Landscape Characteristics, Spatial Distribution, and Formation Mechanism of Danxia Landforms in Shaanxi Province: A Preliminary Study (Postprint)

Authors: Ding Hua, Liao Wenqiang, Duan Fenghao, Yang Wangtun, Ding Hua

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Abstract

Shaanxi Province encompasses a total of 54 Danxia landform sites distributed across the Weibei Uplift and Yishan Slope of the Ordos Basin. Both positive and negative Danxia landforms are present, exhibiting a pronounced regional differentiation pattern along the southwest-northeast axis. Aeolian desert facies sandstone Danxia constitutes the most extensive distribution, characterized by narrow-gully Danxia, wave-type Danxia, and colored hills, with the majority in the youth stage of development. Through application of the nearest neighbor index method and kernel density analysis, the spatial structure type of Danxia landform distribution in Shaanxi Province is identified as agglomerative, featuring two high-density areas (the Yan'an Ganquan-Zhidan-Ansai-Fuxian Danxia region and the Yulin Jingbian Danxia region), one medium-density area (the Zhaojin-Xunyi-Binxian Danxia region), and two low-density areas (the Baoji Jiulongshan region and the Shenmu Gonggegou-Fugu Lianhuachan region). From the perspective of formation mechanism, Mesozoic sedimentation in the Ordos Basin established the material foundation for Danxia landforms; the topographic pattern since the late Yanshanian movement governs the distribution of positive and negative landforms; joint and fracture characteristics exert a critical influence on the landscape pattern of Danxia landforms; and water erosion, wind erosion, and other processes as the dominant shaping forces sculpt the landscape morphology.

Full Text

Characteristics, Spatial Distribution, and Formation Mechanism of Danxia Landform in Shaanxi Province

DING Hua, LIAO Wenqiang, DUAN Fenghao, YANG Wangtun
(Chang'an University, Xi'an 710061, Shaanxi, China)

Abstract: There are more than 54 Danxia landform sites in Shaanxi Province, distributed across the Weibei Uplift and Yishan Slope of the Ordos Basin. The region features both positive and negative Danxia landforms with clear regional differentiation from southwest to northeast. Aeolian desert facies sandstone Danxia covers the widest area, characterized by slit-type gully Danxia, wave-type Danxia, and colored hills, with most landforms in their youth stage. Using nearest neighbor index and kernel density analysis methods, the spatial structure of Danxia landform distribution in Shaanxi Province is found to be agglomerated, with two high-density areas (the Yan'an Ganquan-Zhidan-Ansai-Fuxian Danxia area and the Yulin Jingbian Danxia area), one medium-density area (the Zhaojin-Xunyi-Binxian Danxia area), and two low-density areas (the Baoji Jiulongshan area and the Shenmu Gonggegou-Fugu Lianhuachan area). From a formation mechanism perspective, Mesozoic sedimentation in the Ordos Basin laid the material foundation for Danxia landforms. The topographic pattern since the late Yanshanian period controls the distribution of positive and negative landforms. Joint and fissure characteristics play a key role in the landscape pattern of Danxia landforms, while water erosion and wind erosion are the dominant forces shaping Danxia landform morphology.

Keywords: Danxia landform; landscape features; spatial distribution; formation mechanism; Shaanxi Province

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1 Geological Background of the Study Area

Based on geographical units, Danxia landforms in Shaanxi Province mainly develop in the desert plateau of northern Shaanxi, the loess plateau of northern Shaanxi, and the transitional zone between the Guanzhong Weihe Basin and the northern Shaanxi Loess Plateau (Figure 1). Based on tectonic units, they primarily develop within the Ordos Block (Craton) of the North China Block, with fourth-order tectonic units including the Ordos marginal sea and superimposed intracontinental superimposed basin. The Ordos Basin is a superimposed basin formed through multi-stage tectonic evolution during different periods. During the evolution of the Mesozoic basin, tectonic stress transitioned from early Indosinian movement influence to late Yanshanian movement influence, and the paleoclimate shifted from warm and humid in the Middle to Early Jurassic to arid after the Late Jurassic. A set of red beds developed in the Early Cretaceous, constituting the main material basis for Danxia landforms in Shaanxi Province. Entering the Late Cretaceous, the regional crust generally uplifted, experiencing multiple complex tectonic intermittent uplift activities. Since the Cenozoic, crustal movement has maintained differential uplift and subsidence, developing multiple planation surfaces and river terraces that play an important role in Danxia landform development. According to the current tectonic framework, the Ordos Basin can be divided into five first-order tectonic units: the Yimeng Uplift in the north, the Weibei Uplift in the south, the Yishan Slope in the center, the Tianhuan Sag and western margin thrust belt in the west, and the Jinxi flexural fold belt in the east.

