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Emplacement age and tectonic implications of the brecciated limestone at the edge of the Longmenshan klippe

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Abstract The Longmenshan thrust belt (LMTB) is one of the best natural laboratories for thin-skinned tectonics and has developed a series of NE-SW trending fold-and-thrust structures represented by a series of nappes and klippes, exemplified by the Tangbazi and Bailuding klippe. However, the timing and emplacement mechanism of these klippes are still in dispute. Three possible mechanisms have been proposed: (1) a Mesozoic-Cenozoic southeastward thrusting, (2) a Cenozoic gravity gliding, and (3) glacial deposition. Almost all of these klippes are tectonic and overlaid on folded Late Triassic sandstone except the Tangbazi klippe, which is located in the center of the LMTB and has a narrow tail extending southeastward and covering Jurassic-Quaternary rocks. This geometric relationship is considered the most important stratigraphic evidence to support the post-Cenozoic emplacement of the Longmenshan klippe. Our structural and petrological observations show that the rocks at the front of the Tangbazi and Bailuding structures are brecciated limestone, which is assumed to have been generated by a gravitational collapse and is not characteristic of the massive Permian strata. *Artemisia* pollen, which has been exclusively recognized in post-Late Eocene strata in Central Asia, was found in the matrix of this brecciated limestone. Therefore, our discovery indicates that the brecciated limestone was deposited after the Late Eocene rather than during the Permian as annotated on the geological map. In contrast, unbrecciated, massive Permian limestone overlaid on the folded Late Triassic rocks. Hence, the anomalous relationship of Permian strata overlaying Late Triassic rocks cannot be evidence of Cenozoic emplacement. According to currently recognized bulk strata relationships, we can only be sure that the klippe was emplaced in the post Late Triassic. The petrological characteristics of the brecciated limestone show that it was crumbled before the re-sedimentation of the breccia, implying that the LMTB might have experienced a rapid uplift during the Late Eocene.

Keywords Longmenshan thrust belt, Klippe, *Artemisia*, Brecciated limestone, Thin-skinned structure

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1. Introduction

As typical representations of a thin-skinned structure, klippes have gained much attention from structural geologists all over the world. The LMTB is an important geological boundary that separates the greatly deformed and metamorphosed rocks of the Songpan-Ganzi Fold belt to the NW from the relatively few deformed sediments in the Sichuan Basin (Figure 1). Since the devastating earthquake that occurred in Wenchuan and Lushan, Longmen Mountains has drawn even more interest from researchers. The LMTB has developed a series of NE-SW trending fold-and-thrust structures represented by a series of nappes and klippes, which is

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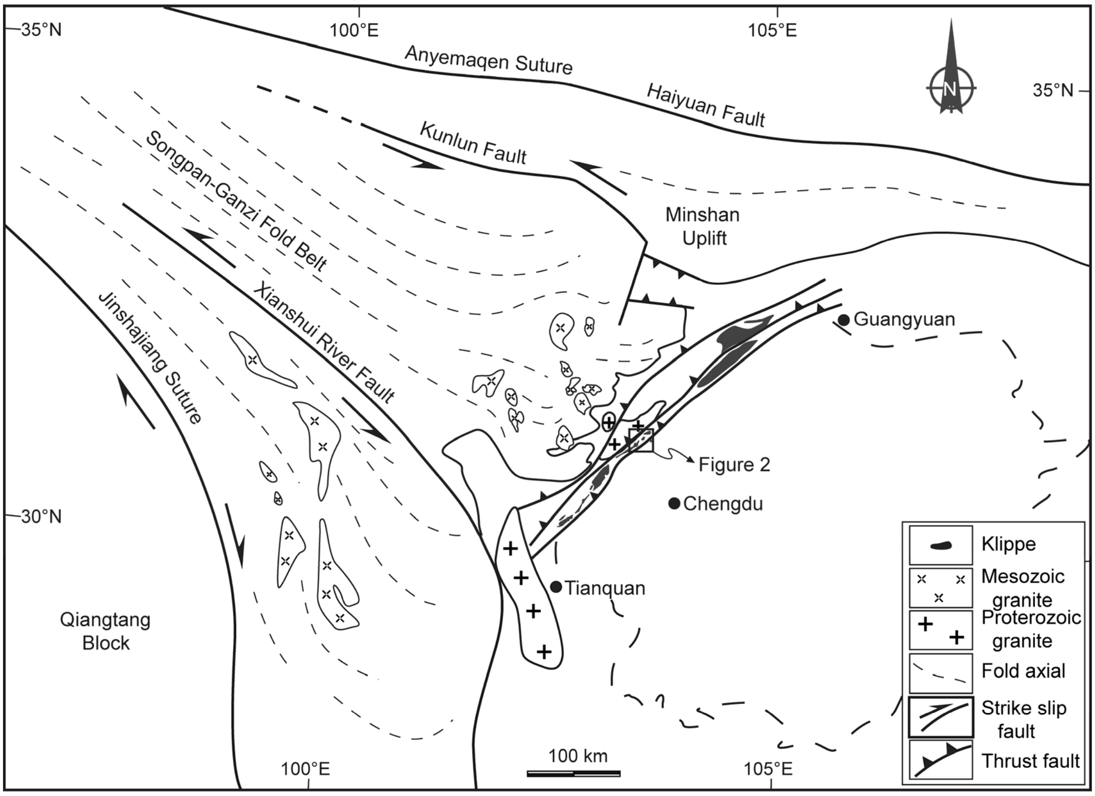

Figure 1 Simplified regional geological map of Longmen Mountains (modified after Harrowfield and Wilson, 2005).

