al., 1998, 1999; Yan et al., 2003; Wang et al., 2005b). Moreover, the general interpretations proposed in these models are not in agreement with the structural features described above. According to our survey, from west to east, we subdivide the Xuefengshan Belt into several zones, which correspond to different deformation types (Figs. 3 and 17). Yan et al. (2003) considered that the Neoproterozoic rocks of the Wuling Mountain and Xuefeng Mountain form a klippe overthrust onto the in situ Paleozoic series. However, structures of the Xuefengshan Belt are not consistent with this interpretation. Indeed, thrusting of older rocks above younger ones can be locally observed. This feature is the consequence of collapse folds formed by gravity sliding along highly dipping layers (Faure et al., 1998). Thus evidence for long-distance thrust is not confirmed by our survey.

In the western part of the Eastern Zone, east of the MXT, cleavage is widespread in Neoproterozoic and Paleozoic strata, and exhibits a fan-like pattern, with a dip to the SE associated with NW-verging folds, whereas in the east, the syn-schistose folds verge to the SE and the cleavage dips NW (Figs. 8 and 11). Top-to-the-SE shearing indicated by folds and thrusts is interpreted as a back-folding or back-thrusting event. The large-scale inversion is well developed in Upper Sinian to Devonian sedimentary rocks where a back-folding boundary can be identified (BFB, Fig. 3b). Superimposed folding shows that SE-vergent folding post-dates the NW-vergent folding.

Two generations of folds with E–W trending and N–S trending hinge lines can be recognized from the regional geological map (BGMRHN, 1988). However, the former one is not documented by field observation. Some authors argue that the E–W trending anticlines are formed by the compression from the Qinling–Dabie orogeny and the Indosinian orogeny. Nonetheless, the dominant structures of the Xuefengshan Belt are produced by the top-to-the-W/NW compression.

In spite of the significant deformation during Early Mesozoic, across the whole belt, the structural relief is greatly modified by the subsequent Cretaceous extensional event in the South China block (Faure et al., 1996; Lin et al., 2000, 2008; Zhou et al., 2006; Shu et al., 2009; Zhu et al., 2010 and reference therein), and therefore the present geography cannot account for the topography of the Early Mesozoic Xuefengshan orogeny as the mountain range has been largely eroded. Similarly, according to our detailed field survey, the Early Paleozoic deformation is poorly registered in the Xuefengshan Belt, and consistent ductile shearing fabrics are widespread in both pre-Devonian and Devonian-Early Triassic rocks. Nevertheless, well preserved structures are all pointing to the Triassic orogeny.

East of the Chenzhou–Linwu fault (Fig. 3), well preserved Early Paleozoic structures are weakly reworked by the Triassic deformation. The Late Neoproterozoic to Ordovician, sedimentary series is deformed by E–W to NW–SE trending folds, with SW-vergence and a NE-dipping slaty cleavage. A ductile décollement that separates the folded sedimentary series from underlying metamorphic rocks is described in Jiangxi Province, east of the study area (Faure et al., 2009). Except in the Yunkai massif, which was strongly reworked during the Early Mesozoic (Lin et al., 2008), the Triassic ductile deformation is relatively weak in the SE part of SCB, and the Early Paleozoic ductile deformation is well preserved without Triassic modification (Li et al., 2010; Wang et al., 2012). Thus, this fault represents the eastern limit of the Early Mesozoic Xuefengshan Belt. To the east, several Triassic granitoids are sporadically distributed with a crust-derived signature, and contemporaneous volcanism is absent (BGMRJX, 1984; Chen and Jahn, 1998; Zhou et al., 2006). This observation is well consistent with other intracontinental belts, such as the Pyrenees, the Alice Springs and the Cenozoic Tianshan. Whereas the well developed intracontinental underthrusting or subduction is proved by seismic profiles, magmatism in the upper plate is absent (Tapponnier and Molnar, 1979; Roure et al., 1989; Choukroune, 1992; Sandiford et al., 2001). A likely explanation would be that the lower continental lithospheric plate is too dry and cold to generate magmatism in the short duration of subduction.

