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Geological Evolution of Longhushan World Geopark in Relation to Global Tectonics

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ABSTRACT: The South China fold belt has experienced a complex series of tectonic events that span 1.0 billion years of earth history. Longhushan (龙虎山) World Geopark is located on the Proterozoic suture between the Yangtze craton and Cathyasia block and highlights the long history of this belt. Collision of the Cathyasia and Yangtze cratons 1.0 billion years ago was associated with the formation of the Rodinian supercontinent where most of the planet's landmasses were amalgamated into one block. Jurassic through Early Cretaceous magmatism was associated with the inland migration of the continental margin arc associated with the penetration of a flat slab after subduction of the Kula-Farallon ridge. Slab roll-back in the Early to Middle Cretaceous opened many extensional basins across the South China fold belt, including the Xinjiang (信江) basin in which Longhushan is located, and these were filled largely with continental red beds deposited by fluvial systems in the hot torrid climate. The beds are richly fossiliferous, including remains of many dinosaurs and dinosaur eggs. Subduction of the Kula-Pacific plate in the Middle Cretaceous caused a short magmatic pulse, and then, the basins subsided slowly through the remainder of the Cretaceous. Cenozoic uplift of the red bed basins was initiated by the India-Asia collision. The uplift was associated with the formation of many faults, joints, and brittle structures that dissected the red bed deposits. Fluvial erosion of the red beds was enhanced along the brittle structures, and different locations have developed very distinctive and structurally controlled geomorphological features including mesas, kopjies, and isolated stone peaks that are known in China as Danxia (丹霞) land-

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forms. Together, these features form Danxia landscapes, and Longhushan World Geopark exhibits a complete range of the Danxia landscapes from juvenile, to mature and to old stages of development. The United Nations Educational, Scientific, and Cultural Organization (UNESCO) World Geopark program ensures that these features and geologic history will be preserved in their pristine state and be available for study and appreciation for generations to come.

KEY WORDS: Longhushan, Cathyasia, South China fold belt, Danxia, red bed, ridge subduction.

INTRODUCTION

The system of UNESCO World Geoparks was established in 2004 to highlight and protect some of the world's most spectacular and important geological sites. As such, scientific studies in and around these parks offer some of the best opportunities to understand important events in earth history and serve as permanent and protected sites where scientific ideas can be tested for generations to come. Longhushan World Geopark is located in the South China fold belt, northeastern Jiangxi Province, encompassing an area of 146.3 km^2 between 116°55′17″–117°27′12″E, and 28°02′55″–28°22′56″N (Fig. 1). The park is located on the northern piedmont of the Wuyi Mountain Range, one of the large-scale fold/basin and range uplifts of the South China fold belt. It is located on the suture zone between the Cathyasia block and Yangtze craton, which collided in the Proterozoic to form the South China block (Chen et al., 1991).

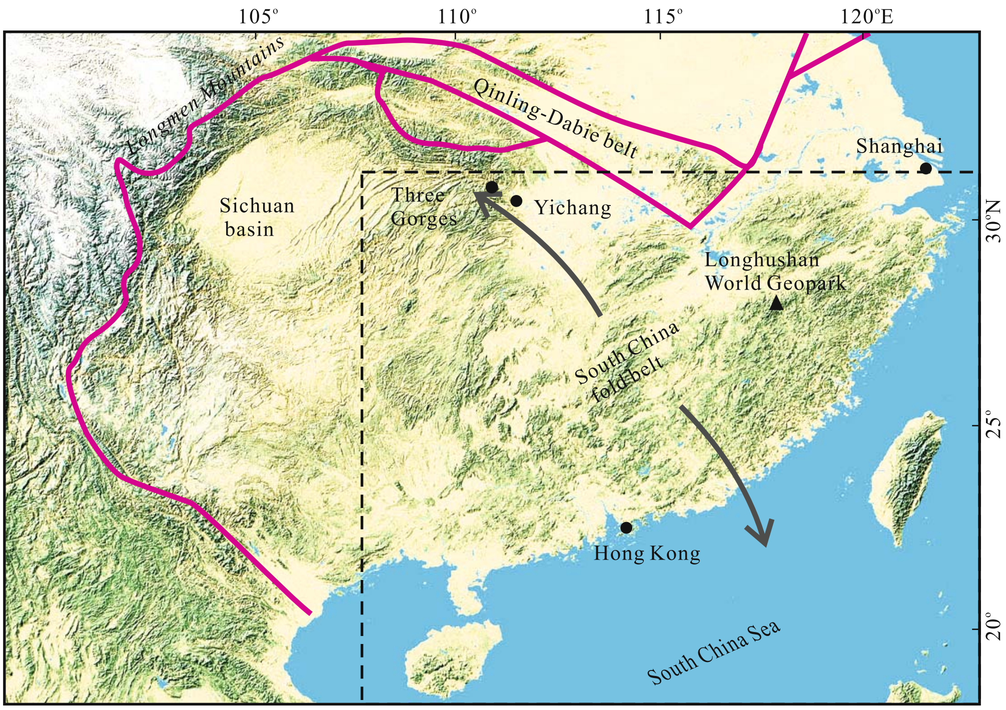


Figure 1. Location of Longhushan in the South China fold belt (modified after Li and Li, 2007).

Rocks in Longhushan World Geopark and the surrounding buffer zone encompass about 1.0 billion years of earth history, including a record of formation of Late Proterozoic supercontinents, their break-up in the Early Paleozoic, and several convergent and divergent tectonic events in the Paleozoic–Mesozoic–Cenozoic times (see recent reviews of the tectonics of China in Zhai et al. (2007, 2006)). This geological history is closely tied with the evolution of advanced life forms on earth, and the park is rich in fossil records. The park also contains spectacular geomorphology (Fig. 2) consisting of red sandstone cliffs and narrow and water-eroded line valleys known in China as Danxia landscapes and landforms (Peng, 2001). In this contribution, we describe the stratigraphy and structural history of the rocks that are exposed in Longhushan Park and relate these data to the complex tectonic events that have affected South China since the Late Precambrian. We then describe how the spectacular Danxia landscape and landforms developed as a consequence of these tectonic events.

Figure 2. Luxi River cutting through kopjies and eroded early mature stage mesa of the Longhushan World Geopark.

GEOLOGICAL SETTING

The transition between the Yangtze craton and Cathaysia craton is occupied in southern Anhui and northern Jiangxi by the Jiangnan belt, Jiangnan uplift (Wang, 1985), or Jiangnan platform uplift (Huang et al., 1987). The Jiangnan belt is typically regarded as the present southern edge of the Yangtze craton, as it is bounded to the south by the Pingxiang-Jiangshan fault zone, a segment of the Proterozoic Beihai-Yichun-Shaoxing suture (Wang, 1985), which separates the two blocks. The tectonic interpretation of the South China block is still a matter of debate. Some authors (e.g., Ren, 1991) argued for a unique block since the Precambrian, without any suture zone in it. In this view, the Jiangnan belt is a simple transitional polycyclic anticlinorium. For many others, the Jiangnan belt is the result of the amalgamation of the Yangtze and Cathaysia blocks (Guo et al., 1985, 1980) but has been interpreted to have formed during collisional events in the Middle–Late Proterozoic (Chen et al., 1991; Rowley et al., 1989; Guo et al., 1985, 1980), Ordovician–Silurian (Haynes, 1988), and Late Paleozoic–Mesozoic (Hsü et al., 1990, 1988). Last, admitting an initial Middle–Late Proterozoic collision, some geologists emphasize the later reworking of the belt due to younger collisional events. Besides the Jiangnan belt itself and to the south and east of it, the presence of several younger suture zones in the South China fold belt (i.e., Early Paleozoic 'Caledonian' and Permian–Triassic 'Indosinian' belts; e.g., Cui and Li, 1983) is debated (Ren, 1991).

Longhushan preserves 1.0 billion years of geological history, as illustrated in the geological map (Fig. 3) and the stratigraphic column (Table 1). This column shows the ages and names of rock units in the park, and their interpreted sedimentary and tectonic settings. Figure 3 is a geological map of Longhushan-Guifeng World Geopark. The park is located on the north slope of Wuyi Mountain Range and bordered to the north by the fault-controlled Xinjiang basin. A variety of intrusive rocks cut strata of the park, including Ordovician tonalite and granodiorite, Silurian tonalite, granodiorite and granite, Triassic granodiorite and granite, Jurassic granite, granodiorite and granite porphyry, and Cretaceous diorite (Chen et al., 1991; Lu, 1964). Intrusive rocks form about 30% of the outcrop area in the park and are especially concentrated in the south.

