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RESEARCH ARTICLE

Origin and Evolution of the South Sichuan Basin Danxia Landform: Insights into Broader Chinese Danxia Landform Development

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Abstract

Danxia landform, recognized for its steep cliffs and red coloration, has drawn significant scientific attention. While Chinese Danxia Landforms are UNESCO World Heritage Sites, their genesis and evolution, particularly in less-explored regions, remain under study. The southern Sichuan Basin, one of China's three largest Danxia outcrop areas, offers a unique case study due to its distinct geological setting and limited research. This study investigates the genesis of Danxia landforms in the southern Sichuan Basin using a multi-faceted approach. Field observations documented geomorphological characteristics and stratigraphy of the Danxia formations. Tectonic analysis, using regional structural data and fault mapping, assessed the impact of tectonic uplift and deformation. The findings suggest that the genesis of Danxia landforms in the southern Sichuan Basin is driven by four factors: (1) thick, well-bedded red sandstones and conglomerates; (2) regional tectonic structures, such as faults and folds; (3) episodic tectonic uplift, creating topographic relief and fluvial incision; and (4) the combined effects of weathering, erosion, and gravity shaping the cliffs. The analysis challenges the prevailing southeast-to-northwest evolutionary model for Chinese Danxia, as the southern Sichuan Basin follows a distinct developmental trajectory, influenced by regional tectonic settings and external forces. This study shows that Danxia genesis is a complex interaction of lithological, tectonic, and geomorphic processes. The findings highlight regional variability and underscore the importance of considering regional tectonic context and external forces in understanding Danxia evolution across China. This research deepens understanding of Danxia genesis and provides insights for conserving these globally significant landscapes.

Keywords: Danxia landform, genesis and evolution, tectonic structures, evolutionary model, south Sichuan basin.

1 Introduction

Danxia landform, a concept first theorized by Chinese scholars, refers to steep cliffs and relevant landscapes that consist of red beds mainly composed by red sandstones. It is famous worldwide for its unique

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brick-red colour. China is the earliest to do systemic research on Danxia landform, since Danxia landforms widely distribute here [1]. According to previous field work, more than 1000 spots have been reported in 28 provinces in China, through the north to Ning'an City in Heilongjiang, south to Qionghai in Hainan, west to Wuqia County in the Xinjiang Uygur Autonomous Region, and east to the coastline in Xiangtan in Zhejiang [2]. Danxia landforms, the precious natural heritage preserved in the long tectonic history, are of great value in aesthetics, science, education, adventure, healthcare and social economy [3, 4]. That's why it has become one of research hotspots in earth science field. Scenic areas and national geological parks have sprung up aiming to protect Danxia landforms, such as Qiyunshan National Geological Park in Anhui, Pingliang Kongtong National Geological Park in Gansu, Chengde Danxia Landform National Geological Park in Hebei, and Guangzhi Mountain National Geological Park in Fujian. Some parks also were awarded the title of World Geological Park by UNESCO. Especially in the 34th UNESCO World Heritage Committee held in Augest 2010, Danxia landforms integrated by scenic areas of Taining in Fujian, Langshan in Hunan, Danxiashan in Guangdong, Longhu Mountain in Jiangxi, Jianglang Mountain in Zhejiang and Chishui in Guizhou were successfully inscribed into the World Heritage List, which marked the concept of Danxia landform has been accepted by the rest of the world and the research on Danxia landform started to boom.

The south of Sichuan basin (SSB for short) is one of the three pivot areas where Danxia landforms largely distribute, north to the Rongxian in Zigong, south to the Gulin County in Luzhou and Chishui in Guizhou [2, 5]. River valleys in SSB usually cut so deeply that brick-red cliffs have such distinct height differences that many waterfalls developed here, which stands in sharp contrast to Danxia landforms in other areas in the Southeast China. For example Danxia Mountain in Guangdong is featured by flat top, steep cliff and gentle mountain foot. Although Danxia landforms in SSB are widely developed, few researches were conducted during the past decade, let alone the genesis. That's why it is not as well-known as the Danxia landform in the Southeast China. The evolution series presented by the aforesaid six world natural heritage parks in China consists of six different stages, namely the early and late stages of youth, early and late stages of prime, early and late stages of decline. The characters of Danxia landforms in SSB are in conformity with typical Danxia landforms at early evolutional stage. Thus, if no thorough research on Danxia landform in SSB is done, it will be hard to completely reveal the genesis and evolution of Danxia landform in China. That is where the significance of this study lies.