In the outer zones of collision belts (e.g. Alpine Jura or Zagros Fold-and-Thrust Belt), décollement zones develop in low strength rocks such as evaporites or black shales to accommodate the bulk regional shortening (e.g. Escher and Beaumont, 1997; McQuarrie, 2004). Below the décollement zone, basement rocks lack strong and pervasive deformation. In the Xuefengshan Belt, a major crustal décollement must be formed at the base of the Proterozoic to Early Triassic sedimentary series in order to accommodate the NW–SE shortening recorded by the D_1 event. The Early Neoproterozoic mudstone and siltstone series corresponds to this décollement zone (Fig. 2). In contrast, other weak layers of the sedimentary sequence are subordinate to the basal décollement. For example, in the Carboniferous limestone and mudstone alternations or Triassic thin-bedded limestone with minor mudstone layers, the pelitic component plays the role of a slip plane as a small scale décollement that generates fault-related folds which are localized in some specific layers (e.g. Figs. 9d and 13b). The bulk compression is hereby mostly accommodated in the basal high strain décollement. Due to the D_3 upright folding, a portion of this high strain discontinuity is exposed in the Chengbu area in the core of a D_3 antiform (Figs. 14 and 18), but the underlying basement is not observed in the Xuefengshan Belt. Thus, we argue that the MXT and other thrusts are rooted in a décollement zone. We interpret the upper crustal deformation responsible for thrusts, folds, and slaty cleavage as thin-skin tectonics underlain by a major décollement, rather than a thick skinned thrusting (Yan et al., 2003). However, a thick skin tectonic style involving the basement of the Eastern Zone cannot be ruled out since seismic data are not available.

A question arises about the eastern extension of the décollement. Two possibilities can be put forward. The simplest one is to assume a single décollement zone that deepens eastward up to the Chengzhou–Linwu fault. Such a structure will develop southeastward for more than 300 km that might be considered as unrealistic. Furthermore, in this case, the origin of the D_2 back folding in the Eastern Zone can be the result of SE-directed thrusting through the décollement (Fig. 18). Another possibility would be to consider that the décollement deepens eastward below the Eastern Zone. In this interpretation, the east of the Eastern Zone would be underlain by a second décollement. Such a geometric pattern may account for the development of the D_2 back folding and back-thrusting that would be rooted within the décollement. Whatever the right interpretation, the intracontinental Xuefengshan Belt is clearly underlain by a high strain layer that separates the upper crustal rocks that deformed by thrusting and folding and the middle to lower crustal rocks that are not exposed. This hidden basement corresponds to a piece of the SCB. In order to accommodate the shortening experienced by the Late Neoproterozoic (Sinian) to Early Triassic sedimentary series, the underlying basement must have experienced intracontinental underthrusting during the Triassic. Since the Triassic deformation is weak east of the Chenzhou–Linwu fault, this fault that represents the eastern tectonic boundary of the Xuefengshan Belt can be interpreted as a back-stop.

5.2. Tectonic implications for the SCB

During the Early Triassic, the SCB underwent several orogenic events along its boundaries. To the north, the SCB subducted beneath the North China Craton (Hacker and Wang, 1995; Faure et al., 1999, Faure et al., 20082008); to the west, the Songpan-Ganzi and Longmenshan Belts record evidence for Triassic deformation (Wallis et al., 2003; Harrowfield and Wilson, 2005; Roger et al., 2008, 2010), and to the southwest, the Ailaoshan-Song Ma Belt separates the SCB from Indochina (Lepvrier et al., 2008, 2011; Carter et al., 2001; Carter and Clift, 2008). The major structural lines of the Xuefengshan Belt are perpendicular to the Qinling–Dabie and North Vietnamese orogens that indicates that the Xuefengshan cannot be simply correlated to these orogens. The influence of these two orogens are limited to the peripheral areas of the South China block with tens-of-kilometers fold and thrust belt towards the inland, while the internal part is dominated by top-to-the-NW shearing and thrusting. The Xuefengshan Belt has been interpreted as the result of the westward progressive collision of the Yangtze Block with the North China Block during the Late Jurassic to Cretaceous (Yan et al., 2003), but the Middle Triassic event, which is clearly postdated by the Late Triassic plutons and the regional Late Triassic unconformity, is not distinguished from the Cretaceous one. Other authors proposed that this belt is the western part of an Early Mesozoic oblique convergent zone, formed due to compression by the more rigid North China and Indochina blocks with a bi-vergent structure, (Chen, 1999; Wang et al., 2005b, 2007c). However, the top-to-the-SE structures in the southeastern part of the SCB are assigned to a Middle Triassic to Late Jurassic event (Chen, 1999), while the Xuefengshan Belt is formed in Middle Triassic.