2.1 Data Sources

This study takes 54 Danxia landform sites as research objects. Vector map data were obtained from the National Geomatics Center of China. Point, line, and polygon layers all adopt GCS_{{{WGS}}_{{1984}}} latitude and longitude coordinates to establish a geospatial attribute database. Google Earth was used to generate spatial distribution maps, with coordinate system projection using ArcGIS 10.5.

2.2 Research Methods

This study utilizes ArcGIS for Desktop technology, applying nearest neighbor index method and kernel density analysis method to investigate the spatial structure type and spatial distribution density of Danxia landforms.

(1) Nearest Neighbor Index Method
From a macro perspective, Danxia landform points can be regarded as point elements. Nearest neighbor distance is a geographical index describing the proximity degree of point features in geographic space. The nearest neighbor index method can determine whether the research objects belong to random distribution, agglomerated distribution, or uniform distribution in terms of spatial structure type. The formula is:

$$R = \frac{\bar{r}_1}{\bar{r}_E}$$

where R is the nearest neighbor index; $\bar{r}_1$ is the mean distance between nearest neighbor points; and $\bar{r}_E$ is the theoretical nearest neighbor distance. When $R = 1$, it indicates random distribution of point elements; when $R > 1$, it indicates uniform distribution; and when $R < 1$, it indicates agglomerated distribution. $\bar{r}_E$ can be expressed by:

$$\bar{r}_E = \frac{1}{2\sqrt{D}}$$

where D is point density, which can be expressed by:

$$D = \frac{n}{A}$$

where n is the number of analyzed objects (here representing the number of Danxia landform sites in Shaanxi Province), and A is the area of the overall region (here representing the regional area, calculated as 3700 km^2).

(2) Kernel Density Analysis Method
Kernel density analysis uses original information of spatial points to measure density variation of research objects and their influence on surrounding areas. This method reflects the characteristic that central intensity gradually decreases with increasing distance. The formula is:

$$f(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right)$$

where n is the number of analysis subjects (here representing the number of Danxia landform sites in Shaanxi Province); h is bandwidth; K is the kernel function; and x_i is the distance from the estimated point x to the analysis subject x_i.

3.1.1 Landscape Quantity and Scale

Danxia landforms in Shaanxi Province span five cities: Baoji, Xianyang, Tongchuan, Yan'an, and Yulin, covering more than ten districts and counties including Chencang District, Binzhou City, Xunyi County, Yaozhou District, Ganquan County, Zhidan County, Ansai County, Fu County, Jingbian County, and Fugu County. The main landscapes (54 sites) are distributed in the Weibei Uplift and Yishan Slope of the Ordos Basin, with a total area of approximately 3700 km^2.

3.1.2 Landscape Type Characteristics

To date, three major Danxia landform regions have been discovered nationwide, mainly concentrated in southeast, southwest, and northwest China. Unlike Danxia landforms in southeastern China (such as Guangdong Renhua Danxiashan) and southwestern China (such as Guizhou Chishui River Valley), Danxia landforms in Shaanxi Province demonstrate unique regional characteristics. Among the 54 Danxia landforms, there are 17 positive landforms, 35 negative landforms, and 2 transitional landscapes. The most distinctive features are slit-type gully Danxia, wave-type Danxia, and colored hills.

