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Upper Cretaceous alluvial fan deposits in the Jianglangshan Geopark of Southeast China: implications for bedrock control on Danxia landform evolution

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Abstract: The Jianglangshan Geopark in the western Zhejiang Province of Southeast China is well-known for its spectacular red-colored sandstone landforms. Little is known about the depositional processes of the conglomerate-dominated Fangyan Formation, the lithologic base of the Danxia landforms in this geopark. Based on detailed field investigation of lithology, sedimentary structures, bed thickness and geometry, five facies are recognized: facies A (matrix-supported cobble conglomerate), facies B (pebble conglomerate), facies C (pebbly sandstone), facies D (fine-grained sandstone) and facies E (mudstone). The results show that streamflow-dominated fans were the main depositional processes responsible for the accumulation of the Fangyan Formation along the mountain fronts. These fan conglomerates form the base for the evolution of the Danxia landscapes owing to the uplift and erosion of the study area. In contrast, the fine-grained sedimentary successions produced by fluvial floodplains in the distal part of the fans were thinner and more easily weathered. Such sedimentary facies distribution patterns were thought to be similar during Late Cretaceous across Southeast China. The Danxia landforms are largely the geographical expressions of the conglomerate-dominated redbeds in the proximal-middle fans.

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Introduction

The bare red walls and cliffs are typical geomorphological landscapes developed in the red-colored conglomerates and sandstones in Southeast China and named as "Danxia landform" for the resemblance of their rocks to rosy red clouds (Peng 2001; Zhao et al. 2014; Peng et al. 2015). The word "Danxia" means literally "reddish rays" or "rosy cloud" during the sunrise or sunset. Research on the Danxia landform has been conducted for more than 80 years in China. These geomorphological features were first named as Danxia landform by Chinese geologists in 1930s (Chan 1938), and have been recognized to be representative of the sub-tropical regions (Young et al. 2009). They commonly develop in sandstone- and conglomerate-dominated sedimentary rocks and thus share similar characteristics associated with sandstone weathering and landscape development in other regions (Turkington and Phillips 2004; Turkington and Paradise 2005; Mustoe 2010; Groom et al. 2015). To date, 1003 Danxia sites have been discovered in 28 provinces, cities and regions of China (Huang et al. 2015). A number of typical Danxia landforms, such as Danxiashan of Guangdong, Langshan of Hunan, Taining of Fujian, Longhushan of Jiangxi, Jianglangshan of Zhejiang, and Chishui of Guizhou Province in Southeast China (Figure 1) were collectively designated as World Natural Heritage sites in 2010.

In recent years, much progress has been made on the description of the appearance, distribution and economic tourism development of Danxia landforms by using field and thin-section observations, uniaxial mechanical strength testing, element geochemistry, and numerical simulation in Southeast China (Peng 2001; Ouyang et al. 2009; Guo et al. 2012, 2013; Zhu et al. 2009, 2015; Peng et al. 2015; Yan et al. 2015). However, these redbeds have received much less attention with respect to depositional environments and processes that resulted in thick accumulations at the basin margin. Therefore, a detailed sedimentary facies analysis is of importance for understanding Danxia landform evolution. The Jianglangshan Geopark in western Zhejiang Province (Figure 1) is one of the typical Danxia landforms in Southeast China (Zhu et al. 2009). The Jianglangshan Geopark possesses Danxia landform features including red coloration, slightly rounded summits, prominent cliffs, and footslopes (Figure 2a). The tourism path from the bottom to the top of the Lang Peak was built in 1990 and composed of about 3500 stone steps, which provides a good opportunity to perform facies description on the nearly continuous uncovered

