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ORIGINAL ARTICLE

Geoheritage Geomorphology of an Alpine Region in Northwest China: Introduction to the Yeliguan National Geopark

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Abstract
The Yeliguan region is located in Northwest China and consists of outcrops from Carboniferous to Quaternary age. This region, affected by the uplift of the northeastern margin of the Qinghai-Tibet Plateau, has been exposed to long periods of alpine environment, making the geoheritage geomorphology easier to read and more aesthetic values to contemplate. The Yeliguan National Geopark presents several geoheritage sites of mainly landscape interest, which gives scientific reference for both geomorphologists and geologists; however, research on this geopark is rare. Based on geological and geomorphological perspectives, we describe Danxia, karst, gravity-flow, and gravity-slide landscapes according to their evolutionary processes and formation mechanisms. The background of lithologic control, weathering processes, seismic events, and alpine climatic conditions played a key role in the characteristic landscapes of this region. Hence, understanding their formation and recognition and discussing the potential for worldwide promotion are vital elements for educating local communities and visitors and providing effective measures for future development.

Keywords Geoheritage · Evolutionary process · Formation mechanism · Alpine environment · Yeliguan · Qinghai-Tibet Plateau

Introduction

As an innovation of the natural and geological heritage protection program, geoparks play a significant role in the development of global geotourism (Zhao and Zhao, 2004; Eder and Patzak, 2004; Burek and Prosser, 2008; Dowling, 2011; Farsani et al., 2011; Newsome and Dowling, 2012; Brilha, 2018). A National Geopark must be an area of national significance and of high geological, scientific aesthetic, and ornamental value, combining natural and cultural landscapes (Zhao and Zhao, 2008). With rising scientific popularization and geotourism, enthusiasm associated with the National Geopark declaration has been continuously driven in the past 2 decades. Meanwhile, local parks have also received a lot of interest and attention by local governments (Dong et al., 2014). By December 31, 2021, 287 members were included in the National Geopark Network in China (Fig. 1).

The large stable basins and mountains, varied and balanced in arid or semi-arid climates of West China (Ding et al., 2007; Buylaert et al., 2008; Li et al., 2019; Guo et al., 2019), and relatively unique geological relics match the essential resources needed for the application of National Geopark status. The Yeliguan National Geopark was recognized by the MLR of China as the seventh on the National Geopark Qualification List. Due to its remote inland location and difficult access, the natural scenery is not well known to tourists, and neither is its scientific value generally appreciated. The objectives of this study are (i) introduce the geoheritage of Yeliguan National Geopark; (ii) analyze the evolutionary processes, and formation mechanisms of the geoheritage; and (iii) assess the potential to upgrade these landscapes as a part of the global geo-sites network.

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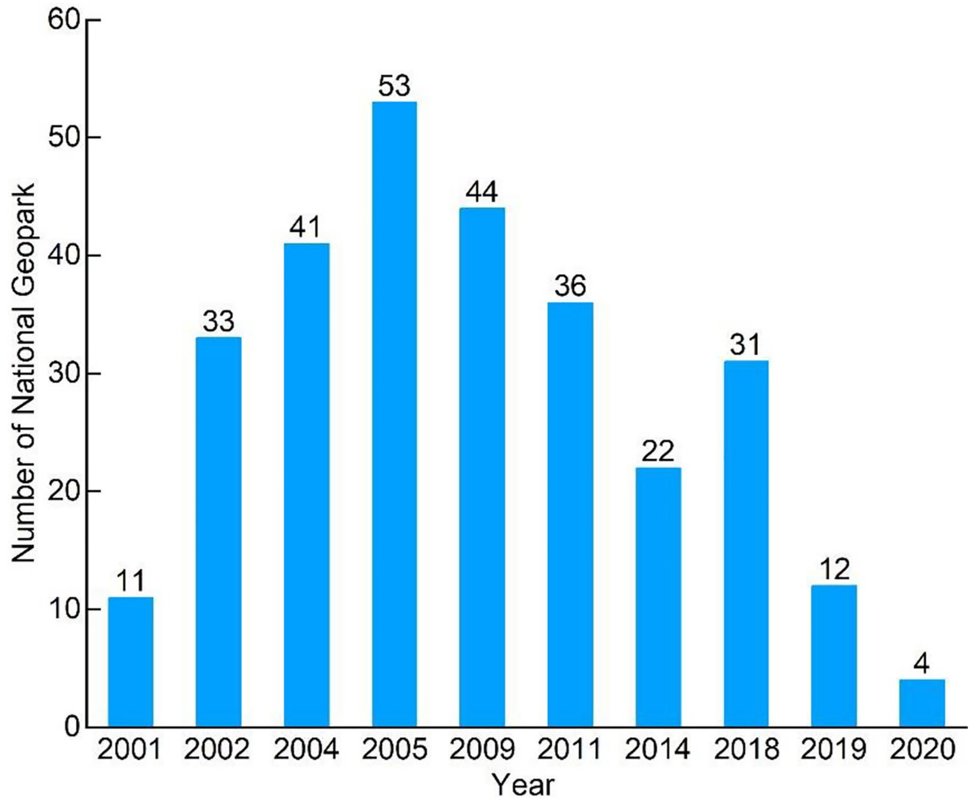


Fig. 1 Number of declared National Geoparks in China from 2001 to 2021. Data has been updated from http://www.geopark.cn/

Study Area

Location

The Yeliguan National Geopark (YNG) is located in northeastern Lintan County, Gannan Prefecture (Fig. 2). Mean elevation mainly ranges from 2100 to 3800 m above sea level, with topography high in the north and south, and low in the center. The park is approximately 160 km north of Lanzhou City, and approximately 90 km to the east is Hezuo City, the capital of Gannan Prefecture. This area includes Yeliguan Town, on the margin of the Plateau, located at 103° 35′ 30″–103° 43′ 42″E, 34° 52′ 35″–35° 02′ 48″ N. This area has ample surface water resources, belonging to the Yellow River system. Yemu River, the main secondary tributary in Yeliguan Town, passes through the middle of the geopark from west to east. This region has a typical alpine climate, with an annual average temperature of only 3.2 ℃, and an annual average precipitation of 518 mm.

The northeastern margin of the Qinghai-Tibet Plateau mainly occupies the Linxia Basin, Qilian Mountains, and adjacent West Qinling mountains. The climate reflects the intersection between the east monsoon region, northwest arid area, and Qinghai-Tibet Plateau alpine region. Due to relatively strong tectonic movement and striking topographic relief, a remarkable global heritage has been formed. Based on protecting these characteristics, Yeliguan National, Hezheng National (Deng, 2003), Gui'de National (Xiao et al., 2013), Kanbula National (Xiao et al., 2012), and Huzhu National Geopark (Chen et al., 2009) were successively established. Additionally, *Platybelodon grangeri* (Gina et al., 2016), *Hezhengia bohlin* (Gina et al., 2017), and *Hipparion fauna* (Zhang et al., 2020a, b) mammalian fossils were excavated in Linxia Basin. Coincidentally, evidence of archaic hominins in the Tibetan Plateau during the Middle Pleistocene, such as Denisovan mandibles and teeth, was also discovered (Chen et al., 2019b, c, a), in Baishiya Karst Cave, Xiahe County, and Gannan Prefecture (Zhang et al., 2020a, b). All the relevant geographic features point to unique scientific values of this region.