The Danxia landforms are developed in the Jurassic and Cretaceous sequences, reflecting complex orogenic and rifting events, including subduction of the Kula, Farallon, and Pacific plates, the collision of the North and South China cratons along the Qinling-Dabie-Sulu collision zone, and the collision

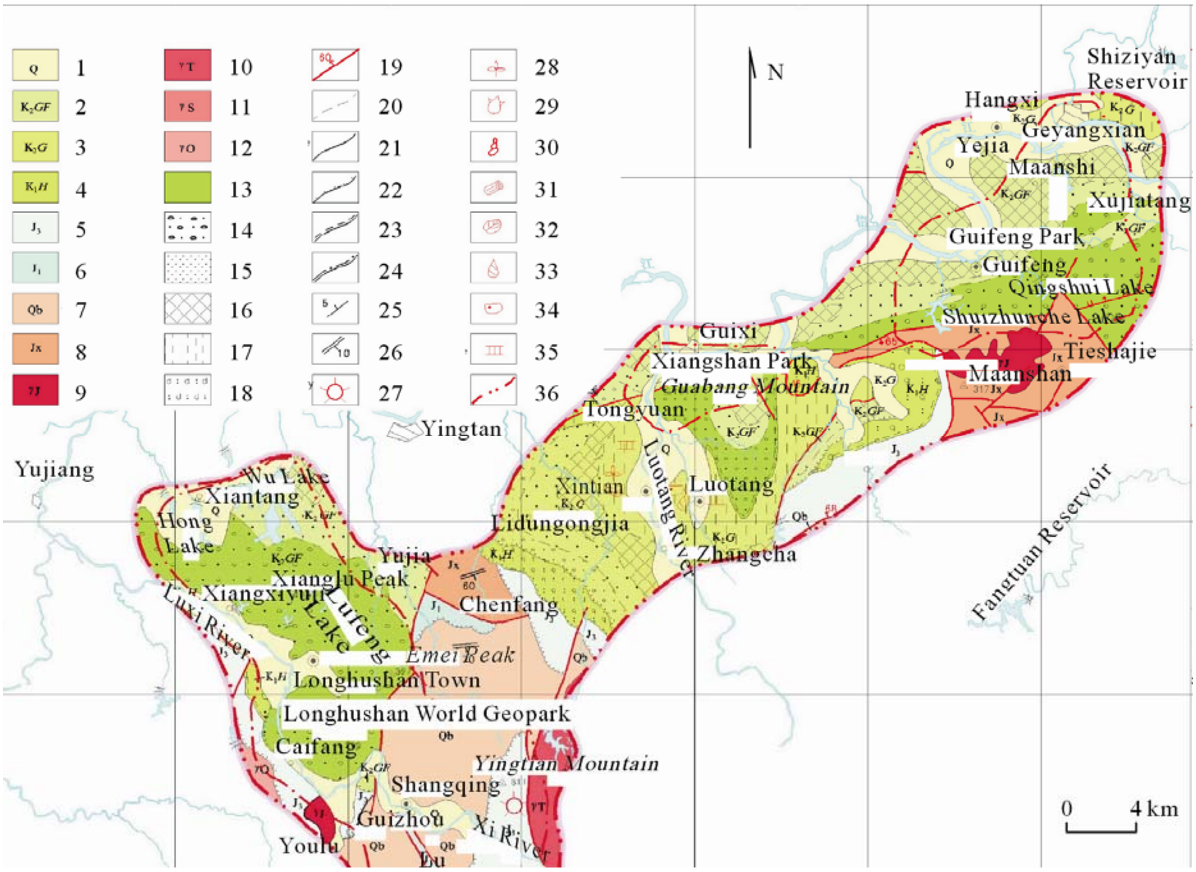


Figure 3. Geological map of Longhushan-Guifeng World Geopark (after Jiangxi Bureau of Geology and Mineral Resources, 1984). 1. Loam, sabulous soil; 2. conglomerate, siltstone, sandstone, mudstone; 3. conglomerate, glutinite with slitstone; 4. conglomerate, glutinite with slitstone; 5. lipanite-tuff; 6. sandstone, siltstone; 7. blasto-sandstone; 8. phyllite, altered tuff blasto-sandstone; 9. Jurassic intrusive rock; 10. Triassic intrusive rock; 11. Silurian intrusive rock; 12. Ordovician intrusive rock; 13. red layer; 14. alluvial proluvial facies; 15. braided river facies; 16. meandering river facies; 17. lacustrine facies; 18. eruptive-sedimentary facies; 19. fault and its occurrence; 20. sedimentary facies boundary; 21. geological boundary; 22. unconformity boundary; 23. parallel unconformity boundary; 24. plano-comformity boundary; 25. stratum occurrence; 26. schistosity occurrence; 27. volcanic crater; 28. plant fossil; 29. bivalve fossil; 30. Gastropod fossil; 31. silicified wood; 32. Conchostracan fossil; 33. Charophyta fossil; 34. Ostracods fossil; 35. gypsum; 36. boundary of the geopark.

of India with Asia (see reviews by Li and Li, 2007; Zhai et al., 2007). Also, the conglomerates contain many clasts of volcanic rocks. Longhushan World Geopark has the most complete sequence of Jurassic volcanic landforms preserved in Jiangxi Province and clearly shows the relationships between the Jurassic volcanics and the Cretaceous conglomerates.

The park preserves an additional 800 Ma of earth history going back to the Mesoproterozoic. The geopark is located on the Beihai-Yichun-Shaoxing suture, where the Yangtze and Cathaysia cratons collided in the Proterozoic. This was only a small part of an event that saw the formation of a giant supercontinent where most of the landmasses of the planet were gathered into one landmass. The formation and breakup of this supercontinent are closely related to the change in life on earth from simple single-celled organisms to complex multicellular metazoan. The strata and their contact relations indicate that the geopark area successively experienced six orogenic events, respectively, named as Sipu, Jingning, Caledonian, Chengjiang, Indo-China (Indosinian), and Yanshanian, with six tectonic cycles as a result.

The Proterozoic collisional suture between the

Yangtze and Cathyasian cratons is preserved in the park zone and buffer boundary, and this is a major tectonic feature of global significance. This collision is one of many that occurred around the world at this time, when most of the world's continents collided to form the supercontinent of Rodinia (e.g., Rogers and