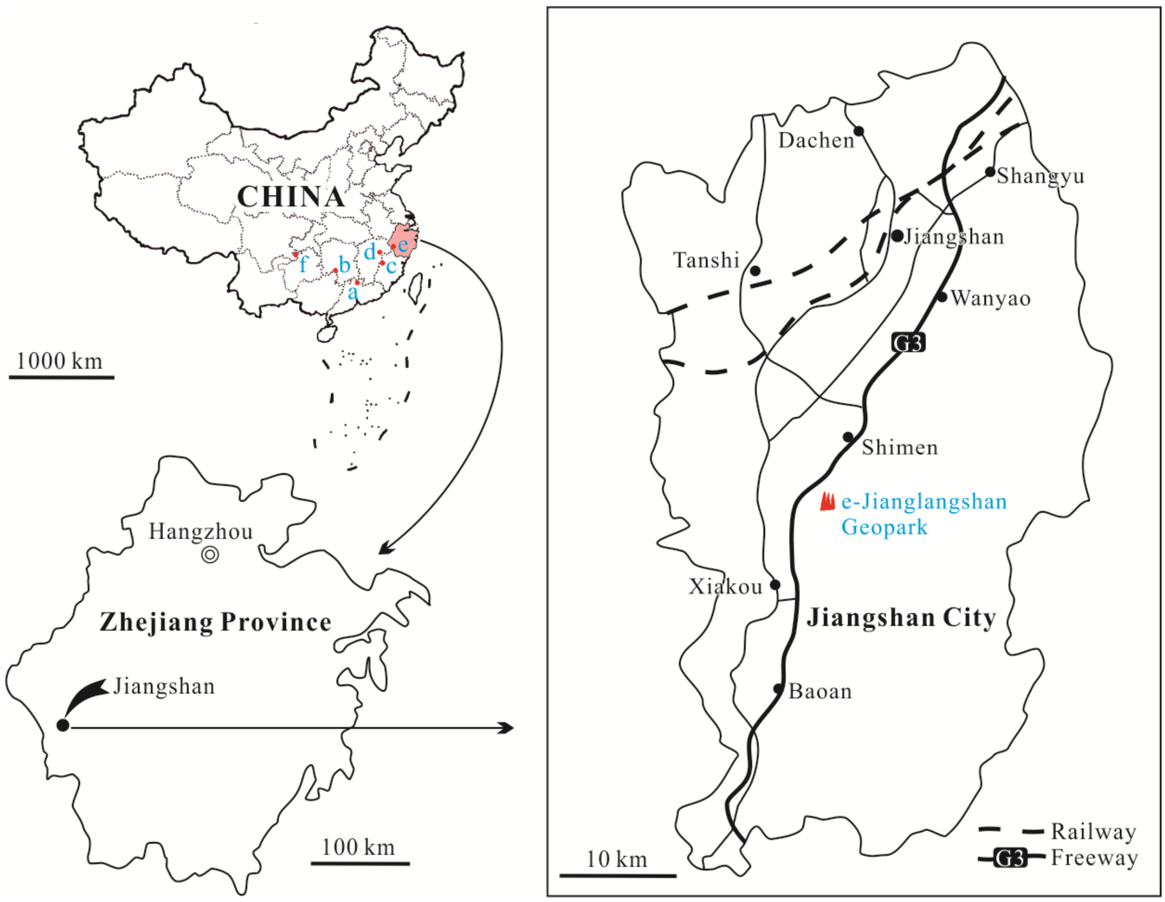

Figure 1 Typical Danxia landforms in Southeast China and the location of the Jianglangshan Geopark study area in Jiangshan City of Zhejiang Province. Typical Danxia landforms include: a-Danxiashan of Guangdong, b-Langshan of Hunan, c-Taining of Fujian, d-Longhushan of Jiangxi, e-Jianglangshan of Zhejiang, and f-Chishui of Guizhou Province.

Figure 2 Overview of the Jianglangshan Geopark. (a) Landscape photograph showing panorama of Danxia landscape elements (slightly rounded summit, prominent cliff, and footslope). The circled person in the left for scale. (b) The narrow path from the bottom to the top of the Lang Peak provides access to observation of the continuous outcrop.

road-cut outcrops (Figure 2b). The significance of this work includes: (1) a detailed sedimentary description and depositional environment interpretation of the scenery redbeds of the Fangyan Formation; (2) the fan conglomerates along the mountain fronts formed the base of the subsequent development of the Danxia landforms; (3) variability of sedimentary facies across the basin should be considered in the study of the Danxia landform evolution.

1 Study Area

The Jianglangshan Geopark (118°33'43"E, 28°31'44"N) is located in the Xiakou Basin of western Zhejiang Province, Southeast China (Figure 1 and 3). The Xiakou Basin was one of the many faulted basins generated by the widespread crustal extension during late Mesozoic in Southeast China (Shu et al. 2009). This basin is a NE-SW trending faulted graben (Figure 3) with an area of about 300 km^2, and is bounded by the Jiangshan-Shaoxing and Bao'an-Xiakou-Zhangcun faults to the northwest and southeast, respectively. To the southwest and northeast, the redbeds non-uniformly overlie the Early Cretaceous granitoids.