Geological Background

Tectonic activity in China is mainly driven by the Siberian, Indian, and Pacific Plates (Wu, 2001), a major tectonic system that exerts primary control of geomorphological evolution (Liu et al., 2019). Generally, complex geological structures formed predominantly in eastern and western China (Li et al., 2002). However, after the large-scale formation of China's Palaeocontinent from the Late Triassic to early Jurassic, tectonic activities closely match existing geopark

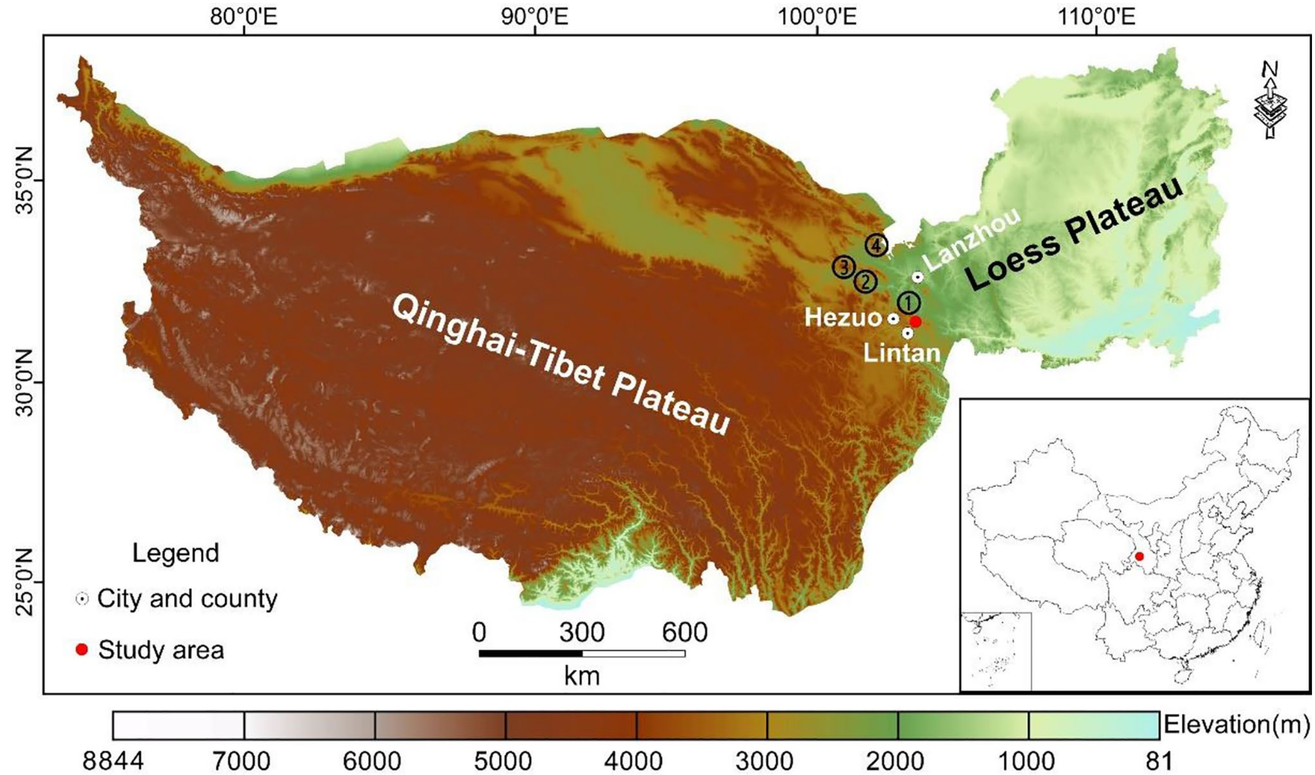


Fig. 2 Study area location, in the transition zone of the Qinghai-Tibet Plateau and the Loess Plateau. (1) Hezheng National Geopark, (2) Kanbula National Geopark, (3) Gui'de National Geopark, and (4) Huzhu National Geopark

landscapes, such as active volcanoes (Wang et al., 2014; Yan et al., 2016a, b) and numerous small or medium-sized depression basins in East China (Wu et al., 2019). The Qinling Orogen is a notable tectonic part of East Asia (Meng and Zhang, 2000), with extraordinary evidence of late mid-Proterozoic to Cenozoic tectonism in central China (Ratschbacher et al., 2003), and which separates the North China block from the South China block and links the Kunlun and Qilian Orogens to the west and the Dabie-Sulu Orogen to the east (Mattauer et al., 1985; Luo et al., 2012). The strata in West Qinling are mainly Devonian to Cretaceous, and the Precambrian basement is rarely exposed (Feng et al., 2002).

YNG is located at the west section of West Qinling Orogen (Fig. 3), and belongs to the East Kunlun-Middle Qinling stratigraphic division, which was mainly exposed in the upper Paleozoic and Cenozoic, and lacking Mesozoic strata. As to the tectonic types, the Devonian-Permian system is dominated by shallow, medium structure, and plastic deformation (Gansu Bureau of Geology and Mineral Resources, 1989; Yan et al., 2016a, b; Wang et al., 2021). The upper Paleozoic was built by marine deposits, and then continental sedimentation assumed dominance in the Cenozoic. Regional magmatic activity was weak and represented by Yanshanian (Jurassic-Cretaceous) intrusive rocks (Luo et al., 2012). Numerous strata are extensively exposed in YNG, mainly from the Carboniferous, Permian, Neogene, and the Quaternary; therefore, YNG is a special segment of the tectonic zone in West Qinling Orogen (Jin et al., 2005; Yang et al., 2018). Folding and faulting affect large areas, so YNG geoheritage is strongly related to the regional geodynamic setting.

Classification of Geoheritage Sites

YNG contains the Yehai, Chibi Yougu, Xiao Maiji, Yemuxia, and Qin'nigou Geo-areas (Fig. 4). The principal YNG geoheritage sites are associated with Danxia, karst, gravity-flow, and gravity-slide landscapes (Table 1), concentrated in the central and northern parts of the park.

Danxia Landscape

As a particular type of nearly horizontal thick-bedded ferrugenous formation associated with erosional conglomerate, sandstone, sandy conglomerate, siltstone, and mudstone, Danxia landscapes are generally believed to have developed from the Mesozoic to Neogene in China, and composed of three basic units: subrounded summit, prominent cliff, and foot slope (Qi et al., 2005; Zhu et al., 2010; Kusky et al., 2010; Li et al., 2013;