Table 1 Summary of the stratigraphy in Longhushan World Geopark

Geological age			Rock formation		Symbol	Lithology	Tectonic environment	Sedimentary environment
Cenozoic	Quaternary	Holocene		Lianxu Formation	$\mathrm{Qh}l$	Ash gray gravel bed, pale yellow loam and sabulous clay with sporopollen; 3-10 m thick	Differential elevation and subsidence	River
		Pleis-tocene		Wangchenggang Formation	$\mathrm{Qp}_{1\text{-}2}w$	The upper is red brown reticulated clay; the lower is tan debris bed; 1-14 m thick		Drift bed
Mesozoic	Cretaceous	Upper	Guifeng Group	Lianhe Formation	K_2lh	The upper consists of brick red-dusty mauve pebbled sandstone, medium-fine sandstone and siltstone; the lower is conglomerate, glutinite and medium-fine sandstone; 2 600 m thick		River
				Tangbian Formation	K_2t	The upper is brick red coarse sandstone, calciferous fine sandstone, siltstone; the lower is quartz-sandstone with brick red debris, fine sandstone, siltstone, developing fossils of dinosaur's eggs; 462 m thick		
				Hekou Formation	K_2h	Dusty mauve conglomerate, glutinite, pebbly sandstone and siltstone, developing fossils of stonewart, dinosaur's eggs and skeleton; 3 687 m thick		
			Ganzhou Group	Zhoutian Formation	K_2z	Dusty mauve calciferous fine sandstone and siltstone interbeds, containing gypsum and mirabilite, and fossils of plants and ostracods; 650 m thick	Tension rifting	Lake offshore
				Maodian Formation	K_2m	Brick red or dusty mauve conglomerate, glutinite, pebbled medium-fine sandstone, siltstone, occasionally interbedded with basalt, containing fossils of plants and silicified wood; 1 200 m thick		River
		Lower	Huobashan Group	Lengshuiwu Formation	K_1l	The upper is pebbly sandstone and conglomerate in colors of purplish gray, green yellow and ash gray, tuff sandstone, fine sandstone and siltstone; the lower is green yellow or dusty mauve fine sandstone, argillaceous fine sandstone, siltstone, and mudstone; over 1 545 m thick		Lake
				Shixi Formation	K_1s	The upper is purplish gray rhyolitic tuff, volcanic breccia, andesite-tuff interbedded with sandstone and mudstone; the lower is conglomerate and glutinite with development of plant fossils; over 1 166 m thick		Volcanic lake basin
	Jurassic	Upper	Wuyi Group	Elinghu Formation	J_3e	Gray or greenish gray rhyolitic tuff and ash interbedded with rhyolite; 1 735 m thick	Collision and contraction	Explosion-eruption
				Daguding Formation	J_3d	The upper is andesite; the medium and lower are rhyolitic tuff interbedded with rhyolite and volcaniclastics; 420 m thick		
				Wuxi Formation	J_3w	Dacite liparite and dacite; 725 m thick		Eruption
				Ruyiting Formation	J_3r	Dark brown tuff, pebbly siltstone, siltstone and layered tuff; 95 m thick		Volcanic lake basin
		Middle	Linshan Group	Zhangping Formation	J_2z	The upper is dusty mauve fine sandstone, siltstone and mudstone interbedded with gray arkose-quartz sandstone; the lower is gray or purplish gray pebbled sandstone interbedded with siltstone with preservation of fossils of bivalves and plants; 716 m thick	Tension downwarping	River and lake
		Lower		Shuibei Formation	J_1s	Ash gray coarse-medium arkose-quartz sandstone, siltstone, sandy shale interbedded black shale and coal, with preservation of fossils of bivalve and plants and silicified wood; 2 185 m thick		

Continued

Geological age			Rock formation	Symbol	Lithology	Tectonic environment	Sedimentary environment
Paleozoic	Cambrian	Upper	Waiguankeng Formation	$Z_2\in_1 w$	The upper is dark coal-bearing two-mica schist interbedded with stripped quartzite; the lower is gray or dark gray pyrite-bearing biotite schist and carboniferous and siliceous slate, with development of fossils of sponge spicule; 636 m thick	Intercontinental sea	Estuary
Neoproterozoic	Sinian	Upper					
Neoproterozoic	Sinian	Lower	Hongshan Formation	NhZ_1h	The upper is dark gray or black hornstoned graphite-biotite or muscovite quartz schist, garnetiferous plagioclase hornstone with bottom layer of carboniferous slate and top layer of ash gray magnetite-specularite two-mica granulite; the medium is yellowish brown muscovite plagioclase granulite, two-mica slate, siliceous two-mica slate, metamorphic moraine conglomerate; the lower is dark gray or greenish yellow silicon two-mica quartz slate with top layer of diopsidite; 915 m thick	Rift trough	Neritic zone
Neoproterozoic	Nanhua						
Neoproterozoic	Qingbaikou		Wanyuan rock Formation	$Qbwy$	Dark gray, brownish gray and gray garnetiferous biotite plagioclase granulite interbedded with siliceous biotite slate and siliceous two-mica slate; 897 m thick	Rift trough	Bathyal environment
Mesoproterozoic			Tieshajie rock Formation	Pt_2ts	The upper is blackish gray sericite phyllite and carbonaceous sandy phyllite with top interbed of metamorphic siltstone and bottom interbed of marble; the lower is greenish gray chlorite-sericite phyllite interbedded with metamorphic spilite and metamorphic quartz keratophyre; 1 300 m thick	Rift trough	Bathyal environment
Mesoproterozoic			Zhoutanyan Formation	Pt_2zt	Dark gray garnetiferous biotite plagioclase gneiss interbedded with biotite plagioclase granulite, containing siliceous two-mica slate; over 1 215 m thick	Rift trough	Bathyal environment

Santosh, 2003). Rodinia then broke up around 700 Ma ago, and the continents recollided in a different con figuration around 550 Ma ago to form the next super-continent, known as the southern supercontinent or Gondwana, which collided with the northern conti-nental landmass of Laurasia, 250 Ma ago to form Pangea (Rogers and Santosh, 2003). Pangea broke up next, and the continents have since then been rear-ranged to form the Asian landmass. Some of the most significant tectonic events that are associated with the formation and deformation of the rocks in Longhushan-Guifeng are associated with the breakup of Pangea, the movement of continental landmasses (such as India) across the Tethys Ocean from Africa/ Australia/Antarctica to Asia, and the subduction of the Kula, Farallon, and Pacific plates beneath present-day Asia. These events are described in detail below.

STRATIGRAPHY

The oldest rocks in the park include a series of Mesoproterozoic metasedimentary rocks, known as the Tieshajie and Zhoutanyan formations, consisting of a more than 1.2 km thick section of bathyal phyllite, metasandstone, marble, and biotite-garnet-plagioclase gneiss, metamorphosed up to granulite grade. These are overlain by a 2.5-km thick Neoproterozoic se-quence including garnet-biotite-plagioclase gneiss of the Wanyuan Formation, and graphite-bearing schists, metaconglomerates, slates, and magnetite-specularite two-mica granulite of the Hongshan Formation. The metamorphic grade of the Precambrian rocks is gener-ally upper amphibolite to lower greenschist facies. Paleozoic rocks consist of a 636-m thick sequence of Cambrian pyrite-bearing schist, siliceous slate, quartz-ite, and coal of the Waiguankeng Formation. A major unconformity separates the Paleozoic and Precambrian rocks from the overlying Mesozoic sequence.

The main sequence of rocks exposed in the park consists of a series of Jurassic and Cretaceous volcanic and sedimentary deposits. Lower Jurassic rocks include more than 2 km of arkose and coarse sandstone interbedded with coal from the Shuibei Formation, whereas the Middle Jurassic includes 700 m of fine sandstone, siltstone and mudstone of the Zhangping Formation. The Lower and Middle Jurassic rocks have sedimentary facies and rock types that are interpreted to represent river and lake environments formed in a continental rift type setting. Upper Jurassic rocks include a 3-km thick sequence of rhyolytic tuff, rhyolite, andesite, and dacite interbedded with pebbly siltstone that are from the Ruyiting, Wuxi, and Elinghu formations. These form a typical continental margin arc sequence and are similar to other Jurassic arc rocks across South China and around the circum-Pacific belt of subduction-related continental arc magmas (e.g., Charvet et al., 1994; Jahn et al., 1990). Volcanic vents and cones are still well preserved, especially in the south of Wuyi Mountain.

The Cretaceous series begins with the 2.7-km thick Huobashan Group, consisting of the Shixi and Lengshuiwu formations. These include rhyolitic tuffs and breccias interbedded with conglomerate and mudstone, overlain by purple and gray sandstone and conglomerate. Rocks of the Huobashan Group, deposited in the Lower Cretaceous, mark the end of continental margin style volcanism in the Longhushan Section of the Xinjiang basin (e.g., Li, 2000).

The Huobashan Group is overlain by the Upper Cretaceous Ganzhou and Guifeng groups, forming a coarse-clastic continental red bed series. The 1.8-km thick Ganzhou Group includes the Maodian Formation at the base, consisting of fluvial red conglomerate, pebbly mudstone, and rare basalt, and is richly fossiliferous with many species of plants and trees preserved. The overlying Zhoutian Formation includes lake deposits consisting of sandstone and siltstone with gypsum interbeds and fossil ostracods. The 6.5-km thick Guifeng Group is entirely fluvial in origin and consists of three formations: the Hekou, Tangbian, and Lianhe. The Hekou Formation contains mauve colored conglomerate, sandstone, and siltstone and has yielded fossils of dinosaurs and dinosaur eggs from the park, whereas the overlying Tangbian Formation contains bright red coarse sandstone, fine-grained sandstone and siltstone, and also fossil dinosaur eggs. The uppermost Cretaceous unit is the Lianhe Formation, containing red pebbly sandstone, siltstone, and conglomerate layers.