In the study area, the Early Cretaceous bedrock consists of rhyolite, tuff, granite with minor amounts of mudstone whereas the Late Cretaceous is predominately composed of continental redbeds occasionally inter-bedded with thin volcanic beds. The red coloration, alluvial conglomerates, non-marine fossils are collectively indicative of continental depositional environments; however, the classification of the Cretaceous redbeds in Zhejiang Province is under debate (Chen 2000; Wu et al. 2015). The surface landscape of the Jianglangshan is mainly formed in the Fangyan Formation. The intercalated volcanic beds in the lower part of the reddish succession in the adjacent Yujiang and Yushan basins of Jiangxi Province were dated at 91±3Ma (Li and Li 2010)

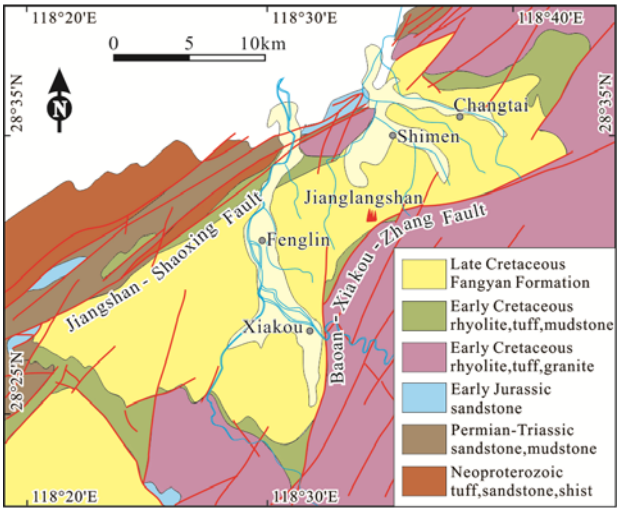

Figure 3 Simplified geological map of the Xiakou Basin (modified from Jiangxi Bureau of Geology 1982).

and 93±1Ma (Wu et al. 2014) by SHRIMP zircon U-Pb dating. In addition, regional stratigraphic correlation shows that the Fangyan Formation was deposited during the Coniacian-Santonian Stage, corresponding to the Hekou Formation in Jiangxi Province (Cao 2013). Therefore, the depositional age of the Fangyan Formation in Zhejiang Province is bracketed from 89 to 85 Ma.

2 Method

Bed thickness, geometry, sedimentary structures and lithology were observed in the outcrop section of the Lang Peak in the Jianglangshan Geopark. Eight conglomerate outcrops were chosen for pebble counting. At each counting location, two hundred pebbles were dug out from the relatively fresh rock surface, and pebble lithologies were recorded and compared with pre-Late Cretaceous strata in the study area. Moreover, the azimuth of the imbrication dip was measured using a compass in the field. Pebble lithology and azimuth measurements were used to constrain sediment derivation and paleocurrents. Sedimentary description and interpretation are mainly based on detailed field observations in conjunction with our previous studies (Guo et al. 2013; Chen et al. 2016) in the adjacent basins of Jiangxi Province.

3 Results

3.1 Facies description

A total of five facies were identified in this work (Figure 4). These include facies A (matrix-supported cobble conglomerate), facies B (pebble conglomerate), facies C (pebbly sandstone), facies D (fine-grained sandstone) and facies E (mudstone).

3.1.1 Facies A: Matrix-supported cobble conglomerate

Facies A is characteristically composed of cobble conglomerate beds, which are structureless, and vary from 30 cm to 100 cm in thickness and extend laterally for several meters (Figure 5a). Generally, these conglomerates fill erosive and shallow channelized bases. They are matrix-supported and poorly sorted with a mud to coarse-sand infill matrix. Clasts are mostly sub-rounded, commonly 3-13 cm in diameter, but range up to 18 cm. Sedimentary structures are absent in most cases.