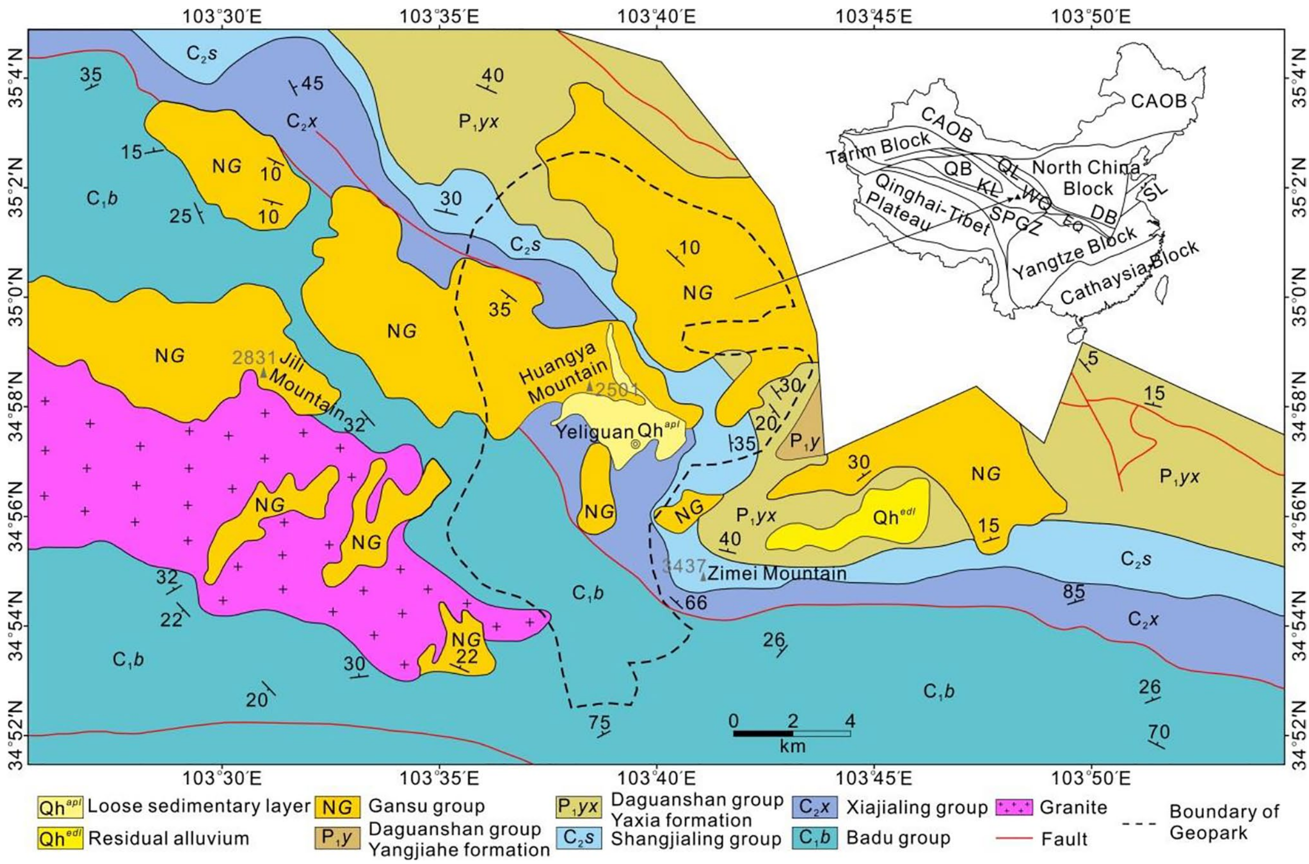


Fig. 3 Geological map of YNG. CAOB, Central Asia Orogenic Belt; QL, Qilian Mountain Belt; QB, Qaidam Belt; KL, Kunlun Mountain Belt; WQ, West Qinling; EQ, East Qinling; DB, Dabie Belt; SL, Sulu Belt

Peng et al., 2015; Chen et al., 2019b, c, a; Guo et al., 2020). Red beds are common in sedimentary sequence, but most (termed continental red beds) formed in terrestrial settings (Song et al., 2017). Marine allochthonous red beds indicate a faster deposition rate, marine flooding or regression, and sinking sea basin (Refaat and Imam, 1999; Melinte-Dobrinescu and Jipa, 2005; Hu et al., 2012; Rong et al., 2012; Haddoumi et al., 2019). Redness in continental red beds is predominantly due to weathering and the presence of ferric oxides, distributed in deltas, lakes, deserts, river floodplains, and alluvial fans (Chen et al., 2017), and sedimentation is just a secondary non-geochemical process (Mader, 1982; Bell, 1989; Hofmann et al., 2000; Parnell et al., 2016). Continental red beds with scarps are generally defined as equivalent to typical rock strata in Danxia landscapes (Guo et al., 2020), which closely reflect climate, geomorphology, hydrographic network, lithology, and tectonics. Nevertheless, little attention has been paid to a detailed description of the stratigraphic Neogene base of Danxia landscapes. The most outstanding YNG Danxia landscapes are shown as Fig. 5 and listed in Table 2.

Karst Landscape

Karst landscape, a kind of singular scenery that develops in soluble rocks and occupies approximately 20% of the ice-free land surface (Ford and Williams, 2007), is especially developed in carbonates and is unique with its lofty relief and underground drainage system (Hart and Schurger, 2005; Hajna et al., 2020; Zumpano et al., 2019). Most landscapes on carbonate rocks are well-karstified, representing a large number of surface and underground terrains, with complex lithology characteristics and geomorphological diversity (Gil et al., 2013; Migoń et al., 2017; Goeppert et al., 2020). The mountainous relief descends in a string of karst plateaus, with a wide stretch of leveled surfaces to lower altitudes. A humid and hot climate is generally considered to exert influence on regional karstification; however, it can develop in other environments, even ranging from tropical to subarctic climates (Brook and Ford, 1978).

Karst processes are considered to be especially sensitive to climate change (Yuan, 1997; Liu et al., 2018), and China has the largest karst area in the world. Apart from