MESOZOIC TECTONIC SETTING AND EVOLUTION

Longhushan World Geopark is located in the South China fold belt (Chen, 1999), a wide area of extensive deformation, including folding and faulting, and associated with igneous activity through much of the Mesozoic (Kuang and Wu, 1996; Chen et al., 1991; Jahn et al., 1990). There has been much controversy about the origin and tectonic evolution of the South China fold belt, and as of the moment, there is no general consensus on its history.

Early workers noticed the intracontinental nature of the orogen and its migration inland from the coastal region during the Triassic (ca. 250–200 Ma) and linked this orogenic event with the initiation of an active plate margin in the western Pacific. Hsü et al. (1990, 1988) used continental collisions within the South China block to explain this wide orogen, but this model received little geological support. Li (1998) invoked far-field stress from the continental collision at the northern margin of the South China block in the Qinling-Dabie orogen to explain the geological history of the orogen.

In a recent analysis, Li and Li (2007) analyzed the timing of deformation and igneous activity in the South China fold belt, noticed that the deformation and igneous activity became progressively younger inland, and proposed a new tectonic model involving the penetration of a flat oceanic slab underneath Asia (Fig. 4), which caused progressive deformation and igneous activity to move inland.

Li and Li (2007) proposed a comprehensive model that includes the progressive penetration of the slab from Permian through Early Jurassic and produced a series of palinspastic maps showing the distribution of different sedimentary facies, deformation and magmatic fronts, and times of igneous activity, which are directly related to the movement of the slab, and its eventual break-off and sinking into the mantle in the Middle Jurassic, causing igneous activity and the formation of basins (the initial volcanics and basins for the Danxia beds) (Fig. 5).

While Li and Li's (2007) palinspastic maps and tectonic correlation are elegant and perhaps the best to date, they did not account for all of the tectonic complexities that have affected the region. Perhaps the most significant is that subduction of different plates, including the Farallon and Kula, before the Pacific plate began subducting beneath Asia, means that several oceanic ridge systems must have been subducted beneath South China. The analysis of Li and Li (2007) is one-dimensional, examining all events on a cross

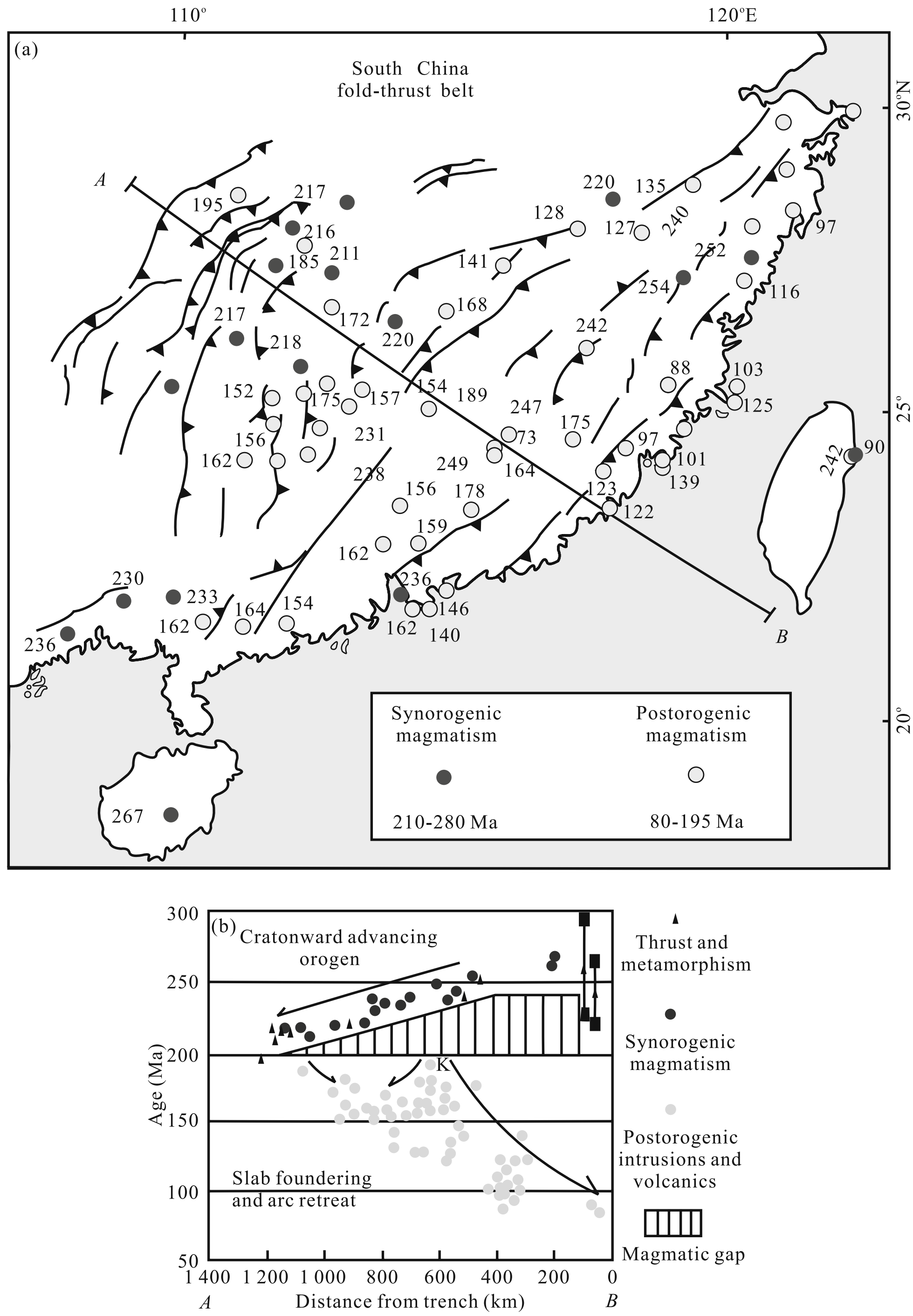


Figure 4. (a) Map of the South China fold belt showing data on ages of structures and metamorphism, and (b) plot of age of deformation and metamorphism across strike showing how deformation and magmatism become younger inland across the belt. Figures are modified from Li and Li (2007).