3.1.2 Facies B: Pebble conglomerate

Facies B comprises the typical conglomerate beds that are most common in the Fangyan Formation of the Jianglangshan Geopark. These conglomerate beds are rich in sedimentary structures such as erosional bases, normal grading, clast alignment and imbrication. Wavy erosional bases are up to 50 cm in relief (Figure 5b) and the conglomerate beds generally vary from 20 cm to 100 cm in thickness. Owing to frequent cut-and-fill processes, pebbly lenses lie within broad, 50-100 m wide erosional bases. The conglomerates are moderately to well sorted, clast- to matrix-supported (Figure 5c) with clast sizes mainly ranging from 0.5-5 cm; occurring in units which are ungraded, normally graded or inversely graded. Outsized clasts range up to 38 cm in diameter with local concentration of pebble-grade clasts in shallow swales (Figure 5c). The clasts are sub-rounded to rounded, and infilled by sand to fine pebble matrix. The platy and elongate conglomerate clasts occasionally exhibit imbrication. Very rapid, lateral variation in texture can be readily observed on outcrops. The thin-bedded sandstone intercalations (Figure 5d) are lens-shaped and occur between the conglomerate beds, but they are commonly cut out by overlying conglomerates.

3.1.3 Facies C: pebbly sandstone

Facies C is characterized by pebbly sandstones that exhibit a gradational contact with the underlying conglomerates (facies B) and a sharp top boundary with the conglomerates of the next unit (Figure 5b). They are mostly structureless, but parallel bedding can be locally observed. These sandstone beds are laterally lensoid with a thickness less than 40 cm and minor amounts of pebbles dispersed throughout.

In addition, the pebbly sandstones comprise the sandstone divisions of the sandstone-mudstone alternations (Figure 5e, f). The sandstone divisions have comparatively flat and sharp bases with a thickness from 20 cm to 100 cm. Individual beds can be easily traced laterally for several tens of meters. The boundaries between the two divisions are flat and sharp, but not erosive. Some of them display normal grading, although most sandstone beds are ungraded with dispersed pebble-grade clasts.

3.1.4 Facies D: Fine-grained sandstone

This facies can either be intercalated between the conglomerate or sandstone beds (Figure 5d), or separate beds extending several tens of meters laterally (Figure 5g). In the former cases, the sandstone beds are lenticular and often cut out by the overlying conglomerate units. In the latter cases, they are extensive laterally with a thickness ranging from 30 cm to 80 cm. Normal grading and parallel bedding can be observed. They are fine- to medium-grained with minor amounts of small dispersed pebbles.

3.1.5 Facies E: mudstone

Facies E is comprised of mudstone layers that are 20-100 cm thick with less than 5 % randomly scattered fine pebbles. This facies is composed of mudstone divisions of the pebbly sandstone-mudstone alterations (Figure 5e, f), where they are tabular to lenticular and less than 20 cm in thickness, and contain sporadically scattered pebble- to fine cobble-grade clasts. Polygonal desiccation mudcracks were observed on the upper

