RESEARCH ARTICLE

Impacts of rock properties on Danxia landform formation based on lithological experiments at Kongtongshan National Geopark, northwest China

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Abstract

As an erosional landform, the formation processes of Danxia landform are controlled by internal and external forces as well as lithologic properties. Using field data, we studied the role of lithologic properties on the formation of Danxia landform in Kongtongshan National Geopark, northwest China, through a series of experiments, including uniaxial compressive strength, identification analysis under polarizing microscope, X-ray diffraction analysis, inductively coupled plasma-mass spectrometry analysis, and scanning electron microscopy. The results show that the diagenesis degree, mineral composition, cement composition, degree of cementation, geochemical composition and element contents, and micro-structure influenced the structure and anti-weathering and anti-erosion abilities of the Danxia rock mass. Differential weathering of rock in different environments was an important force shaping the different types of Danxia landform. Weathering failure of the Danxia rock mass was the result of multiple combined factors; as well as lithology, other factors, such as those induced during tectonic uplift (i.e., faulting, jointing, and fracturing) and climate, cannot be neglected. Therefore, lithology played an important role in the structural development of Danxia landform, and different lithologies influenced its weathering rate and formation processes. Our findings can provide a reference for revealing the microscopic development of Danxia landform in arid and semi-arid areas.

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Introduction

The term 'Daxia landform' was originally defined by Chinese geologists [1] and refers to erosional landscapes developed on continental red beds and characterized by scarp slopes [2,3]. It has been the subject of research for more than 80 years in China. The formation of Daxia landform reflects the evolutionary characteristics of the continental crust since the Mesozoic and has great value both aesthetically and for scientific research [4]. In August 2010, 'China

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Danxia' was inscribed on the list of World Natural Heritage Sites, resulting in substantial attention from geoscience scholars [5].

The evolutionary processes and formation characteristics of Danxia landform are the topics of greatest concern [6–12]; however, relevant research is predominantly qualitative rather than quantitative. Some recent studies have attempted to use quantitative approaches [13–15]; for example, Yan *et al.* [16] simulated the evolutionary processes of Danxia landform using a channel-hillslope integrated landscape development (CHILD) numerical model. In addition to macroscale studies on the development of Danxia landform, studies have analyzed the formation of microscale or individual landscapes, such as bedding-controlled caves, horizontal grooves, honeycomb caves, potholes, and natural bridges in Danxia landform areas [17–19].

Although the term 'Daxia landform' is not as popular in other countries as in China, extensive international research has been conducted on continental red beds and the development of sandstone and conglomerate landforms [20–25]. Many spectacular red bed landscapes outside China have a similar appearance to Danxia landform, such as the 'rose-red' cliffs of Petra, Jordan [26]. Most red beds are globally distributed in arid and semi-arid regions and are typically evaluated as arid-area landforms [27].

Currently, research on Danxia landform has mainly focused on the evolutionary processes, classification, and qualitative description of its geomorphic features, especially in humid southeast China. Thus, more research is required on the microscopic factors affecting the formation and evolution of Danxia landform, especially in arid and semi-arid areas [28]. The aim of this study is to clarify connections between geomorphic features of Danxia landform in Kongtongshan National Geopark (hereinafter KNG) in the semi-arid region of northwest China and lithological characteristics derived from field investigation and experimental analysis. Through this study, we quantitatively reveal the general development process of Danxia landform in the semi-arid region of northwest China, and provide relevant empirical cases for earth scientists studying areas with similar geomorphology.

Study area

The KNG is located in the west suburban area of Pingliang city, Gansu Province, approximately 12 km from Kongtong District (geographical coordinates: 35°27'08"–35°35'08"N, 106°27'16"–106°36'00"E) (Fig 1), covering an area of 83.6 km². It lies in the temperate and semi-humid climate region, with a mean annual precipitation of 574.0 mm, a mean annual evaporation of 1455.8 mm, and a mean annual temperature of 8.5°C. The average temperature is -5.1°C in winter and 21.0°C in summer, with 178 frost-free days. It is cold and dry in winter and spring, yet hot and humid in summer and autumn. There is a dense river network in the KNG area, with a drainage area of 185.6 km², which relies on precipitation for recharge.

Geologic setting

Geologically, Kongtongshan is situated on the east side of the Liupanshan fault zone, the southwestern margin of Ordos Basin, the northern side of the Qinling fold belt, and the southern margin of Helanshan fold belt. The NS or NNE-trending Qingtongxia-Guyuan Fault, Jingfushan Fault, and Taitongshan Fault form a group of parallel duplex anticlines (Fig 2). Ages for the main strata exposed in the KNG are Ordovician (O), Permian (P), Triassic (T), Cretaceous (K), and Quaternary (Q) (Fig 3).

Ordovician strata are mainly distributed in Erdaogou, Sandaogou, and Taitongshan, which belong to the Middle Ordovician Sandaogou Formation (O_{2s}). The attitude of beds is 247°–219°, the joint direction is relatively scattered, and the dominant joint orientation is 295°–300°. The Permian Shiqianfeng Formation stratum (P_{2sh}) is mainly exposed in the

Fig 1. Location of Kongtongshan National Geopark in China.

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southeastern part of the KNG. It is a coarse red terrestrial detrital sediment with a bed attitude of $266^{\circ} \angle 22^{\circ}$ and a group of X-shaped joints oriented $75^{\circ} - 80^{\circ}$ and $345^{\circ} - 350^{\circ}$. Triassic strata include the Upper Triassic Yanchang Group (T_3), including the lower group (T_{3yn1}) and middle group (T_{3yn2}), and are mainly distributed in YanzhiXia, Tanzheng Lake, and Shiwan Gorge. It is a very thick coarse terrestrial detrital sediment with a bed attitude of $264^{\circ} \angle 20^{\circ}$ and a group of dominant joints oriented $5^{\circ} - 10^{\circ}$. Cretaceous strata include the Lower Cretaceous Sanqiao Formation (K_{1s}) and the Heshangpu Formation (K_{1h}), which lie unconformably over the Triassic and Permian strata (Fig 4C). The Sanqiao Formation (K_{1s}) belongs to foothill debris and is exposed in Yanzhixia, Xiangshan, and Zhongtai with a bed attitude of $220^{\circ} \angle 35^{\circ}$. The Heshangpu Formation (K_{1h}) is exposed on the western edge of the KNG and has a small distribution area. It exhibits near horizontal bedding with an attitude of $325^{\circ} \angle 11^{\circ}$ and a group of dominant joints extending in the direction of $350^{\circ} - 355^{\circ}$. Quaternary strata (Q) are exposed on the northeast and west sides of the KNG and comprise an aeolian loess layer with a group of joints extending in the direction of $355^{\circ} - 360^{\circ}$.

