ANALYSIS OF SANDSTONE WEATHERING OF THE ROMAN THEATER IN PETRA, JORDAN

by

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Abstract

From ongoing research examining weathering influences and rates in the sandstone architecture of Petra, Jordan, a number of environmental variables have been identified. From a carved Theater built under Vitruvian standards during the first century AD, a two-meter sampling scheme was used to measure the presently weathered surfaces from the original stonemason dressed surfaces. 526 surface recession measurements were made on the Theater's vertical and horizontal surfaces and correlated to intrinsic variables as sandstone lithology, matrix-to-clast ratios, density, and matrix chemistry (Si, Ca, Fe, Al concentrations) and to extrinsic variables like annual solar flux (amount of total insolation).

A number of important factors were found to influence the deterioration of the sandstone surfaces. When iron concentrations in the rock matrix exceeded 2%, an abrupt decrease in overall weatherability is indicated until weathering is found to have decreased below measurable limits at 4%. It is speculated that matrix iron acts as a sandstone clast binding agent, reducing clast disaggregation. In sandstone strata with matrix calcium concentrations exceeding 11%, weathering was accelerated when annual sunlight levels exceeded 5,000 megajoules/m^2 (an amount typical of unobscured southern faces). It is speculated that the increased heating is responsible for irregular calcite micro-crystal expansion and contraction causing micro-fracturing, increased clast disaggregation, and subsequent weathering.

This research is also producing important information on the rates of surface recession–sandstone decay. Mean recession rates ranged from 13-66mm/millennium on horizontal surfaces and from 7-18mm/millennium on vertical surfaces. Gross differences in recession rates were attributed to the extrinsic influences of moisture availability (slope) and insolation (aspect), while minor differences were attributed to intrinsic characteristics of matrix chemistry (iron, calcium, silica, alumina), sandstone density, and clast-to-matrix ratios.

Key words: sandstone, weathering, erosion, Petra, Jordan

Introduction

As natural processes continue to work and tourism continues to grow, important architectural and archaeological sites like Petra, may be deteriorating faster than conservation efforts are able to decrease this decay. So, theoretical and applied weathering studies are vital to the preservation and conservation of Petra's unique architecture and history. However, there exists a great paucity in previous research that examines these environmental influences affecting sandstone weathering and erosion in arid climates like southern Jordan (Saunders and Young 1983), the direction of this study.

Weathering and erosion rate studies for sandstone in arid climates are rare. Early investigations of the processes responsible for sandstone weathering in the American Southwest were documented by Bryan (1922, 1928) and Blackwelder (1929). Similar research in arid region sandstone weathering mechanisms later established the importance of the relationship of weathering to mass wasting (i.e. Schumm and Chorley 1966), lichen overgrowth (i.e. Jackson and Keller 1970; Jones *et al.* 1980), case hardening (Conca and Rossman 1982), tafoni development (i.e. Mustoe 1983), salt (i.e. Smith and McGreevy 1988; Young 1987), and insolation (i.e. Blackwelder 1933; Sancho and Benito 1990; Robinson and Williams 1992). Schmidt (1985, 1989) examined scarp retreat and mass wasting to quantify weathering rates, while Meierding (1993) investigated sandstone carving legibility as a function of weathering mechanisms. In addition, recent research has identified a number of weathering thresholds as being responsible for rock decay in Petra (Paradise 1995). This indicates that sandstone weathering may be operating in episodic fluctuations, and not in a linear manner, as previously believed.