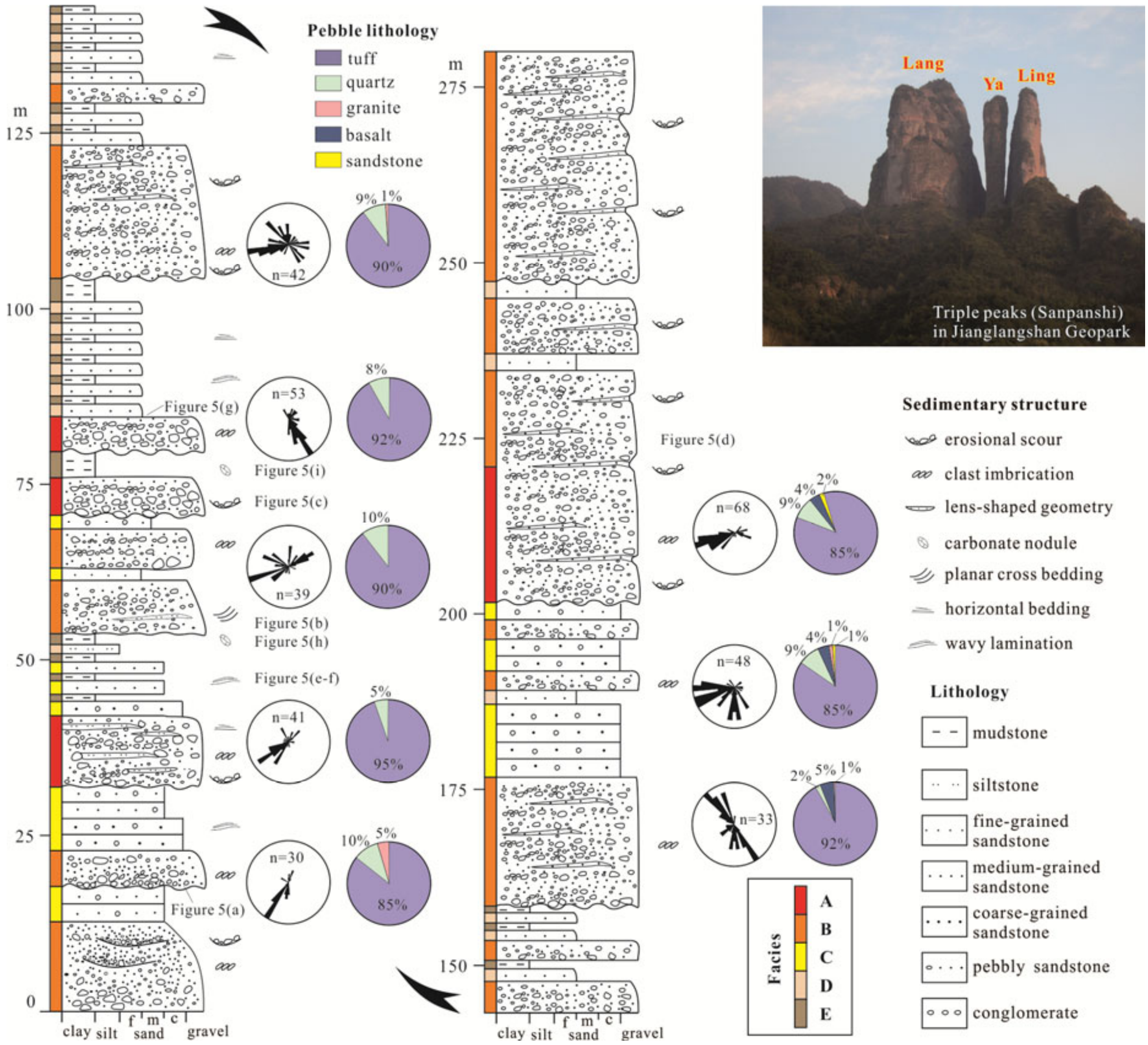

Figure 4 Stratigraphic section of the Fangyan Formation (89-85 Ma) along the Lang Peak region in the Jianglangshan Geopark. (Paleocurrent diagrams to the right of the column were plotted based on field azimuth measurements of pebble imbrication in coarse-grained lithofacies units. Pie charts of pebble lithology indicate that pebbles are dominantly composed of tuffs.)

bedding surfaces. In some cases, the structureless mudstones are rich in abundant small (normally 1-4 cm in diameter) irregularly-shaped carbonate nodules (Figure 5h, i).

3.2 Facies interpretation

3.2.1 Facies A: Matrix-supported cobble conglomerate

Both the textural immaturity and lack of sedimentary structures indicate that facies A is a sedimentary expression of rapid erosion and accumulation in the vicinity of a mountain front (Blair and McPherson 2009). The variable amounts of matrix that infiltrated the cobbles of the bed were possibly derived from disaggregation of shattered clasts. Thus, facies A is interpreted as a proximal fan deposit.

3.2.2 Facies B: Pebble conglomerate

The diagnostic characteristics including the clay to pebble matrix, poor sorting, clast alignment and imbrication, variable clast-size, vertical grading, lack of cross-stratification and few erosive bases collectively suggest that facies B was deposited by debris-flows on areally extensive alluvial fan lobes (Bull 1972; Steel 1974; Nemec and Steel 1984; Blair 1999; Blair and McPherson 2009; Imaizumi et al. 2016). The clast-supported gravels in the uppermost of the units (Figure 5c) resemble sieve deposits probably formed by a passing fine-