Materials and methods

Ethics statement

For this study, field investigation and rock sampling in the KNG were approved by the Kongtongshan Management Committee, and we strictly complied with the regulations of the committee in the field. We confirmed that no animals were killed specifically for this study.

Sampling sites

Five sets of conglomerate strata (O_{2s} , K_{1s} , K_{1h} , T_{3yn} , and P_{2sh}) are exposed in the KNG. Among them, T_{3yn} and K_{1s} are the main strata controlling the formation of Danxia landform

Fig 2. Geological structure map of Kongtongshan National Geopark (KNG). Fig 2 is excluded from this article's CC-BY license. See the accompanying retraction notice for more information.

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Fig 3. Geological map of the KNG. Fig 3 is excluded from this article's CC-BY license. See the accompanying retraction notice for more information.

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in the KNG. The very thick conglomerate layers of the Triassic and Cretaceous formed various geological landscapes, such as escarpments, stone walls, stone pillars, rock caves, valley, colluvial rock blocks, and pictographic Danxia landforms (Fig 4). Compared with the red Danxia landform in southeastern China, the Danxia landform in the KNG shows a gray-brown color, which could be attributed to a large number of algae on the rock surface. Red bedrock cemented by hematite can be observed after removing the weathering crust.

Twenty-four conglomerate samples and four cave samples were collected from the KNG during a field investigation. The conglomerate samples were collected from Mt. Elephant and Hudiedong Cave in Yanzhixia Scenic Area, Candle Peak and A Thread of Sky in Wutai Scenic

Fig 4. Geomorphic features of Danxia landform in the KNG. (a) Candle Peak, (b) Mt. Elephant, (c) an unconformable contact at Wendaogong, (d) caverns at Yanzhixia, (e) V-shaped valley at Yehu bridge, (f) narrow gorge (A Thread of Sky), (g) vertical joints at Five-finger Peak, (h) escarpment at Nantai, and (i) colluvial rock block in Yanzhi River (Erlang stone). Fig 4C and 4D panels are excluded from this article's CC-BY license. See the accompanying retraction notice for more information.

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Area, and Mt. Taitongshan, marked as “KT”. The cave samples, marked as “HDD”, were collected from Hudiedong Cave in Yanzhixia Scenic Area.

Experimental methods

A series of experiments were conducted, including uniaxial compressive strength tests, identification analysis under polarizing microscope, X-ray diffraction (XRD) analysis, inductively coupled plasma mass spectrometry (ICP-MS) analysis, and scanning electron microscopy (SEM).

The uniaxial compressive strength tests followed the DL/T5368-2007 Standards of Rock Experiment procedures of Water Conservancy and Hydropower Engineering of the Chinese Ministry of Water Resources (2007) [29]. First, rock samples were cut into 10×5 cm cylindrical test pieces with a height to diameter ratio of 2:1. Second, rock samples for the dry experiment were air-dried for 48 h under natural conditions, and rock samples for the wet experiment were soaked in distilled water for 48 h, then the surface water was wiped off. The upper and lower pressed areas and height of the samples were measured with a caliper, and the weight of the samples were weighed with a balance. Then, the uniaxial compressive strength experiment was conducted with the YAW-42061 microcomputer controlled electro-hydraulic servo pressure testing machine (Fig 5A) in the Rock Mechanics Laboratory, School of Engineering, Sun Yat-sen University. Table 1 shows the results of the uniaxial compressive strength experiment, raw data can be found in S1 File.

Fig 5. Photographs of main laboratory equipment. (a) The YAW-42061 microcomputer controlled electro-hydraulic servo pressure testing machine. (b) Polarizing microscope (BX51-P). (c) Inductively coupled plasma mass spectrometer (iCAP Qc). (d) PANalytical Empyrean X-ray Diffractometer. (e) Philips Quanta 400 FE Environment Scanning Electron Microscope.

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A polarizing microscope is the main research tool for crystal optics. To identify the mineral composition and structural characteristics of rock samples, first, according to the experimental objective used to select the appropriate Danxia rock samples, rock samples were ground into slices using a rigorous program in the Rock and Mineral Identification Laboratory, School of Earth Science and Geological Engineering, Sun Yat-sen University. This involved standard cutting of rock samples (size: $20 \times 20 \times 5$ mm), grinding of the bonding surface, fixed bonding, drying of the resin adhesive, cutting of thin sections (thinning to 0.5 mm), and grinding (thinning to 0.03 mm), polishing, and capping of slides. Identification was then carried out under a BX51-P polarizing microscope of Olympus Corporation (Fig 5B). Table 2 shows the identification results of selected samples under a polarizing microscope, photographs of the corresponding samples under polarized microscope could be found in the S2 File.

In order to analyze the geochemical content of the elements in these rock samples, inductively coupled plasma mass spectrometry (ICP-MS) analysis was performed with an inductively coupled plasma mass spectrometer (iCAP Qc) (Fig 5C), manufactured by American Thermo Fisher at the Testing Center of Sun Yat-sen University. First, the rock samples were ground into powder and sieved through a 200-mesh screen. Samples weighing 0.25 g (accurate to 0.0001 g) were placed into 200 mL PTFE beakers, wet with a few drops of water, followed by 5 mL hydrochloric acid, 5 mL nitric acid, and 10 mL hydrofluoric acid, and heated on a 200°C

Table 1. Uniaxial compressive strength results of rock samples from the KNG.