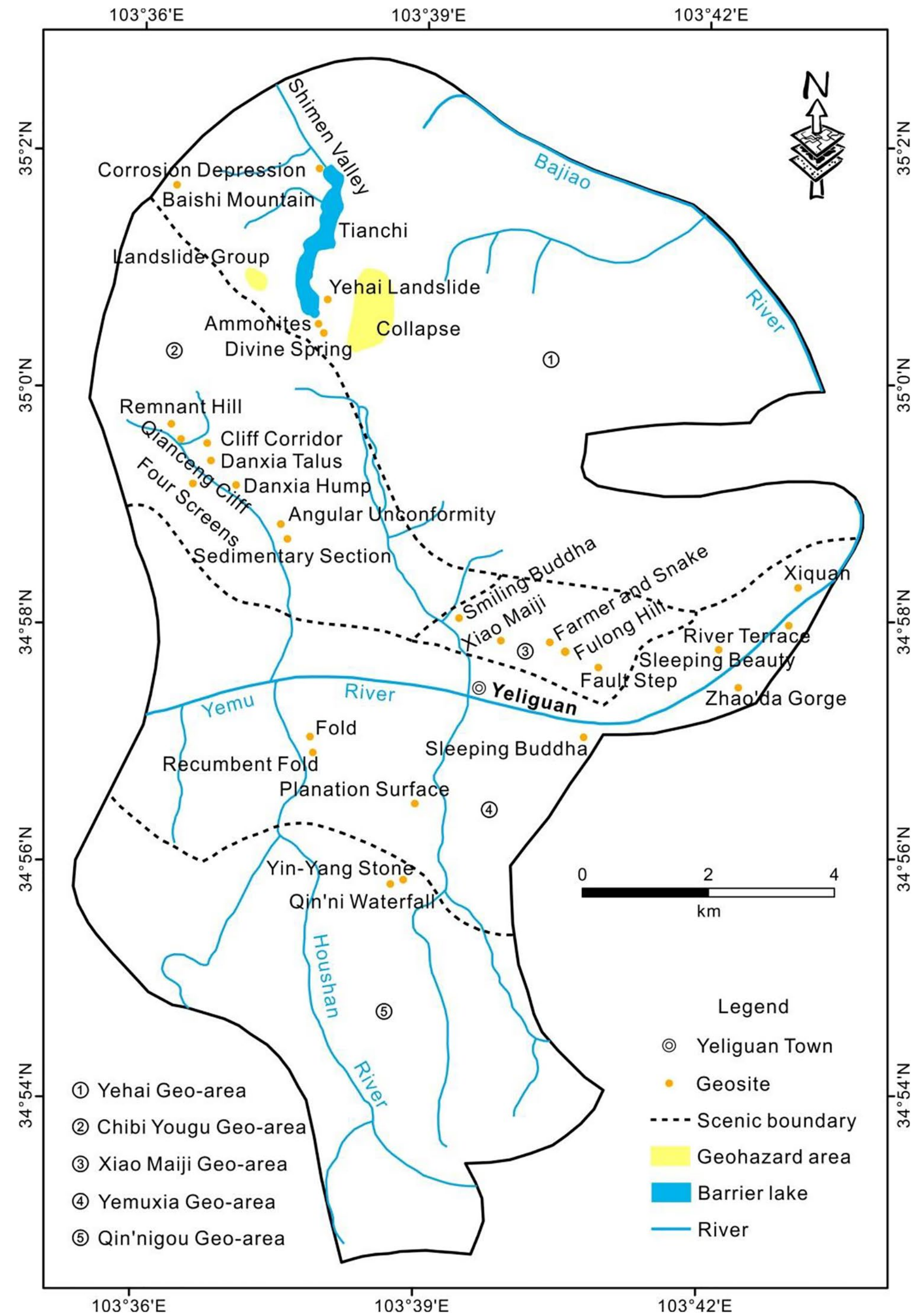


Fig. 4 Distribution of major YNG geoheritage sites

the aforementioned research, karst landscapes have been studied on Yunnan-Guizhou Plateau and all along parts of South China, mostly within the framework of karst dynamics theory and methods (Jiang et al., 2012; Szczygieł et al., 2018), while paying less attention to the karstification of the Qinghai-Tibet Plateau and its margin. The most outstanding karstic geoheritage elements are shown as Fig. 6 and listed in Table 3.

Gravity-Flow and Gravity-Slide Landscapes

Geohazard events that occur globally, like landslides, debris flows, rock collapses, and earthquake-triggered barrier lakes, have received much more attention in recent decades (Cecioni and Pineda, 2009; Huang et al., 2012; Pavlova et al., 2017; Cigna et al., 2018; Fan et al., 2019; Fepuleai and Németh, 2019). These surface processes

Table 1 The principal YNG geoheritages and type classification

Class	Sub-class	Major geoheritage
Stratigraphic section	Stratotype	Sedimentary section
Structural geology section	Unconformity	Angular unconformity
	Fold and deformation	Recumbent fold
Fossil record	Paleontological fossil	Ammonites
Karst landscape		Sleeping Buddha, Sleeping Beauty, Corrosion Depression, Baishi Mountain, Xiquan
Danxia landscape		Sipingfeng, Yarlang, Qiancengya, Sphinx, Mesa Xiao Maiji, Smiling Buddha, Yin-Yang Stone
Fluvial landscape	River	River terrace, Yemu River, Bajiao River, Shimen River
Hydrologic landscape	Waterfall	Qin'ni Waterfall
	Spring	Divine Spring, Yinma Spring
Tectonic landscape	Gorge	Zhaodaxia, Yemuxia
Gravity-flow and gravity-slide landscape	Collapse	Collapse
	Landslide	Yehai Landslide, Landslide Group
	Barrier Lake	Tianchi

Fig. 5 Major geoheritage site of YNG Danxia landscapes. **a** Mesa. **b** Sipingfeng. **c** Yarlang. **d** Xiao Maiji. **e** Peak cluster. **f** Yin-Yang Stone

cause a series of environmental effects, including vegetation destruction, ecosystem degradation, and soil erosion. However, geohazards can occasionally shape new landscape dimensions, playing an effective role in popular science education, such as comprehending geological movement. In this regard, most hazard scenes have been managed and controlled in China, and only a fraction of featured hazard resources have been effectively utilized as a part of geopark.

Gravity-flow and gravity-slide are the main disturbances in YNG, including landslide, rock collapse, and barrier lake (Table 4), and concentrated in the Yehai Geo-area, where

Fig. 6 Major geoheritage site of YNG karst landscapes. **a** Sleeping Buddha (photo by Minghui Shi). **b** Dissolution depression. **c** Yinma Quan

they remain free from anthropogenic intervention and retain natural elements, highlighting the original characteristics of geohazard relics Fig. 7, which are a prerequisite to ensuring YNG nature.

Discussion

Formation Mechanism of Geoheritage Sites

Danxia Landscape

The evolution of the Danxia landscape is related to geology, from regional uplift to bedrock lithology (Young et al., 2009; Chen and Guo, 2017), and also to environmental characteristics, emphasizing the impact of regional climate change. Moreover, the relatively dry climate required for Danxia landscape formation tallies with the regional climate in the northeastern Qinghai-Tibet Plateau during the early to middle Holocene (Wu et al., 2020). Meanwhile, the near horizontal occurrence of Neogene strata in Danxia landscapes indicates that no significant crustal deformation occurred since the Neogene, which probably reflects an erosion and planation period with relatively stable structure. Accompanied by weathering, large-sized alcoves and recesses develop along conglomerate cliffs, are similar in shape, are located in the same geographical environment, and develop along the bedding planes to evolve into horizontal weathering cavities, with smooth concave overhangs and upward growing trends (Fig. 8). The evolution stage and main characteristic of YNG Danxia landscapes are summarized in Table 5.

