Postprint: Analysis of Characteristics and Genesis of Danxia Landform in Wensu Grand Canyon, Aksu, Xinjiang

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Abstract

Due to the landscape-forming rocks being predominantly sandstone and conglomerate with calcareous and ferruginous cementation, Danxia landforms possess distinctive landscape characteristics and formation mechanisms, and have become highly valued tourism resources due to their significant scientific and aesthetic value. Research on Danxia landforms in the humid southeastern regions is relatively extensive, but studies on Danxia landforms in the arid climatic zones of northwestern China remain scarce. Taking the Aksu Wensu Grand Canyon in Xinjiang as the study area, this study investigates the characteristics and genesis of Danxia landforms in this region through field surveys, microscopic observation of samples, salt chemistry and elemental geochemistry experiments, and the ArcGIS hypsometric integral (HI) method. The results show that: (1) The study area exhibits canyon, peak, and peak forest landscapes, characterized by the development of cliff talus slopes and caprock pillars. The landscape-forming rocks are primarily Neogene fluvial red conglomerates and sandstones, with the harder conglomerate layers providing favorable conditions for the formation of caprock pillars. (2) The red beds are located near the Wensu salt dome, with rocks containing high salt concentrations. The main salt types are chlorides, sulfates, and nitrates. Most major elements in the weathered debris samples from cliff caves have been leached relative to the parent rock, indicating that chemical weathering remains relatively active under arid climatic conditions. (3) Hypsometric integral analysis reveals that the southern part of the study area has an HI value of 0.61, indicating a youthful stage, while the northern part has an HI value of 0.38, indicating an old stage, suggesting significant differences in the overall geomorphic evolution and development stages. Although precipitation in the study area is low, fluvial erosion is pronounced, and tectonic activity is also a major factor influencing the evolution of Danxia landforms.

Full Text

Preamble

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Features and causes of Danxia landscape in the Wensu Grand Canyon of Aksu, Xinjiang, China

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Abstract: Danxia landforms exhibit unique landscape characteristics and formation mechanisms due to their scenic rocks being predominantly sandstones and conglomerates cemented by calcareous and ferruginous materials. These landforms have become important tourism resources with high scientific and aesthetic value. While research on Danxia landforms in humid southeastern China is well-established, studies on Danxia landforms in the arid climate of Northwest China remain relatively scarce. This study investigates the Wensu Grand Canyon in Aksu Prefecture, Xinjiang, through field surveys, microscopic sample observations, salt chemistry and elemental geochemistry experiments, and hypsometric integral analysis using ArcGIS. The results reveal: (1) The study area presents canyon, peak, and peak forest landscapes, featuring well-developed steep-cliff mudflow films and cap rock columns as distinctive characteristics. The landscape-forming rocks are primarily Neogene fluvial red conglomerates and sandstones, with harder conglomerate layers providing favorable conditions for cap rock column formation. (2) The red beds are located near the Wensu salt dome and contain high salt content, with chlorides, sulfates, and nitrates as the main salt types. Most major elements in weathering debris samples from cliff caves have been leached relative to surface rocks, indicating that chemical weathering remains active under arid climatic conditions. (3) Hypsometric integral values show the southern part of the study area is in the early stage, while the northern part is in the late stage, demonstrating significant variation in geomorphic evolution stages across the region. Although precipitation is low, fluvial erosion is pronounced, and tectonism constitutes a major factor influencing Danxia landscape evolution.

Keywords: Danxia landscape; arid climate; salt weathering; Aksu

Danxia landforms have undergone nearly a century of research and gained international recognition in the geomorphological community. Over 1,000 Danxia landform sites have been discovered nationwide, concentrated in southeastern China, the Sichuan Basin, and the Qilian Mountains region. Previous studies have provided important insights into the fundamental characteristics and genesis of Danxia landforms through field observations and analyses of rock compressive strength, acid erosion resistance, salt chemistry, and elemental geochemistry. Most research has focused on southeastern China, providing valuable experience for studying Danxia landforms in Northwest China's arid regions.

In recent years, investigations and conservation efforts for Danxia geoheritage resources in Northwest China have advanced research progress in Gansu and Shaanxi provinces.