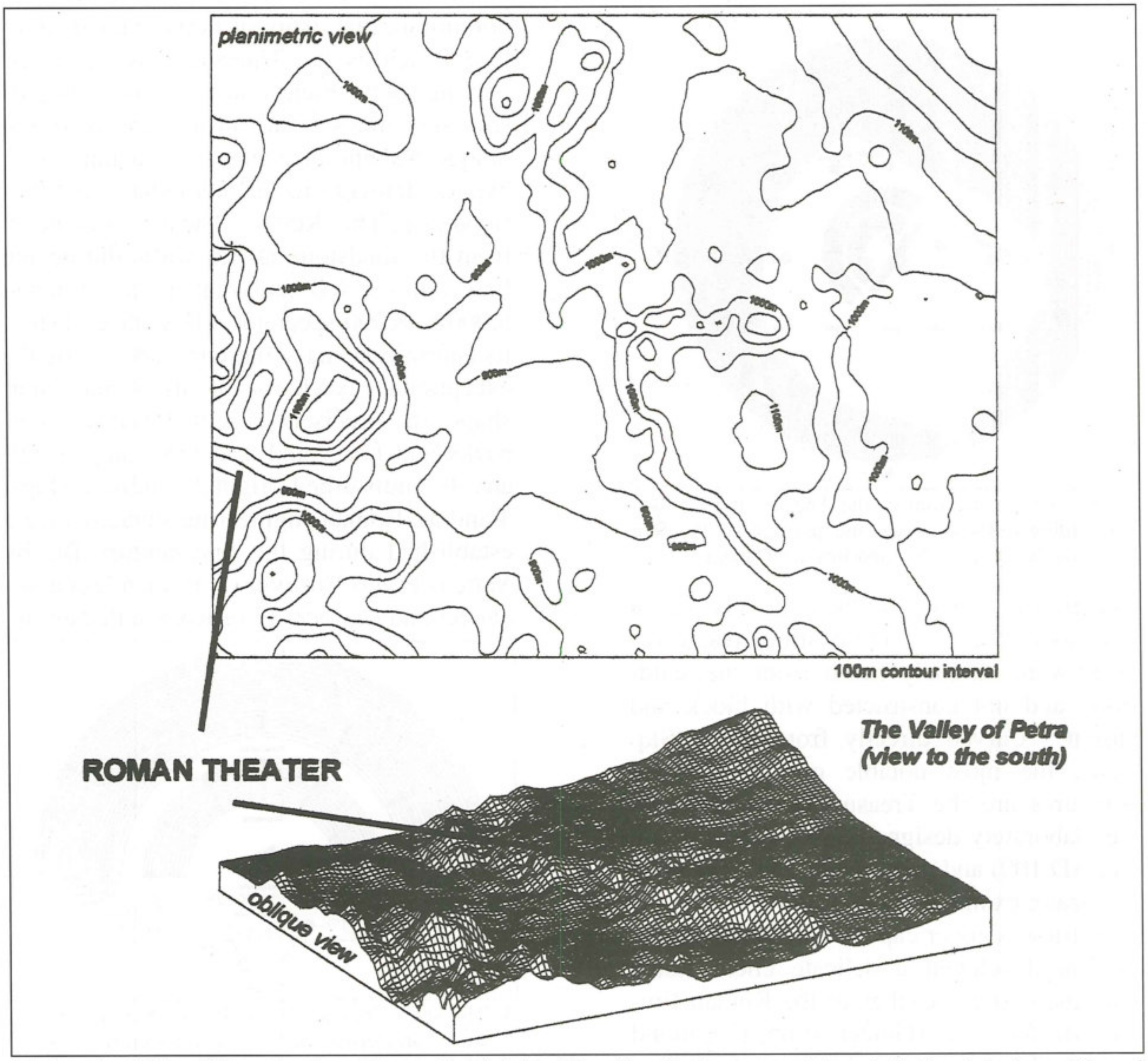
In the weathering-limited arid landscape of Southern Jordan, the rate of erosion is limited by the rate of weathering. This is clearly the case in the Valley of Petra where minimal amounts of sand derived from sandstone weathering can be observed on the bare sandstone, but instead may be observed in recesses or as accumulated masses in the Valley. Therefore, by examining how the hewn surface of dressed sandstone Theater has changed since its construction approximately 2000 years ago, weathering influences and rates may be assessed. The primary focus of this investigation was to examine the various mechanisms and rates responsible for sandstone weathering in an arid climate by controlling lithology, time and the initial surface condition.

