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Original article

Gravity-induced stress as a factor reducing decay of sandstone monuments in Petra, Jordan

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ABSTRACT

Recent work has shown that gravity-induced stress within a landform due to vertical loading reduces weathering and erosion rates, contrary to commonly held hypotheses. The purpose of this investigation is to evaluate the negative feedback between stress and weathering of sandstone monuments at the Petra World Heritage Site in Jordan via field observations, salt weathering experiments, and physical and numerical modeling. Previous studies on weathering of Petra monuments have neglected the impact of stress, but the ubiquitous presence of stress-controlled landforms in Petra suggest that it has a substantial effect on weathering and erosion processes on manmade monuments and natural surfaces. Laboratory salt weathering experiments with cubes of Umm Ishrin sandstone from Petra demonstrated the inverse relationship between stress magnitude and decay rate. Physical modeling with Střeleč locked sand from the Czech Republic was used to simulate weathering and decay of Petra monuments. Sharp forms subjected to water erosion decayed to rounded shapes strikingly similar to weathered tombs in Petra. The physical modeling results enabled visualization of the recession of monument surfaces in high spatial and temporal resolution and indicated that the recession rate of Petra monuments was far from constant both in space and time. Numerical modeling of stress fields confirmed the physical modeling results. This novel approach to investigate weathering clearly demonstrates that increased stress decreases the decay rate of Petra monuments. To properly delineate the endangered zones of monuments, the potential damage caused by weathering agents should be combined with stress modeling and verified by documentation of a real damage.

1. Introduction

Weathering of manmade sandstone monuments is an important problem studied by a variety of approaches [1–4]. Gravity-induced stress (hereafter "stress") is a phenomenon that is widely considered to limit the stability of sandstone monuments if rock strength is exceeded, and its effect on weathering or erosion rate is generally neglected [5–7]. However, Bruthans et al. [8] demonstrated that stress plays a crucial role in the origin of common natural sandstone landforms like pillars, arches, alcoves, and pedestal rocks, and showed that these landforms are actually stress-controlled wherein stress causes the rock to resist weathering. Various weathering and erosion processes (e.g., salt and frost weathering, raindrop impact, overland flow and slaking) proceed faster on surfaces with lower stress and are considerably less erosive in areas with higher stress. Erosion and weathering are coordinated by the stress field to reshape the original rock exposure into a new geometry where low-stress portions (i.e., portions with low loading) are removed. This idea is supported by evidence from both physical modeling with real sandstone under controlled conditions and numerical modeling.

The effect of stress on weathering and decay might be readily observable at manmade sandstone monuments exposed for sufficient time. The Petra World Heritage Site in Jordan, with well dated monuments, is an excellent laboratory to investigate clearly defined long-term weathering rates. Several hundred tombs were carved in Paleozoic sandstones by the Nabatean civilization in Petra between 200 B.C and 150 A.D. [9]. Similar Nabatean tombs can also be found at generally lesser known Al-Hijr (Madâin Sâlih) site in northern Saudi Arabia. Reported recession rate of tomb facades

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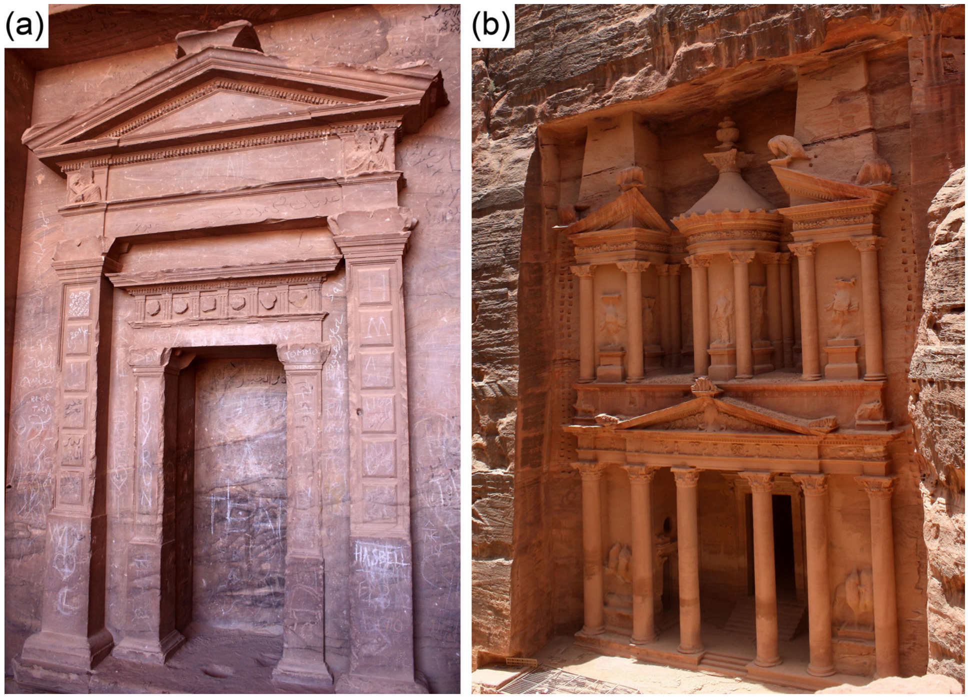