Sampling sites	Stratigraphic age and lithology	Stress direction	Sample number	Testing state	Destructive load	Uniaxial compressive strength
					KN	MPa
Hudiedong Cave	Cretaceous conglomerate	Axial force	KT-1	Dry	95.65	50.05
			KT-2	Dry	133.50	71.55
			KT-3	Dry	125.80	65.98
			KT-4	Wet	68.98	36.22
			KT-5	Wet	57.84	30.25
			KT-6	Wet	58.67	31.54
Candle Peak	Cretaceous conglomerate	Axial force	KT-7	Dry	118.32	61.81
			KT-8	Dry	124.00	64.88
			KT-9	Wet	57.26	29.92
			KT-10	Wet	64.98	35.51
A Thread of Sky	Cretaceous conglomerate	Axial force	KT-11	Dry	128.25	67.08
			KT-12	Dry	115.30	60.43
			KT-13	Wet	74.37	39.62
			KT-14	Wet	61.89	32.77
Mt. Elephant	Triassic conglomerate	Axial force	KT-15	Dry	145.96	76.31
			KT-16	Dry	134.74	70.99
			KT-17	Dry	131.80	68.93
			KT-18	Wet	92.42	48.55
			KT-19	Wet	71.32	37.27
			KT-20	Wet	79.86	41.89
Taitongshan	Permian conglomerate	Axial force	KT-21	Dry	191.38	100.34
			KT-22	Dry	176.20	92.34
			KT-23	Wet	141.80	75.84
			KT-24	Wet	137.04	72.32

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heating plate to completely dissolve the sample. Then, 10 mL perchloric acid was added and it was heated to the wet salt state. After reducing the temperature slightly and adding 5 mL nitric acid, the sample was heated on the plate to dissolve all salts, removed, and cooled to room temperature. The test solutions were transferred to 250-mL volumetric flasks, diluted with water,

Table 2. Identification results of selected rock specimens under a polarizing microscope.

Sample number	Sampling site	Lithology and rock formation	Lithological features
KT-1	Hudiedong Cave	Conglomerate K_1s	Quartz accounts for 50%, feldspar 35%, and cement 3%, with dominant argillaceous cementation and minimal calcium cementation. Cementation is contact cementation, with a particle supporting structure. The gravel content is 60%, with large diameters, medium sorting and roundness, and a roundness degree from sub-rounded to sub-angular.
KT-7	Candle Peak	Conglomerate K_1s	Quartz accounts for 60%, feldspar 25%, and cement 5%, with dominant argillaceous and ferruginous cementation, and lesser calcium cementation. Cementation is basal cementation, with a matrix supporting structure. The gravel content is 45%, with medium sorting and roundness, and a roundness degree from sub-rounded to sub-angular.
KT-12	A Thread of Sky	Conglomerate K_1s	Quartz accounts for 30%, feldspar 40%, and cement 10%, with mainly calcite cementation. Cementation is basal cementation. The gravel content is 70%, > 2 mm in diameter, poorly sorted, and poorly rounded, with a roundness degree from sub-angular to angular.
KT-15	Mt. Elephant	Conglomerate T_3yn	Quartz accounts for 20%, feldspar 40%, and cement 10%, with mainly ferruginous cementation. Cementation is void and contact cementation. The gravel content is 50%, with large diameters, poor sorting and low roundness, with degrees of roundness varying from sub-angular to angular.

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Table 3. Inductively coupled plasma mass spectrometry (ICP-MS) analysis results of element contents of samples from the KNG.

Sampling sites	Sample number	Fe*	Na*	Mg*	Al*	K*	Ca*	Cr	Co	V	Ni	Cu	Ga	Mn	As	Se	Rb	Sr	Ba	Pb	B
Hudiedong Cave	KT-1	2.34	0.06	4.71	3.2	1.63	3.5	43.12	29.81	69.21	18.54	8.15	44.17	574.69	22.47	7.44	60.84	139.74	189.46	8.76	68.66
	KT-2	2.52	0.23	2.05	5.84	2.44	3.51	58.32	48.32	50.24	50.38	24.43	45.76	643.21	28.74	12.24	57.61	275.22	227.98	9.07	102.32
	KT-3	1.96	0.11	2.66	4.07	2.98	3.82	47.39	34.86	79.1	32.92	12.57	43.34	603.04	20.82	9.98	64.22	185.89	207.71	9.68	79.9
Candle Peak	KT-7	2.02	0.03	3.85	3.18	1.87	4.45	40.75	26.46	66.85	29.84	5.15	40.11	591.24	11.25	10.27	74.21	142.72	205.71	11.21	68.72
	KT-8	1.78	0.04	2.84	3.92	2.43	4.11	55.58	31.02	61.67	33.7	16.76	49.03	459.76	33.42	8.35	101.64	169.12	319.52	16.31	81.43
A Thread of Sky	KT-11	2.57	0.04	1.19	3.81	2.21	3.83	48.22	34.87	49.76	38.61	16.64	49.02	491.27	31.28	8.74	50.46	140.13	321.24	12.65	38.71
	KT-12	2.95	0.02	1.02	4.84	1.89	3.61	74.91	24.61	74.67	24.97	23.12	55.23	389.25	49.12	7.89	154.21	117.67	305.47	10.97	105.73
Mt. Elephant	KT-15	2.83	0.05	2.73	4.13	2.2	2.89	43.62	33.58	68.58	37.52	10.53	42.84	698.78	19.86	8.42	100.27	249.58	331.85	16.31	99.86
	KT-16	2.92	0.04	1.95	3.67	2.14	2.38	37.45	35.35	89.39	34.27	14.56	56.31	587.52	34.32	8.78	81.91	258.44	236.53	13.28	71.11
	KT-17	1.43	0.03	2.18	3.22	2.09	3.88	31.28	37.12	81.21	31.02	18.59	69.78	676.26	48.79	9.14	63.55	267.31	341.22	19.25	42.37

the units of the elements labeled by “*” are %, the others are $\mu\text{g/g}$ (ppm).