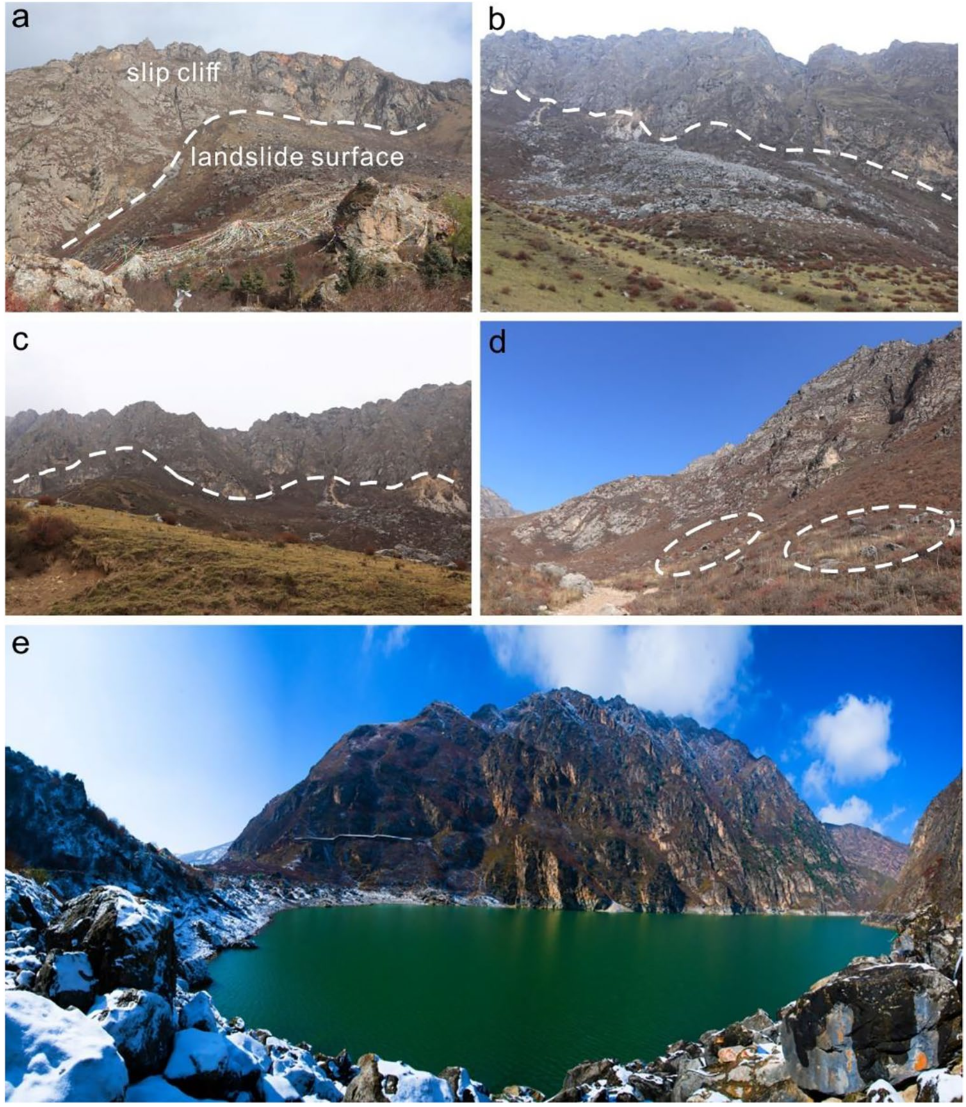


Fig. 7 Major geoheritage site of YNG gravity-flow and gravity-slide landscapes. **a** Yehai Landslide, **b**, **c** Landslide group. **d** Collapse. **e** Barrier lake (photo by Yun Gao)

Karst Landscape

Karstification is the dissolution or deposition of carbonate in the carbon cycle and its associated water cycle and calcium cycle system (Yuan et al., 1990; Yuan, 1997). In alpine mountainous regions, biological metabolism and its driving effect on the carbon cycle are not as strong as in the tropics, and the carbonate dissolution rate by natural water

Table 2 Summary of geoheritage sites of Danxia landscapes

Geo-area	Name of geosite	Main characteristic
Chibi Yougu	Mesa	It sustains the general mesa form with planar top surface, which is bounded from all sides by steep cliffs (Fig. 5a)
	Sipingfeng	Four cliffs are arranged side by side (Fig. 5b)
	Yarlang	A long corridor on both sides of the canyon, about 150 m high and 500 m long, the cliff is straight and steep, and the wind erosion groove is well-developed (Fig. 5c)
	Sphinx	A vertical rock mass, subjected to water erosion, wind erosion and then collapse, forming a face-like body
Xiao Maiji	Xiao Maiji	A typical type of cone-shaped hill with convex top and rough cliff surface (Fig. 5d), named after the similarity with Mt. Maiji in Tianshui City, Gansu Province (He et al., 2021a, b)
	Peak cluster	A series of columns of different sizes, and formed by water erosion, weathering, and gravity (Fig. 5e)
Qin'nigou	Yin-Yang Stone	It consists of Yin Cave (a circular cave with open grooves) and Yang Pillar (a straight and steep pillar), surrounded by coniferous forest in the south of the geopark (Fig. 5f)

Table 3 Summary of geoheritage sites of karst landscapes

Geo-area	Name of geosite	Main characteristic
Yemuxia	Sleeping Buddha	A karst peak cluster with conical shape at the top, and completely connected at the base. The karst peak cluster trends east–west, for about 10 km and a relative height difference of 400 m, which is formed by strong vertical dissolution, and looks similar to a lying Buddha (Fig. 6a)
Tianchi Yehai	Dissolution depression	Located on the south side of Baishi Mountain, has a similar morphological character with Yinma Quan (Fig. 6b). Similarly, the rudiment of the dissolution depression is a “funnel” formed by the dissolution of flowing water in the early stage
	Yinma Quan	An approximately circular karst lake, with an area of about 300 m^2, and depth of nearly 2 m (Fig. 6c), with bedrock walls formed of Carboniferous medium-thick layered limestone. A karst funnel formed by water erosion in the initial stage, then developed into a sinkhole and expanded after seasonal rainfall to form a karst depression

Table 4 Summary of geoheritage sites of gravity-flow and gravity-slide landscapes

Geo-area	Name of geosite	Main characteristic
Tianchi Yehai	Yehai Landslide	Yehai Landslide is located at altitudes of about 2900 m, with clastic and carbonate bedrock of the Shangjialing in the Carboniferous. The landslide surface is fan-shaped, with a large amount of gravel accumulation and sparse vegetation coverage. The slip cliff is about 100 m high and 150 m wide, with a slope of 70 to 90° and obvious “round-backed armchair” characteristic (Fig. 7a)
	Landslide group	It comprises a series of sliding of bedrock weathered sliding layers and slope deposits, composed of several single landslides, basically set up in a parallel array (Fig. 7b, c). The landslide bodies also belong to the clastic and carbonate rocks of the Shangjialing formation of the Carboniferous, with an average slope of 35°, and slopes covered with alpine meadow
	Collapse	Rock collapse, characterized by falling debris, is widespread on mountain slopes in the geopark. At the foot of the slope, riprap colluvium of different gravel diameter accumulates (Fig. 7d). Individual collapse material and boulders basically vary in size from 0.5 to 1.5 m
	Barrier lake	Tianchi, a rare category of earthquake-induced lake in alpine mountainous areas in NW China, located at altitudes of about 2610 m, with a depth in the middle of 30 m and covering an area of 1.2 km^2 (Fig. 7e)

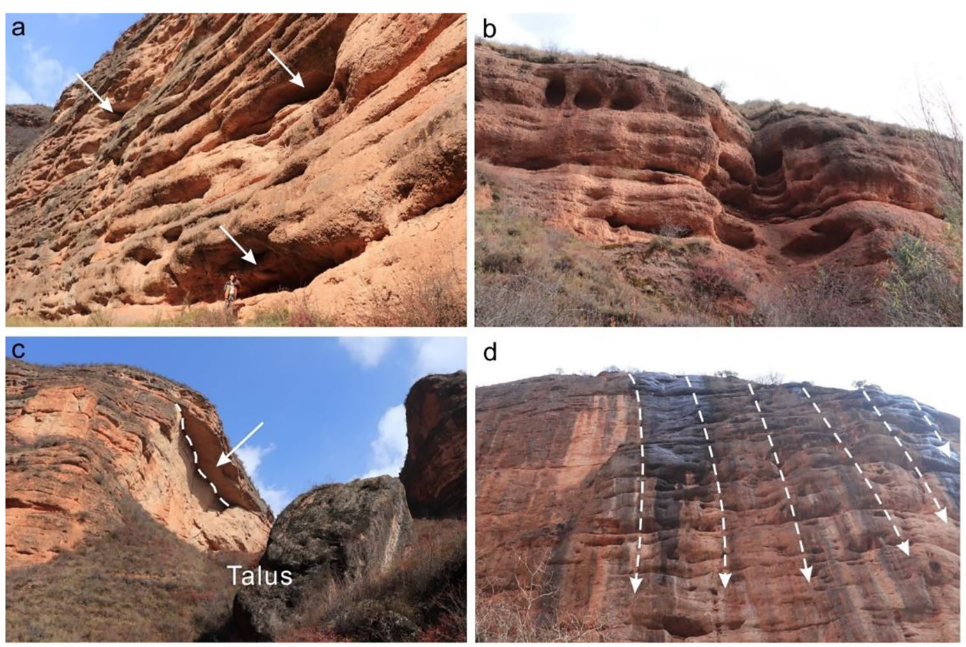
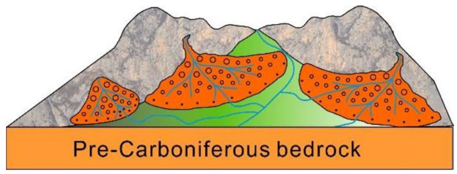
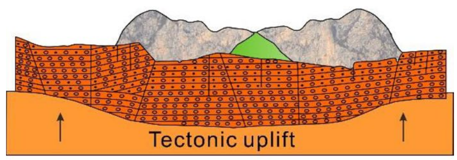
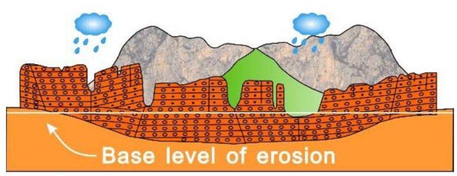
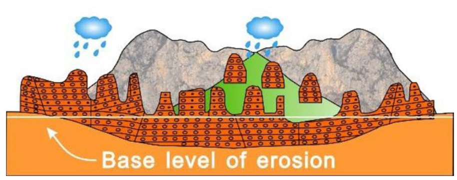