Study Site

The Valley of Petra is a striking terrain that evolved through the incision of Paleozoic sandstones and extrusive igneous rocks, after the removal of capping Cretaceous limestones. The extensive weathering and erosion that produced the steeply-walled valleys in this region has been linked to a lowered base-level from the genesis and seismic activity of the Dead Sea Rift since the Cretaceous Period (ca.125 my)(Osborn 1985). The ruined City of Petra lies in a valley that drains the Jordanian limestone highlands into the Wādī ‘Arabah–the border between Jordan and Israel. Situated at approximately 900 m asl, Petra lies in a crescent-shaped valley (30°19'N 35°20'E) and is surrounded by vertical sandstone cliffs (mostly from *Umm Ishrin* Formation) that rise 100m above the valley floor (Fig. 1).

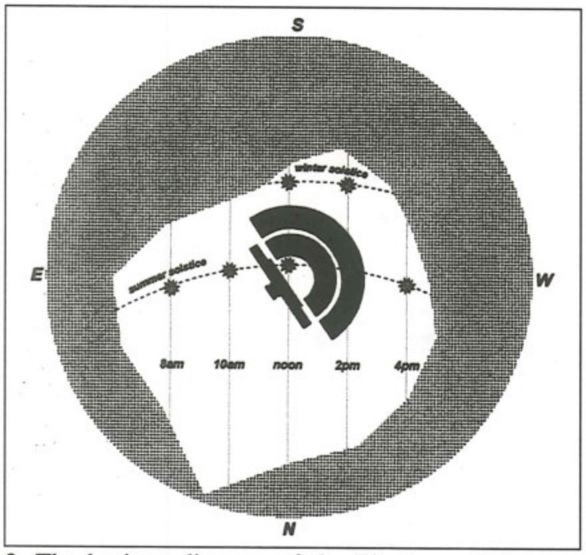
The arid climate of this region is typified by mild, relatively rainy winters, and hot, dry summers. Only periodically affected by Mediterranean cyclonic cells moved by the mid-latitude westerlies, local rainfall occurs when winter low barometric cells pass through northern Israel and Jordan with annual means of approximately 130 mm of rain (Jordan Meteorological Division 1971). Occasionally, however, fronts move north from Africa and bring torrential downpours and flooding from a combination of cyclonic flow, orographic lifting, and convectional propagation. These infrequent floods and not the local winds may be the dominant means responsible for the removal of the weathering-produced sands. During the summer months (May-August) 1990-1998, the orientation of the Theater along the as-Sīq wall was observed to shield the sand veneer in the Theater from the strong katabatic winds (>20m/s) often observed in the valley, and recorded in nearby Wādī Mūsā (Jordanian Meteorological Division 1971). 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. In Wādī Mūsā, recorded January mean temperatures range from 6° to 12°C, and August temperatures vary from 15° to 32°C (Jordanian Meteorological Division 1971) (Figs. 2 and 3).

It is Petra's setting, however, that has made this site an ideal laboratory for the study of architectural deterioration and



1. The ruined City of Petra lies in an obscured and defensible valley that has assured the relatively original condition of its monuments.