Qi Deli et al. calculated the age of Danxia landforms and crustal uplift rates at Kongtong Mountain through dating analysis, offering new perspectives on stratigraphic classification disputes. Li Tongguo et al. analyzed the distribution characteristics and sedimentary environments of red beds around Lanzhou, proposing tourism value and development prospects. Peng Xiaohua et al. examined Danxia geoheritage in the Yan'an area of northern Shaanxi, discussing development mechanisms from structural, stratigraphic, and lithological perspectives combined with external forcing factors. Pan Zhixin et al. analyzed geological structures and rock characteristics of Danxia landforms in northern Shaanxi through field investigations, comparing them with Antelope Canyon in the western United States. Based on observations of cave micro-landforms on different cliff orientations at Yongning Mountain, northern Shaanxi, combined with microscopic structure analysis and salt chemistry and elemental geochemistry studies, it was concluded that microclimate is the primary factor causing differences in cave distribution and spatial patterns. Ding Hua et. al. explored the development and utilization value of Danxia geoheritage in northern Shaanxi.

Research in Xinjiang has primarily focused on tourism development of geoheritage resources, with less emphasis on the genesis of Danxia landforms. The Wensu Grand Canyon in Aksu, Xinjiang, located in the temperate arid region of the Eurasian continent, develops Danxia landscapes including steep cliffs, mesas, and peak forests. It represents a typical example of Danxia landforms in Northwest China's arid climate zone and holds significant scientific research value and tourism development potential. This study summarizes the characteristics of red bed development in the Wensu Grand Canyon and analyzes Danxia landform features and controlling factors through field observations, microscopic sample analysis, salt chemistry and elemental geochemistry experiments, and hypsometric integral methods, aiming to better understand Danxia landform genesis and provide scientific support for effective protection and rational development of Danxia geoheritage resources in Northwest China's arid regions.

1 Study Area Overview

The Wensu Grand Canyon is located in Wensu County, Aksu Prefecture, Xinjiang Uygur Autonomous Region (Fig. 1), covering a total area of 200 km^2 between 80°28 50 –80°45 01 E and 41°33 54 –41°44 35 N. The study area experiences a typical temperate continental arid climate with scarce precipitation, high evaporation, dry conditions, and a long frost-free period. Meteorological data from Aheqi County (78.45°E, 40.93°N) for the past 40 years (Fig. 2) show that the mean annual temperature ranges between 6.5–7.5°C, exhibiting a warming trend with approximately 5–7 year cycles. The lowest mean annual temperature was 5.14°C (1984), while the highest reached 8.12°C (2022). Annual precipitation varies significantly, with a minimum of 15.75 mm (1985) and a maximum of 649.48 mm (1998), showing an overall increasing trend. The average wind speed has generally decreased, ranging from 2.03 $m \cdot s^{-1}$ (2013) to 3.87 $m \cdot s^{-1}$ (1973). Wind speeds were higher in the 1970s–1980s, relatively lower in the early 21st century, with 2013 as a turning point, after which wind speeds increased compared to 2013.

Geotectonically, the study area is situated in the Cenozoic depression zone between the southern Tianshan Mountains and the northern Tarim Basin—the Kuqa Piedmont Depression. Dense joints are well-developed along the Wensu Grand Canyon, with main structural lines trending NW-SE and strata generally dipping to the south. Adjacent strata include Neogene Miocene red mudstone and sandstone interbedded with gypsum layers; Pliocene brownish-red sandstone and conglomerate; Paleogene Paleocene-Eocene red mudstone and sandstone; and Early Cretaceous brownish-red mudstone, sandstone, and conglomerate. Exposed strata in the Wensu Grand Canyon are primarily Neogene Pliocene and Miocene formations, with dense river networks forming thick fluvial clastic deposits, mainly composed of red conglomerate and sandstone with minor argillaceous rocks. The study area is divided into southern and northern sections based on two tributary regions, with a fault located near the northern part (Fig. 3).

2 Data and Methods

During field investigations in the Wensu Grand Canyon, a total of 9 samples were collected. Samples AKS-1, AKS-2, and AKS-3 are weathering debris; AKS-4 is fresh surface rock from a collapsed cliff, lithologically red fine-grained sandstone; AKS-6 and AKS-7 are samples from inside and outside the same cave, respectively, with salt crystallization inside and dry, loose conditions outside; AKS-8 and AKS-9 are weathering debris, with the external sample AKS-8 and internal sample AKS-9 being coarse-grained sandstone.