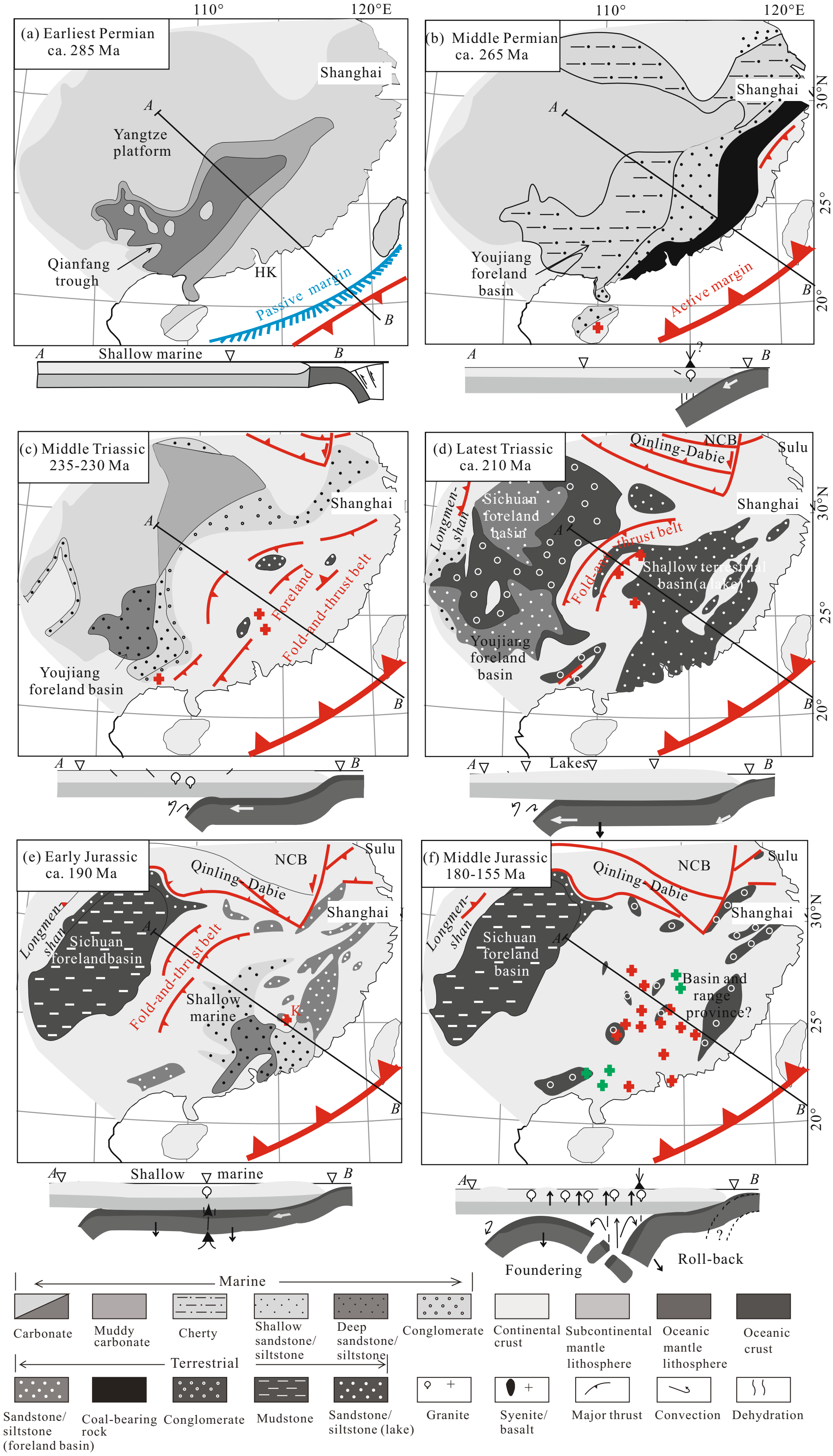


Figure 5. Palinspastic maps (modified from Li and Li, 2007) showing how the surface tectonic and sedimentary environments changed, perhaps in response to penetration of a flat subducting slab beneath the South China fold belt.

sectional line, whereas the geological processes are three dimensional.

Figure 6 (from Kusky et al., 2007a, b) shows the general plate tectonic interactions between these plates since the Late Paleozoic and shows clearly that the Kula-Farallon ridge must have been subducted beneath South China sometime ~260–220 Ma ago (Permian–Triassic), and the Kula-Pacific ridge was subducted beneath the South China fold belt about 100 Ma ago (Cretaceous). The subduction of oceanic ridges beneath continents at convergent margins has profound effects on the geologic development of the overriding continental plate (see Bradley et al., 2003 for a review).

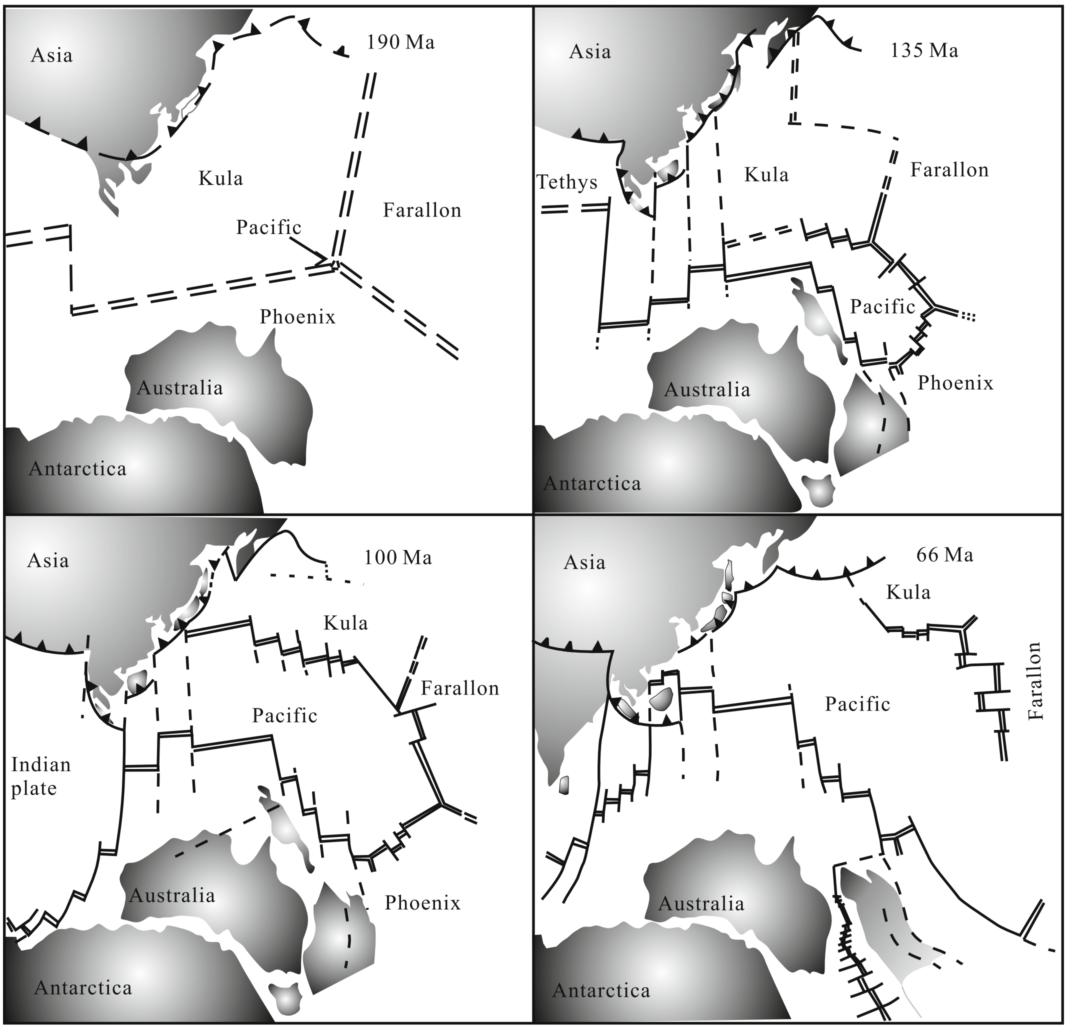


Figure 6. Interactions between Asia (including the South China fold belt) and Antarctica in the past 200 Ma, showing that at least two ridges have been subducted beneath the South China fold belt, which would have profound effects on the geology and tectonics of the region (from Kusky et al., 2007a, b).

When a ridge subducts, the ridge meets the convergent margin, and the hot upwelling mantle and magma typical partially melt the accretionary prism, forming a belt of near trench magmatic rocks. As the oceanic plates subduct, they continue to spread apart beneath the continent, but they stop producing oceanic crust since there is no seawater to cool the magma. Therefore, at a depth of 50–100 km, only hot and dry upwelling mantle is located beneath the arc on the overriding plate, and the lack of water and magma deprives the arc of melts, so as the gap (slab window) between the spreading plates moves under any part of the arc, the magmatism ceases, and the arc becomes temporarily inactive. Ridge subduction is also associated with anomalous deformation, since the ridge is a >1-km topographically high feature being forced beneath the continent. Since the plates are in constant motion with respect to each other, the boundary (called a triple junction) where the three plates meet and the underlying slab window where the oceanic plates have continued to spread move along the continental margin at rates that may exceed 20 cm per year (Bradley et al., 2003; Kusky et al., 2003). Thus, one of the hallmarks of ridge subduction is that the features described above (near trench magmatism, anomalous deformation, and cessation of arc magmatism) are diachronous and move along the continental margin at rapid rates. Therefore, tectonic analysis of the South China fold belt is more complex than the one-dimensional model presented above. However, more data and further work are needed to test which effects can be related to the penetration of a flat slab beneath the South China fold belt and which may be related to ridge subduction. Additionally, these models are not mutually exclusive. When a ridge is subducted, the trailing plate is young, hot, and buoyant, and it may trigger to change from normal to flat slab subduction (Kusky and Young, 1999). These diachronous events may be associated with the diachronous initiation of many of the Danxia basins of South China.