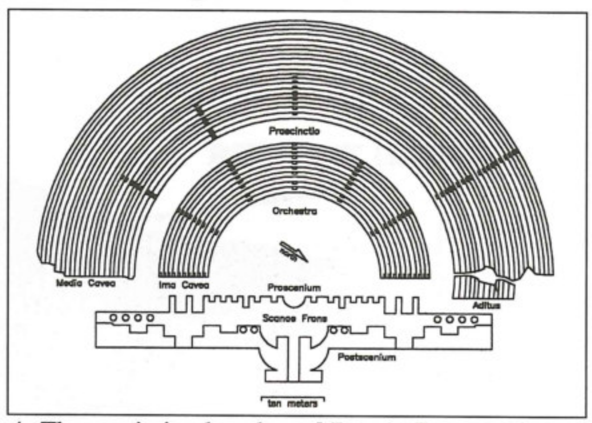
weathering. Unknown to the Western world until its discovery in 1812 by the Swiss explorer J.L. Burckhardt, Petra was the site of extensive Edomite, Nabataean, Roman, Byzantine, Umayyad, and Crusader occupation (700 BC - AD 1300) (Negev 1986) and a significant crossroads for Asian trade with the Mediterranean and for Indian Ocean trade with the Black Sea. The Valley of Petra was easily defended because of its surrounding, towering cliffs and its restricted entry. Only two small routes enabled entry into the Valley - a steep and nearly impassable wadi (Wādī aṣ-Ṣiyyagh) connecting Petra to the Wādī 'Arabah, and a narrow defile (as-Sīq) joining Petra with the biblical Spring of Moses ('Ayn Mūsā) in nearby Wādī Mūsā. Of great interest to archaeologists, architects, geomorphologists and tourists are the numerous Nabataean and Roman tombs, buildings, and structures constructed and hewn from the local Paleozoic sandstones. Completed from early Nabataean development (ca. 200 BC) through Roman annexation (ca. AD 150), several tombs, enclosures, buildings, and



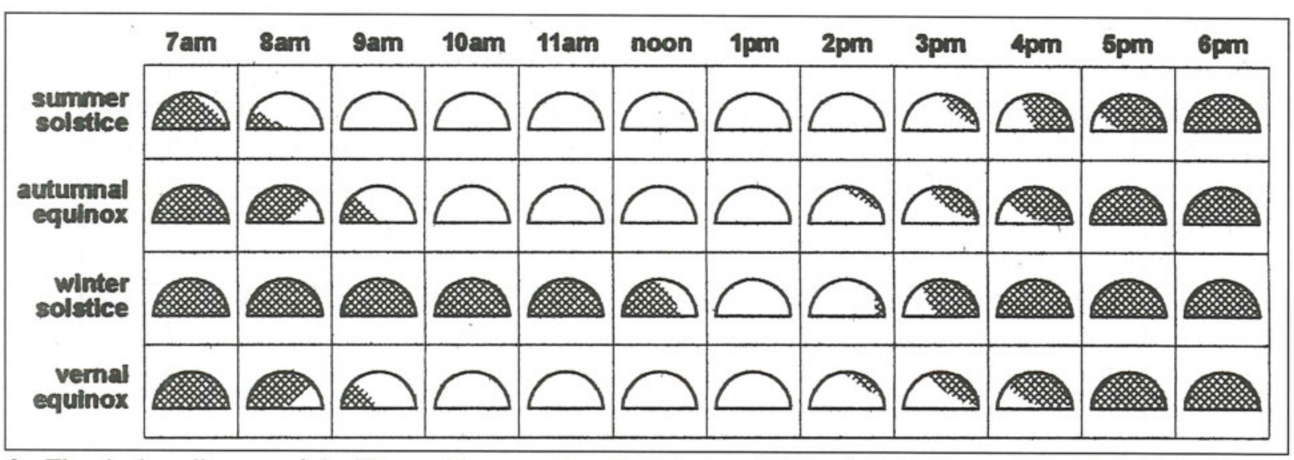
2. The horizon diagram of the Theater and the surrounding cliffs illustrate the passage of the Sun across the Outer as-Sīq and Roman Theater.

theaters were built from the relatively friable sandstone. Many of these structures, however, were uniquely hewn from the sandstone and not constructed with block and mortar. Carved directly from the as-Sīq walls, the most notable of these carved structures are the Treasury or al-Khaznah, the elaborately designed and executed tomb (ca. AD 100) and the Theater, the large open air theater examined in this study.