Sandstone samples (AKS-2, AKS-4, AKS-6, AKS-7, AKS-8, AKS-9) were analyzed under scanning electron microscopy (SEM) to examine surface morphological characteristics. Combined with energy-dispersive X-ray spectroscopy (EDS) images and elemental spectra, the main chemical compositions were semi-quantitatively analyzed based on element content and atomic percentages. Additionally, sample AKS-1 was ground into powder, dried, and mixed with deionized water at a 1:5 ratio to prepare a solution. After 24 hours, the supernatant was used for salt chemistry experiments. A Leici DDSJ-308A conductivity meter measured solution conductivity, while inductively coupled plasma optical emission spectrometry and ion chromatography determined major anion and cation concentrations to identify salt types. X-ray fluorescence (XRF) measured major element contents to explore micro-weathering mechanisms during cave development. The hypsometric integral (HI) method was applied using ArcGIS hydrological analysis techniques to extract watershed information from DEM data (30 m resolution) and analyze the geomorphic evolution stage of the

Wensu Grand Canyon.

3.1 Danxia Landform Characteristics

The Wensu Grand Canyon exhibits gentle strata attitudes with various Danxia landscape types (Fig. 4), including peaks, cliffs, stone columns, peak forests, canyons, and caves. Peak forests formed by separated peak groups are prominent, along with numerous vivid micro-landforms such as stone columns, mushroom rocks, mudflow films, grooves, through caves, and niches. Sedimentary bedding structures are conspicuous on vertical profiles (cliffs), indicating vertical variations in sediment grain size.

Cap rock columns and mudflow films are two distinctive Danxia landforms in the study area. Cap rock columns feature a conglomerate layer covering the column top, with the main body being purplish-red sandstone and the cap being grayish-purple conglomerate with relatively low mud content, dense cementation, and high hardness, resulting in stronger weathering resistance and relatively protruding caps after weathering. Mudflow films refer to thin mud layers covering cliffs, formed by mud flowing down from mountain tops during rainfall and rapidly losing water, resembling miniature forests—hence the name, also called mud milk films.

3.2 Sample Microstructure Characteristics

Following previous research methods, SEM images of six sandstone samples were classified based on rock surface smoothness, fracture porosity, and graininess to summarize particle surface structures and morphological characteristics. Statistical results show that rock debris particles have good roundness, poor sorting, rough surfaces, and well-developed pores (Fig. 5). Cracks are common, with chemical dissolution pits (Fig. 6a), silica (Fig. 6b), and surface phosphorus scraping (Fig. 6c) showing certain directionality. Debris surfaces are mostly covered by weathering products (such as clay, cement, and clay minerals) with salt crystals attached.

3.3 Sample Salt Chemistry Experiments

Sample conductivity results show large variations between maximum and minimum values. Samples AKS-1, AKS-3, and AKS-6 exhibit high conductivity, with AKS-6 showing the highest value at 66.62% higher than AKS-7. Different samples have varying conductivity values, reflecting different external dynamic conditions such as wind and water flow. Higher conductivity indicates higher salt solution ion concentration. Samples AKS-6 and AKS-8 collected inside caves show much higher conductivity and ion concentrations than external samples AKS-7 and AKS-9, proving that favorable temperature and humidity conditions inside caves facilitate water accumulation and condensation, moisture migration through rock pores causing salt dissolution and recrystallization.

The salt chemistry experiment results indicate that red bed rocks and weathering debris contain abundant salts, mainly chlorides, sulfates, and nitrates. The main anions are Cl^-, SO_4^{2-}, and NO_3^-, with Cl^- being most abundant. The main cations are Na^+, Ca^{2+}, and Mg^{2+}, with Na^+ showing the highest content. Therefore, the salt composition is dominated by chlorides and sulfates as anions, and calcium and sodium salts as cations. Na_2SO_4 (mirabilite) is most abundant, accompanied by gypsum and $MgSO_4$. K^+ and Ca^{2+} have similar atomic radii and can substitute for each other, with atomic ratios approaching 1:1:3, suggesting potassium feldspar.