2 Geological setting

Tectonically, SSB is located on the northwest margin of Yangtze block, also the convergent hinge of Yangtze block, Qinling-Qilian Mountain -Kunlun Mountain orogenic belt and northern Qiangtang-Sanjiang orogenic belt (Figure 1), where underwent fierce multiple-stage interaction of the plates and finally gave rise to the current basin-like landform. Longquanshan-Santai-Bazhong-Zhenba fault belt and Huayingshan fault belt divide the whole Sichuan basin into three tectonic units, namely west Sichuan depression area, central uplift belt and east Sichuan high-cliff fold area [6]. The study area in this paper cross lies on the northwest margin of Yangtze block and the southeast of the central uplift belt and eastern Sichuan high-cliff fold area (Figure 1).

The strata in the study area are dominated by Mesozoic and Palaeozoic strata, while Cenozoic and Proterozoic strata are seldom seen (Figure 2). Proterozoic strata are composed by upper Sinian. Paleozoic strata consist of Cambrain, Ordovician, Silurian and Permian strata. Mesozoic strata, including Triassic, Jurassic and Cretaceous strata, are widely spotted. There are several large faults in this area, such as Huayingshan fault, Emei-Yibin fault, Naxi fault, Xinglongchang fault, Rongxian-Weiyuan fault, Hebaochang fault, etc [8]. Huayingshan fault, the fundamental fault, about 500km in length, starts from Dazhou in the north and stretches to Rongchang and Yibin in the north [9]. It is composed by 2 (or 3) main faults with NE strike and SE dip that control the distribution of Triassic and lower Jurassic strata. Meanwhile, it is also the boundary fault that separates the Central uplift belt and East Sichuan high-cliff fold area. Emei-Yibin fault lies on the southwest part of SSB, trending NW. It starts from Ya'an and extends to Yibin via the study area with a rough length of 220 km.

3 Distribution of Danxia landforms in SSB

In the south of Sichuan basin, Danxia landforms mainly distribute in the cities of Yibin, Leshan, Luzhou and Zigong, and the first three cities also famous for their Danxia landforms –related scenic areas, such as Bamboo Sea in south Sichuan, giant Buddha in Leshan,