the best natural laboratory for thin-skinned tectonics. Dozens of klippes are distributed in the center section of LMTB, such as the Jianfengding, Dayudong, Tiantaishan, Tangbazi (Shi, 1994)(Figure 2). These thrusts have important significance for the tectonic evolution of the southeast Yangtze Block and the uplift process of the Tibetan Plateau. The timing of the emplacement of these klippes is very important; it would greatly contribute to the elucidation of the emplacement mechanism and might even allow an explanation of the uplift process of the Longmen Mountains and the whole Tibetan Plateau. However, the timing and emplacement mechanism of these klippes are still in dispute. Almost all geometry, kinematic and geochronological analysis suggest a Mesozoic thrusting mechanism of these klippes (Xu et al., 1992; Burchfiel et al., 1995; Chen and Wilson, 1996; Zheng et al., 2014) except a special strata stack relationship in the center of the LMTB that suggest a Cenozoic thrusting mechanism (Yan et al., 2011), gravity gliding mechanism (Meng et al., 2006) or glacial deposition (Han et al., 1994, 1999; Zhou and Ruan, 2006). The special strata stack relationship, a narrow tail belongs to the Tangbazi klippe extending southeastward and covering Jurassic-Quaternary rocks (Figure 2), bring many confusions to unravel the real thrust sequences of the LMTB. The Bailuding klippe, the Tangbazi klippe and the Gexianshan klippe, located in the center of Longmen Mountains, are considered as typical klippes in the area, and provide a perfect location to research their timing and emplacement mechanism as well as the uplift scenario of the entire LMTB.

2. Regional geological setting and research status

The LMTB originates in Guangyuan and merges with the Micang Mountians to the northeast, ends at Tianquan and is truncated by the Xianshui River Fault to the southwest. The LMTB is about 500 km long and 35–50 km wide and regionally composed of three faults that strike northeast and steeply dip to the northwest (Figure 1). A continuous southward (Yan et al., 2011) or southeastward thrust since the Late Triassic (Luo, 1991; Xu et al., 1992; Chen et al., 1994a) and extensive uplifting induced by the collision of the Eurasian and the Indian plates during the Cenozoic formed the highest mountains and caused the landscape to exhibit greater relief than anywhere else on the Tibetan Plateau (Clark and Royden, 2000; Kirby et al., 2002; Hubbard and Shaw, 2009). Field observations have shown that both overturned folds and thrusts intra nappes and klippes consistently demonstrated a southeastward thrust (Burchfiel et al., 1995; Xu et al., 1992; Jia et al., 2006). Seismic data further revealed that the collision of Eurasian and Indian plates during the Cenozoic resulted in different deformation characteristics along the LMTB (Jia et al., 2003, 2006).

The klippes and nappes along the LMTB are mainly composed of Devonian to Early Triassic strata and each klippe has different types of strata (Figure 2). The Tangbazi and

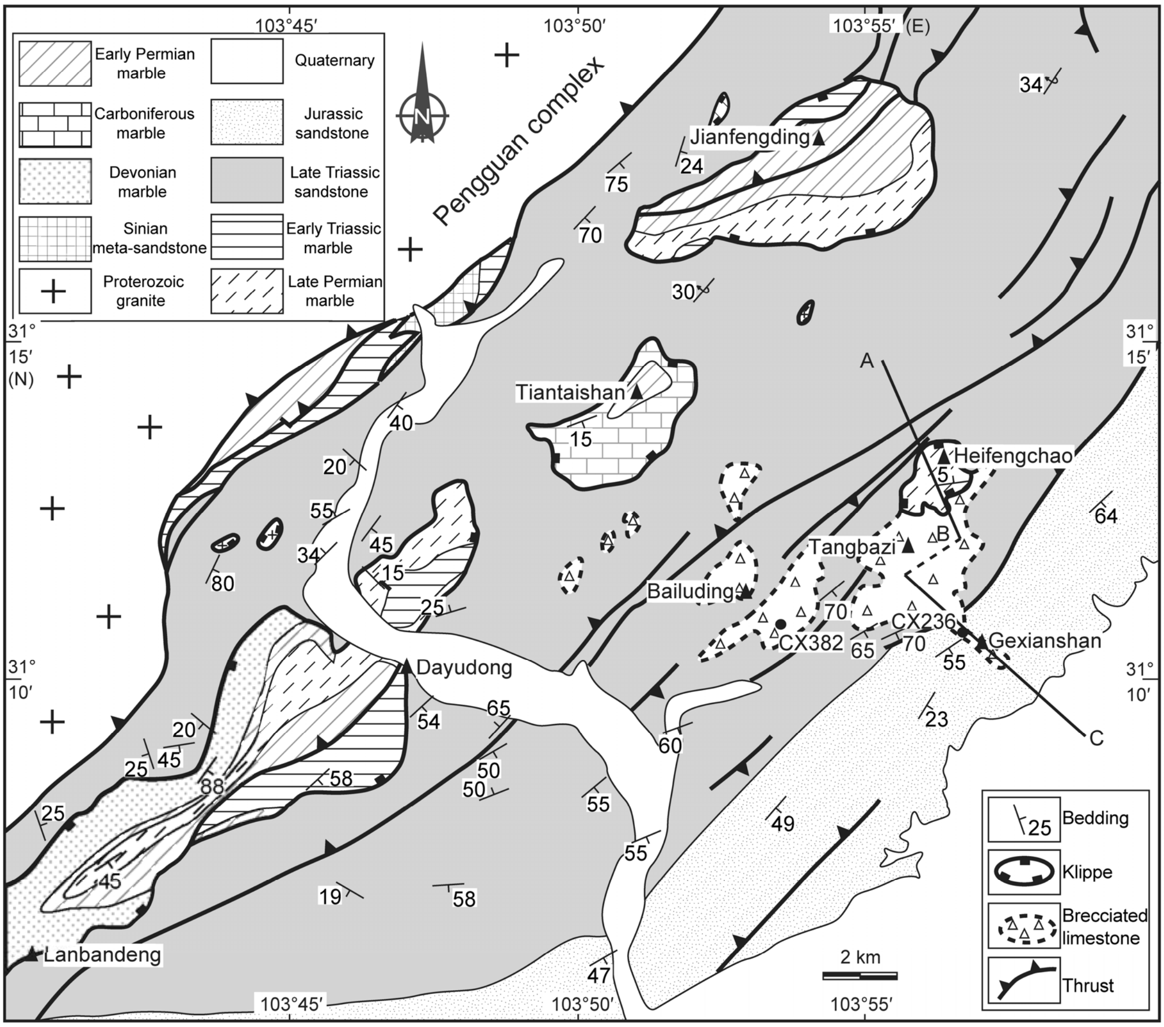

Figure 2 Geological map of the Pengguan klippes (modified after Regional 1∶200000 Geological Map of Guanxian, 1976).