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and shaken to evaluate the element contents using a plasma mass spectrometer. The results are shown in Table 3.

In order to detect the mineral composition of samples, powder X-ray diffraction (XRD) analysis was performed with a PANalytical Empyrean X-ray Diffractometer (Fig 5D) at the Testing Center of Sun Yat-sen University. First, the rock samples were ground into a fine powder using an agate mortar and pestle and sieved through a 300-mesh screen. The ground powder (1–2 g) was placed into a groove of the glass specimen holder, pressed with a flat glass plate, the excess powder outside of the groove or above the plate surface of the sample was scraped off, and the sample was flattened again to obtain a flat and smooth sample surface. We used $\text{CuK}\alpha$ radiation, operating at 40 kV and 40 mA, and scanned from 3° and 80° (2θ) at a scan rate of 5° (2θ) min^{-1} . Fig 6 shows the XRD patterns of this experiment, raw data can be found in S3 File.

Scanning electron microscopy (SEM) was employed to investigate the surface morphology of the rock samples. SEM analysis was also conducted at the Testing Center of Sun Yat-sen University using a Philips Quanta 400 FE Environment Scanning Electron Microscope (FEI, Holland) coupled with an INCA energy dispersive X-ray spectrometer (EDS, Oxford, England) (Fig 5E). The rock powder samples were fixed to the sample stage with conductive tape, and samples whose surface was not fixed were gently blown off with a rubber suction bulb. After samples were firmly adhered, a metal conductive film was placed on the sample surface with an ion sputtering apparatus to ensure good electrical conductivity of the samples. Fig 7 shows the SEM photomicrographs of the surfaces of cave specimens.

Results and discussion

Tables 1–3 show the uniaxial compressive strength results, the identification results of selected rock specimens under the polarizing microscope, and ICP-MS analysis results of element contents of rock samples from the KNG. Fig 8 shows photos of the lithological differences and morphology of rock samples after rock failure in the study area. As can be seen in Table 1, the average uniaxial compressive strengths of rock samples in dry and wet states, respectively, are ordered from highest to lowest as follows: Permian Mt. Taitong (96.34 MPa vs. 74.08 MPa) > Triassic Mt. Elephant (72.08 MPa vs. 42.57 MPa) > Cretaceous Skyline (63.75 MPa vs. 36.19 MPa) > Cretaceous Candle peak (63.34 MPa vs. 32.72 MPa) > Cretaceous Hudiedong cave (62.53 MPa vs. 32.67 MPa).

Fig 6. XRD patterns of rock samples from Hudiedong cave. Qtz = quartz, Cal = calcite, An = ankerite, and Dol = dolomite. Fig 6 is excluded from this article's CC-BY license. See the accompanying retraction notice for more information.

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Photographs of the lithological differences (Fig 8) indicate a greater gravel content and larger particle size in Cretaceous, Triassic, and Permian strata. Gravels in Cretaceous strata have large diameters and are poorly sorted, with a low degree of cementation. There are clear traces of exfoliation from parent rocks (Fig 8A). The gravel in Triassic and Permian strata is smaller than in Cretaceous strata, the degree of cementation between gravels is higher, and the color of Triassic strata is a brighter red (Fig 8B and 8C). Photographs of the morphology after rock failure reveal that the Cretaceous rock sample from Hudiedong Cave shows shear failure after stress application (Fig 8D). The Triassic rock sample from Mt. Elephant shows shear failure along a weak interface; the test specimen is broken along this weak interface, and large gravels are observed on the shear fracture surface (Fig 8E). The Permian rock sample from Mt. Taitongshan shows brittle failure after stress application. A loud noise was heard when the stress reached the maximum destructive load, resulting in spraying of lithic fragments (Fig 8F).

The following features can be summarized from the experimental results. The uniaxial mechanical strengths of all samples in the dry state are larger than those in the wet state, indicating that Danxia rock body is more susceptible to erosion during the rainy season or in a humid environment. In terms of the stratigraphic age of rock samples, the uniaxial mechanical strengths of Permian rock samples are the largest, followed by Triassic rock samples, then Cretaceous rock samples. We have verified that the higher the diagenesis degree, the higher the uniaxial compressive strength. This test shows that the difference of uniaxial mechanical

Fig 7. SEM photomicrographs of rock sample surfaces from Hudiedong Cave. (a) HDD-1, (b) HDD-2, (c) HDD-3, and (d) HDD-4. Fig 7 is excluded from this article's CC-BY license. See the accompanying retraction notice for more information.

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strength between rock bodies in dry and wet environments is an important factor governing anti-weathering and anti-erosion capability. Of course, the tensile strength and degree of cementation cannot be neglected when considering the weathering and destruction of an exposed rock body.

Formation of Danxia cave

In the conglomerate layer in the KNG, many caverns of various scales have developed on the cliff walls (Fig 4D). The Hudiedong Cave (35°34'18"N, 106°29'45"E) is one such cave in the Cretaceous Sanqiao Formation (K_1s) in Yanzhixia Scenic Area. Rock layers in this cave have been severely weathered, with a 2–10 cm thick weathered crust on the cave wall and a 5–10 cm thick sedimentary debris layer on the cave floor. The entrance of the cave is controlled by two sets of joints, which extend in directions of NW 300° and NW 350°, respectively. A pillar divides the cave into two connected parts (Fig 9A and 9B), and water erosion traces are observed at the entrance (Fig 9C).

The average uniaxial compressive strengths of rock samples from Hudiedong Cave in dry and wet conditions are 62.53 MPa and 32.67 MPa, respectively, which are the lowest values of all tested samples. The identification results of Table 2 show that gravels account for 60% and

Fig 8. Photographs of lithological differences and morphologies of rock samples after rock failure. (a) Cretaceous strata lithology, (b) Triassic strata lithology, and (c) Permian strata lithology. Post-rock failure morphology of (d) the Cretaceous rock sample from Hudiedong Cave, (e) the Triassic rock sample from Mt. Elephant, and (f) the Permian rock sample from Mt. Taitongshan.