Fig. 1. Characteristic well-preserved original shapes of monuments in Petra: a: portal in a chamber across from Ad Deir (Monastery); b: Al Khazna (Treasury). Human and animal figures in Al Khazna were damaged artificially (iconoclasm), not due to the weathering.

and other outer sandstone surfaces range from 0 to 350 mm/kyr ("kyr" is 1000 of years) [10–13]. Salt weathering, flowing water during rain storms, hygric swelling, and insolation are considered the major weathering processes responsible for sandstone decay [9,11,13]. In many cases, monuments carved by the Nabateans have degraded into pillars and arches and rectangular openings have become rounded, suggesting that weathering is controlled by stress fields. However, the effect of stress on weathering has not been considered in previous studies on Petra [9–14].

The purpose of this study is to assess the effect of stress on weathering and decay of monuments carved into sandstone in Petra. This is accomplished by four complementary approaches:

- document landforms that appear to originate from the negative feedback between stress and weathering on manmade monuments and natural rock exposures;
- evaluate the relationship between stress and decay rate via salt weathering experiments;
- perform physical modeling experiments on simplified down-scaled replicas of Petra monuments to simulate weathering processes;
- develop numerical models to evaluate stress-controlled erosion of replica monuments over time.

2. Geological settings and material characteristics

2.1. Petra sandstone monuments

Petra is situated in southern Jordan on the eastern rim of Dead Sea rift valley at an elevation of 900–1100 m a.s.l. [15]. Mean annual precipitation is 298 mm and rain occurs mainly during winter [16]. Mean annual temperature is 22 °C [17]. Cambro-Ordovician sandstones, which host Nabatean monuments, were deposited on the Precambrian igneous basement complex and are covered by Lower Cretaceous sandstones [15]. Two formations within the Cambro-Ordovician sequence are exposed: the Umm Ishrin formation overlain by the Disi formation [9,13]. Umm Ishrin and Disi sandstones (total thickness of ∼500 m) were deposited in an alluvial braided plain and dip gently to the east (09°) [15]. The ∼400 m thick Umm Ishrin sandstone consists of multicolored medium-coarse grained and well sorted quartz combined with highly variable proportions of authigenic kaolinite, hematite, goethite, and subordinate calcite as a cementing material [18]. Total porosity varies between 4 and 21% and matrix content varies between 7 and 50% [13]. The ∼100 m thick Disi formation consists of mostly whitish-beige color coarse-grained sandstone with prevailing quartz and subordinate feldspar. Secondary quartz and clay minerals are the main cementation components with minor hematite and calcite. Diagenetic cementation is characterized by syntaxial quartz overgrowth [9].

2.2. Weathering of Petra sandstone

The ancient city of Petra is a unique architectural/historical monument with columns, cornices, metopes, triglyphs and friezes carved into sandstone [19]. Many shapes like tomb chambers were originally rectangular with mostly rectangular openings (Fig. 1). The weathering of artificial forms in Petra has resulted in rounded shapes remarkably similar to those commonly found in surrounding natural sandstone cliffs and also in cliffs of the same lithology over a wider area [20]. Tafoni, channels, cavities, rillen, stonelace, pits and spalled surfaces are found on both natural and manmade monuments [11,14]. Wedekind and Ruedrich [9] recognized two kinds of tafoni:

- horizontal alveolar running below and markedly above ferruginous zones with water-damping effects that bring salt-rich moisture to the sandstone surface;
- vertical with narrow strips of temporary flowing water from storms.

Salt weathering is one of the most important factors controlling deterioration of Petra monuments based on field evidence and the high sensitivity of Umm Ishrin sandstone to salt weathering