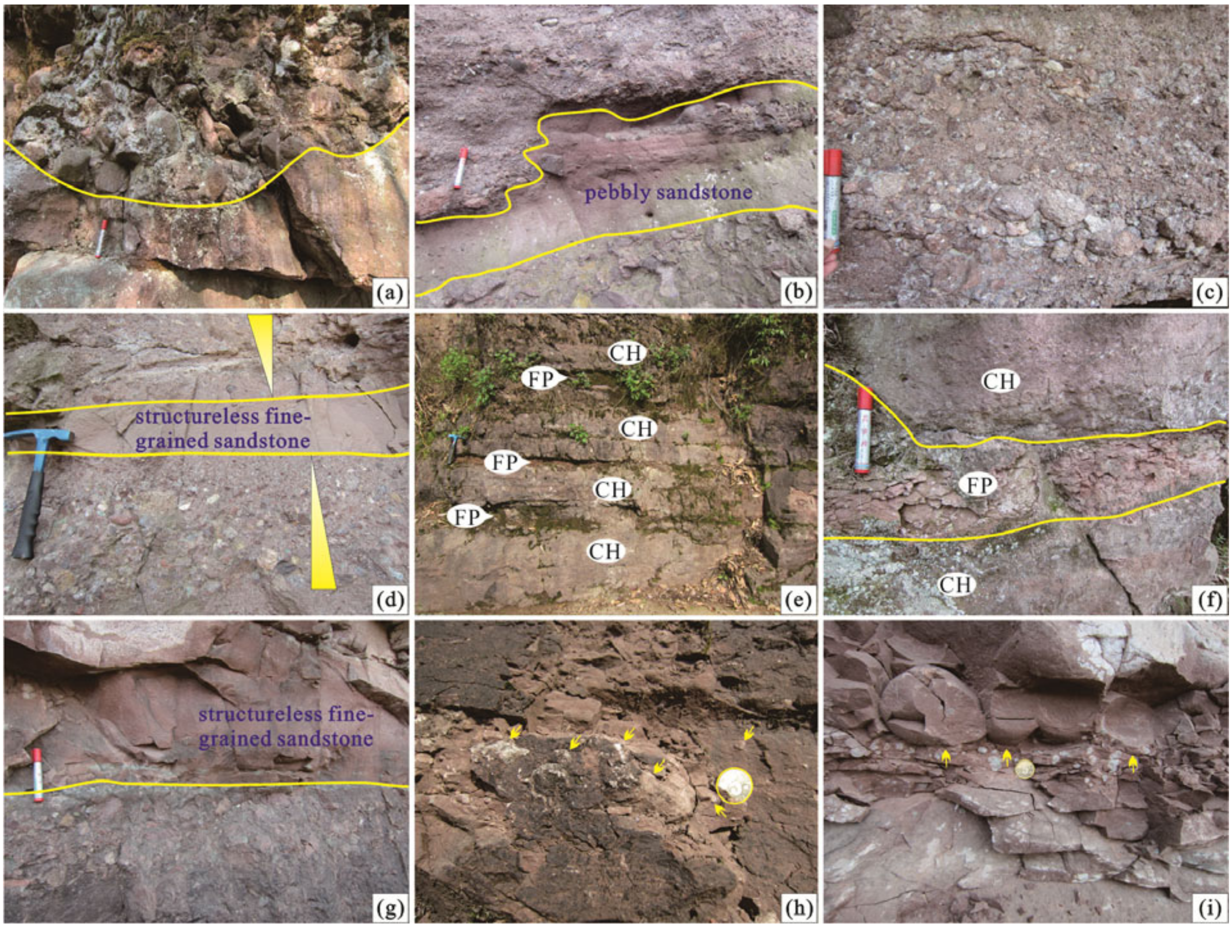

Figure 5 Typical outcrop photos showing diagnostic sedimentary fabrics. (a) Disorganized matrix-supported conglomerate and erosional base (facies A); (b) Sharp and erosional base below the conglomerate bed; (c) Concentrated pebble mantle; (d) The structureless fine-grained sandstone are interbedded between the normal graded conglomerate below and the inverse graded conglomerate above; (e) Alternations of channel sandstone (CH) and floodplain mudstone (FP); (f) Close-up of the sandstone-mudstone units in Figure 5(e); (g) The structureless sandstone bed is underlain by disorganized conglomerate bed; (h) The structureless mudstone bed with abundant carbonate nodules (yellow arrow); (i) Carbonate nodules (yellow arrows) and grey mottles in mudstone. The marker pen in (a), (b), (c), (f), (g) is 12 cm long. The hammer in (d) and (e) is 27 cm long, and the coin in (h) and (i) is 2.5 cm in diameter.

grained flow within the permeable framework of clasts (Major 1998). Clast alignment and imbrication are suggestive of high viscosity and shear strength due to high matrix strength and low water concentration (Sohn et al. 1999). The rare erosive relationship between conglomerates and pebbly sandstones possibly imply a laminar flow with a high apparent viscosity rather than normal traction currents, whereas the lack of sedimentary structures and the poor sorting with matrix-supported outsized clasts support a high sediment/water concentration and a wide range of clast sizes during transportation (Steel 1974; Sohn et al. 1999). The inverse grading was likely produced by clast collision, with upward displacement of large clasts due to combination of dispersive pressure with kinematic sieving (Jullien et al. 1992).