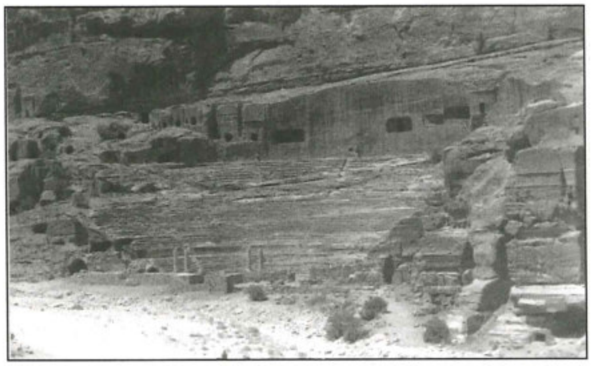
Petra was never captured by Roman forces, but developed a delicate client status with the eastern reaches of the Roman Empire: *Arabia Felix* (Glueck 1965, Hammond 1965). It was during this period of condominium, that many of Petra's hewn structures, such as the Theater, were built displaying both high construction standards (i.e. meticulous stone surface dressing) and unique Nabataean engineering features (i.e. bypass drainage to accommodate torrential flooding). The Roman Theater was hewn from the sandstone as-Sīq walls during the first century AD and seated an estimated 6,000 to 8,000 spectators (Hammond 1965). Its enormity is made more remarkable by the exceptional exactness of its semicircular shape, the precisely executed vertical seatbacks and horizontal seat tops, and its relatively undisturbed original condition (Figs. 4 and 5). Roman engineering standards were established during the first century BC by Marcus Pollio Vitruvius, a Roman legion architect and engineer. For Roman theater de-



4. The semi-circular plan of Petra's Roman Theater was characteristic of Vitruvian design from the 50 BC to AD100 (ima cavea, media cavea only).



3. The shadow diagram of the Theater illustrates the advancing sunlight and shadows across the Theater throughout the year.



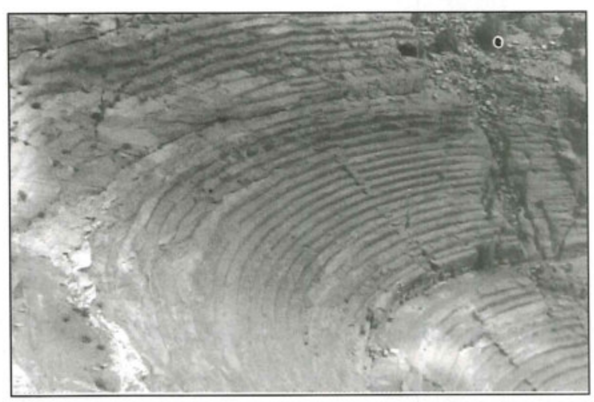
5. The Theater is carved directly from the Paleozoic Umm Ishrin Formation sandstone and is situated below towering cliffs in the Outer as-Sīq.

sign, Vitruvian canon prescribed vertical walls and horizontal surfaces oriented at specific angles for acoustical rectitude (±5°), simple accessibility, and overall aesthetics (Vitruvius BC 50). The engineering criteria recommended by Vitruvius were so definite that it has enabled historians to identify the structures of his design, of his building authority, or contemporary to his works (Blake 1947). The strict adherence to the Vitruvian prescribed angles, proportions, and design were implemented by the architects and workers that completed the Theater in Petra.

The Theater in Petra was chosen for this analysis of sandstone weathering for a number of reasons: the hewn nature of the theater ensures that it has not been moved or rebuilt since its construction; the time of its construction is recorded; the semi-circular shape affords over 180° of aspect; the bench seat arrangement provides nearly vertical (±5°) and horizontal (±5°) slopes; the limited accessibility of Petra has assured its relatively minimal contact with humans until recent years (i.e. foot-tread, automobile exhaust), and that the Theater is Vitruvian in design and construction standards (Blake 1947; Hammond 1965). This original adherence to strict construction standards is the key to this research design.