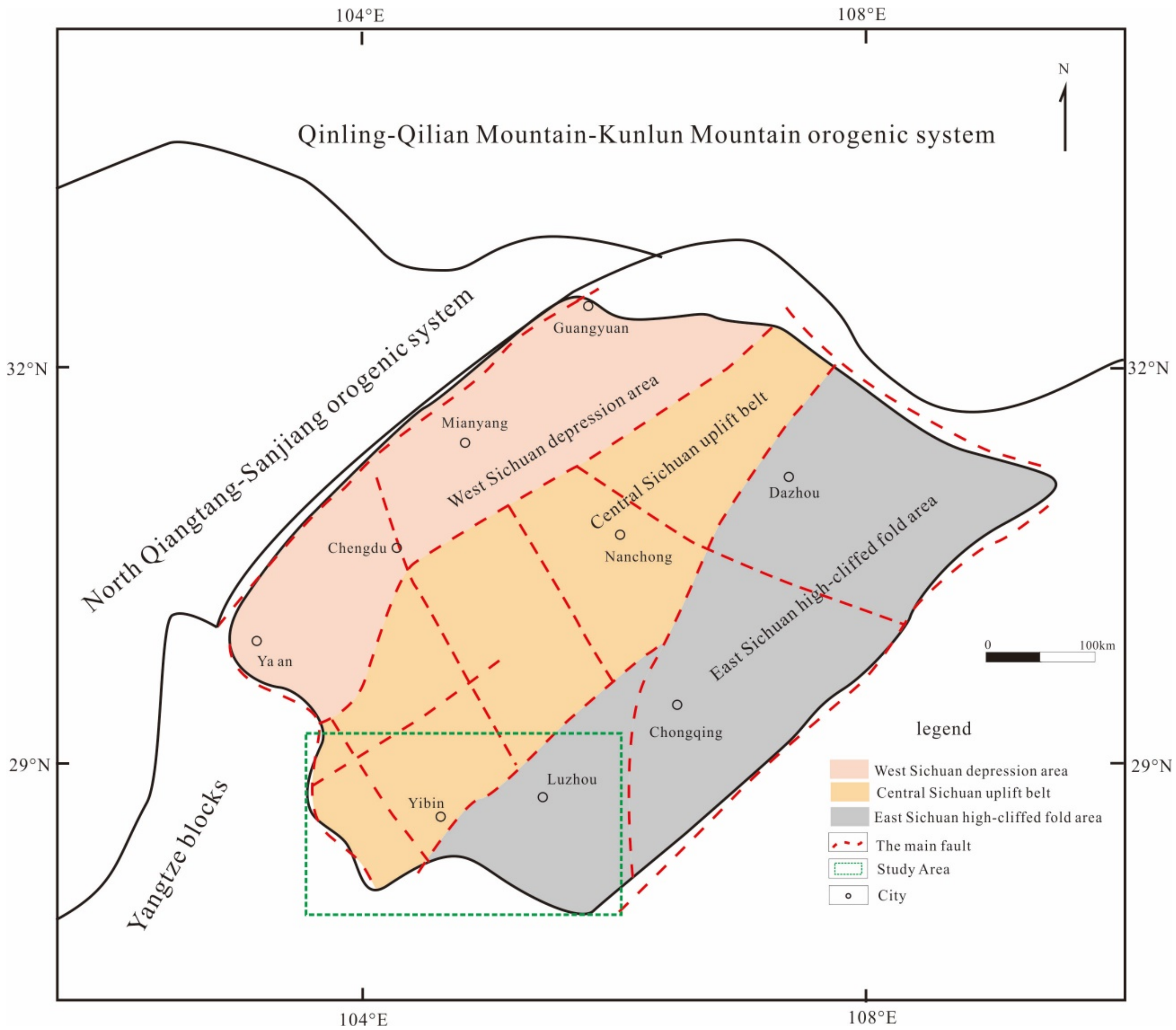

Figure 1. Tectonic location of the Sichuan Basin and the study area [6, 7].

and Huangjinglaolin in Luzhou. Luzhou is the one that better took advantage of its tourism resource, with nine maturely-developed scenic areas. Relatively speaking, more chances are left to Yibin and Leshan to further explore their Danxia landform resource (Table 1).

Danxia landforms are seldom seen in Zigong that the exploration of Danxia landform lags behind schedule. Jianshan-Feilongxia, Jinhua Alsophila valley and Wutiaogou, three scenic areas relying on Danxia landform, are under construction. Owing to the implementation of Feilongxia Project and Tourism Fast Track Project, it is hopeful for Zigong to build the first four-star scenic area based on Danxia landform resource.

4 Genesis of Danxia landforms in SSB

Based on the field work and tectonic analysis, we concluded that the genesis of Danxia landforms in South Sichuan is highly related to the regional strata, regional structures, tectonic uplift, and external forces.

4.1 Regional strata

The brick-red beds offer material basis for the formation of Danxia landforms. The red beds are classic strata and usually deposit in the inland lake or river, composed by conglomerate, sandstone and mudstone, with rhythmic bedding. Mesozoic is the main period when most red beds formed in China, featured by colours from purplish red, gray purple to dark red. Micro photos of samples revealed that the

Table 1. Distribution of Danxia landforms in South Sichuan.

City	Scenic area	Honor	Location
Yibin	Bamboo Sea	National Four-Star Scenic Area	N28°27′43.440″;E105°00′52.130″
	Qi Donggou	National Four-Star Scenic Area	N28°40′10.553″;E105°01′13.790″
	Pingshan Baxianshan	National Three-Star Scenic Area	N28°47′17.179″;E104°01′17.805″
	Shengtian Hongyan Mountain	National Four -Star Scenic Area	N28°41′49.177″;E104°45′34.398″
	Kejiu Hongyan Mountain	National Two-Star Scenic Area	N28°22′19.220″;E104°26′35.884″
	Yuntai Mountain	Provincial Forest Park	N28°59′19.168″;E104°52′20.592″
	Shicheng Mountain	Provincial Forest Park	N28°30′38.588″;E104°20′17.518″
