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Assessment of tafoni distribution and environmental factors on a sandstone djinn block above Petra, Jordan

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ABSTRACT

Through the measurement of tafoni dimensions on an isolated, and unrecorded ‘djinn block’ in Petra’s Ordovician Disi Sandstone, minimum surface recession were prevalent on eastern and western faces ranging from 10 to 127 mm/millennia. Moderate tafoni development was identified on northern aspects ranging from 105 to 110 mm/millennia. While on southern vertical faces, the greatest development ranged from 120 to 220 mm/millennia. Solar flux was correlated to the measured tafoni cell dimensions and revealed a minimal recession rate (and depth) of approximately 10–45 mm/millennia above which northern influences increased deterioration ‘moderately’ up to 110 mm/millennia, and southern influences had the greatest exacerbating effect with a maximum recessional rate of 220 mm/millennia – producing the greatest recession of nearly one inch (22 mm) each century. It is speculated that weathering accelerated on shaded (northern) faces through more frequent and longer spans of wetting and drying cycles, in addition to the effects of lichen and cyanobacteria overgrowth. While on regularly sunlit surfaces (southern), increased solar flux (up to ~3000 MJ/m^2/year) accelerated deterioration though more rapid, and extreme heating and cooling cycles. As rarely documented, tafoni on eastern faces were the smallest, and they were only slightly larger on western faces. Slightly increased heating from afternoon temperatures, in tandem with the incidence of frontal precipitation is attributed to the only slightly larger tafoni found on western faces (than on eastern aspects).

Introduction

As natural processes continue to alter landscapes, and tourism continues to increase, important world heritage sites like Petra, Jordan, may be deteriorating faster than conservation efforts are able arrest the decay. So, theoretical and applied stone weathering studies are vital to the preservation and conservation of Petra’s unique sandstone hewn architecture. With more than 800 carved tombs, façades, structures, and monuments, and nearly one million visitors each year (PNT, 2012), Petra is exhibiting accelerated deterioration which necessitates more, in-depth sandstone weathering research (Paradise, 2010). There exists a noticeable paucity in research that examines the environmental influences affecting sandstone weathering and erosion in arid climates like southern Jordan (Young, Wray, & Young, 2009, 314 pp.).

By examining historic structures where original surfaces can be determined and dated, Petra represents a natural environment for geomorphological research. Prior research using historic structures has included gravestones (Meierding, 1993), bridge piers (Takahashi, Suzuki, & Matsukura, 1994), and churches (Trudgill et al., 2001). The majority of this research, however, has been conducted at humid temperate, coastal, or polluted sites. Petra in the sprawling southern desert of Jordan, with its numerous hewn structures, represents an ideal outdoor laboratory for stone weathering research (Mottershead, 2000). Petra’s early builders, the Nabataean (200 BC–300 AD) and Roman (100–300 AD) stonemasons used particular techniques to remove, carve and dress this friable sandstone. With Petra’s ‘building boom’ occurring roughly 1800–2100 years ago, we are able to estimate the time at which these surfaces were exposed (Paradise, 2005).

In arid climates, sandstone weathering and erosion studies are slowly increasing in number (Turkington & Paradise, 2005). Early descriptions of weathering features (i.e. tafoni, stonelace) and architectural deterioration in the Mediterranean Basin can be found in Herodotus (c.450BCE), Strabo (25CE, 516 pp.), and Pliny (50CE) during the Classical period. Once westerners actively explored the

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Levant during the 19th century, notable studies were written by Stephens (1837, 473 pp.) and Burton (1879).

It isn't until the 20th century that research begins to address the conceptual development of weathering theory and its influences (Paradise, 2005). Bryan (1922, 1928) and Blackwelder (1929) for example, both discussed influences related to the often unusual features on found sandstone outcrops in arid lands like stonelace and tafoni. These are some of the first works in English that focused on sandstone weathering conceptually, and not just casual descriptions of weathering features (tafoni), coatings (varnish), or accumulations (scialbatura).

Research followed in arid regions that finally established the importance of various relationships to stone weathering that included mass wasting (i.e. Schumm & Chorley, 1966), lichen overgrowth (i.e. Jones, Wilson, & Tait, 1980), case hardening (Conca & Rossman, 1982), tafoni development (i.e. Mustoe, 1983), salt (i.e. Smith & McGreevy, 1988), and insolation (i.e. Robinson & Williams, 1992; Sancho & Benito, 1990). In prior research, Paradise (1995) identified weathering factors and thresholds in Petra that indicated that the regional sandstone weathering was operating through episodic fluctuations, and not in linear manner, as previously examined, with insolation (solar flux) as the primary influence exacerbating disaggregation.