3.4 Sample Element Geochemistry Characteristics

Major element test results (Table 2) show that SiO_2 content is highest (43.67%–74.93%, averaging 66.62%), indicating quartz constitutes a large proportion. Al_2O_3 is second highest (5.47%–13.40%, averaging 10.44%). TFe_2O_3 shows similar high-content characteristics. In contrast, cave interior sample AKS-6 has higher Al_2O_3 content than external sample AKS-7, indicating migration of soluble components from inside to outside during weathering and demonstrating that chemical weathering remains active in arid environments.

The relative migration behavior of chemical elements in weathering debris compared to parent rock can be calculated using the formula:
%change = [(X /I) - 1] × 100
where X is the content of the element to be tested in weathering products, I is the content of the reference element in weathering products, X is the content of the element to be tested in parent rock, and I is the content of the reference element in parent rock. When %change < 0, the element is relatively leached; when %change > 0, it is relatively enriched. Using surface rock (AKS-4, AKS-3, AKS-2, AKS-1) as parent rock and other samples as weathering products, with Al_2O_3 as the reference element, the relative migration characteristics of major elements show that SiO_2, TFe_2O_3, and other major elements have negative %change values, indicating leaching, while Na^+, Ca^{2+}, and other ions are enriched when %change is positive, demonstrating the important influence of salt crystallization on rock weathering.

3.5 Danxia Landform Evolution Stage

Strahler proposed the hypsometric integral method, advancing Davis's erosion cycle theory from qualitative description to quantitative analysis. The hypsometric integral (HI) is calculated using the relief ratio method:
HI = (H_{mean} - H_{min}) / (H_{max} - H_{min})
where H_{mean} is the mean elevation, H_{max} is the maximum elevation, and H_{min} is the minimum elevation. Using ArcGIS hydrological analysis, watershed information was extracted to obtain the HI distribution in the Wensu Grand Canyon (Fig. 10). HI values indicate erosion cycle stages: HI ≥ 0.6 represents the early (youth) stage with convex curves; $0.4 <$ HI < 0.6 represents the

equilibrium or mature stage with S-shaped curves; HI ≤ 0.4 represents the late (old) stage with concave curves, indicating fully stable watershed conditions.

Analysis of the watershed east of the Yiganqi Aiken River shows HI = 0.52, indicating a mature stage. Further analysis of the southern and northern regions reveals the northern watershed has HI = 0.38 (late stage), while the southern watershed has HI = 0.61 (early stage), demonstrating significant differences in geomorphic evolution stages.

4 Discussion

4.1 Tectonic Controls

Tectonic activity is the primary internal force controlling Danxia landform development in the Wensu Grand Canyon. The southern Tianshan piedmont and Kuqa Depression experienced intense deformation due to continuous compression from the north, forming fault zones. The Kuqa Group deposition gradually affected the uplift area in the late stage, causing thrust deformation. The late Cenozoic was a strong compression period when the study area's structural deformation mainly formed. Influenced by intense neotectonic movement, the red beds developed faults and folds with well-developed vertical joints. The development of Paleogene mud-gypsum-salt rocks in the Kuqa foreland depression may have been influenced by late Himalayan activity. During the middle-late Himalayan orogeny, the Tianshan fold system intensified, and fault activity strengthened. The Kuqa Depression has experienced multiple tectonic events since the Mesozoic, with weaker early Yanshan activity and stronger late Himalayan compressive stress. During the Pliocene deposition period, the southern Tianshan piedmont uplifted strongly while the piedmont subsided relatively, enhancing compressive stress and forming thick deposits in the depression area. The clearly distributed red beds in the canyon were folded by compression and cut by faults, forming diverse Danxia landscapes through fluvial erosion (Fig. 3).

4.2 Structure and Composition of Landscape-forming Rocks

The landscape-forming rocks are Neogene red and yellowish-brown conglomerates and sandstones with low cementation degrees and obvious weathering and spalling. SEM images (Fig. 5) show sandstone debris particles with good roundness, scaly weathering surfaces, abundant intergranular fractures, and large pores. Sample AKS-4 is fresh red fine-grained sandstone from a collapsed cliff, while AKS-9 is fine-grained conglomeratic sandstone from outside a cave. Conductivity values show AKS-9 > AKS-4, indicating fine-grained sandstone weathers more easily than conglomeratic sandstone. Conglomerate has stronger weathering resistance than sandstone, forming the distinctive cap rock columns (Fig. 4). Ion concentration and conductivity results are consistent, showing higher ion concentrations correlate with higher salt enrichment and faster weathering rates. The main anions are Cl^-, ${SO_4}^{2-}$, ${NO_3}^-$, and the main cations are Na^+, Ca^{2+}, Mg^{2+}. Therefore, Na_2SO_4 (mirabilite) is most abundant in cave salts, accompanied by gypsum and $MgSO_4$, which destroy rock structure through crystallization expansion.