	Danshan Bishui	Provincial Key Cultural Relics Protection Unit	N28°47′35.423″;E104°26′23.082″
	Baizhuhai, Renhe	Provincial Forest park	N28°30′34.302″;E105°09′05.819″
	Hongyanwo,Shigu		N28°49′22.236″;E104°49′50.392″
	Huahai Tianyuan		N28°49′01.884″;E104°42′44.236″
	Guankou park		N28°46′15.112″;E104°57′06.111″
	Huishigou		N28°49′54.966″;E104°32′29.092″
Leshan	Leshan Giant Buddha	National Five-Star Scenic Area World Cultural & Natural Heritage	N29°32′48.407″;E103°46′08.508″
	Foot and middle of Emei Moutain	National five-Star Scenic Area World Cultural & Natural Heritage	N29°34′38.064″;E103°24′13.896″
	Muchuan Zhuhai	National Forest Park National Three-Star Scenic Area	N28°52′34.831″;E103°57′48.307″
	Qianfoyan	National Key Cultural Relics Protection Unit; World Irrigation project Relic National Three-Star Scenic Area	N29°45′14.089″;E103°32′26.669″
	Pingqiang Xiaosanxia	Provincial Scenic Area	N29°42′53.454″;E103°45′28.077″
	Mabian Danxia		N28°48′03.373″;E103°42′08.621″
	Liaoqingyan		N28°51′01.022″;E103°59′24.622″
	Yunfeng Mountain		N29°12′00.000″;E104°08′09.215″
	Ziyun Mountain		N29°07′21.437″;E103°59′12.013″
	Biyunshan	County Cultural Relics Protection Unit	N29°39′39.607″;E103°39′47.785″
Zigong	Feilongxia- Jianshan	National Four-Star Scenic Area	N29°16′03.482″;E104°38′54.977″
	Jinhua Alsophila Valley	World Geopark	N29°15′24.597″;E104°08′37.395″
Luzhou	Huangjin Laolin	National Four-Star Scenic Area	N28.270055°;E105.728539°
	Tianxiandong	National Four-Star Scenic Area	N28°42′53.891″;E105°24′38.128″
	Qingxigu	National Four-Star Scenic Area	N28°43′49.200″;E105°15′21.896″
	Fobao Scenic Area	National Forest Park National Three-Star Scenic Area	N28°39′37.924″;E106°08′22.335″
	Huagaoxi Nature Reserve	National Nature Reserve	N28°16′16.534″;E105°32′38.368″
	Fangshan	National Three-Star Scenic Area	N28°49′13.596″;E105°20′39.382″
	Qingliangdong	National Key Cultural Relics Protection Unit	N28°20′52.764″;E105°19′03.044″
	Danshan	Provincial Scenic Area	N28°11′51.262″;E105°29′26.162″
	Dongwo Valley	National Three-Star Scenic Area	N28°54′21.459″;E105°31′19.950″
	Bijiashan	National Two-Star Scenic Area	N28°48′51.172″;E105°47′28.057″