Gexianshan klippe are mainly composed of Permian light grey medium-thickness massive limestone and dolomitic limestone and contain micro-fossils such as Fusulinid, Brachiopoda, Bryozoa. Further west, the Dayudong and Jianfengding klippe contain different tiny Early Triassic strata, and its biostratigraphic age has been determined by Lamellibranchia such as *Claraia* (BGMRSP, 1991)(Figure 2).

The timing of these klippes is still in dispute (Xu et al., 1992; Burchfiel et al., 1995; Meng et al., 2006). Traditionally, a Mesozoic thrust model has been proposed, based on following evidence: (1) the newest strata involving in the thrust belt is a Late Triassic Xujiahe Formation (Xu et al., 1992; Dirks et al., 1994; Chen and Wilson, 1996; Worley and Wilson, 1996); (2) the sedimentary environment confirmed that the Xujiahe Formation belongs to a typical foreland basin (Chen et al., 1994b; Li et al., 2003); (3) the results of ^{39}Ar/^{40}Ar dating of the newly formed mica and U/Pb dating of the syn-tectonic granite zircon in Longmen Mountains area are exclusively 153–232 Ma (Zhou et al., 2002; Huang et al., 2003; Yan et al., 2008, 2011; Lu et al., 2010); (4) isotopic dating of authigenic illite isolated from the bottom boundary fault of the largest Baishi-Goujia klippe combined with zircon fission track dating of the hanging wall of the Yingxiu-Beichuan fault zone that constrained the emplacement age of the Longmenshan klippe between 171 and 180 Ma (Zheng et al., 2014); (5) regional unconformity between extensively folded Late Triassic strata and relatively weak deformed Jurassic strata exists in the center and north segment of the LMTB (BGMRSP, 1991; Xu et al., 1992; Burchfiel et al., 1995; Chen and Wilson, 1996; Jia et al., 2006); (6) both overturned fold and layer-parallel slip in each klippe and nappe consistently exhibit top-to-SE movement (Xu et al., 1992; Chen and Wilson, 1996; Burchfiel et al., 1995; Jia et al., 2006; Yan et al., 2011), and (7) the thermal characteristics revealed by Raman spectroscopy of carbonaceous material just beneath the klippe indicate a temperature greater than 400°C, suggesting that the klippes have a tectonic origin (Robert et al., 2010). In addition, the LMTB lacks a typical Cenozoic foreland basin and a massive Cenozoic deformation record

(Xu et al., 1992; Burchfiel et al., 1995). Most of the klippes, such as the Tiantaishan klippe, the Jianfengding klippe and the Dayudong klippe, occur on folded Late Triassic strata (Figure 2). Taken together, the evidence cited above strongly suggests that the emplacement of the Longmenshan klippes are intrinsically related to an extensive regional thrust.

The Tangbazi-Gexianshan klippe is composed of Permian limestone, which forms a long narrow tail extending eastward and sits on Upper Jurassic strata overlaying continuous Cretaceous-Eocene sequences (Figures 2 and 3). This phenomenon clearly shows that the klippe must have been emplaced post-Eocene, which is the foundation that supports the argument that the entire klippe belt in Longmen Mountains was formed during the Cenozoic (Bian, 1980; Li, 1989; He, 1992; Shi, 1994; Han et al., 1994, 1999; Burchfiel et al., 1995; Meng et al., 2006; Jia et al., 2006; Han, 2006; Han et al., 2008, 2009; Zhou, 2006; Zhou and Ruan, 2006). Actually, Bian et al. (1980) first reported this special "tail"; their field observations and detailed structural analysis almost demonstrated the Indosinian (Triassic) deformation in LMTB, except for this strange "tail". Finally, they proposed a Cenozoic modification to explain the reason for this unusual strata. Burchfiel et al. (1995) claimed that the main deformation period of the LMTB occurred between Late Triassic to the Jurassic, giving the same reasons as Bian (1980), a partial reactivation during the Cenozoic. The narrow "tail" of Gexianshan is a suite of brecciated limestone (Shi, 1994; Han et al., 1994, 1999; Burchfiel et al., 1995; Meng et al., 2006). Shi (1994) suggested this brecciated limestone was formed by a southeastward gravitational slip induced by a large gravitational gradient (because of the extreme altitude on the margin of the Tibetan Plateau). A combined strain variation from the extension in the rear to a contraction in the leading edge of the klippe has led to the proposal of a gravity-driven generation during the Cenozoic (Wu and Lin, 1991; Wu et al., 1999; Han et al., 1994, 1999; Shi, 1994; Meng et al., 2006). Other researchers think that the characteristics of the brecciated limestone in Gexianshan are approximately similar to glacial erratic boulders and they think that the Longmenshan klippe is the result of glaciation in Tibetan Plateau during the Pleistocene (Han et al., 1994, 1999; Zhou, 2006; Zhou and Ruan, 2006).

In summary, the composition, timing and mechanism of the Gexianshan narrow "tail" are of vital importance to explain the timing and the emplacement mechanism of the Longmenshan klippe. In order to clarify these issues, detailed field observations, petrological and paleontological analyses have been done.

3. Petrological characteristics

Field observations show that the leading edge of Tangbazi and Bailuding "klippe" is completely brecciated limestone and the diameter of the breccia ranges from 0.5 to 15 cm (Figure 4(a), (b)). Some of the breccia are lightly rounded while the majority have a conserved angular shape (Figure 4(a), (b)). Although the shallow ground allowed extensive weathering, several outcrops could be seen and fresh breccia was common. All of the brecciated limestone is uniform and devoid of any sign of a stack rhythm or layer characteristics. Especially in a cross-section from a cement quarry near the Biluding "klippe", similar brecciated limestone was evident everywhere (Figure 4(a)). The breccia is completely angular and relatively depth of color than the agglutinate. Both the breccia and agglutinate are composed of pure limestone plus a minor pelitic component; however, impurities cannot be recognized with the naked eye.