4.3 Climate

The study area has an arid climate with low precipitation but obvious fluvial erosion, dominated by physical weathering. Rocks are significantly affected by frost heaving in winter. Sandstone particles have numerous pores and large fractures, easily becoming water-saturated with high water content. Cold climate accelerates water freezing within rocks, causing intense frost heaving. The study area also experiences wind erosion, with some gravels falling under gravity to form caves. Weathered debris in sandstone interlayers forms mud slurries when encountering seasonal water flow, ultimately creating mudflow films on cliffs.

In terms of microclimate, humidity and temperature differ significantly between inside and outside cliff caves. Cave interiors generally have higher relative humidity and lower temperature variation than exteriors due to sheltering. Samples from inside caves (AKS-6, AKS-8) show much higher conductivity and ion concentrations than external samples (AKS-7, AKS-9), proving that favorable temperature and humidity conditions inside caves facilitate water accumulation and condensation. During precipitation, humidity at cave entrances exceeds interior levels, creating relatively dry interior conditions where salt solutions in rock pores become supersaturated and crystallize, favoring salt accumulation. Periodic wet-dry cycles accelerate cave weathering processes.

4.4 Salt Weathering

The red beds contain abundant salt interlayers, with the Wensu Salt Dome National Geopark located approximately 10 km southeast of the study area. Repeated dissolution and crystallization of salt minerals accelerate rock weathering. Salt layers began crystallizing and depositing during the Oligocene, then developed into salt anticline structures during the intense Himalayan movement with well-developed fractures and joints. In the late Cenozoic, gypsum-salt rocks flowed and accumulated under strong compression, causing brittle deformation of salt layers. Prevailing northwest monsoons in the study area also bring external salts through dust storms and precipitation, which carry salts to rock surfaces and infiltrate into microfractures or pores. Salt crystallization expansion causes rock particle disintegration.

Salt chemistry experiments demonstrate that red bed rocks and weathering debris contain abundant salts, mainly chlorides, sulfates, and nitrates. Most major elements in weathering debris show negative %change values, indicating leaching of soluble components like SiO_2 and TFe_2O_3. However, positive %change values for Na^+, Ca^{2+}, and other ions indicate enrichment of salt cations, demonstrating salt crystallization's important influence. Higher conductivity and ion concentrations inside caves than outside indicate that salt weathering destroys rock structure through crystallization expansion, with main salt minerals being chlorides, sulfates, and nitrates.

5 Conclusions

(1) The Wensu Grand Canyon in Aksu represents a typical area for Danxia landform development in arid climates, characterized by red peaks, cliffs, canyons, cap rock columns, and mudflow films. The landscape-forming rocks are mainly Neogene red and yellowish-brown conglomerates and sandstones, providing the material foundation for Danxia landform development. The study area's structures trend NW-SE with strata generally dipping to the south, and tectonism plays an important role in Danxia landscape evolution.

(2) Hypsometric integral analysis shows the southern watershed has HI = 0.61 (early stage), while the northern watershed has HI = 0.38 (late stage), indicating significant differences in geomorphic evolution stages. This may relate to more developed faults in the north causing more fractured rock structures that are susceptible to weathering and erosion.

(3) SEM images show well-developed chemical dissolution pits. Major element analysis reveals highest SiO_2 content and lower soluble component contents. Compared with surface rocks, most major elements in weathering debris samples are relatively leached, but positive %change values for Al_2O_3 and enrichment of Na^+, Ca^{2+}, and other ions indicate important salt crystallization effects. Higher conductivity and ion concentrations inside caves than outside demonstrate that salt weathering destroys rock structure through crystallization expansion, with main salt minerals being chlorides, sulfates, and nitrates.

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