major contents of the sandstone are quartzes, feldspars and mica, and the minor minerals include hematite and limonite that act as cement. That explains why the rocks are commonly reddish.

The strata in the study area rang from Triassic to Cretaceous. All red beds where we collected sample can be plotted in Cretaceous strata as Figure 3 shows. Hence, more specifically, the Cretaceous strata are the material basis of Danxia landforms in SSB.

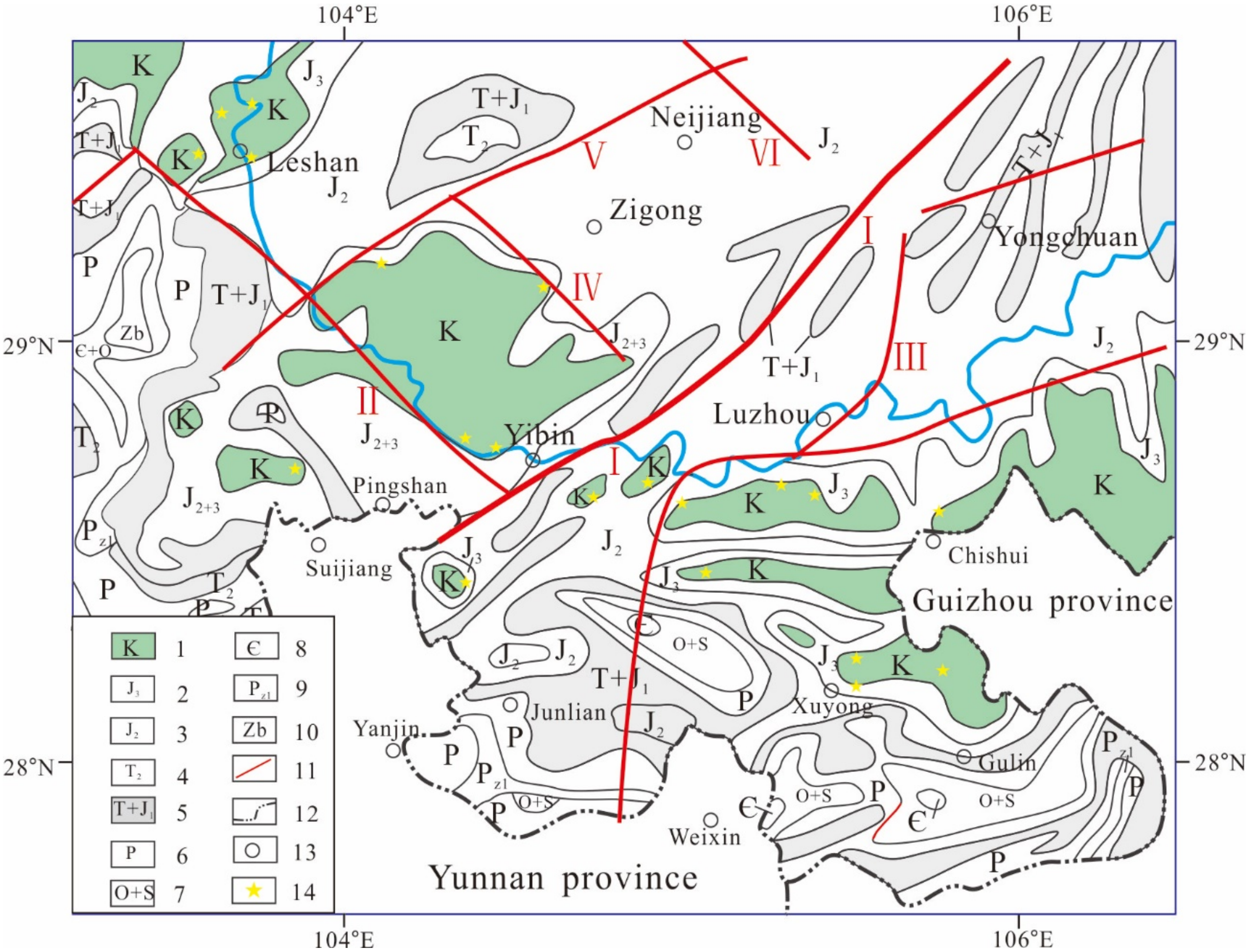

Figure 2. Distribution sketch of the strata and major faults in the study area. 1. Cretaceous; 2.upper Jurassic; 3.middle Jurassic; 4.middle Triassic; 5.Triassic-lower Jurassic; 6. Permian; 7.Ordovician -Silurian; 8. Cambrian; 9.lower Palaeozoic erathem; 10.upper Silurian; 11. fault; 12.provincial boundary; 13.city; 14. Scenic area with Danxia landform; I. Huayingshan fault; II. Emei-Yibin fault belt; III. Naxi fault; IV. Xionglongchang fault; V. Rongxian-Weiyuan fault; VI. Hebaochang fault.

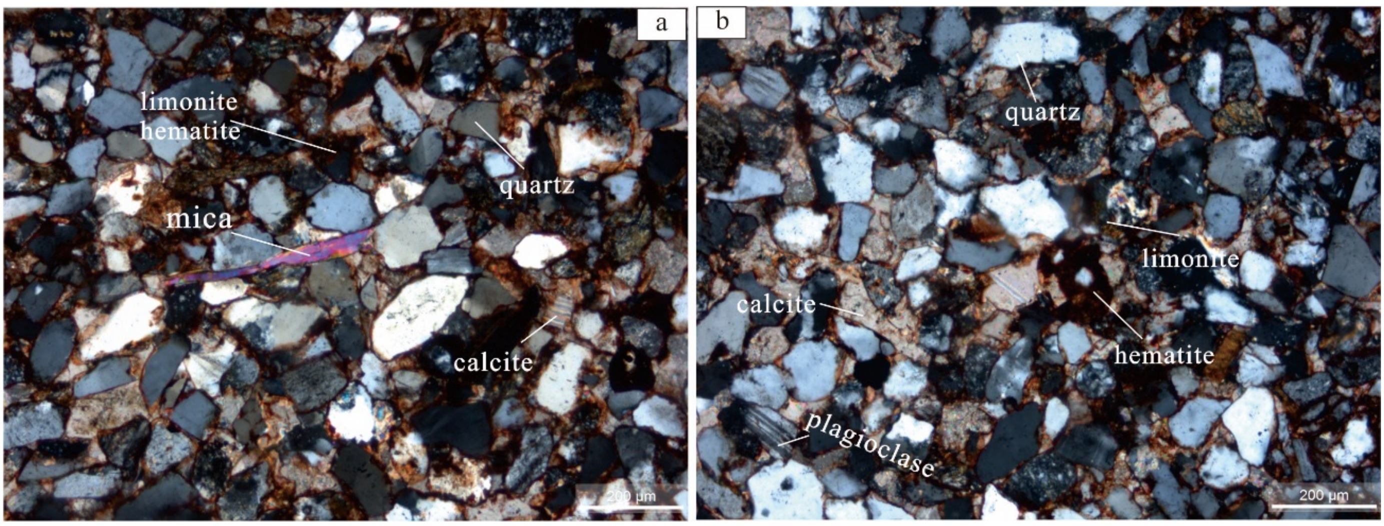

Figure 3. Micro photos of sandstone from Cretaceous samples in this study area.

Figure 4. Outcrops of Danxia landform in South Sichuan. a.joints preserved in Bijiashan; b-d. joints preserved in Kejiu Hongyanshan.

4.2 Regional structures

4.2.1 Joints

Regional structures control the formation of Danxia landform and affect its evolution. Large-scale regional structures almost determine the scale and distribution of Danxia landforms, while small-scale structures often affect the final appearances and forms [10]. Speaking of the regional structures controlling the formation of Danxia landform, we usually refer to joints, faults and bedding. As Figure 4 shows, joints occur widely in the red beds, with high dip angle ranging from 60° to 90°. These joints can be classified into two groups according to their trends (group A trending 40° 90°; group B trending 300°~350°.) Their cutting relation can be observed easily and clearly at Bijiashan. Two groups of joints are preserved in rocks at Woniushi scenic spot at Bijiashan (Figure 5). Judged from their cutting relation, the first group developed earlier than the second group. They together cut the whole rock into several rectangles. Commonly the joints control the finally form of the brick-red beds. For example, the steep single cliff or wall-like mountain is always shaped by a group of steep joints, while the quadrate and house-like Danxia landform is controlled by at least two groups of joints that cutting each other.