Methodology

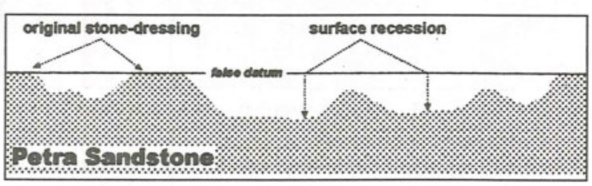
It was the Vitruvian canon with its engineering exactitude that permitted the hypothetical reconstruction of the original pre-weathered surfaces from the present state of the sandstone Theater. Since numerous original stone dressing tool marks are visible across the Roman Theater's seatbacks, seat tops and walkways (*itinera*), a false datum was established by using *Brunton® Pocket Transits, Abney* and laser levels and leveling cords to determine the pre-weathered dressed sandstone surface. This allowed the determination of the amount of sandstone weathered and eroded since the Theater's construction approximately 2,000 years ago. For the surface measurements, only the lower portions (*ima and media cavea*) of the Theater were used (Figs. 2, 4 and 6). These two sections (*cavea*) were used since the upper portion (*summa cavea*) was restricted to plebeian and prolaterian usage and was typically constructed to less precise standards (Vitruvius BC 50) and therefore more difficult to estimate its pre-weathered condition and level. The original stone dressing marks (parallel grooves ranging up to 5 mm in depth) were located on every other seating row, and the false datum was then established - through conventional plane leveling. Starting above the *aditus*, at the Theater's stage-left side, and at intervals of 2 m, millimeter measurements were taken (using an Ultratest® pin micrometer) from



6. The recessed surfaces were measured from the ima cavea and media cavea of the Theater. The enclosed nature of the Roman Theater in the Outer as-Sīq of Petra permits the seasonal balance between a weathering-limited (winter) and erosion-limited (summer) environments.

the false datum to the present sandstone surface at the seat bench back (vertical slope) and the seat top midpoints (horizontal slope). This sampling scheme was used since the differing arc lengths of the Theater's stepped conical form, in tandem with the spaced sampling sites ensured a quasi-random sampling strategy across the Theater. The examination of Roman stone dressing tools and recently dressed sandstone at the University of Rome demonstrated that the originally dressed surface displayed undulations ranging from 5 mm. Accordingly, in addition to the micrometer's minimal error of 1mm (Ultratest® manual), an accumulated measurement error envelope of ±6 mm was established (Fig. 7).

Although previous research indicated that only minor lithological variability was present in the *Umm Ishrin* Formation sandstone of Petra (Barjous 1989), field observation indicated that these minor variations affected localized weathering in the Theater. Therefore, 62 microscopic lithological samples were collected from the *ima* and *media cavea* to examine the variability in sandstone composition. Since the prior research and preliminary field observations indicated that there was little variability in the *Umm Ishrin* sandstone clast size, orientation, and form, it was the variability of sandstone matrix chemistry that was used in the study as having the greatest effect on weathering. Conventional petrological, backscatter scanning electron microscopy, and wavelength dispersive electron microprobe analysis (JEOL model JXA-8600) were used to determine various lithological matrix variables. One main sandstone bed (#1-2) and



7. This diagram represents the false datum line stretched from the remaining stone-dressing grooves.

seven smaller lenses were identified (#A-G) from field observation and lab analysis (See Fig. 3 and Table 2). Sandstone density was determined through conventional Jolly Balance methods (Hurlbut 1971) and ranged from 1.93 to 4.06 grams/cm^3. While clast-to-matrix ratios were determined through the use of *CAD* software and ranged from 15.7 to 53.9%. The *SEM* micrographs of the various lithological sub-units were digitized into *autoCAD v.13* which enabled the instantaneous estimation of clast-matrix ratios (Fig. 8).

Finally, solar flux was calculated on the various slopes and aspects of the Roman Theater in the hopes of identifying a relationship between weathering and insolation. Using conventional formulae for longitude/latitude, elevation and slope (Sellers 1965), the annual accumulated solar flux was estimated in annual megajoules per square meter for each slope and aspect. For the Roman Theater in Petra, the total annual megajoules/m^2 ranged from 176 on vertical, obscured northern aspects to 5410 for horizontal, exposed southern aspects.