Samples collected from the leading edge of the Tangbazi and Biluding klippe were designated as CX236 and CX382, respectively (Figure 2). Thin sections were made from these two samples and observed under a polarization microscope. A characteristic high white interference color could be recognized under Crossed Polarized Light (CPL). The breccia was mainly composed of bioplastic limestone and partially composed of micro-crystal and dolomitic limestone. The

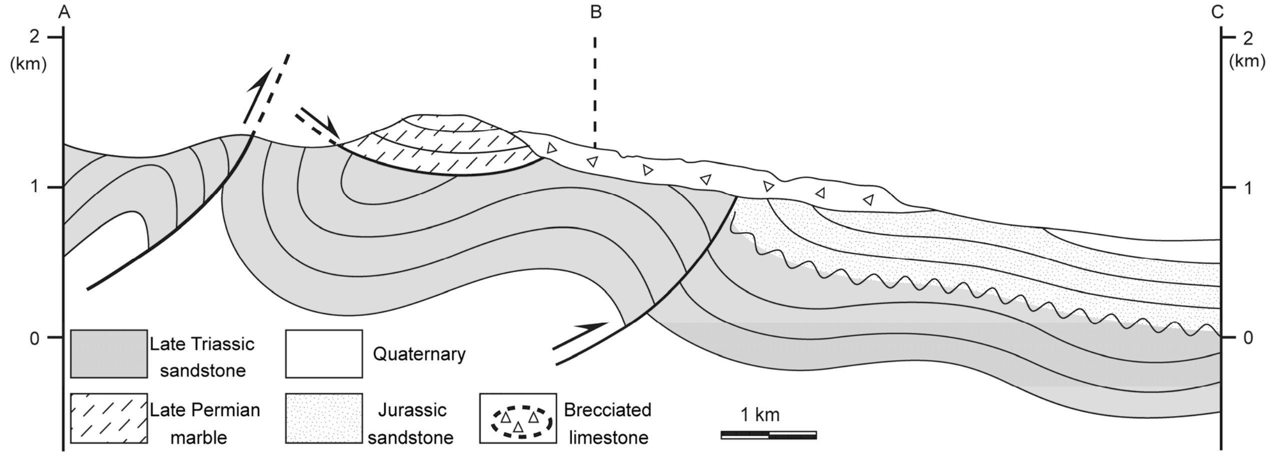

Figure 3 Cross-section of the Tangbazi area. The location is shown in Figure 2.