CENOZOIC TECTONICS

Cenozoic tectonics in South China are dominated by the collision of India with Asia, which caused the uplift and deformation of many of the Danxia basins (Fig. 7). As India crashed into Asia starting about 50 Ma ago, the convergence continued causing the uplift of the Himalaya and Tibet plateau and caused much of eastern Asia to be pushed out of the way in a mechanism called tectonic escape, forming many faults, basins, and mountain ranges (e.g., Gilder et al., 1991). Deformation associated with this collision is quite

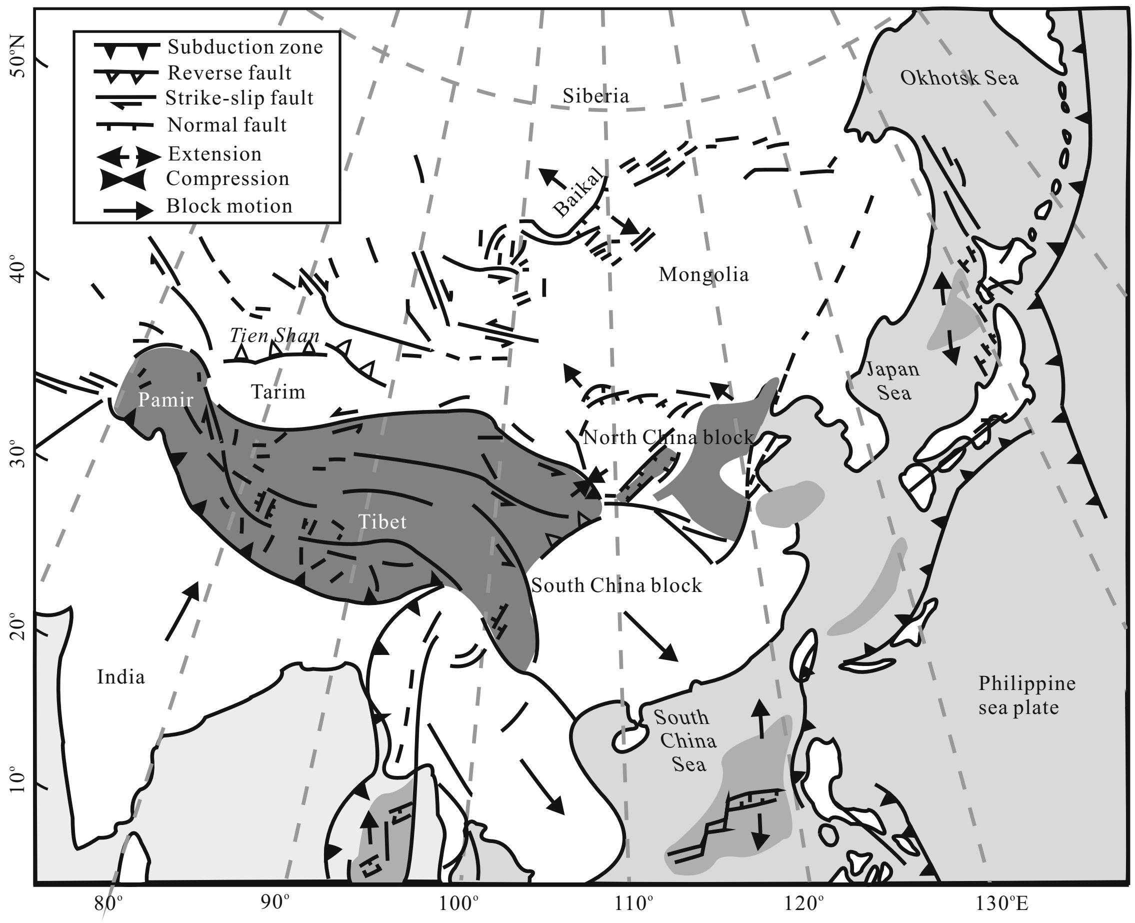


Figure 7. Cenozoic tectonic features of Asia, showing how South China is moving away from the India/Asia collision, either by motion of rigid lithospheric blocks, or with the help of sub-crustal mantle flow. This has caused extensive deformation and faulting in the South China fold belt, and the development of basin and range types of topography (Kusky et al., 2007a, b).

complex. At depth, there are a couple of subcrustal regions where the mantle is flowing rapidly toward the east and southeast, perhaps dragging parts of the overlying crust with it, forming basin and range types of geological provinces. In other places, this flow has encountered stiff deep basement blocks (such as the Sichuan basin) and flowed upward to form high mountain ranges (Longmen Mountain in this case), or around the blocks. In any case, as this subcrustal flow advanced across eastern Asia, it would have a diachronous effect on the uplift and extension and deformation of many of the Danxia basins. These effects need further testing, with the caution that much of the deformation is certainly not related to subcrustal flow,

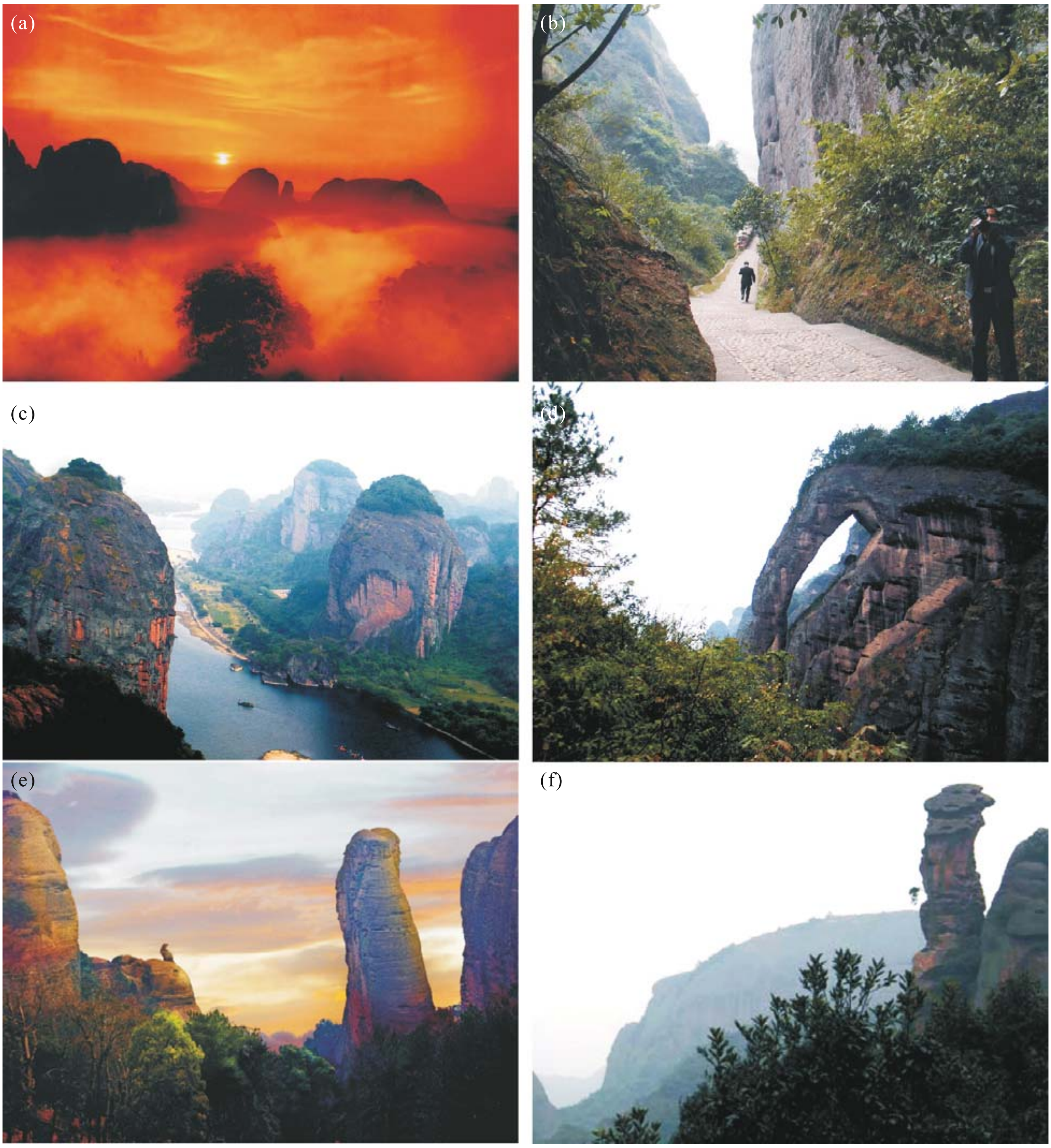


Figure 8. Representative Danxia landforms and landscapes from Longhushan World Geopark. (a) Matue stage Danxia of Longhushan; (b) narrow joint controlled canyon cutting Danxia mesa; (c) Luxi River flowing through steep Danxia peaks in Longhushan World Geopark; (d) elephant rock; (e) entrance to Guifeng Geopark; (f) isolated stone pillar.

but to the transmission of stress through the lithosphere, to accommodate the indentation of India into a fragmented collage of microblocks that make up Asia (e.g., Molnar and Tapponnier, 1975).