(1) Obvious Regional Differentiation of Positive and Negative Danxia Landforms

Danxia landforms develop in the southwestern margin, southern part, central part, and northeastern part of the Ordos Basin in Shaanxi Province, with both positive and negative landforms present. From southwest to northeast, they exhibit a regional differentiation pattern of positive landforms (dominated by mesas and peak clusters) → negative landforms (dominated by gully-type Danxia) → positive landforms (dominated by wave-type Danxia) → negative landforms (dominated by gully-type Danxia) → positive landforms (dominated by colored hills). Among negative Danxia landforms, slit-type Danxia canyons are numerous and unique, with the Ganquan Yucha Canyon Group in Yan'an being the most typical. Known as the "natural seam wonder of the Loess Plateau" and "China's Antelope Canyon," it is characterized by narrowness, multiple bends, vertical height, and steepness.

(2) Aeolian Desert Facies Sandstone Danxia Landscapes Have the Widest Distribution

Based on lithology, Shaanxi Province has aeolian desert facies sandstone Danxia and fluvial-lacustrine/alluvial-proluvial sandy conglomerate Danxia. The southwestern and southern margins of the Ordos Basin are dominated by fluvial-lacustrine and alluvial-proluvial conglomerate Danxia landforms. The central part of the Ordos Basin is dominated by aeolian desert facies sandstone Danxia. The northeastern part is dominated by fluvial facies sandstone Danxia landforms. Among these, aeolian desert facies sandstone Danxia has the widest distribution and largest scale.

(3) Youth-Stage Danxia Dominates, with Local Mature and Decline Stages

Based on Davis's erosion cycle theory, Danxia landform evolution can be divided into six stages: early youth, late youth, early maturity, late maturity, early old age, and late old age. Comprehensive analysis shows that youth-stage Danxia is generally represented by "narrow gullies" and "lane valleys," maturity stage by peak clusters, window-frame palaces, stone walls, and stone pillars, and old age by isolated residual peaks, pillars, and mounds. As red beds continue to uplift and experience further fluvial erosion and collapse, the underlying bedrock gentle slopes are exposed, forming quasi-plain gentle slope colored hills, which represents the decline stage.

In the southwestern margin and southern part of the Ordos Basin (Baoji Chencang Jiulongshan and Tongchuan Yaozhou Zhaojin-Xiangshan), mesas coexist with peak clusters and forests, with the base not completely dissected, reflecting characteristics of late youth to early maturity. In the middle-lower part of the Ordos Basin (Yan'an Ganquan-Zhidan-Ansai-Fuxian area), the large number and wide distribution of slit-type canyons indicate a youth stage. In the middle-upper part of the Ordos Basin (Jingbian Longzhou wave-type Danxia), preliminary judgment based on rock erosion amount and morphology suggests a youth stage. In the northeastern part of the Ordos Basin (Fugu Lianhuachan colored hills), the exposed Lower Triassic Liujiagou Formation indicates that previous Cretaceous strata have been completely denuded, exposing the underlying bedrock gentle slope surface, representing a typical decline stage of Danxia landforms.

3.2.1 Spatial Structure Characteristics

Using ArcGIS 10.5 to calculate the average nearest neighbor index, the results are shown in Figure 8. With a z-value of -6.4033 and $P < 0.01$, the results are statistically significant. The calculated nearest neighbor index $R = 0.6881$ (<1), indicating that the spatial distribution of Danxia landforms in Shaanxi Province exhibits agglomerated structural characteristics.

[Figure 8: see original paper]

3.2.2 Spatial Distribution Density

Using ArcGIS 10.5 kernel density analysis, Figure 9 shows that Danxia landforms in Shaanxi Province present a multi-center distribution pattern in space, with two high-density areas, one medium-density area, and two low-density areas.

(1) High-Density Areas
The Yan'an Ganquan-Zhidan-Ansai-Fuxian area contains 31 Danxia landform sites, mainly located in the middle-lower part of the Yishan Slope, dominated by negative landforms (gully-type Danxia). The Yulin Jingbian area contains 17 sites, mainly centered in Longzhou Township, located in the middle-upper part of the Yishan Slope, developing both positive and negative landforms. Controlled by geological structure, lithofacies, lithology, and climate conditions, wave-type Danxia landforms are formed.