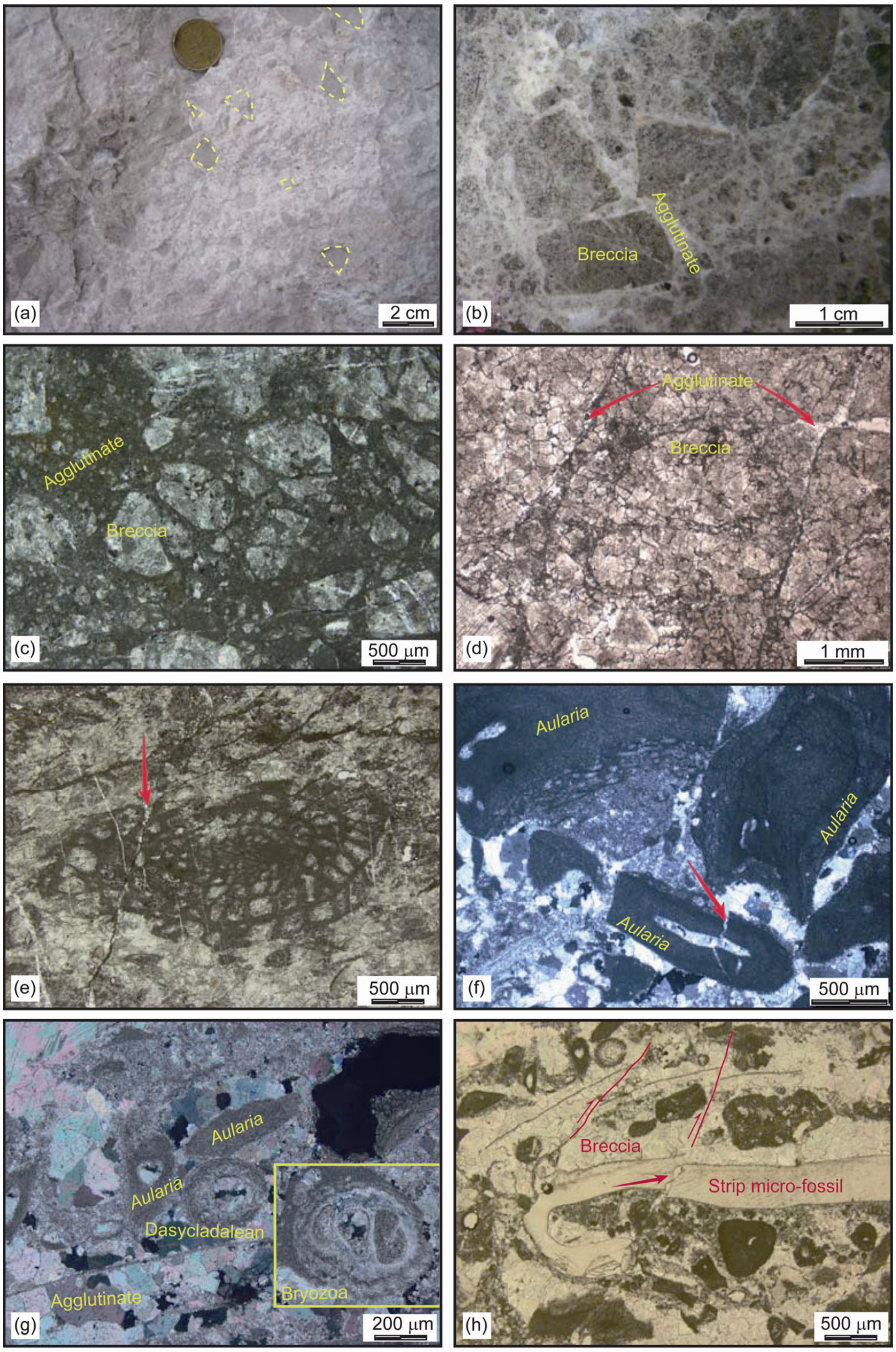

Figure 4 Photographs of the crumbled breccia. (a) Field photograph of CX382 breccia; (b) field photograph of CX236 breccia; (c) micrograph of CX236, CPL; (d) micrograph of CX382, PPL; (e) Fusulinid in the breccia of CX236 with micron fracture (marked with red arrow), PPL; (f) *Aularia* in the breccia of CX236 with micron extension fracture (marked with red arrow), CPL; (g) Bryozoa and Dasycladalean in the breccia of CX236, CPL; (h) strip micro-fossil in the breccia of CX236 with zigzag fracture (marked with red arrow), PPL.

agglutinate was mainly calcareous with a tiny pelitic component (Figure 4(c)). Numerous micro-paleontological fossils had developed in the CX236 breccia, such as Fusulinid (Figure 4(e)), *Aularia* (Figure 4(f), (g)), Bryozoa (Figure 4(g)), Dasycladalean (Figure 4(g)) and a long strip micro-fossil (Figure 4(h)), which confirmed the protolith of the breccia was classified as a typical bioplastic limestone; the fossil assemblage and characteristics indicate that the protolith breccia is from the Upper Permian Changxing stage or Wujiaping stage (Yang, 1988; Sha et al., 1990; BGMRSP, 1991). Some Fusulinid and *Aularia* evidence micro-cracks with no evident relative displacement from filling carbonates (Figure 4(e), (f)). A strip micro-fossil had a tiny crack with a displacement of approximately tens of microns and the fracture had a zigzag shape (Figure 4(h)). The fossil in the breccia was nearly preserved in its original sedimentary status with no sign of any ductile deformation or evident displacement (Figure 4(e), (f), (h)). No micro-fossils were found in thin sections of CX382 and its optical characteristics suggest dolomitic limestone properties (Figure 4(d)). Both the optical characteristics of the breccia and the fossil abundance in the breccia definitely indicate that CX236 and CX382 are different, which indicates that the protoliths of these two breccias belong to strata from different ages. The protolith of the breccia of CX382 is composed of dolomitic limestone without any fossils and might indicate Early Triassic strata in the Longmen Mountains area (Sha et al., 1990).

4. Pollen analysis

The timing and mechanism of the generation of the brecciated limestone are of vital importance in understanding the timing and the emplacement mechanism of the Longmenshan klippe. In order to identify its actual age, we extracted pollen from the samples CX236 and CX382 (the sample locations are shown in Figure 2). In order to avoid pollution from modern pollen, all brecciated limestones were sampled from the inner core of a cement quarry.

4.1 Pollen extraction and identification

The brecciated limestone was smashed to pieces with a hammer, sifted (diameter of 0.45 μm), and the 100 g of powder that passed through the sifter was collected. Lycopodium spore tablets (27637 grains) were added to the samples to facilitate pollen concentration calculations. To improve the sample clarity, the samples were treated with hydrofluoric acid (Moore et al., 1991) and the residues were further concentrated by centrifugation. The pollen residues were suspended in glycerol. A Leica DM 4000 B microscope at ×400 was used to count pollen grains.

Samples CX236 and CX382 contained the same species of pollen, varying only in diversity and quantity. Three principal types of pollen were recognized: *Artemisia*, Moraceae, and Chenopodiaceae. *Artemisia* has short spines on its thick-walled cypselasis, nearly rounded with three colporates (Figure 5(a)–(c)) and the colporates gradually narrow toward the poles (Figure 5(b)). Moraceae are nearly rounded or elliptical with an average size of 25.5 μm×28 μm and contain 3 to 4 colporates (Figure 5(d), (e)). The grains usually appeared on the cypesela and a bit beyond the pollen outline (Figure 5(d)). Chenopodiaceae is rounded or