Recently, the South China fold belt was interpreted as a 1300-km wide intracontinental orogen (Li and Li, 2007). The

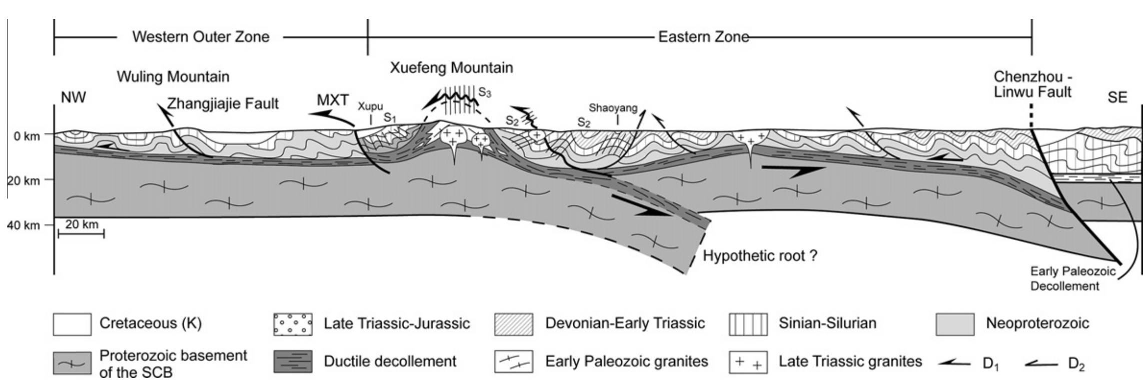

Fig. 18. Interpretative bulk cross-sections of the Xuefengshan Belt (located in Fig. 3): The Triassic décollement, observed in the core of the D_3 anticlines, separates the upper crust deformed by NW-directed folding and thrusting, and the middle-lower crust deepening to the SE. The Xuefengshan Belt is intruded by late Triassic peraluminous granitic plutons. SE of Shaoyang, the pre-Devonian series are folded by S-verging folds, but these folds parallel to the line of section are not represented. East of the Chenzhou–Linwu fault, the Triassic deformation is weak. The main structure developed during the Early Paleozoic orogeny corresponds to S or SE-verging folds underlain by a décollement (cf. Faure et al., 2009).

temporally and geographically restricted Late Triassic terrestrial or lacustrine basins represent post-orogenic deposits, and the Early Triassic marine limestone strata of Hunan and Jiangxi provinces both indicate similar platform depositional environment (BGMRJX, 1984; BGMRHN, 1988). However, at the scale of the SCB, the radiometric ages of the Triassic plutons, ranging from 250 Ma to 210 Ma, are randomly distributed (Ding et al., 2005; Chen et al., 2006, 2007a, 2007b; Wang et al., 2007a; Li and Li, 2007; Li et al., 2008). These granitic plutons do not show a magmatic trend younging from SE to NW that might be related to the progressive flat-slab subduction of the Pacific plate as proposed by Li and Li (2007).