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contain argillaceous and calcareous cement with a low degree of cementation, making it easily eroded by running water. According to the ICP-MS results, the Ca, Fe, and Mg contents in the sample are high. The XRD patterns (Fig 6) also verify that the peaks of corresponding carbonate minerals, such as calcite, dolomite, and ankerite, are more prominent. The SEM photomicrographs (Fig 7) indicate that rock samples containing a large amount of clay mineral components typically have a loose surface structure, with micro-cracks and corrosion pits developed on the surface. These particles are cemented in line contact or point contact patterns, with some carbonate cement filling in gaps between particles. As water infiltrates these cracks, carbonate cements are eroded and migrated, eventually forming calcareous deposits on the cave walls and cave floor.

Using the analysis results of these experiments, we infer the formation mechanism of Hudiedong Cave. In the Cretaceous conglomerate layer in the KNG, the gravel content is high, the grain size is large, the degree of cementation is uneven, and pores and cracks have developed in the cement. The combination of flowing water and CO_2 in the air generates CO_3^{2-} , and water containing CO_3^{2-} corrodes and migrates away from the calcareous cement and other mineral substances along the cracks [30]. Long-term chemical erosion results in destruction of the rock structure, and gravels with low cementation degree and large particle size gradually peel off from the parent rocks (Fig 9D). Continuous weathering and shedding of rock layers therefore produced the Hudiedong Cave, gradually increasing its size. Turkington and Phillips [31] described cave formation as ‘differential weathering of a rock surface’, which represents ‘areas of material loss surrounded by intervening areas of stable rock surface’.

In addition, a unique aspect of Hudiedong Cave is that the entrance of cave is divided into two parts by a conglomerate pillar. The formation mechanism of such a pillar has been

Fig 9. Geomorphic features of Hudiedong Cave. (a) External features of Hudiedong Cave, (b) view of the exterior from inside the cave, (c) water drainage channel, and (d) gravel exfoliation.

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researched by many scholars. For example, Nicholas and Dixon [32] believed that pillars are formed to exploit localized intense fracturing by weathering and erosion, and Grab *et al.* [33] suggested that pillars form due to fast weathering of weak rock under a resistant cap rock. During our field investigation, we found that the pillar in Hudiedong Cave was created by erosion along nearly vertical fractures. There is a negative feedback relationship between stress and surface retreat of pillars [34]; i.e., the greater the stress at the eroding surface, the slower the erosion exerted on it. Continuous peeling of gravels in the cave occurs because, as the horizontal section area of the pillar decreases, the stress in the conglomerate pillar increases and its erosion rate decreases. Therefore, stress at the pillar is more concentrated (Fig 10) and the damage is less affected, resulting in the unusual stone pillar landscape. As mentioned previously, after a long geological period, caves such as Hudiedong Cave, Xuanhe Cave, and Moon Cave eventually developed on these Cretaceous strata.

Fig 10. Sketch of the stress field distribution around the pillar in Hudiedong Cave (denser red lines indicate a higher stress magnitude).

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Formation of Danxia stone pillar

Candle Peak (35°32′53″N, 106°31′18″E) is located on the south side of Yaowang Cave in Wutai Scenic Area. The stone pillar is 50-m high with a pine tree approximately 7-m tall at the top, with a milky white crystalline streak (Fig 4A). The average uniaxial compressive strength of rock samples from Candle Peak under dry and wet conditions are 63.34 MPa and 32.72 MPa, respectively, which is similar to the uniaxial compressive strength of rock samples from Hudiedong Cave. The softening coefficient is 0.516, indicating that the rock body is significantly affected by water flow. Under a polarizing microscope, these rock samples exhibit argillaceous cements, low cementation strength between particles, poor water resistance, and weak weather resistance. According to the ICP-MS test results, the Ca content is the highest in Candle Peak samples. More active chemical ions, Ca^{2+} , Na^{2+} , Mg^{2+} , K^{+} , etc. are prone to leaching away and migrating in a warm, humid climate [35]; therefore, traces of calcium cement precipitation are observed on the stone pillar.

During our field investigation, we concluded that Candle Peak is not an isolated landscape; it was originally integrated with the surrounding mountains. Long-term water erosion and differential weathering along two intersected joints, which extend SE 120° and NW 345°, and vertical joints separated it from the surrounding mountains and created this stone pillar landscape.

Formation of Danxia narrow gorge

The scenic spot known as A Thread of Sky ($35^{\circ}32'53''\text{N}$, $106^{\circ}31'18''\text{E}$) is located in Wutai Scenic Area (Fig 4F). Geomorphologically, it is a Danxia narrow gorge. The average uniaxial compressive strength of rock samples from A Thread of Sky in dry and wet conditions are 63.75 MPa and 36.19 MPa, respectively. Table 2 shows that the cement between particles is basal cementation with high strength and strong calcite cementation. Therefore, they are the most resistant rock samples of all the Cretaceous samples, but the presence of a fault zone makes it the most vulnerable site to erosion. From the test results of ICP-MS, it can be seen that the contents of constant elements Ca, Mg, K, Na, and trace element Mn in these rock samples are low; these elements have been leached away during long-term water erosion. The chemical properties of Fe and Al are relatively stable but they exhibit poor solubility; thus, they exist in relatively high contents.

Based on the field survey and experimental results, we can infer the formation process of this narrow gorge. A fault zone with a strike of $\text{SW } 204^{\circ}$ was formed in this area during the process of structural uplift. Deformation controlled by the fault zone damaged the rock structure and this belt became a pioneering zone of weathering and erosion. Erosion by water flow along the fault and joint belt washed away the chemical elements in the rock body, further damaging the rock, and continuous water erosion deepened and widened the joint zone, gradually forming a narrow and deep V-shaped valley landscape (Fig 4E). Further erosion of the V-shaped valley resulted in the formation of the narrow gorge landscape (Fig 4F) and further widening of the narrow gorge led to the valley landscape. Therefore, a V-shaped valley is the initial development stage of a narrow gorge, while a narrow gorge is a geomorphological feature describing a V-shaped valley deepened and widened by long-term headward erosion.