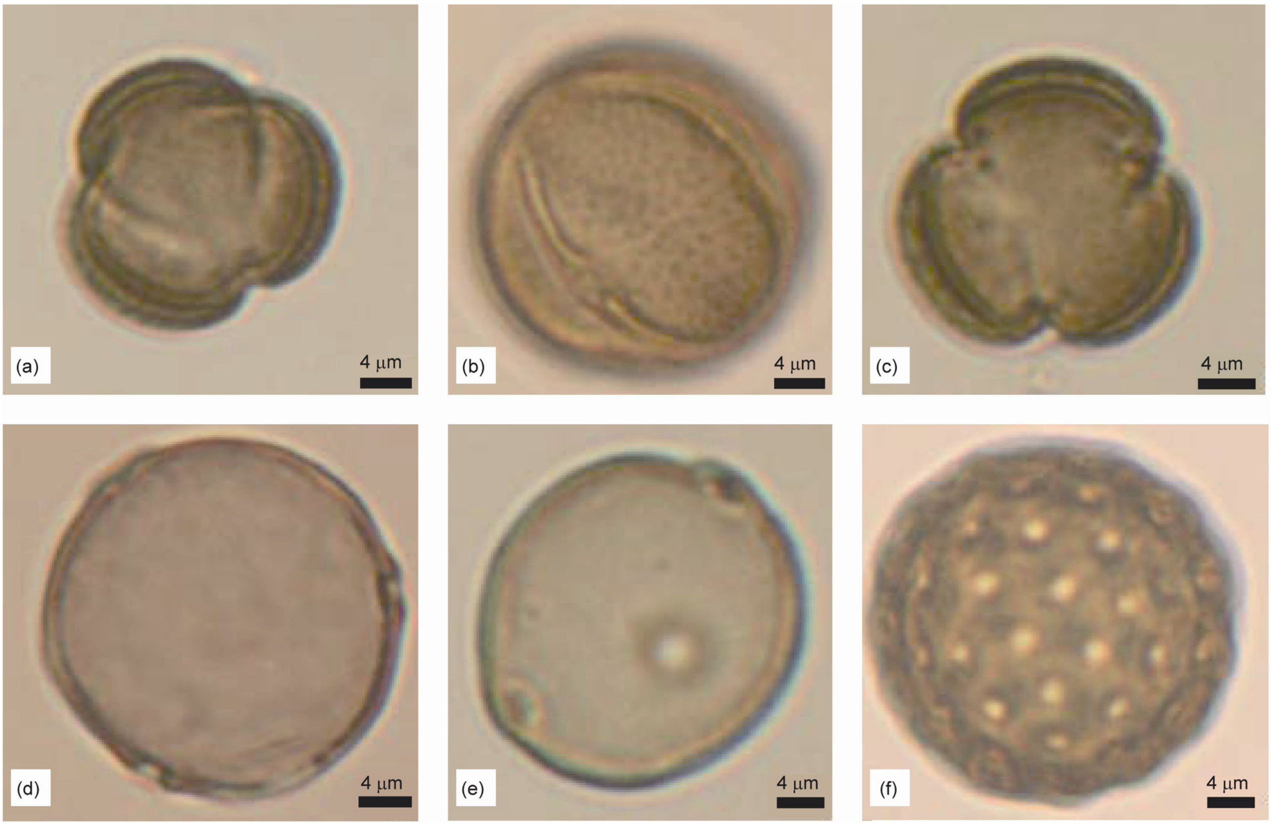

Figure 5 Photographs of pollen extracted from the crumbled breccia. (a) Side view of *Artemisia*; (b) equatorial view of *Artemisia*; (c) polar view of *Artemisia*; (d) polar view of Chenopodiaceae; (e) equatorial view of Chenopodiaceae; (f) Moraceae.

semi-rounded with a diameter between 12 and 30 μm. Approximately 16–90 holes are well distributed on its thin and transparent cypesela; the outline of this pollen has a wave-like contour. Measurements of these three pollen grains obtained by detailed microscopic counting at a 400 magnification and equal proportion calculation are shown in Figure 6.

4.2 Results

The columns in Figure 6 show that the maximum grains of *Artemisia* in CX236 and CX382 were greater than 1000 and 4000, respectively, which is sufficient to prove that the pollen was contained in the brecciated limestone. The pollen was colored and uniform, which is completely different from the modern pollen (Sun et al., 1997). The similarity of the pollen status in CX236 and CX382 allows the further conclusion that the vegetal assemblage that prevailed in the Longmen Mountains area was exclusively arid or subarid vegetation (Miao et al., 2011), totally unlike the modern vegetation in this area.

The earliest reported Asteraceae fossils recorded are probably those found in the Eocene of the western Tarim basin, south Xinjiang (Zhang and Zhan, 1991), which are characterized by medium to long spines. Nevertheless, *Artemisia* in this study had short spines and thick-walled cypesela, which appeared slightly later (Wang, 2004) (Figure 5). Wang (2004) suggested there were three major stages in *Artemisia*'s evolutionary history based on its morphological data: (1) *Artemisia* did not become abundant until the middle to late Miocene; (2) it became highly developed during the Pliocene and became the principal genus in north China; (3) the quaternary was a major period for the diversification and further worldwide expansion of *Artemisia*. *Artemisia* became abundant from the Miocene to the Pliocene in Tibet, Tarim and Ningxia (Wang, 1996; Zhang et al., 2000; Wu et al., 2002). Since the protolith of the breccia is Permian bioplastic limestone, we can conclude that *Artemisia* originates exclusively from the agglutinate. That is to say, the timing of the brecciated limestone and the appearance of the *Artemisia* is simultaneous. The origin and development of plants are considered to be closely related to environmental trends. *Artemisia* grows mainly at arid and semiarid temperatures and is usually considered as an indicator of moderate to low precipitation (Wu, 1995; Wang et al., 2004; Miao et al., 2011), whereas Chenopodiaceae indicates a saline to non-saline desert environment (Miao et al., 2011). These two taxa have been often used as an indicator of an arid or semiarid paleo-climate (Miao et al., 2011).

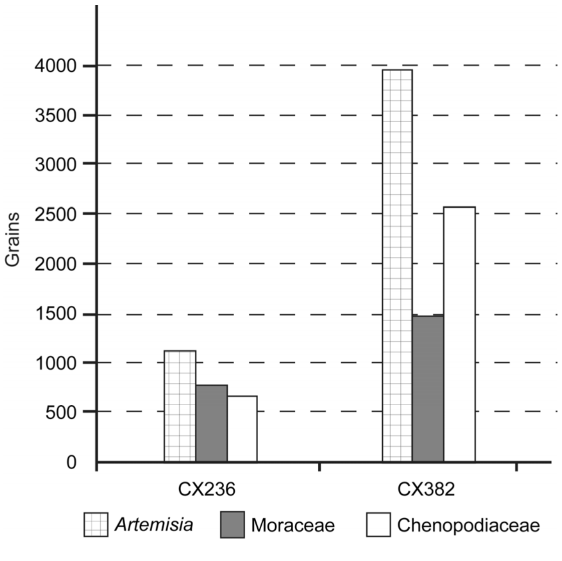

Figure 6 Histogram showing the statistical quantities of the pollen.

5. Discussion

Detailed field observations and petrological analysis indicate that the brecciated limestone of the Tangbazi and Gexianshan have some typical characteristics as follows: 1) the majority are angular-shaped breccia but fewer weak rounded breccia also exists and the diameter of the breccia ranges from several millimeters to tens of centimeters (Figure 2; Figure 4(a), (b)); and 2) the breccia and the agglutinate are totally consumed when sufficient hydrochloric acid is added, leaving only a thin pelitic film floating on the solution, combined with a characteristic high white interference color observed under CPL (Figure 4(c)). We believe the breccia and the agglutinate are composed of carbonate with a small pelitic component. Post-Eocene *Artemisia* extracted from this suite suggests that the "tail" is a product of breccial resedimentation in the Cenozoic rather than a Permian strata as depicted on the regional geological map.

