Exfoliation weathering deterioration of red sandstone relics: a case study in Tongtianyan Grottoes, China

China University of Geosciences, Wuhan & Kyushu University, Student Member, Kunpeng Wang
Kyushu University, Fellow Member, Noriyuki Yasufuku
China University of Geosciences, Wuhan, Nonmember, Guangli Xu

1. Introduction

Grottoes dug in sandstone with thin layers of mudstone and shale account for more than 80% of the total number of Chinese grottoes. Sandstone is one of the most common rock types in China (Li, 2011). However, red sandstone has short diagenesis, low intensity, and poor cementation, which make it easy for weathering to occur under the influence of natural factors (Turkington and Paradise, 2005).

The Tongtianyan Grottoes, known as "the First Grottoes in Southern China", are located in the city of Ganzhou, Jiangxi province, China, and are the largest cave temples in eastern China and southern China. The grottoes were carved into red sandstone palisades during the period from the late Tang Dynasty (755–763 AD) to the Republic of China (1912–1949 AD). In China, the Danxia landform is a special landform characterized by red sandstone cliffs. Different from the grottoes located in arid climate regions, the Tongtianyan Grottoes have the lowest latitude (25°45′N) among all the grottoes in China, and the stone relics are under a perennially warm and humid environment.

Unfortunately, the monuments in the Tongtianyan Grottoes have suffered from various forms of weathering deterioration, which can be summarized as five types: exfoliation, bio-weathering deterioration, crack, erosion, and loss, due to their long histories and environmental factors, such as the temperate humid climate. Exfoliation accounts for 40% to the total number of weathering deteriorations, which is the most serious weathering deterioration of stone relics in the Tongtianyan Grottoes.

Exfoliation is that granules on the surface of stone relics disintegrate into powder to flaking, or detachment of thin stone flakes parallel to the surface of stone relics. The most culturally valuable part is the surface of stone relics, because the art of inscriptions and statues is carved on the surface of the rock. If the surface of the stone relics is peeled off, its artistic value will disappear.

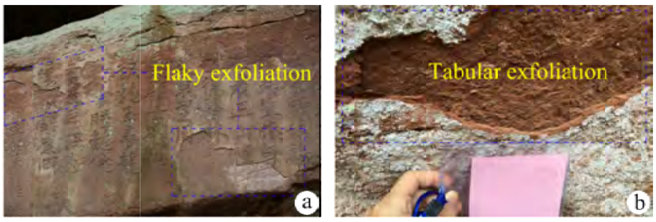

Fig. 1 a Flaky exfoliation; **b** tabular exfoliation (There is the sampling point of weathering sandstone samples. The thickness of tabular exfoliation is approximately 10 mm.)

2. Methodology and materials

Detailed investigations have been conducted to analyze the mechanisms of the weathering deterioration of the stone relics based on different aspects of geo-environmental characteristics, which include geographic position, weather and climate, geography and landform, stratum and lithology, hydrogeology.

On the relevant issues of weathering deterioration, the most meaningful research depths are just a few centimeters (Li, 2011). For example, the maximum weathering depth of the stone relics in the Yungang Grottoes (Datong City, Shanxi Province, China) is only approximately 38 mm, and the weathering depth of the stone relics in the Baodingshan Grottoes (Dazu District, Chongqing Municipality, China) is between 20 and 40 mm; both of the grottoes were built in the sandstone. However, what is the degree of weathering within several centimeters depth of the weathering rock surface? This problem has been sparsely researched.

Therefore, the samples (sampling in the rock of Fig. 1b) at the range of 40 mm from the surface in the Tongtianyan Grottoes are analyzed by X-ray diffraction (XRD) and X-ray fluorescence (XRF).

3. Results and discussion

The variation trend of the mineral composition and chemical composition content with changing depth are shown in Figs. 2 and 3.

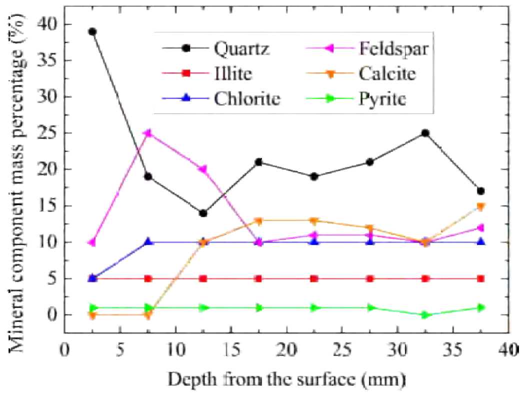

Fig. 2 Mineral component mass percentages at different depths from the surface (the quartz mass fraction in Fig. 2 is its actual value minus 40%)

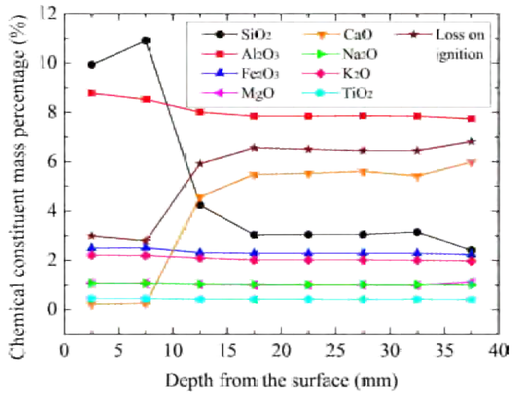

Fig. 3 Chemical constituent mass percentages at different depths from the surface (the SiO_2 mass fraction in Fig. 3 is its actual value minus 70%)

Why the mineral composition (quartz, feldspar, calcite) and chemical composition (SiO_2, Fe_2O_3, CaO, loss on ignition) change with the depth significantly? Joints have developed in the rocks in the Tongtianyan Grottoes. The developed joints provide precipitation with plentiful channels to infiltrate into the rock. Water infiltrating the inside rock flows out from the surface of the rock through evaporation. In this process, the water dissolves salt within the rock and migrates it to the rock surface. The salt precipitation is separated out on the surface of the rock accompanied by the evaporation of water (Mccabe et al., 2011; Barzoi and Luca, 2013; Jiang et al., 2015), making the precipitation area off-white on the surface of the rock. After rain, the precipitation infiltrates into the interior rock through the joints and evaporates from the surface of the rock, as shown in Fig. 4.