Formation of Danxia pictographic landform

Pictographic landforms refer to landscapes with outstanding pictographic characteristics that may display personification or imitate birds and beasts. Mt. Elephant ($35^{\circ}33'40''\text{N}$, $106^{\circ}31'10''\text{E}$) is located on the bank of the Yanzhi River in Yanzhixia Scenic Area and was developed in the Triassic Yanchang Formation (T_{3yn}) (Fig 4B). Mt. Elephant was originally a Danxia mesa. The mesa was controlled by unloading joints during regional tectonic uplift, forming an arc-shaped joint surface roughly parallel to the mesa slope. The front of the mesa is controlled by two sets of arc-shaped vertical joints. The stress became concentrated at the upward turn point, destroying the rock structure first. Under long-term water erosion, the joint surface has been eroded into an arc-shaped vertical groove. We predict that this arc-shaped vertical groove will be slowly eroded into a through-cave over time.

Table 1 indicates that the average uniaxial compressive strength of rock samples from Mt. Elephant in dry and wet conditions are 72.08 MPa and 42.57 MPa, respectively, with a softening coefficient of 0.591, indicating that the rock mass is greatly affected by water flow. According to Table 3, the high Fe content explains why the bedrock is red on the fresh collapse surface. In addition, other oxidizing metal elements such as V, Mn, Ba, and Pb have high contents; thus, it can be inferred that the conglomerate layer in the KNG might have been in an oxidizing environment characterized by high temperature and dryness during the diagenetic stage. Identification results under polarizing microscope show that gravels account for 50% of the sample and exhibit large diameters, poor sorting, and poor roundness; the degree of roundness ranges from angular to sub-angular. These characteristics indicate that the gravels were deposited locally during the diagenetic process; therefore, the sediment is closer to the provenance of sedimentary rocks. This conclusion has been confirmed by previous research. Yang *et al.* [36] examined the sedimentary age of detrital zircons for KNG conglomerate

samples by LA-ICP-MS. The results showed that the ages of detrital zircon were 380–479 Ma, 561–1198 Ma, 1285–1982 Ma, 2319–2612 Ma, and 2714–2764 Ma, respectively. According to the distribution characteristics of zircon age and previous research results [37], we suggest that the main material of the KNG conglomerate comes from the West Qiling-North Qilian orogenic belt (Fig 2) and the sedimentary age of the conglomerate is middle to late Triassic. Therefore, the Triassic conglomerate layer in the KNG reflects the sedimentary response of orogenic processes near Mt. Qinling and Mt. Qilian in a high temperature and dry environment.

In this study, we have discussed the formation processes of Danxia cave, Danxia stone pillar, Danxia narrow gorge, and a Danxia pictographic landform, revealing that Danxia landform formation is the result of multiple factor interaction. These difference factors induce the different topographic features of Danxia landform. Comparing the four morphogenesis events of the Danxia landform, we conclude that:

1. The joints and faults formed in the process of tectonic uplift are important factors controlling Danxia landform formation. Vertical joints controlled the formation of the stone pillar at Hudiedong Cave, Candle Peak, and the stone pillar corridor at Five-finger Peak (Fig 4G). The cross joints at the entrance to Hudiedong Cave divided the cave into two connected parts. The intersected joints at Candle Peak caused it to gradually separate from the surrounding mountains. The two sets of arc-shaped vertical joints in the front of Mt. Elephant controlled the formation of the “elephant nose”. In addition, a fault zone with a strike of SW 204° at A Thread of Sky was a pioneering zone of weathering and erosion.
2. Weathering, erosion, and collapse characterize the entire formation process of the Danxia landform, with colluvial deposits ranging from small gravels to large blocks weighing a few tons (Fig 4I). Gravels in Hudiedong Cave gradually peeling away from the parent rocks was the main cause of cave enlargement. Continuing erosion and collapse expanded a V-shaped valley into a narrow gorge. Mt. Elephant displays clear fresh collapse surfaces. Furthermore, on the foothills of Mt. Elephant, Candle Peak and the escarpment at Nantai (Fig 4H) are vegetation-covered and gently inclined colluvial heaps.
3. Lithology is also an important factor in Danxia landform formation. Lithological differences lead to differences in the ability of a rock body to withstand weathering; i.e., the mechanical properties, mineral composition, degree of cementation, geochemical content of elements, and arrangement and contact modes of micro-structural units of the rock body all affect the ability of a rock body to withstand weathering. Furthermore, most of these factors are influenced by each other. The Cretaceous Sanqiao Formation (K_1s) and Triassic Yanchang Group (T_{3yn}) are the main strata controlling the formation of the Danxia landform in the KNG. K_1s has low diagenesis degree, weak cementation, and high element content with more active chemical properties, resulting in weak resistance to erosion and long-term weathering and erosion of flow water. Therefore, it became the main strata controlling landform formation, leading to formation of Hudiedong Cave, Candle Peak, A Thread of Sky, etc. within this rock layer. T_{3yn} is exposed less in the KNG and has a higher diagenesis degree, strong cementation, and a low element content with more active chemical properties; thus, T_{3yn} has a stronger anti-erosion ability than K_1s , and landscape development is less pronounced than that of K_1s . Mt. Elephant is a typical Danxia pictographic landform within Triassic strata.