Breccia can be classified as explosion breccia, karst breccia, fault related breccia, glacial drift breccia or crumbled breccia according to its genesis. The genesis of the Bailuding and Tangbazi breccia by explosion is the last consideration because of its location far away from magmatism. Karst breccia usually appears where carbonates are well distributed, originating from the collapse of karst caverns or from water transportation. However, the appearance of arid to semiarid *Artemisia* and Chenopodiaceae is unlikely in such a humid karst water environment, so breccial generation via karst collapse is also unlikely. The breccia in Tangbazi and Bailuding shares nearly the same characteristics; a few researchers think that the breccia is a kind of fault cataclasite at the bottom boundary fault of the klippe (Shi, 1994). However, we discovered many Permian fossils in the breccia, such as Fusulinid (Figure 4(e)), *Aularia* (Figure 4(f), (g)), Bryozoa (Figure 4(g)), Dasycladalean (Figure 4(g)) and long strip micro-fossil (Figure 4(h)). The fossils in the breccia were almost preserved in their original sedimentary status with no sign of any ductile deformation nor evident displacement which would indicate a cataclysm (Figure 4(e), (f), (h)). The zigzag shape fracture preserved in the strip fossil (Figure 4(h)) is an index of instantaneous transtension in place. If the cataclasite fault movement model is correct, straighter boundaries and more fragile displacement should exist in these micro fossils, which is not compatible with their observed characteristics (Figure 4(e), (f), (h)). More importantly, *Artemisia* in CX382 is nearly four times more abundant than CX236 (Figure 6). There are two possible reasons for the difference in abundance during the formation of the brecciated limestone: (1) pollen abundance is differentiated by the distance between the regions (Miao et al., 2011), however, the distance between Bailuding and Tangbazi is less than 3 km, which is too short to account for the observed differences, and (2) the morphology and quantity of the *Artemisia* has been evolving since the Eocene (Miao et al., 2011). This evolution of the diversity might be the only reason for the difference in abundance in one area. The huge pollen differences observed in CX382 and CX236 indicate a different timing of the breccia at these two sites, which is at odds with a bottom boundary fault movement model that requires synchronous timing of the breccia along the whole fault.

Another possible mechanism is glacial drifting. The brecciated limestone could have arisen from massive pieces of limestone smashed by large ice sheets on the Tibetan Plateau and frost-splitting during the Quaternary before the re-sedimentation and cementing of the breccia (Han et al., 1999). However this explanation is contested by the following facts: (1) A great deal of Carboniferous to Permian limestone is exposed in the hinterland of the LMTB at higher elevations and lower temperatures, which is a condition likely to form glacial breccia, but no sign of such brecciated limestone has been found until now; (2) *Artemisia* isolated from the brecciated limestone is definitely unlike the Quaternary pollen, but the glaciation in Tibetan Plateau occurred during the Pleistocene (Li et al., 2004). This mechanism does not make sense with respect to time.

Crumbled breccia refers to generation by a gravitational collapse or landslide because of a scarp or a steep slope. Weakly rounded and angular breccia coexist in the samples. The components of the agglutinate were governed by the environment while the crumbling occurred. Only this mechanism could cause the instantaneous extension to form a zigzag fracture (Figure 4(h)). Immediate sedimentation and cementation are the key factors that allowed the preservation of these micro-structures. No further continuous deformation and movement occurred so the fragile relative displacement in the micro-fossils is not very evident. So we can conclude that the brecciated limestone in the research area is crumbled breccia.

The micro-fossil assemblage in CX236 date its protolith to the Late Permian, which is concordant with the nearby intact limestone from Heifengchao klippe (Sha et al., 1990; BGMRSP, 1991) (Figures 2 and 4). The protolith of CX382 may indicate Lower Triassic strata due to the dolomitic interference color and lack of fossils in the breccia (Sha et al., 1990). The different time reflected by the *Artemisia* abundance differences indirectly indicate that at least two collapse events occurred in the Longmen Mountains area. A high gravity gradient was required for crumbling to occur. Furthermore, a large scale collapse along the LMTB (Figure 2) was required for a quick uplifting during this time. So, we arrive at the conclusion that the elevated topography in this area required at least a two-phase growth, which agrees well with the low temperature dating results (30–25 and 15–10 Ma) (Wang et al., 2012).

According to the field observations, we redefined the distribution of the brecciated limestone and separated the Cenozoic crumbled breccia from Permian limestone in the Tangbazi and Bailuding areas (Figures 2 and 3). The intact Permian limestone showed the original bedding while the breccia was distributed irregularly. Part of the brecciated limestone has a narrow “tail” extending southeastward and covering Jurassic-Quaternary rocks, creating an anomalous stratigraphic relationship of Permian limestone sited on a Jurassic strata (Figures 2 and 3), which is a phenomenon caused by a Cenozoic gravitational collapse. Coincidently, the boundary of the “tail” in Gexianshan agrees well with the isoheight contour line (BGMRSP, 1991), which indicates that the timing of the “tail” is too recent to have been destroyed by weathering. After the removal of the brecciated limestone, the main part of the Tangbazi klippe just rests on a folded Late Triassic strata and is far away from the Jurassic rock (Figure 3). It is unreasonable to postulate a Cenozoic emplacement of the klippe based on the aforementioned stratigraphic overlay relationship. In our opinion, the timing and emplacement mechanism of the klippe in the LMTB belt is more likely intrinsically related to the regional thin-skinned structure during the Mesozoic.