Although some authors suggest that west-directed subduction did not start until ~125 Ma (Engebretson et al., 1985), Triassic NW-directed subduction is preferable, as suggested not only by Permian arc magmatism in Hainan Island to the south, but also by Early-Middle Triassic high pressure blueschist facies metamorphism of an Ar–Ar age at ~245 Ma in the Japanese islands (Faure and Charvet, 1987; Faure et al., 1988; Li et al., 2006). Therefore, it is likely that the Paleo-Pacific subduction was ongoing during Early Mesozoic, and probably started in Late Permian. According to our study, the Xuefengshan Belt was not generated until Early Mesozoic west of the Chenzhou–Linwu fault that represents the potential weak zone. Moreover, in the southeastern margin of the South China block, compressional deformation is recorded since Middle Triassic, with a delay of ca. 20 My to the arc-related magmatism (Chen, 1999), and Late Permian to Early Triassic plutons are interpreted as A-type granites emplaced in a transtensional setting (Wang et al., 2005a). Thus it is inferred that a transition from extension to compression occurred in Early Triassic, probably on account of the shallowing of the subducted plate angle. Consequently, in the center of the South China block, the Xuefengshan orogeny took place during Middle to Late Triassic. However, the over-1300 km flat-slab subduction is not supported as the Early Mesozoic deformation occurred simultaneously in center (the Xuefengshan Belt), and the southeastern margin of the SCB, rather than a propagating orogeny. Although still speculative, in the present state of knowledge of the SCB geology, the far-field effect of the Paleo-Pacific subduction model accounts well for the structural features described in this paper, and the overall tectonic evolution of the Xuefengshan Belt.

5.3. Insights for intracontinental orogenic belts

In the past 20 years, numerous intracontinental orogens have been studied by multidisciplinary approaches (Hendrix et al., 1992; Avouac et al., 1993; Choukroune, 1992; Hand and Sandiford, 1999; Sandiford et al., 2001; English and Johnston, 2004; Faure et al., 2009; Charvet et al., 2010 and enclosed references). In East Asia, several intracontinental belts have been reported, such as the Cenozoic Chinese Tianshan (Tapponnier and Molnar, 1979; Avouac et al., 1993), the Yanshan–Yinshan belt (Davis et al., 1998; Darby et al., 2001), and the Early Paleozoic South China belt (Faure et al., 2009; Charvet et al., 2010; Li et al., 2010). Comparable to the Xuefengshan Belt, high-grade metamorphic rocks of a Cenozoic age are poorly outcropped or even absent in the Cenozoic Tianshan Belt, while the exposed basement rocks are Paleozoic orogenic products overprinted by Cenozoic brittle deformation (Avouac et al., 1993; and reference therein). The Yanshan–Yinshan intracontinental belt, however, demonstrates an Archean unit-involved thin-skinned fold-and-thrust system above a low angle main thrust fault (Davis et al., 1998, 2001; Darby et al., 2001; Darby and Ritts, 2007). In this belt, the Precambrian rocks are often overlain directly by Jurassic to Cretaceous sedimentary formations, lacking the entire Paleozoic sequence. The Early Paleozoic South China belt is analogous to the Xuefengshan Belt with a basal décollement, except that the late orogenic events exhumed the high-grade metamorphic rocks (e. g. Faure et al., 2009). However, in the Xuefengshan Belt, based on the absence of middle-lower crustal rocks, we propose a thin-skinned model that lower crust was consumed by underthrusting along the Chenzhou–Linwu Fault without migmatite or eclogite exhumed to the surface.

To the contrary, in the Alice Springs and the Pyrenees belts, for example, deep crustal or lithospheric structures are revealed by seismic profiles. These typical intracontinental belts are characterized by thick-skinned tectonics, induced by remarkable crustal displacement or continental subduction (Goleby et al., 1989; Choukroune, 1992). However, the Xuefengshan Belt is a particular chain with a more than 10-km-thick sedimentary cover and a regional high-strain décollement zone but no exposure of high-grade metamorphic rocks. Thus a thin-skinned tectonic evolution is preferred here. Among the intracontinental belts, the Early Paleozoic South China belt and the Yanshan–Yinshan belt both suggest a thin-skinned structure by basal thrust faulting. Nevertheless, without detailed seismic data, the deep structure of the Xuefengshan is not well constrained, and thereby a thick-skinned model cannot be completely ruled out.

As a regional back-stop boundary for the Xuefengshan Belt, the Chenzhou–Linwu fault played an important role in the Early Mesozoic tectonics. This fault is also considered to be the potential suture zone between the Yangtze block and the Cathaysia block during the Neoproterozoic collision (Wang et al., 2007c).