Conclusions

The evolution of the Danxia landform is the result of a combination of internal and external geological forces. Using field data, this study comprehensively analyzed the role of lithology in

the development of the Danxia landform through multiple laboratory analyses. The following conclusions are drawn:

1. The mechanical properties of conglomerate samples in the KNG verified that the older the sedimentary age, the higher the diagenesis degree, and the higher the uniaxial compressive strength. The average values of uniaxial compressive strength were ranked from the highest to the lowest as follows: Permian conglomerates (dry 96.34 MPa vs. wet 74.08 MPa) > Triassic conglomerates (dry 72.08 MPa vs. wet 42.57 MPa) > Cretaceous conglomerates (dry 63.21 MPa vs. wet 33.86 MPa). As for rock samples collected at the same site, uniaxial mechanical strengths in dry conditions were larger than those in wet conditions and the higher the diagenesis degree, the more brittle the fracturing of the Danxia rock mass.
2. Mineral characteristics indicated that the mineral composition, contact patterns, cementation composition, and degree of cementation influenced the internal structure of Danxia rocks. Rock bodies with harder granular minerals (quartz, feldspar) had higher contents of ferruginous cementation and basal cementation with strong mechanical properties; therefore, the weathering resistance ability was correspondingly stronger.
3. The geochemical content of elements in the rock samples did not only depend on the basic composition of the material in the source area, it was also affected by weathering, migration, and transformation during the diagenetic process. From the experimental results of ICP-MS and XRD, we conclude that active elements, including Ca, Na, Mg, and K, are easily leached and migrated in a humid and warm climate, which results in damage of the rock structure. Metallic elements with high oxidizing capabilities, such as Fe, V, Mn, Ba, and Pb, are indicators of the paleo-environment for the formation of these sedimentary rocks. A higher content of these elements suggests that conglomerates in the KNG might have been formed in a hot and dry oxidizing environment.
4. SEM photomicrographs of samples from Hudiedong Cave showed that the arrangement and contact modes of micro-structural units in the Danxia rock body controlled the micro-structural features, which in turn determined the physical properties of the rock body and the weathering mechanism. Damage to the interstitial material structure in the Hudiedong Cave, as well as the dissolution and migration of calcareous cements in the interstitial material, resulted in severe weathering of rocks in Hudiedong Cave.

Supporting information

S1 File. Raw data set of uniaxial compressive strength test.
(ZIP)

S2 File. Thin section photographs.
(ZIP)

S3 File. Raw data set of XRD analysis.
(ZIP)

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Author Contributions

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References

1. Chen GD. Red rock series of Guangdong Province. Q. Natl. Univ. Sun Yat Sen (Nat. Sci. Ed.). 1935; 6 (4): 1–30. Chinese.
2. Feng JL, Zhu HS. Geology and mineral resources of Qujiang, Renhua, Shixing and Nanxiong, Guangdong Province. Ann. Guangdong Guangxi Geol. Surv. 1928; 1: 38–42. Chinese.
3. Zeng ZX, Huang SM. Red bed landform in Southeast China. J. South China Normal Coll. (Nat. Sci. Ed.). 1978; 1: 56–73. Chinese.
4. unesco.org [Internet]. Pairs: World Heritage Committee; c2018 [cited 2018 Nov 7]. Available from: <https://whc.unesco.org/en/sessions/31COM>.
5. Peng H, Pan ZX, Yan LB, Scott S. A review of the research on red beds and Danxia landform. Acta Geogr. Sin. 2013; 68(9): 1170–1181. Chinese.
6. Ma CM, Zhu C, Peng H, Zheng CG, Xiang FS, Sun YF, et al. Danxia landform genesis of the Qiyun Mountain, Anhui Province. J. Geogr. Sci. 2006; 16(1): 45–56. <https://doi.org/10.1007/s11442-006-0105-3>
7. Zhu C, Peng H, Li Z, Zhang G, Li L, Yu J, et al. Age and genesis of the Danxia landform on Jianglang Mountain, Zhejiang Province. J. Geogr. Sci. 2009; 19(5): 615–630. <https://doi.org/10.1007/s11442-009-0615-x>
8. Ouyang J, Zhu C, Peng H, Yu JB, Li L, Zhou RL, et al. Types and spatial combinations of Danxia landform of Fangyan in Zhejiang Province. J. Geogr. Sci. 2009; 19(5): 631–640. <https://doi.org/10.1007/s11442-009-0631-x>
9. Chen LQ, Guo FS. Upper Cretaceous alluvial fan deposits in the Jianglangshan Geopark of Southeast China: implications for bedrock control on Danxia landform evolution. J. Mt. Sci. 2017; 14(5): 926–935. <https://doi.org/10.1007/s11629-016-4024-1>
10. Jiang YB, Guo FS, Hu ZH, Liu LQ, Wu ZC. A study on the features of Danxia landform and its landscape types in Xinjiang Basin. J. Mt. Sci. 2010; 28(4): 505–512. Chinese.
11. Kusky TM, Ye M, Wang J, Wang L. Geological evolution of Longhushan World Geopark in relation to global tectonics. J. Earth Sci. 2010; 21(1): 1–18. <https://doi.org/10.1007/s12583-010-0009-0>
12. Guo FS, Jiang YB, Hu ZH, Liu LQ, Li H. Evolution and genesis system features of Danxia landform in Longhushan World Geopark. J. Mt. Sci. 2011; 29(2): 195–201. Chinese.
13. Zhang W, Oguchi T, Hayakawa YS, Peng H. Morphometric analyses of Danxia landforms in relation to bedrock geology: a case of Mt. Danxia, Guangdong Province, China. Open Geol. J. 2013; 7: 54–62. <https://doi.org/10.2174/1874262901307010054>
14. Qiu JT, Li PJ, Yu ZF, Li P. Petrology and Spectroscopy Studies on Danxia Geoheritage in Southeast Sichuan Area, China: Implications for Danxia Surveying and Monitoring. Geoheritage. 2015; 7(4): 307–318. <https://doi.org/10.1007/s12371-015-0160-1>
15. Zhu C, Wu L, Zhu TX, Hou RF, Hu ZN, Tan Y, et al. Experimental studies on the Danxia landscape morphogenesis in Mt. Danxiashan, South China. J. Geogr. Sci. 2015; 25(8): 943–966. <https://doi.org/10.1007/s11442-015-1212-9>
16. Yan ZZ, Du XP, Fan XT. Numerical simulation of the evolutionary process of Danxia landforms. Phys. Geogr. 2015; 36(4): 322–336. <https://doi.org/10.1080/02723646.2015.1033047>