(2) Medium-Density Area
The Zhaojin-Xunyi-Binxian area has 4 Danxia landform sites, located in the northern part of the Weibei Uplift and the transitional zone between the Guanzhong Weihe Plain and the northern Shaanxi Loess Plateau, mainly featuring Danxia mesas and cliffs.

(3) Low-Density Areas
These include the Baoji Jiulongshan area and the Shenmu Gonggegou-Fugu Lianhuachan area, mainly featuring Danxia mesas and Danxia colored hills respectively.

[Figure 9: see original paper]

3.3.1 Mesozoic Sedimentation in the Ordos Basin Laid the Material Foundation

The Ordos Basin developed as a Mesozoic sedimentary basin on the Paleozoic North China Craton basement, with basin construction mainly occurring from the Late Triassic to Early Cretaceous. During this period, the Ordos Basin was an east-gentle, west-steep, north-south oriented dustpan-shaped basin. Alluvial fan-lake depositional systems developed in the western basin margin, desert-river-lake depositional systems developed in the eastern gentle slope area, and alluvial fan-river depositional systems developed along the north-south long axis direction. In terms of strata and constituent materials, roughly bounded by the line of Yan'an, Zhidan, Wuqi, and Qingyang, the southern part is mainly fluvial and alluvial-proluvial facies, characterized by conglomerate, conglomeratic sandstone, and sandstone with developed cross-bedding and relatively hard rock layers. The northern part is mainly aeolian accumulation systems, characterized by thick to massive layers, with quartz and feldspar as main minerals, and developed large-scale oblique bedding with well-developed sandstone fractures and poor cementation and low hardness. Mesozoic sedimentation in the Ordos Basin provided abundant material basis for the composition and spatial distribution of Danxia landform landscapes in the Weibei Uplift and Yishan Slope, forming fluvial-lacustrine and alluvial-proluvial facies-dominated Danxia in the Weibei Uplift, aeolian desert facies-dominated Danxia in the middle Yishan Slope, and fluvial facies-dominated Danxia in the northeastern Yishan Slope.

3.3.2 Topographic Pattern Since Late Yanshanian Period Controls Positive and Negative Landform Distribution

During its construction, the Ordos Basin experienced multi-cycle inland depression, multi-phase thrust nappe in the western basin margin, uplift and tilting in the eastern basin, and continuous retreat of depositional range from east to west. Since the Late Yanshanian period, the basin has experienced overall uplift and denudation, as well as Cenozoic peripheral fault depression dynamic evolution. Due to Yanshanian movement, the Shanxi block in the east of the Yishan Slope rose and uplifted, tilting the eastern part of the basin westward and transforming the area into a gentle monocline dipping west, changing the regional structure from high-north-low-south to high-east-low-west. This is reflected regionally by positive Danxia landforms mainly developing in the north and east, negative landforms in the middle-lower part, and positive-negative transitional landforms in between. The Weibei Uplift was a south-dipping slope during the Proterozoic-Paleozoic. Due to Yanshanian movement uplift and Cenozoic Weihe Basin fault subsidence, the Weibei Uplift presents a southeast-dipping stepped slope, with the southwestern margin and southern part being higher than other areas due to multi-phase thrust nappe in the western margin, developing positive landforms such as Danxia mesas and cliffs.

3.3.3 Joint and Fissure Characteristics Play a Key Role in Landscape Pattern

Since the Mesozoic, the Ordos Basin has always shown characteristics of overall vertical movement without significant tectonic effects, with underdeveloped folds and faults. Based on field observation and measurement, the landscape-forming strata have little structural deformation, with rock layers typically composed of multiple sets of parallel bedding, oblique bedding, and cross-bedding. Rock layers are relatively gentle with dip angles nearly horizontal (oblique bedding and cross-bedding dip angles mostly 10°-20°, maximum not exceeding 30°), with each set of oblique bedding generally 1-6 m thick and dip directions generally 100°-200°, representing near-horizontal and gently inclined Danxia landforms that reflect the nature of a long-term stable craton block (platform). The distribution of Danxia landform landscape patterns is strictly controlled by joint and fissure structural systems. Gully-type Danxia orientations are basically consistent with joint and fissure orientations (Figure 10). In the wave-type Danxia landform of Jingbian Longzhou, most are cut by two or more sets of joints and fissures, providing channels for water and wind erosion (Figure 11).