3.2.3 Facies C: pebbly sandstone

As intercalations between the conglomerate beds (Figure 5b), the irregular pebbly sandstone beds were likely deposited by low energy stages of a laminar flow at the end of flooding events. Moreover, the pebbly sandstone beds alternate with mudstone beds to form the regular bedding patterns (Figure 5e). These alternations are thought to have been deposited by sandy braided streams. The sandstone member represents stream channel deposits whereas the overlying mudstone member represents overbank sediments.

3.2.4 Facies D: Fine-grained sandstone

The lack of sedimentary structures, lenticular bed geometries and stratigraphic relationship with conglomerate beds indicate that facies A was the depositional expression of the later non-catastrophic discharge of flooding events (Blair and McPherson 2009). In contrast, when the fine-grained sandstone beds are 30-80 cm thick and extend for several tens of meters, they are interpreted as deposits of lacustrine environments owing to absence of structures except for horizontal beddings in few outcrops.

3.2.5 Facies E: mudstone

The abundant carbonate nodules scattered within the mudstone beds are paleosols, developed by pedogenesis under a prevalent arid climate during Late Cretaceous in SE China (Chen 1997). But the pedogenic carbonate nodules are indicative of seasonal precipitation (Tabor and Myers 2015). This type of mudstone, altered by pedogenesis over a wide area, is suggestive of lengthy episodes of landscape stability (Kraus 1999).

4 Depositional Environments

Facies A and B are characterized by cobble- to pebble-grade clasts with occasional occurrence of outsized clasts, mud to coarse sand matrix, basal erosional surfaces, clast imbrication and alignment. All of these sedimentary features are suggestive of streamflow-dominated alluvial fans. Facies C could either be the part of an alluvial fan succession because of the intimate relationship with conglomerate, or the sandstone division of a braided stream succession. At last, facies D and E are dominantly composed of fine-grained sediments, which were deposited in low-energy environments such as floodplain or lacustrine. Therefore, the depositional environments are envisaged to have consisted of alluvial fans at the mountain fronts, braided streams in the middle fans, and floodplains or lakes in the distal areas (Figure 6). This paleogeography was probably representative of the intracontinental extensional basins during Late Cretaceous in Southeast China (Shu et al. 2009; Wu et al. 2015; Chen et al. 2016), and shares significant similarities with the Cenozoic Basin and Range Province in western North America (Gilder et al. 1991).

According to pebble counting results at the eight conglomerate outcrops (Figure 4), pebbles of the Lang Peak are dominantly composed of volcanic tuffs with an average of 89.11%, and minor amounts of gravels are composed of quartz, basalt, granite and sandstone, with average percentages of 7.81%, 1.76%, 0.94% and 0.38%, respectively. By comparison with the outcropped strata in the study area (Figure 3), the Early Cretaceous volcanic rocks are inferred to be the dominant source rocks dispersing significant sediments to the basin.

The preferred orientations of the oblate and elongate clasts from the Fangyan conglomerates are plotted in Figure 4. According to the rose diagrams to the right of the measured section in the Lang Peak area (Figure 4), the sediments were mainly derived from the southwest and northeast for the lower part, and the west and south for the upper part of the Fangyan Formation. However, the provenance was more enigmatic during the deposition of the middle part of the Fangyan Formation, when source terranes from the southeast, west, and northwest possibly contributed vast volume of sediments to the basin. The changes in paleocurrents and provenance are probably indicative of syn-depositional fault activities on the basin margins which further controlled the paleo-catchment areas. Therefore, both the sediment dispersal and facies distribution patterns were likely influenced by tectonism during basin development.

5 Implications for Danxia Landform Evolution

During the past several decades, landscape evolution has attracted much attention from geomorphologists, and weathering has been interpreted as playing a crucial role in shaping the landscapes (Turkington and Phillips 2004; Turkington and Paradise 2005; Mustoe 2010; Tucker and Hancock 2010; Groom et al. 2015; Zhu et al. 2015). The red-colored steep cliffs, Danxia landforms including those in the Jianglangshan Geopark, develop mainly in the Cretaceous sedimentary bedrock in Southeast China. The modern Danxia landform has been inferred as the product of multistage evolution involving weathering (Guo et al. 2012), fluvial erosion and rock fall along the steep joints and fractures caused by uplift and faulting of the originally near-horizontal strata (Peng et al. 2015 and reference therein). As a result, the Danxia landforms are characterized by flat top uplands, steep cliffs with foot-slopes grading into floodplains.