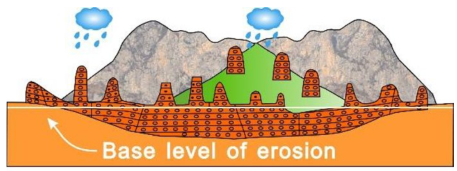
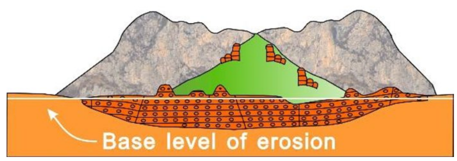
Fig. 8 Selective weathering and sapping features of alcoves and recesses along the cliff. **a** Well-developed horizontal alcoves and recesses **b** Multiple adjacent honeycomb structures. **c** The in-situ disintegration of cliff due to unloading joints and weathering is the initial feature of escarpment retreat. **d** Pathways of water sapping down the cliff by white dotted lines

Table 5 The evolutionary stage and main characteristic of Danxia landscapes

Simplified evolution model	Description	Evolution period	Source
	Continental red beds of coarse-grained sediments were rapidly deposited in alluvial-proluvial fans	I (Carboniferous - Permian)	Du et al., 1998 Liu et al., 2001 Ratschbacher et al., 2003
	Precipitation-induced floods eroded the Neogene strata along the structural fractures, beginning to form erosion grooves	II (the early Pleistocene)	Dong et al., 2011
	The crust rose further, vertical water erosion intensified, resulting in the formation of peak clusters, stone pillars and other micro landforms	III (the late Early Pleistocene)	Cao, 1996
	Wind erosion constantly remoulded the gullies, peaks and peak columns of the early erosion, forming landscapes of differential weathering	IV (Neotectonic period)	Cao, 1996

is relatively slow, making it unsaturated for a long time (Cinkus et al., 2021). The long dissolution process makes the carbon cycle here mainly manifested as carbonate dissolution, and so YNG karst landscapes are mainly karst-tectonic gorges (Table 6) and karst grottos (Fig. 9). The initial stage of grotto formation is believed to be mainly by solution processes along vertical joints and piping on bedding planes, whereas in the last stage the widening is mainly by erosion and collapse, forming big shafts and sinkholes (Piccini and Mecchia, 2009

Table 5 (continued)

	Mesa and rock peaks surrounded by steep cliffs evolved into scattered residual columns and monadnock	V (Holocene)	-
	The scattered debris piles became undersized, until they completely disappeared, forming quasi-flat and undisturbed gentle slopes	VI (Holocene)	-

Gravity-Flow and Gravity-Slide Landscape

Pre-seismic Stage The compressive tectonic stress produced by the collision and convergence of the Indian and Eurasian plates was transferred to the West Qinling Mountains in the Cenozoic (Guo et al., 2009), and produced two main faults near the Yehai Geo-area on the northern edge of the West Qinling Mountains (Lintan-Minxian-Dangchang and Guanggaishan-Dieshan Faults). Several historical destructive earthquakes occurred in this fault zone, decreasing the stability of the massif near Shimen Gorge (Zheng et al., 2007a, 2007b; Yuan et al., 2014). Meanwhile, the deep relief of the Shimen Gorge was emerging near Yehai, provided the initiating slope for gravity-flow and gravity-slide during emplacement.

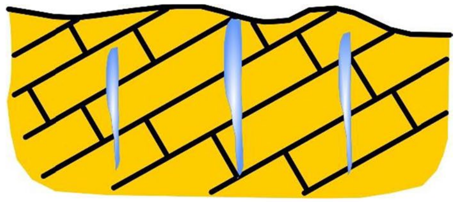
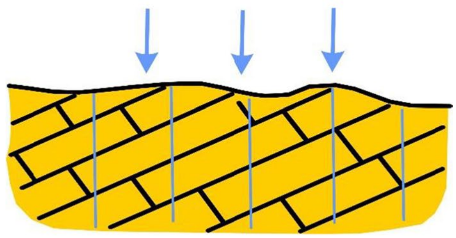
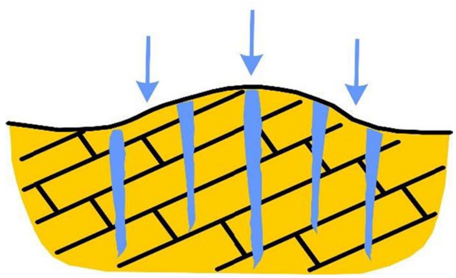
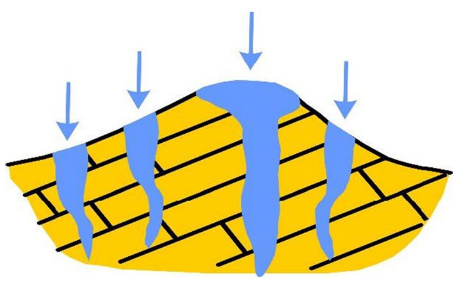
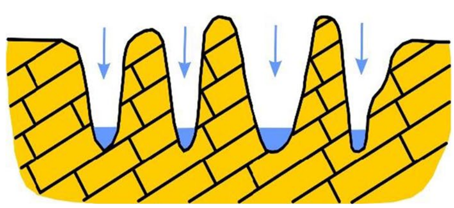
Formation Stage In 1765, an earthquake occurred at the junction of Kangle, Zhuoni, and Lintan Counties, causing the Yehai landslide, which dammed the Shimen River, to form a barrier lake. After 72 years, another earthquake occurred at the border of Lintan and Minxian Counties, making the loose rock mass of the back wall slide again (Liu et al., 2006). As a result, the debris materials of the landslides were continuously deposited to the north by Shimen River, forming the northern Yehai landscapes (Fig. 10), which reflect the matching of these relics with seismic events.