Prior research separates weathering factors into intrinsic effects; those affected by the characteristics of the substrate such as lithology, and those affected by extrinsic effects like climate, and human contact. The weathering of Petra's sandstone architecture can be similarly analyzed in terms of recessional surface features related to variability in rock composition and/or caused by weathering influences such as insolation, running water, human touch, etc. Prior research emphasized the importance of intrinsic agents like rock composition and petrologic integrity, but current research indicates that extrinsic influences like climate and human contact (tourism) may also be significant (Paradise, 2010).

This paper will address the distribution of tafoni, possible weathering factors, and recession rates by examining one isolated hewn block (djinn block) that exhibits four differing aspects all within a few meters, and carved from one relatively uniform sandstone unit that is located high above the influence of tourists in Petra. Although broader examination is needed to answer many of these complex and interconnected factors of aridland rock weathering, this isolated block represents an ideal site for narrowing the complicated environmental variables that can plague similar research in deserts. By examining how the hewn surface of a dressed sandstone block has changed since its dressing and 'construction' approximately 2000 years ago, tafoni dimensions and their associated rates may be assessed. Most research in Petra has examined the weathering of its renowned Umm Ishrin Sandstones, however the Disi sandstone in this study represents a rare sandstone in which weathering processes and features may be assessed and analyzed, but without the possible effects of tourism due to its isolated location.

Environmental setting

It is Petra's setting, however, that has made this site an ideal laboratory for weathering and erosion studies. Unknown to the Western world until 1812, when it was 'discovered' by the Swiss explorer and geographer J.L. Burckhardt, Petra was the site of extensive Edomite, Nabataean, Roman, Byzantine, Umayyad, and Crusader occupation (700 BC–AD 1300) and a significant crossroads for Asian trade with the Mediterranean and for Indian Ocean trade with the Black Sea (Taylor, 2002) (Fig. 1).

Of greatest interest to archaeologists, architectural historians, and geomorphologists are the numerous Nabataean and Roman tombs, monuments and structures hewn and/or constructed from the local Paleozoic sandstones. Completed over five hundred years (c. 200 BC–300 AD) from early Nabataean development through Roman annexation, several tombs, buildings, and public centers were carved directly and/or constructed from the relatively friable sandstone. Much like its classical days, when Petra was already a pilgrimage site for visitors to Jebel Haroun (the legendary burial chamber of Moses' brother, Aaron), today tourist numbers to the valley have increased dramatically to reach one million tourists 2013-2014 (PNT 2011).

Petra is situated in a roughly crescent-shaped valley, surrounded by fault-defined steep sandstone cliffs rising to 100 m above the valley floor, at an elevation of 900–1000 m (30°19′N, 35°20′E). The arid climate of Petra and the region is typified by mild, relatively rainy winters, and hot, dry summers. Only periodically affected by Mediterranean cyclonic cells moved by the mid-latitude westerlies, local rainfall occurs when winter low pressure cells cross Israel and Jordan producing annual precipitation means of approximately 130 mm of rain. Occasionally, fronts move north from Africa and bring torrential rains and flooding from a combination of cyclonic flow, orographic lifting, and convectional propagation. It may be these low frequency, high magnitude floods, and not the more frequent (and low magnitude) regional winds that may be responsible for the removal of the weathering-produced sands across the area. Most precipitation is recorded as rainfall since subzero temperatures are relatively rare and when they do occur quickly rise during winter daylight hours. Minor amounts of snow fall annually but are fairly insignificant contributors to total precipitation. Also since the precipitation falls predominantly as frontal-induced, the direction of most rainfall is from the west and southwest across Negev from the Mediterranean (Paradise, 1995).

In nearby Wadi Musa, recorded January mean temperatures range from 6° to 12 °C, and August temperatures vary from 15° to 32 °C (Jordanian Meteorological Division, 1971). It should be noted that meteorological data from Petra have not been recorded since the 1970s since no climate-meteorological equipment and data-logging apparatus may be stationed in the valley due to continual thefts of the monitoring instrumentation.

Fig. 1. Petra is located in southwestern Jordan, between the Wadi Araba at the border of Jordan and Israel, and the uplands of central Jordan. The ruined city is situated in a fault-bound valley of Paleozoic sandstones, against Jordan's limestone highlands (to the east).