Because the Cretaceous sedimentary strata in Southeast China are dominantly composed of the continental redbeds, the Danxia landforms are widespread in this area. The underlying bedrock is predominantly the result of rift basin infilling within the late Mesozoic Basin and Range Tectonic System in Southeast China (Wang and Shu 2012), and it constitutes the lithologic base supporting the spectacular present-day Danxia landforms.

Many previous studies thought it was a uniform development of Danxia landform evolution caused by river erosion after deposition. Moreover, simulation modeling indicates that the Danxia evolution resulted from fault-block uplift followed by fluvial incision leading to the present-day landscape (Yan et al. 2015). However, the deeply incised Danxia cliffs are mostly found at the basin margin. In addition, remote sensing analysis shows that the Danxia landforms are mainly distributed along the basin margin and dominated by resistant alluvial fan conglomeratic bedrock (Jiang et al. 2010). In the mountain front areas, alluvial fan processes are envisaged to have been active and responsible for thick accumulations of conglomerate-dominated reddish sedimentary

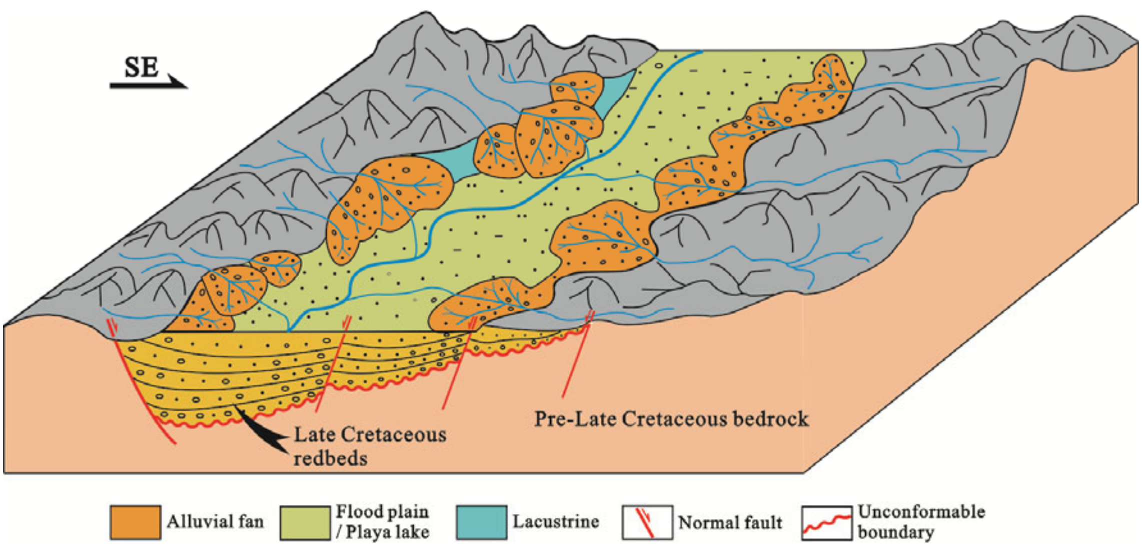

Figure 6 Generalized depositional scenery of the Fangyan Formation in the Jianglangshan Geopark. Danxia landscapes are mainly observed in the alluvial fan conglomeratic redbeds.

succession. These processes have also been recognized in the Yongfeng-Chongren (Chen et al. 2016) and Xinjiang basins (Guo et al. 2013) in Jiangxi Province. Therefore, we suggest that the dissimilarities of the sedimentary facies across the basin should be fully considered in the study of the Danxia evolution modeling.

6 Conclusions

(1) The conglomerate-dominated redbeds of the Fangyan Formation in the Jianglangshan Geopark were deposited by streamflow-dominated fans during the Late Cretaceous. These coarse-grained facies form the lithologic base for the subsequent evolution of the Danxia landform features. The Danxia landform locations are controlled by the combination of lithologic facies and positions of fault systems. Therefore, the normal faults along the basin margins should be responsible for the spatial positions of the Danxia landforms.

(2) The resistant cliffs of the Danxia landforms are associated with conglomerate-dominated bedrock, whereas lowlands are underlain by more easily eroded fine-grained lithofacies. Therefore, stratigraphic analysis and sedimentary facies maps are key components necessary to fully model Danxia landform evolution.

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