The study variables follow:

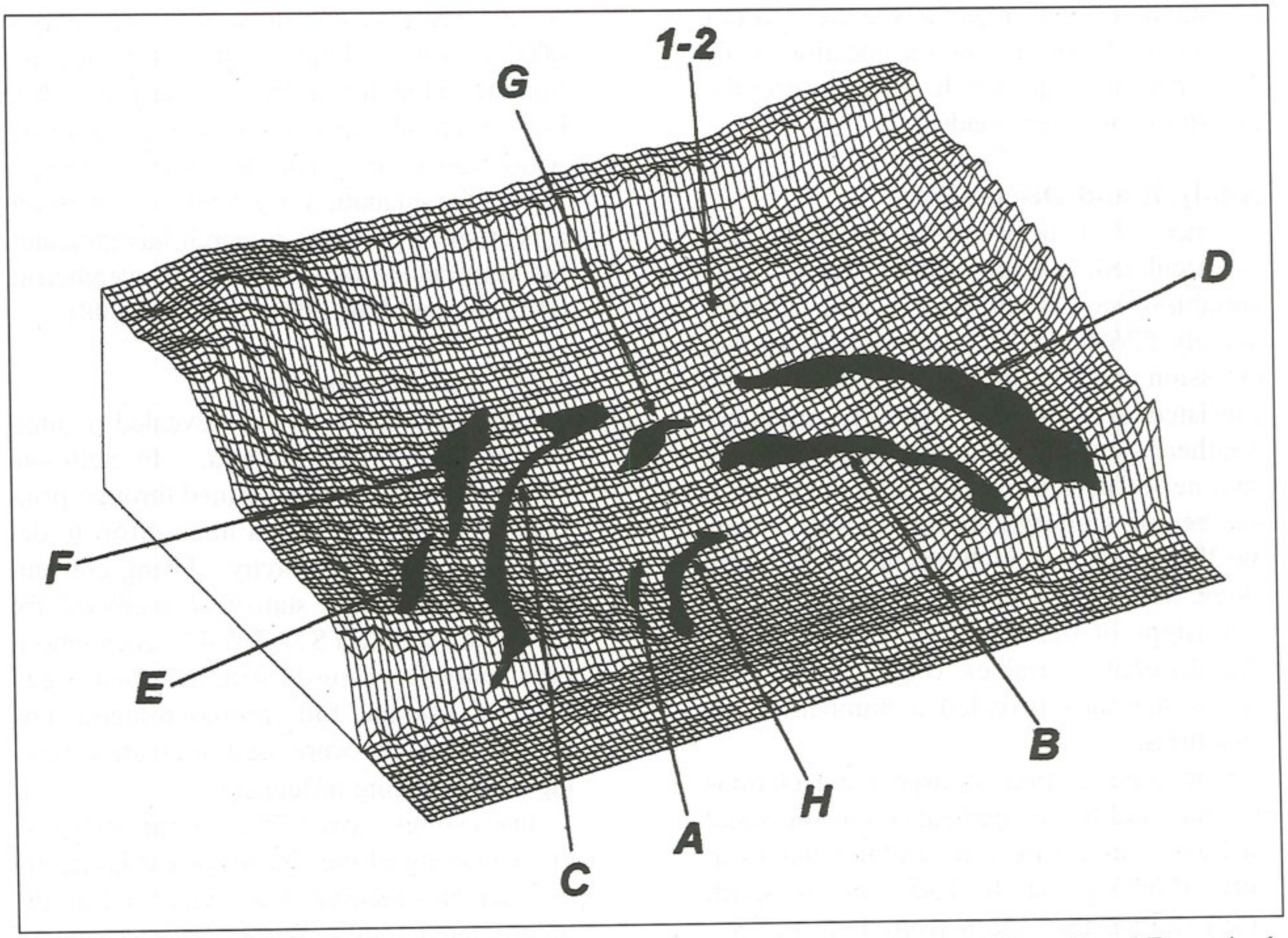
dependent variable:

surface recession measurements (mm)

independent variables:

- aspect (000°N)
- slope (0°, 90°)
- annual solar flux (megajoules/m^2)
- sandstone density (gm/cm^3)
- sandstone clast-to-matrix ratios (%)
- principal matrix constituents (%Al, %Si, %Fe, %Ca)