[Figure 10: see original paper]

[Figure 11: see original paper]

3.3.4 Water and Wind Erosion as Dominant Forces Shaping Danxia Landform Morphology

Danxia landform landscape formation results from endogenic and exogenic geological processes. Besides lithological material and geological structural conditions, forces such as water and wind are crucial for landscape formation.

For "gully-type Danxia," water erosion plays a significant role in landscape formation. Under regional tectonic uplift background, seasonal water converges and gathers, eroding along joints or fissures, mainly through vertical downcutting and lateral erosion, forming potholes distributed along joint and fissure directions. As water continues to erode, various potholes connect to form "gully-type Danxia."

For "wave-type Danxia" in Jingbian Longzhou, compound wind-water erosion is evident. Particularly noteworthy is wind erosion. This area is located in the transition zone between the Loess Plateau and the Mu Us Desert, with a semi-arid continental monsoon climate. According to Jingbian County records and previous research, the area mainly has two dominant wind directions: northwest and southeast, with northwest winds occurring frequently, being strong with many powerful gusts. The area is dominated by sand-bearing winds, with an average annual wind speed of 6.00-9.99 $m \cdot s^{-1}$, average annual strong wind days of 15.2 d, maximum wind force reaching level 8, and long duration. Wind-carried sand particles abrade along rock joint and bedding surfaces, forming wave-type Danxia landforms.

For "colored hills" in Fugu County, located in the northeastern Ordos Basin, continuous uplift since the Yanshanian movement, combined with subsequent water erosion and wind erosion, has exposed the underlying Lower Triassic Shiqianfeng Group Liujiagou Formation (T_1l), reflecting the depositional environment and oxidation-reduction conditions during sediment formation. When Fe^{3+} content is high and Fe^{3+}/Fe^{2+} ratio is high, strata colors are mainly purple-red, brick-red, and brown-red. When Fe^{2+} content is high and Fe^{3+}/Fe^{2+} ratio is low, strata colors are mainly white, gray, and black. Different color strata thickness reflects the duration of depositional environments. Subsequent water and wind erosion intensify rock fragmentation, with numerous gullies on rock surfaces (Figure 12).

[Figure 12: see original paper]

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4 Conclusions

(1) There are more than 54 Danxia landform sites in Shaanxi Province, concentrated in the Weibei Uplift and Yishan Slope of the Ordos Basin. Among them, there are 4 sites in the southwestern margin, 4 in the southern part, 42 in the central part, and 4 in the northeastern part.

(2) In terms of landscape types, both positive and negative Danxia landforms coexist with obvious regional differentiation patterns. Aeolian desert facies sandstone Danxia has the widest distribution, mainly as near-horizontal or gently inclined Danxia. The landscape is characterized by gully-type Danxia, wave-type Danxia, and colored hills. In terms of development stage, youth-stage Danxia dominates, with local mature and decline stages.

(3) Using nearest neighbor index and kernel density analysis methods, the spatial structure type of Danxia landform distribution in Shaanxi Province is agglomerated, with two high-density areas (Yan'an Ganquan-Zhidan-Ansai-Fuxian Danxia area and Yulin Jingbian Danxia area), one medium-density area (Zhaojin-Xunyi-Binxian Danxia area), and two low-density areas (Baoji Jiulongshan area and Shenmu Gonggegou-Fugu Lianhuachan area).

(4) From the formation mechanism perspective, Mesozoic sedimentation in the Ordos Basin laid the material foundation for Danxia landforms. The topographic pattern since the Late Yanshanian period controls the distribution of positive and negative landforms. Joint and fissure characteristics play a key role in the landscape pattern of Danxia landforms, while water

erosion and wind erosion are the dominant forces shaping Danxia landform morphology.

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Note: Figure translations are in progress. See original paper for figures.