Fig. 4 Precipitation infiltrates into the rock through the joints and evaporates from the surface of the rock

We can choose chemical weathering indices (LOI, WPI, and WI) that are sensitive to the degree of rock weathering to evaluate the degree of rock weathering at different depths (Gupta and Rao, 2001; Topal, 2002). The change graphs between the LOI, WPI and WI and depth are shown in Fig. 5.

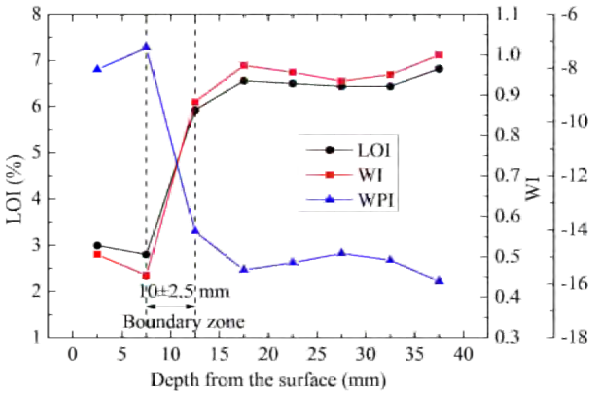

Fig. 5 Relationship between the chemical weathering indices (LOI, WPI and WI) and depth

It can be clearly observed that within the scope of the 10 ± 2.5 mm depth from the rock surface, the chemical weathering indices of the LOI, WPI, and WI show high variability. (This range value is the same as the thickness of tabular exfoliation at the sampling point in Fig. 1b, where the weathering sandstone samples were taken.) With the range of 10 ± 2.5 mm in terms of the depth for the boundary zone, the weathering degree of rock has large differences on the two sides of the boundary zone. The outside rock of the boundary zone has stronger weathering than the inside. There is a clearly shown large difference in the degree of weathering of rock and a large difference in the chemical composition, which also means the rock has a large difference in terms of performance. The rock is under the action of outside factors, for example, temperature. Even if there is a consistent temperature change in the inner and outer sides of the rock boundary zone, it will generate an incompatible strain in the boundary zone inside and outside because of the different lithologies, which can produce shear stress at the boundary zone. When the shear stress reaches the strength of the rock at the boundary zone, the rock at the boundary zone will exhibit breakage.

In fact, under the effect of air humidity, the moisture of the rock along the depth direction is also different. On the one hand, the water produces softening action in the rock, so the clay minerals in sandstone will swell, leading to a reduction in the strength of the rock. On the other hand, due to the different degrees of moisture content, its influence on the properties of rock is different. It enlarges the difference in lithology along the depth. That causes the destruction of stone relics under the action of temperature. Under the action of temperature changes, rocks of different depths from the surface have absolute differences in temperature, stress and strain (Smith et al., 2011). This explains the principle of flaky (stratiform and tabular) exfoliation in the aspect of temperature-moisture coupling.

4. Conclusions

The Tongtianyan Grottoes were built in red sandstone with gentle processes, typical of the Danxia landform. This type of rock has a low strength, high porosity, and good water permeability. The well-developed joints provide plentiful channels for the precipitation to infiltrate the rock. Water infiltrating the inside rock dissolves salt within the rock and migrates it to the rock surface by flows out from the surface of the rock through evaporation.

The quantitative test and chemical weathering indices (LOI, WPI, and WI) indicate that the degree of weathering exhibited large differences between the outside and inside of the boundary zone. Using a depth which is 10 ± 2.5 mm from the rock surface to divide the areas, the rock outside of the boundary zone has much stronger weathering than that inside. Flaky (stratiform and tabular) exfoliation generally occurs at the boundary zone of stone relics.

References

Barzoi SC, Luca AC (2013) Significance of studying the petrography and mineralogy of the geological environment of old rupestrian churches to prevent their deterioration. A case study from the South Carpathians. J Cult Herit 14: 163–168.

Gupta AS, Rao SK (2001) Weathering indices and their applicability for crystalline rocks. Bull Eng Geol Env 60: 201–221.

Jiang GH, Guo F, Polk JS (2015) Salt transport and weathering processes in a sandstone cultural relic, North China. Carbonates Evaporites 30: 69–76.

Li HS (2011) Character and evaluation method of historical rock deterioration. Ph.D. Thesis, China University of Geosciences, Beijing, China, p 14.

Mccabe S, Mckinley JM, Gomez-Heras M, Smith BJ (2011) Dynamical instability in surface permeability characteristics of building sandstones in response to salt accumulation over time. Geomorphology 130: 65–75.

Topal T (2002) Quantification of weathering depths in slightly weathered tuffs. Environ Geol 42: 632–641.

Turkington AV, Paradise TR (2005) Sandstone weathering: a century of research and innovation. Geomorphology 67: 229–253.

Smith BJ, Srinivasan S, Gomez-Heras M, Basheer PAM, Viles HA (2011) Near-surface temperature cycling of stone and its implications for scales of surface deterioration. Geomorphology 130: 76–82.