4.2.2 Faults

Large-scale fault usually decides the framework of regional geology and the spatial distribution of strata, some of which are large enough to cut through the crust and are called basement rift. Small faults can reshape the landscape and form the ultimate outcrops [11]. As Figure 2 shows, strata and Danxia landforms in South Sichuan are obviously controlled by large-scale faults, especially by the Huayingshan basement rift which determined the deposit of Triassic and lower Jurassic strata and divided the Cretaceous red beds into two parts in SSB. On the west side of Huayingshan fault, Cretaceous strata mainly distribute in Xuzhou district of Yibin, Muchuan, Jianwei and the central part of Leshan City, while on the east side, the Cretaceous strata concentrate in the counties of Jiang'an, Changning, Xuyong and Hejiang. Frequent earthquakes took place in counties of Junlian, Gongxian and Changning Yibin recently must be relevant to the movement of

Figure 5. Joints preserved at Woniushi at Bijiashan scenic area.

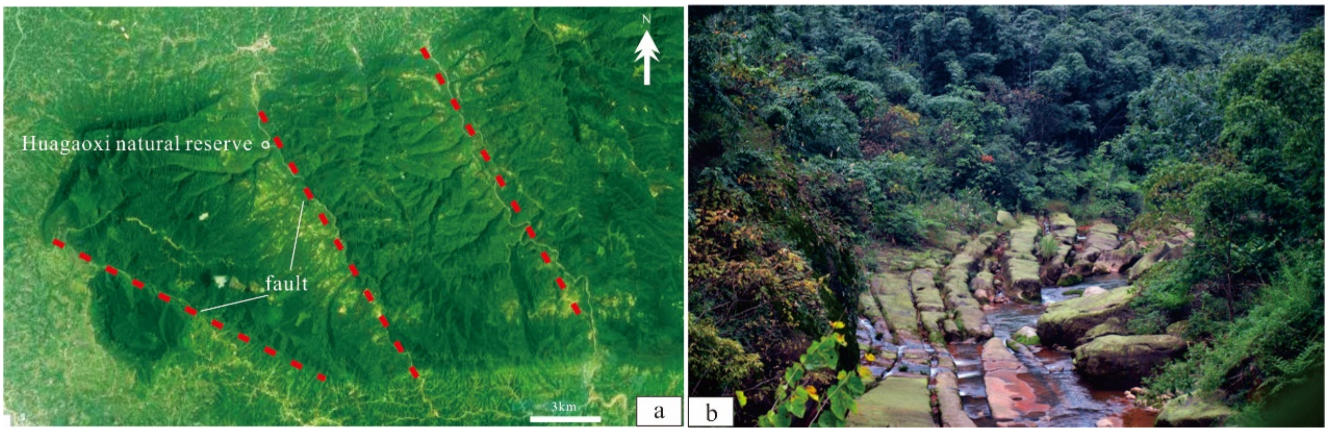

Figure 6. Faults satellite image and picture of a valley at Huagaoxi Natural Reserve.

Huayingshan fault. Other faults, such as Emei-Yibin fault, Xinglongchang fault and Rongxian-Weiyuan fault control the formation of Danxia landforms in Yibin and Zigong.

During the formation process of Danxia landform, like joints, faults also play essential role in determining the appearance of Danxia landforms, especially in the scale and distribution pattern. As Figure 6 shows, serial deep NE-trending faults are preserved at Huagaoxi National Reserve, cutting the horizontal red beds into blocks and give rise to several deep valleys. The cliffs at both sides of the valley are typical red beds, indicating that the fault do control the appearance and distribution of Danxia landforms.

4.3 Tectonic uplift and evolution

Crust uplift after the formation of red beds constrains the evolution of Danxia landforms. It lifted deeply-buried strata to the erosion surface. If there is a long-term stable period after the crust lifting, it will facilitate the Danxia landform's evolution from birth to decline. The magnificent Danxia landforms

Figure 7. Weathered pebbly sandstone at Guankou scenic area.

we see today are the result of millions of year's erosion and evolution.

Scholars have adopted fission track to calculate the uplift pace. Theoretically, the fission track age of minerals is considered the time when the mineral cooled due to the uplift of crust, because the mineral gets cooler when it is carried to the shallower depth during the uplift process [12]. Previous studies concluded that since late Cretaceous, Sichuan basin have undergone discrepant erosions because of the collision of plates or blocks. During80∼20Ma, it is slowly uplifted and cooled, but from about 20Ma the uplift accelerated and entered erosion stage. The uplift and erosion of Sichuan basin have reaches about 2,500m in average, with more than 4,000m erosion thickness along the margin of the basin [13]. Research based on fission track of the apatite collected from different depths revealed the time limit of the uplift of the south margin since Mesozoic. It started from 95∼60 Ma and lasted to 2 Ma. During 5Ma∼2Ma, a widespread fast uplift event occurred, which is considered to be the result of Himalayan tectonic movement .It is the two stages of crust uplift that lifted the red beds deposited in Cretaceous to the erosion surface and exposed them under the external forces which worked together to give rise to the Danxia landforms in SSB.