Regional Comparison of Geoheritage Sites in China

Danxia landscapes in China are mainly concentrated in Southeast China, Sichuan Basin, and the Qilian-Liupan regions (Yan et al., 2019). Among the three regions, different climatic zones and tectonic controls over the red beds produce patchy landscape combinations, with large differences in geomorphology and landscape characteristics. In terms of morphological characteristics, northern arid and semi-arid areas are characterized by selective and salt weathering, obvious layered or flaky spalling, rough surfaces, and recently formation of special types, such as grayish yellow wave and steep slopes. The YNG Danxia geosites enrich the category and showcase their distribution in the Northwest China margin, rather than the hinterland of the Qinghai-Tibet Plateau, as they form unique characteristics due to the alpine climate and stratigraphic Neogene base.

In National or UNESCO Global Geoparks in China, there are few barrier lakes formed by paleo-earthquake, especially in high-altitude and low-latitude areas. Hence, we present a brief review of the characteristics of associated barrier lakes, mainly related to seismic events (Table 7). Many gravity-flow and gravity-slide relics in YNG were produced after earthquakes, and the barrier lake, Yehai, may be the highest-altitude-barrier lake found and documented so far in the margin of the Qinghai-Tibet

Table 6 The evolutionary stage and main characteristic of the karst-tectonic gorge

Simplified evolution model	Description	Evolution period
	The stable fissures and hydrologic configuration necessary before vertical karstification can begin	I
	The fissures provided a natural foundation for the rapid erosion and guided direction of water flow	II
	The expanding catchment area of gullies made the flow direction more concentrated and the erosion more intense	III
	Unroofing due to runoff sapping and ceiling collapse of karst windows to form a narrow gully	IV
	Persistent widening and deepening of the gully to form a gorge	V

Plateau. Mechanical weathering of the rock mass in this alpine environment is also inferred to contribute to the process initiating gravity-flow and gravity-slide. Raising the awareness of local residents and geotourists of aspects of the gravity-flow and gravity-slides and the surface-modifying effect of such mass movements is also important.

The Paleo-karst in the Qinghai-Tibet Plateau is not uncommon, but less so than South China. Macroscopically, by the time the main planation plane in the carbonate formations begins to disintegrate, the karst landform is already being gradually exposed. The climate, surface, and hydrogeological systems coevolved in YNG, forming diverse geomorphological combinations of karst-tectonic gorge-peak cluster-karst grotto-dissolution depression, which record the geologic history of the gradual uplift of earth's crust since Neotectonic movement. These landscapes also showcase the evolutionary processes of corrosion and incision of the northeastern marginal areas of Qinghai-Tibet Plateau.

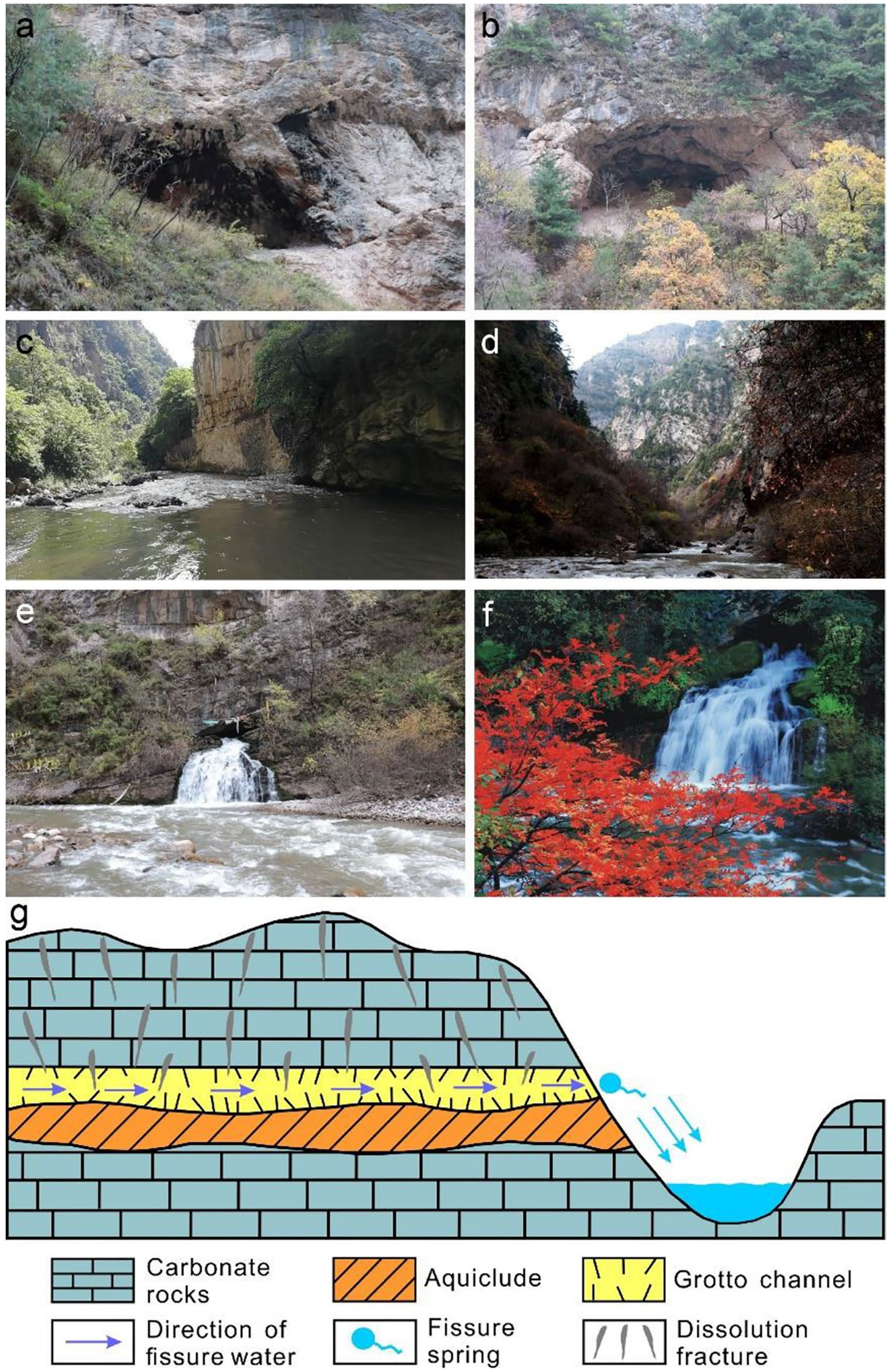


Fig. 9 Karst-tectonic gorge and karst grotto. **a**, **b** Poorly developed karst grotto. **c**, **d** Yemuxia, karst-tectonic gorge. **e**, **f** Xiquan, a fissure spring. **g** Simplified model of Xiquan. The grottos can form if a karstic pipeline exists, allowing the movement of water along fissures. Successively, conduits are formed when pipeline moves the weathered carbonate rock away along bedding plane to spring

Potential for YNG as Global Geoheritage Sites

For educational purposes, starting with geomorphological nomenclature of single geoheritage-related processes and resulting geoforms, we analyzed and characterized the main geomorphological components of broadly large dimensions based on their topographical and structural features. The evolution processes and several types of Danxia, karst, gravity-flow, and gravity-slide landscapes were represented. In particular, the selected global geoheritage sites give an overview of the study area geology.