17. Zhu C, Peng H, Ouyang J. Rock resistance and the development of horizontal grooves on Danxia slopes. *Geomorphology*. 2010; 123(1–2): 84–96. <https://doi.org/10.1016/j.geomorph.2010.07.002>
18. Peng H, Ren F, Pan ZX. A review of Danxia landforms in China. *Z. Geomorphol. (Suppl.)*. 2015; 59(1): 19–33. https://doi.org/10.1127/zfg_suppl/2015/S-00173
19. Yan LB, Peng H, Hu Z, Kasanin-Grubin M, Greif V, Chen Z, et al. Stone pillar rockfall in Danxia landform area, Mt. Langshan, Hunan Province, China. *Phys. Geogr.* 2016; 37(5): 327–343. <https://doi.org/10.1080/02723646.2016.1218244>
20. Kodama K, Takeda T. Paleomagnetism of mid-Cretaceous red beds in west-central Kyushu Island, southwest Japan: paleoposition of Cretaceous sedimentary basins along the eastern margin of Asia. *Earth Planet. Sci. Lett.* 2002; 201(1): 233–246. [https://doi.org/10.1016/S0012-821X\(02\)00691-X](https://doi.org/10.1016/S0012-821X(02)00691-X)
21. Dill HG, Kadirov O, Tsoy Y, Usmanov A. Palaeogeography of Neogene red bed sequences along the Aksa-Ata River in the Parkent–Nurekata intermontane basin (Tien Shan Mountains, Uzbekistan): With special reference to the magnetic susceptibility of siliciclastic rocks. *J. Asian Earth Sci.* 2007; 29(5–6): 960–977. <https://doi.org/10.1016/j.jseaes.2006.07.006>
22. Peters CA. Accessibilities of reactive minerals in consolidated sedimentary rock: An imaging study of three sandstones. *Chem. Geol.* 2009; 265(1–2): 198–208. <https://doi.org/10.1016/j.chemgeo.2008.11.014>
23. Young RW, Wray RAL, Young ARM. *Sandstone landforms*. 1st ed. New York: Cambridge University Press; 2009. pp. 223–226.
24. Soreghan GS, Benison KC, Foster TM, Zambito J, Soreghan MJ. The paleoclimatic and geochronologic utility of coring red beds and evaporites: a case study from the RKB core (Permian, Kansas, USA). *Int. J. Earth Sci.* 2015; 104(6): 1589–1603. <https://doi.org/10.1007/s00531-014-1070-1>
25. Bankole OM, El Albani A, Meunier A, Rouxel O, Gauthier-Lafaye F, Bekker A. Origin of red beds in the Paleoproterozoic Franceville Basin, Gabon, and implications for sandstone-hosted uranium mineralization. *Am. J. Sci.* 2016; 316(9): 839–872. <https://doi.org/10.2475/09.2016.02>
26. Paradise TR. Sandstone weathering and aspect in Petra, Jordan. *Z. Geomorphol.* 2002; 46(1): 1–18. <https://doi.org/10.1127/zfg/46/2002/1>
27. Goudie AS, Viles HA. The nature and pattern of debris liberation by salt weathering: a laboratory study. *Earth Surf. Process. Landf.* 1995; 20(5): 437–449. <https://doi.org/10.1002/esp.3290200505>
28. Peng H, Pan ZX, Qiu ZW. Weathering pattern and development process of bedding-controlled caves at Mt. Danxiashan, China. *Z. Geomorphol. (Suppl.)*. 2015; 59(1): 165–182. https://doi.org/10.1127/zfg_suppl/2015/S-00179
29. Ministry of Water Resources of the People's Republic of China. *Testing Procedures of Water Conservancy and Hydropower Engineering to Rock Experiments*. Beijing: The Publishing House of Water Conservancy and Hydropower Engineering; 2007. Chinese.
30. Guo GM, Li LH, Yang ZF, Tao B, Qu YX, Zheng J. Weathering mechanism of the Cretaceous argillaceous siltstone caverns, Longyou, China. *Bull. Eng. Geol. Environ.* 2005; 64(4): 397–407. <https://doi.org/10.1007/s10064-005-0004-3>
31. Turkington AV and Phillips JD. Cavernous weathering, dynamical instability and self-organization. *Earth Surf. Process. Landf.* 2004; 29(6): 665–675. <https://doi.org/10.1002/esp.1060>
32. Nicholas RM, Dixon JC. Sandstone scarp form and retreat in the land of standing rocks, Canyonlands National Park, Utah. *Z. Geomorphol.* 1986; NF 30(2): 167–187. <https://doi.org/10.1127/zfg/30/1986/167>
33. Grab SW, Goudie AS, Viles HA, Webb N. Sandstone geomorphology of the golden gate highlands national park, South Africa, in a global context. *Koedoe*. 2011; 53(1): 1–14. <https://doi.org/10.4102/koedoe.v53i1.985>
34. Bruthans J, Soukup J, Vaculikova J, Michal F, Jana S, Alan L. M, et al. Sandstone landforms shaped by negative feedback between stress and erosion. *Nat. Geosci.* 2014; 7(8): 597–601. <https://doi.org/10.1038/ngeo2209>
35. Chen S, Wang X, Niu Y, Sun P, Duan M, Xiao Y, et al. Simple and cost-effective methods for precise analysis of trace element abundances in geological materials with ICP-MS. *Sci. Bull.* 2017; 62(4): 277–289. <https://doi.org/10.1016/j.scib.2017.01.004>
36. Yang H, Xin BS, Fu JH, Yao JL, Wang DY. LA-ICP-MS U-Pb dating of detrital zircons from Kongtongshan Formation conglomerate in the Southwestern margin of Ordos Basin and its tectonic significance. *Geol. Rev.* 2014; 60(3): 677–692. Chinese.
37. Zhao WZ, Wang XM, Guo YR. Restoration and tectonic reworking of the late Triassic basin in western Ordos Basin. *Pet. Explor. Dev.* 2006; 33(1): 6–13. Chinese.