4.4 External forces

Regional structures and crust uplift are both the inner processes of the earth. External forces, such as weathering, erosion, transportation, deposition and diagenesis also play indispensable role in the formation of landforms. As for the external forces relevant to the formation of Danxia landform in South Sichuan, we refer to weathering and fluvial erosion.

Weathering processes can be classified into chemical, physical weathering and biological ones. The process is always slow and affected by climate, moisture and temperature. For example, the distance from water usually hastens weathering discrepancy. As Figure 7 shows, the weathering of the same layer is much more obvious at the spot near a waterfall at Guankou scenic area than those far from the waterfall.

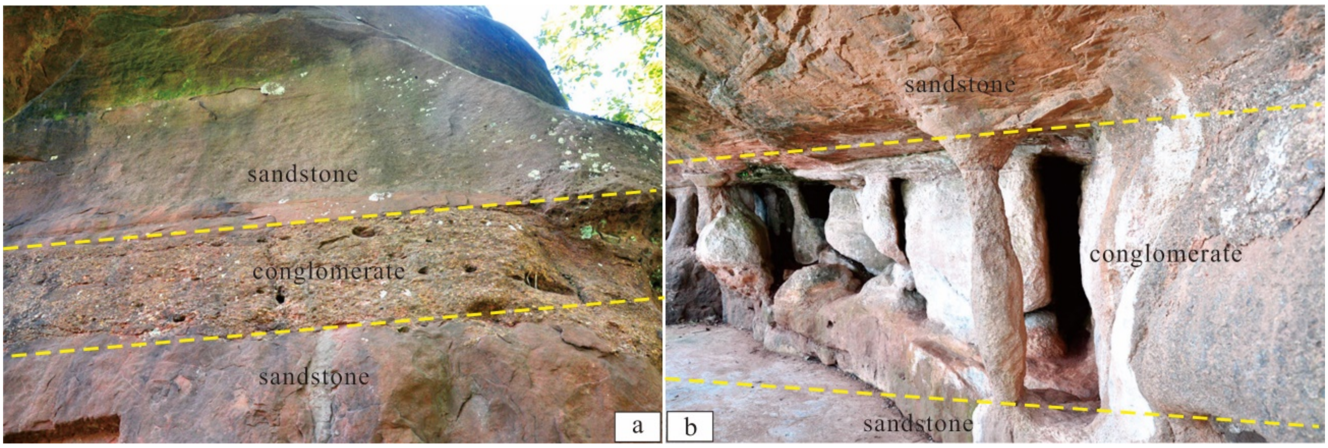

Figure 8. Weathered conglomerate at Bijiashan scenic area.

5 Indication to the evolution of Danxia landforms in China

The evolution process is rather complicated. Generally, it initiates from the tectonic uplift which leads to small fractures even fault, the weakest part of rock layers and the preferential part where weathering usually starts. As the weathering and erosion processing, Danxia landform will finish its life circle from birth to growth till death. Peng et al. [14] classified Red beds in China into six stages with reference to the Method of Area –Height Ratio came up with by A.N. Strahler, namely early and late stages of youth, early and late stages of prime, early and late stages of decline, presented by red beds in Chishui, Taining, Langshan, Danxiashan, Longhushan and Jianglangshan respectively. Peng not only described the landscape features but also proposed relevant quantitative indexes that have been widely accepted as a popular model to explain the geomorphic evolution stages for a long period. However, further researches overturned Peng's conclusion. Quantitative analysis based on area-height integral was conducted on ASTER DEM data, and the result proved the evolution stages of Longhushan and Danxiashan in Peng's previous classification is contrary to the truth [15], indicating there are shortcomings in Peng's model that merely takes the geomorphic features of landscape into consideration and temporal relation shouldn't be ignored.

Red beds in SSB and Chishui in Guizhou were classified into the early stage of youth according to Peng's model which should be featured by less 20% erosion amount and constant primary planation surface. However, it is difficult to explain what we observed in fields at the study area and Danxiashan in Guangdong by reference to Peng's model.

First, red beds at their early youth stage are considered to just suffer mild erosion that plateaus and valleys often develop widely. But in the study area, amount of isolated mountains can be spotted in the study area, such as Bijiashan, Danshan, Shichengshan, and Kejiu-Hongyanshan, etc. Most Cretaceous strata around these mountains have been eroded away to get the odder Jurassic strata exposed (Figure 2), which suggests the erosion amount is more than 20%, similar to features at the decline stage.