Furthermore, in intracontinental tectonics, an internal weak zone is the place to localize the deformation induced by the compressional stress developed in response to subduction or collision at plate margins, and thereby triggers an intracontinental deformation. In the Pyrenees orogen, the most intense Cenozoic deformation was accommodated within the pre-orogenic continental rifts basins opened during the Cretaceous (Choukroune, 1992). The Alice Springs orogen is a reactivated Paleozoic belt superimposed upon the Neoproterozoic-Early Paleozoic Petermann orogen (Hand and Sandiford, 1999; Sandiford et al., 2001). The Late Paleozoic Tianshan orogen was compressed and uplifted again during the Cenozoic, due to the Indo-Asia collision (Hendrix et al., 1992; Avouac et al., 1993). Therefore, the weak zone along which an intracontinental belt will develop is a pre-existing crustal weak zone such as a rift, or a regional fault zone formed during an older orogeny, along which the continental crust has been rheologically softened. In our case, the Jiangshan–Shaoxing Fault, which is the northern part of the Chenzhou–Linwu Fault, was reworked during the Early Paleozoic orogeny, suggesting a weak zone in the South China block. During the Late Paleozoic, a continuous marine sedimentation was recorded in the South China block, and in some places, the thickness of sedimentary rocks approaches to 10–12 km. As the load increases, the geotherm and temperature facilitate the weakening of the previous weak zone. We thereby infer that the Early Mesozoic Xuefengshan Belt was an intracontinental belt developed as a result of the reactivation of the Neoproterozoic Chenzhou–Linwu fault.

The geodynamic cause of intracontinental orogens is still a matter of debate. Far-field effects of either remote flat-slab subduction or continental collision are the favored interpretations (e.g. Dickinson and Snyder, 1978; Avouac et al., 1993; English and Johnston, 2004). Nevertheless, a peripheral compressional stress perpendicular to the orogenic belt is a prerequisite to the formation of an intracontinental orogen, no matter this push is originated from subduction, collision, or ocean ridge extension.

6. Conclusion

Our new structural data, combined with previous works, allow us to establish the following statements.

1. The Xuefengshan Belt can be divided into two tectonic zones. (1) The Western Outer Zone is characterized by box-fold structures with gravity collapse folds and layer slip in the fold hinges; and (2) The Eastern Zone represents the most complex domain in which ductile deformation is coeval with weak greenschist facies metamorphism. NW-directed thrust and folds associated with a pervasive axial planar slaty cleavage are reworked by two superimposed deformation events. The folded Neoproterozoic to Early Triassic sedimentary series is never overthrust by old basement rocks.
2. The bulk architecture of the whole belt results from polyphase deformation. The D_1 event, characterized by a top-to-the-NW ductile shearing, is responsible for the main structure of the Xuefengshan Belt. The D_2 event, observed in the Eastern Zone, corresponds to a back-folding and back-thrusting stage with NW-dipping cleavage. The deformed rocks belong to the upper continental crust, which is underlain by a ductile décollement zone that can be observed in a few places due to the granite emplacement. As a whole, the Xuefengshan Belt is the result of a NW–SE shortening that involved the entire Early Triassic to Late Neoproterozoic sedimentary upper crust of the SCB. The Proterozoic basement of the SCB is not involved in the bulk structure of the Xuefengshan Belt.
3. The main deformation of the Xuefengshan Belt began after the Early Triassic and was completed before the deposition of the Late Triassic continental to lacustrine terrigeneous deposits, and also before the emplacement of the Late Triassic peraluminous granitic plutons. The deformation lasted around 20 Ma, from 245 Ma to 225 Ma.
4. The geodynamic setting of the Xuefengshan Belt remains speculative. In spite of lack of reliable geophysical data on its deep crustal structure, the Xuefengshan Belt is interpreted as an Early Mesozoic intracontinental orogen, in which southeastward underthrusting of the SCB accommodated the folding and thrusting of the upper crustal sedimentary rocks. This Middle Triassic orogen possibly originated as a far-field effect of the northwestward Pacific subduction below the SCB.

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