An updated model of the brecciated limestone and the klippe is shown in Figure 7. First, a southward (Yan et al., 2011) or southeastward thrust beginning in the Late Triassic (Xu et al., 1992; Burchfiel et al., 1995; Chen and Wilson, 1996) pushed the Permian strata covering onto the folded Late Triassic rock (Figure 7(a)). The main thrust activity did not cease until the Jurassic. Then the folded Triassic rocks are unconformity overlain by Jurassic sandstone. The elevated topography began to grow because of the high angle thrust beginning in the Early Cretaceous (Chen et al., 1994b; Zeng and Li, 1995; Yan et al., 2011), which accelerated the erosion of the earlier placed Permian limestone sheet (Figure 7(b)). By the Eocene, the topography of Longmen Mountains has achieved a high altitude and a limestone collapse caused the incorporation of contemporary pollen (Figure 7(c)). Finally, the brecciated limestone was naturally selected, presenting the aspects seen today (Figure 7(d)).

6. Conclusions

According to detailed field observations and petrological

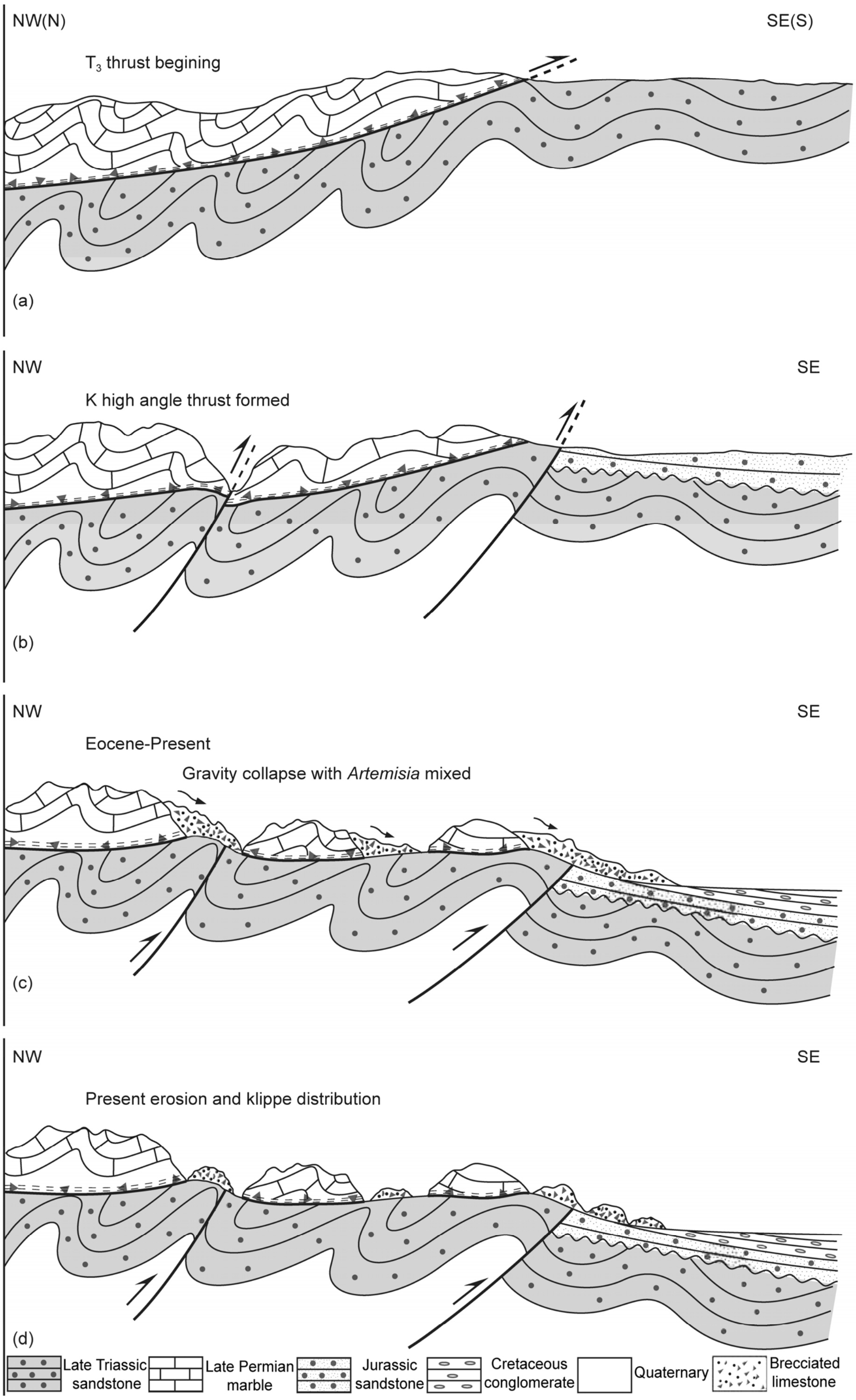

Figure 7 The evolutionary model of the Longmenshan thrust belt.

analyses, we recognized totally two different parts of the Gexianshan and Tangbazi klippe: crumbled breccia and a massive klippe (Figures 2 and 3). The post-Eocene age of the brecciated limestone could be verified by the plethora of Cenozoic pollen contained in the agglutinate, which is contradictory to the Permian dating annotated on the geological map. Furthermore, the large-scale of the crumbled breccia in the Longmen Mountains area indicated rapid uplifting and the achievement of high altitude.

The pollen abundance differences demonstrated a different age for the crumbled breccia in Bailuding and Tangbazi, further indicating the existence of at least a two-phase growth of the elevated topography, which agrees well with the low temperature dating results (30–25 Ma and a 15–10 Ma rapid uplifting).

After removal of the Cenozoic brecciated limestone, the massive klippe, the main part of the Heifengchao klippe was sited on a folded Late Triassic strata (Figure 3). The leading edge of the klippe is far away from the Jurassic boundary. A conclusion that a previous Cenozoic emplacement should be based on the relationship between the crumbled breccia and the underlying concordantly deformed Jurassic-Eocene rocks is unreasonable. A combination of regional isotopic data and field observations indicate a Mesozoic thrust model of the klippe in the center of the LMTB.

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