DEVELOPMENT OF DANXIA LANDFORMS IN RELATION TO TECTONICS

Longhushan-Guifeng offer a spectacular variety of Danxia landforms developed in the Jurassic–Cretaceous sandstones and conglomerates (Fig. 8). The park is in the late mature to the old stage of development according the classification of Peng (2001) and exhibits many isolated single peaks, hoodoo-peaks, steep cliffs, collapse structures, and joint-controlled topography. Figure 10 (after Peng, 2001) illustrates some of the range of different Danxia landforms across the park.

The Danxia landforms in Longhushan and Guifeng are clearly controlled by differential weathering along joints and some minor faults, and these structures are young and thus probably related to the India/Asia collision. There has been some effort to map these structures using satellite imagery and aerial photography (Fig. 9), though more effort should be put into this and correlate these structures with regional tectonics.

The Danxia landforms in the park show a wide range of forms and different stages of development, ranging from juvenile to mature to old age landforms.

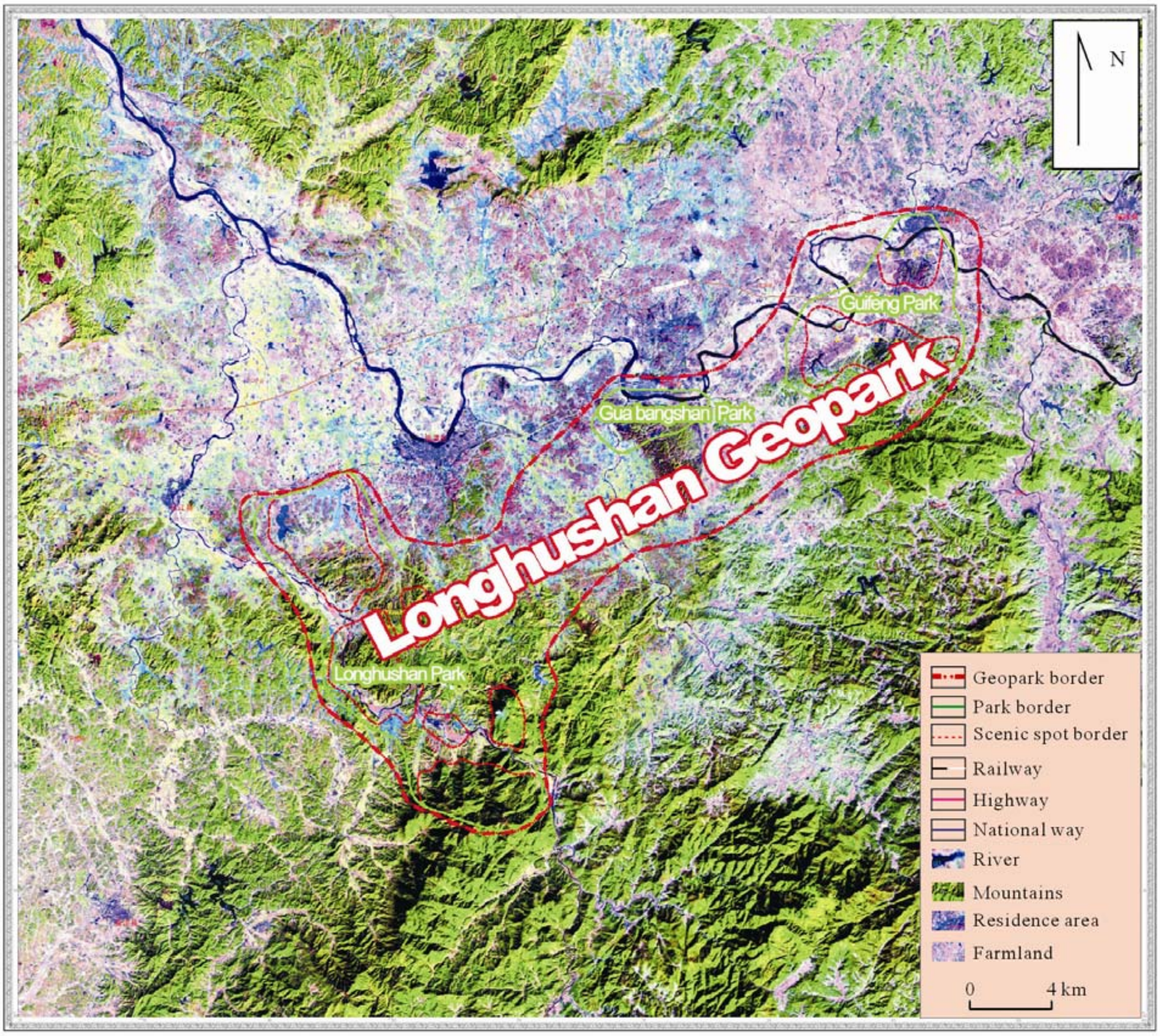
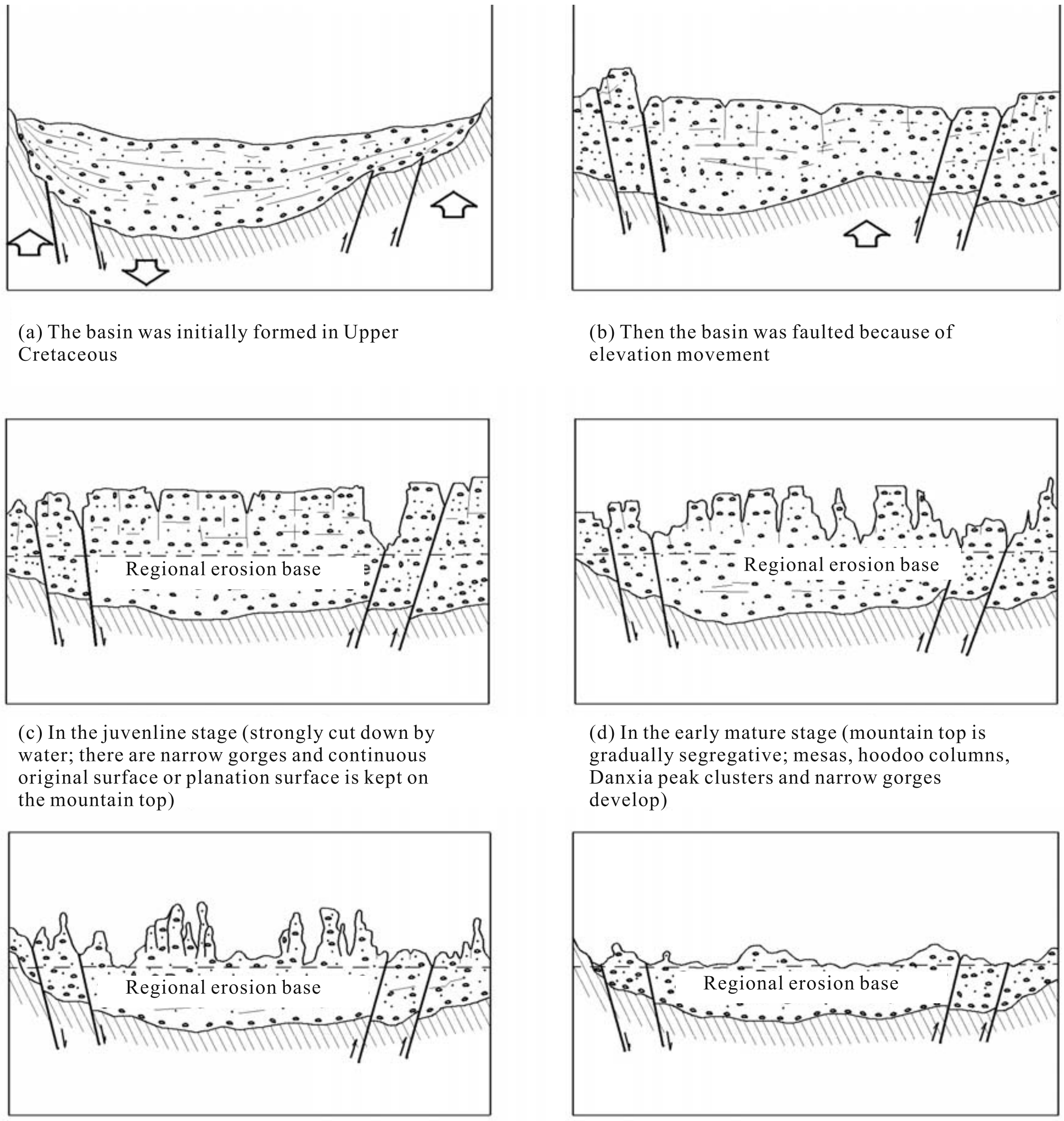


Figure 9. Landsat image of the Longhushan World Geopark. Wuyi Mountain is to the south, and the Xinjiang basin to the north.