Secondly, distinct discrepancies have been observed between the red beds in this study area and those at Danxiashan in Guangdong in rock property, regional structure, tectonic uplift and external forces.

1. Discrepancy in rock property
   Although the strata in this study area and in Danxiashan are both belong to Cretaceous, those in Danxiashan are composed by larger-grained conglomerates and sandstone, such as Yangyuanshi and Shuangrushi at Danxiashan. Conglomerates in these relics are more resistant to weathering than sandstones. However, sandstones dominate in the strata in SSB while conglomerates are barely seen which exist as thin bedded layers at Bijiashan and Guankou. These conglomerates layers are less resistant to weathering than thick sandstones layers that it facilitates the formation of caves (Figure 8).

2. Discrepancy in regional structure
   Large-scaled joints widely developed in Danxiashan, which contribute significantly to the formation of Danxia landforms [16]. The intensity and density of the joints decided the final geomorphic features of the landscapes. The study area is located on a rigid plate that most

fault developed on the magin of Sichuan basin rather than in the centre [17]. Although most steep cliffs in SSB are related to joints, compared with those in Guangdong, they are much smaller both in quantity and in scale.

3. External forces
Danxiashan lies in the southeast coastline, under the subtropical humid monsoon climate, where monsoon prevails. The moisture and salt in the air exacerbate the weathering and erosion to red beds. The study area lies in Sichuan basin which had undergone multi-stage tectonic movements in geological history. The surrounding high mountains stop the humid air from seas. Unique climate is generated in the lower basin. Wind is always weak around the year that weathering process is quite slow here, which is distinctly different from the coastline area.

4. Tectonic uplift
Red beds in this area have undergone twice tectonic movements, around 90∼20Ma and 20∼0Ma respectively. During the second tectonic movement, especially around 5Ma, a large-scaled uplift took place. Researches on the regional evolution in Guangdong, Hunan, Yunnan and Huizhou uncovered that these areas also underwent similar uplift movements. Tang concluded that two uplift evens happened in the adjacent areas of Hunan and Guizhou, Fanjingshan cove around 92∼72Ma and 15∼0Ma, around 85∼60Ma and 19∼0Ma in Mayang basin, around 79-40Ma and 25-0Ma in Zhijiang basin, and around 78-25Ma and 15-0Ma in the base of Xuefengshan [18]. Uplift movements of Nanxiong basin and Zhujiangkou basin in Guangdong around 80-60Ma and 5Ma are also reported in recent years [19, 20]. Three tectonic uplift movements happened in Yunnan-Guizhou plateau have also been reported, at around 82.3Ma, 27.6Ma and 5.9Ma, respectively [21]. A consensus has been reached on the background of these tectonic uplift movements, which goes that the uplifts happened around 90-20Ma is related to the subduction of Pacific plate, while the latest uplifts happened around 20-0Ma closely associated with the collision between Indian plate and Eurasian plate.

The six Danxia landforms natural heritages are all located in the south of China where red beds underwent two obvious tectonic uplifts. The development time of Danxia landform is not in particular order. The discrepancies among red beds in different scenic areas should be mainly decided by regional structural feature and rock property rather than the different stages which they are undergoing. It is reasonable to use the life-cycle model proposed by Peng to explain the evolution of red beds in the same place, but as for red beds in different areas far apart from each other, it is quite difficult to tell the exact sequential order due to the complicated genesis.

6 Conclusion

Based on our research findings, we draw three key conclusions regarding the development of Danxia landforms in the South Sichuan Basin (SSB) and their implications for understanding Chinese Danxia evolution:

1. The genesis of SSB Danxia is fundamentally shaped by the interplay of tectonic uplift and lithological characteristics. Two major uplift phases exposed the region's iron-rich Cretaceous red beds to weathering and erosion. Regional-scale faults controlled the distribution of red bed outcrops, while smaller-scale structures influenced specific landform development. This highlights the crucial role of both regional tectonic history and local geological conditions in shaping Danxia landscapes.

2. While two major uplift events affected red beds across Southeast China, there is no evidence for a uniform, temporally sequential development of Danxia landforms. Instead, regional tectonic settings, including fault activity, uplift history, and variations in rock properties, play a significant role in shaping individual Danxia landscapes. This challenges the prevailing evolutionary model that posits a simple southeast-to-northwest developmental progression.

3. Our findings underscore the importance of considering regional tectonic context and the interplay of diverse geomorphic processes when interpreting Danxia landform evolution across China. This necessitates further research to refine our understanding of the factors controlling Danxia development in different regions. These insights are crucial for developing effective conservation and management strategies that address the unique geological and geomorphic characteristics of individual Danxia landscapes.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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