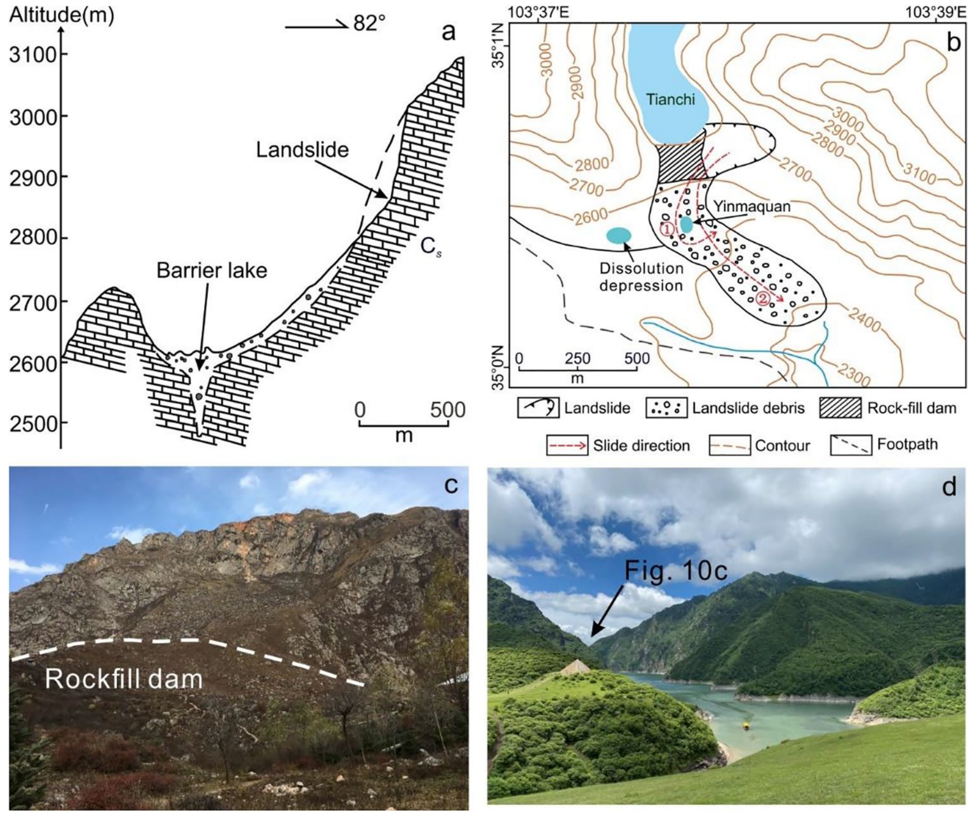


Fig. 10 Formation characteristics of barrier lake (Yehai). **a** Profile chart of Yehai landslide. **b** The rockfill dam formed by the first landslide mass forced the debris of the landslide to move southward. In addition, due to the large difference of terrain height between the east and the west along the movement direction, the debris of the sliding mass rotated anticlockwise and moved forward for a distance of about 600 m. **c** General view of the rockfill dam. **d** The northern boundary landscape of Yehai

Compared with South China Danxia landscapes, those in YNG are located in transition zones of alpine arid, low to high elevation, the Qinghai-Tibet Plateau, and the Loess Plateau, with sparse hydrographic net and low vegetation coverage; the spatial distribution of geoheritage sites is mainly the NW trend. We selected Danxia landscapes in South China, the World Heritage Sites (Zhu et al., 2015), for comparison as they are obvious sites for red and morphological features and are comparable at a lithological and erosional degree to YNG geoheritage sites, despite being located in different tectonic, climatic, and geomorphic settings.

Surface and underground karstification in YNG is weak, and the landscapes that form are basically micro-landforms. Similarly, karst landscapes in South China, the World Heritage Sites (He et al., 2021a, b), as some of the most spectacular examples of tropical to subtropical karst morphology, were also chosen for comparison as they have distinctive scarce soils and rugged topography (Chen et al., 2012). They are also comparable in climate forcing and geotectonic extent to the YNG geoheritage sites. Neotectonic movement is conducive to karst morphology preservation during different periods in Quaternary, and owing to the solubility of karstification, these karst YNG geoheritage sites record Neotectonic movement.

Moreover, the Qinghai-Tibet Plateau uplift was a major tectonic event for Asia in the Cenozoic (Zachos et al., 2001; Li et al., 2014; Zhang et al., 2018), and had a strong impact on the regional differentiation of landforms in China. Within uncertainties in uplift history, there is a scenario in which the main Qinghai-Tibet Plateau uplifted first, and was then followed by uplift of the marginal Qinghai-Tibet Plateau, which continuously shaped Danxia, karst, gravity-flow, and gravity-slide landscapes, relics that prominently display numerous geological records related to paleogeography and paleoclimate changes. Thus we learn that although these landscapes have common worldwide characteristics, their concentration and development in the same place are rare and notable. These landscapes thus represent significant geoheritage features that deserve recognition and conservation, providing a clear indication of geological changes and landscape evolution through regional erosion, karstification, and geohazards and can be thought of in popular terms as geological event indicators.

Conclusions

In this study we briefly introduced the main characteristics and evolution processes of YNG geoheritage. Our main points are summarized below:

(1) The continental red beds of the Gansu Group in Neogene strata formed the basis for the evolution of Danxia land-

Table 7 Main characteristic of earthquake-induced barrier lake in National Geopark or UNESCO Global Geopark

Name of geopark	Location	Altitude of barrier lake	Area of barrier lake	Main characteristic	Source
1. Yeliguan National Geopark	Study area	2600 m	1.2 km^2	In 1765, an earthquake occurred near YNG, causing Yehai landslide and blocking up Shimen River	Liu et al. (2006)
2. Qinling Zhongnanshan UNESCO Global Geopark	Xi'an City, Shanxi Province	1100 m	0.3 km^2	In 780 BC, a great earthquake happened with magnitudes of 8 or more, may trigger the landslide and block up the river channel	Lv et al. (2014)
3. Yigong National Geopark	Linzhi City, Tibet Autonomous Region	2225 m	15 km^2	In 2000, a large-scale rock avalanche dammed the Yigong Zangpo River, forming an extensive rockslide barrier lake	Delaney and Evans (2015); Zhou et al. (2016)
4. Qianjiang Xiaonanhai National Geopark	Chongqing City	670 m	2.87 km^2	In 1856, an earthquake happened in Xiaonanhai Town, may resulted from the superposition of multiple tectonic earthquakes or from a pure mountain collapse	Wang et al. (2019)

scapes. Most sections of the Gansu Group in Neogene strata are monotonous and extremely thick conglomerate strata, reflecting the accumulation state of alluvial-proluvial fans with rapid deposition. Large-sized alcoves and recesses along the cliffs show selective weathering and small-scale-geomorphologic control.

(2) The karst landscapes involve geomorphological combinations of karst-tectonic gorge-peak cluster-karst grotto-dissolution depression, primarily controlled by groundwater-flow processes and lack of external water supply, representing the evolutionary processes of corrosion and incision of the northeastern marginal areas of the Qinghai-Tibet Plateau.

(3) Seismic events in 1765 and 1873 played a key role in shaping gravity-flow and gravity-slide landscapes, and the Yehai barrier lake, which may be the highest-altitude barrier lake found and documented so far in the margin of the Qinghai-Tibet Plateau. Our reported descriptions could also be regarded as a basic scientific background for landslides, collapses, and barrier lakes in Northwest China.

The formation of YNG geoheritages is related to the uplift of the northeast margin of the Qinghai-Tibet Plateau, but our research based on these landscapes has yet to indicate that there is a quantitative and qualitative relationship between them. Nonetheless, we have come to realize that these landscapes could greatly improve knowledge of the Quaternary geology and landscape development in the study area, presenting a sound promotion potential.

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Declarations

Competing Interests The authors declare no competing interests.

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