These appear to be related to distance from some of the main faults bounding the uplifted area of the park and Wuyi Mountain to the south, from the Xinjiang basin in the north.

Most of the landforms in Longhushan are early mature-stage Danxia landforms. The variety of geomorphic forms include peak clusters with steep cliffs and flat tops, mesas, peak clusters with rounded tops, isolated peaks, hoodoos, and kopjes. The Danxia landforms step down into the basin, which were last seen as isolated peaks (kopje, koppie, or inselberg) jutting out of the farmland and rice patties surrounding the park. A complete series of geomorphic development is shown by the following peaks in the park: the juvenile stage (the stone walls in Guifeng); →the early mature stage (mesas in Guifeng Scenic Spot); →the late mature stage (round hoodoos and Yamen Stone in the Xianshuiyan Scenic Spot); →early old stage (red cliffs, kopjes, isolated peaks, and hoodoo columns in the Mazuyan Scenic Spot and Xiangshan Park); and



(a) The basin was initially formed in Upper Cretaceous

(b) Then the basin was faulted because of elevation movement

(c) In the juvenline stage (strongly cut down by water; there are narrow gorges and continuous original surface or planation surface is kept on the mountain top)

(d) In the early mature stage (mountain top is gradually segregative; mesas, hoodoo columns, Danxia peak clusters and narrow gorges develop)

(e) In the late mature stage (trunk valley is close to the erosion base; hoodoos develop near the valley and Danxia peak clusters develop faraway from the valley)

(f) In the old stage (trunk valley and major branches reach to the erosion base; valley plain, red hills, stone towers and kopjes occur with intervals)

Figure 10. Peng's (2001) classification of Danxia landforms in relation to a proposed evolutionary sequence for Danxia basin.

Table 2 Brief overview of the geological evolution of Longhushan World Geopark

Geological age		Isotopic age (Ma)	Crustal movement	Sedimentary formation	Magmatic activity	Tectonic phase and event	
Cenozoic (Kz)	Quaternary (Q)		Xishan Phase II	Continental unconsolidated accumulation		Differential elevation and subsidence	
	Neogene (N)	2.6	Xishan Phase I			Active continental margin phase	Tension rifting from India/Asia collision
	Paleogene (E)	23.3 65	Yanshan Phase VI				
Mesozoic (Mz)	Upper Cretaceous (K_2)	96 137	Yanshan Phase V	Continental clastic sediment occasionally interbedded with basic lava	Basic magmatic eruption		Tension rifting (Kula/Pacific ridge subduction)
	Lower Cretaceous (K_1)	154	Yanshan Phase IV	Lacustrine fine clastic rock interbedded with acid lava	Acid magmatic eruption		Faulting Collision and contraction from Kula-Farallon ridge subduction
	Upper Jurassic (J_3)	227	Yanshan Phase III	Continental volcaniclastic rock and lava	Neutral or acid magmatic intrusion and eruption		
	Middle and Lower Jurassic (J_{1-2}) Upper Triassic (T_3)	250	Indo-China movement	Continental coal-bearing clastic rock-mottled clastic sedimentary rock	Neutral or acid magmatic intrusion and basic magmatic eruption		Extension
	Middle and Lower Triassic (T_{1-2})	410				Tethyan tectonic phase	
Paleozoic (Pz)	Permian (P) Carboniferous (C) Devonian (D)		Caledonian movement				
	Silurian (S) Ordovician (O) Cambrian (∈)	543 680 760		Estuarine coal-bearing fine clastic rock and silicalite	Neutral and acid magmatic intrusion	Caledonian tectonic cycle and orogenic phase	
Neoproterozoic (Pt_1)	Sinian (Z)					Formation and break up of Gondwana supercontinent	
	Nanhua	800		Neritic clastic rock interbedded with tillite			
	Qingbaikou (Q_b)	1 000	Chengjiang movement Jinning movement Sipu movement	Marine clastic rock interbedded with volcaniclastic rock			
Mesoproterozoic (Pt_2)				Marine sand-clay clastic rock		Sipu tectonic cycle and Cathaysia formation phase: amalgamation of Rodinia supercontinent	

→the late old stage (erosion plains between the three parks). The sketch (Fig.10) shows the evolution of these different stages during the dissection of the basin along joints. In this model (from Peng, 2001; Fig. 10), continental red beds are deposited in a subsiding fault-controlled basin in the Upper Cretaceous, forming sequences that may be several kilometers thick. At some later time, the basin is uplifted and cut by numerous joints, which become eroded by water, progressively downcutting the tableland topography forming the range of Danxia landscapes from juvenile to mature stages. The critical things to note, therefore, are the times of basin subsidence, and the times of uplift to relate the formation of Danxia landscapes to global tectonic events.

SUMMARY: RELATIONSHIP OF THE DEVELOPMENT OF LONGHUSHAN STRATA AND STRUCTURES TO GLOBAL TECTONIC EVENTS

Table 2 summarizes how the strata of Longhushan relate to the tectonic events described above. The aim of this section is to compare the different stages of the basin development and its uplift and deformation to the regional and global tectonic events described above and to determine if a correlation can be made between different stages of Danxia evolution and these tectonic events.

Some of the correlations between geological units and structures in Longhushan World Geopark with global tectonic events are clear. The strong deformation in the Mesoproterozoic and Neoproterozoic basement rocks are related to the formation of the Supercontinent Rodinia, its break-up, and reamalgamation into the supercontinent of Gondwana. The >600-m thick Cambrian Waiguankeng Formation represents a stable platform sequence deposited on the trailing edge of a fragment that rifted off of Gondwana; at this time in earth history, many small fragments of continental material were breaking off the southern supercontinent and moving north across the Tethys Ocean to amalgamate to form Asia (see Zhai et al., 2006; Li, 1998).

The origin of the Jurassic to Cretaceous volcanic and plutonic rocks correlate with the establishment of an active continental margin beneath the South China fold belt, with the propagation of deformation and magmatism inland initiated by the subduction of the Kula-Farallon ridge, changing the previously steep subduction into a shallow slab subduction and causing the deformation and magmatism to propagate inland. This continued through the Early Cretaceous, at which time slab roll-back re-established steep subduction and caused extension in the South China fold belt, initiating the formation of the Xinjiang and other Danxia basins. The environment at this time on the continents was hot and dry, and the coarse fluvial sediments deposited in the basins were rich in iron, giving them a red color. Dinosaurs roamed through the basins, leaving their fossil remains. The basins subsided throughout the Cretaceous, becoming a few to more than ten kilometers deep. A brief interval of mafic magmatism in the Upper Cretaceous may be related to a second ridge subduction event, when the Kula-Pacific ridge interacted with the South China convergent margin and passed as a triple junction forming the second ridge subduction event.

Uplift was initiated in Tertiary, and it still continues through the present. The entire region is responding to the India/Asia collision that was initiated about 50 Ma ago, caused the uplift of the Himalaya and Tibet-Qinghai plateau, and initiated the southeastward tectonic escape of South China away from the collision zone. This uplift is a complex interplay of many forces, including the tectonic stresses transmitted through the lithosphere, breaking the continent into many small microblocks that are all moving southeastward relative to each other, and a subcrustal mantle flow moving in the same direction that may be exerting a drag or pull on the overlying crust, initiating deformation in some zones.

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