Before the study was undertaken, however, a number of assumptions had to be made. First, that the processes affecting the weathering and erosion today are of similar rates since the Theater's construction and that the climate has not varied greatly. Since the Theater's construction, although minor climatic oscillations have occurred in Southern Jordan (Danin 1983; Zohary and



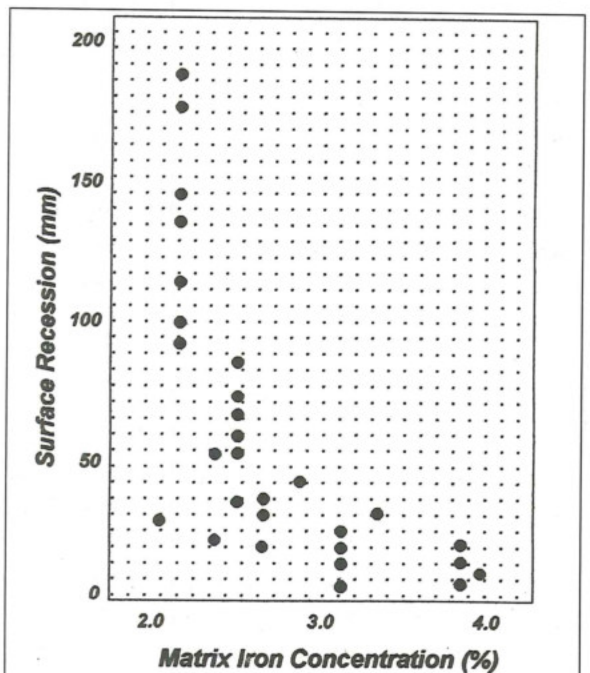
8. This diagram of Petra's Roman Theater exhibits the various sandstone strata (1,2,A-G). Strata D and F contained high concentrations of matrix calcium.

Hopf 1988), it is assumed that these fluctuations have been averaged over the last two millennia and that the weathering mechanisms and rates are valid for the long term. Second, the surface recession has not been enlarged by abrasive erosion, thus implying the removal of weathered by-products by overland flow. No evidence of surface abrasion from fluvial bedload, eolian abrasion, or livestock herds was observed in the Theater. Though these forces must be at work in the Theater, it is well protected from overland flow by Nabataean diversion channels, from wind-blown particles due to its sheltered location in the as-Sīq, and from grazing due to its complete lack of vegetation. Also, although current tourist levels are very high, in the early 1990s when these measurement were made, tourist numbers were dramatically less. Third, the moisture content was not determined in the sandstone of the Theater because it varies seasonally depending upon the wetting event (i.e. snow, dew, ponding). Distribution of moisture retention is important in the study of weathering (Robinson and Williams 1989; Matsukura and Matsuoka 1991), and since sandstone weatherability is probably correlated with lithological variability, its effects on spatial weathering patterns are difficult to separate from lithology. Fourth, it can be concluded that the sandstone samples were representative of the different strata in the Theater. The samples were chosen to characterize the mean qualities of the varied strata. Fifth, of greatest importance is the primary assumption that the Theater adhered to original Vitruvian standards. Initial building standards were made to the dictated definitions of Vitruvius for the location of the false datum from which surface recession measurements were made.

Analysis and Discussion

Once all of the variables were measured or calculated, a large data matrix of these variables was established. With approximately 526 horizontal and vertical surface recession measurements, the data matrix consisted of over 3000 spatially organized weathering-related data, the most extensive data net of its kind at this scale known. A number of scattergrams were created from the Theater data as a whole and for each lithologic bed in order to reveal the relationships of the sandstone surface depths and different variables (Figs. 9 and 10). These diagrams revealed a number of associations.

One modification to aspect correlations was required for its applications to statistical analysis. Since aspects ascend in value from north (000°) to south (180°) and to north again (359°), the values from 181° to 359°



9. This scattergram shows the relationship of weathering surface measurements to the percentage of matrix iron concentration.

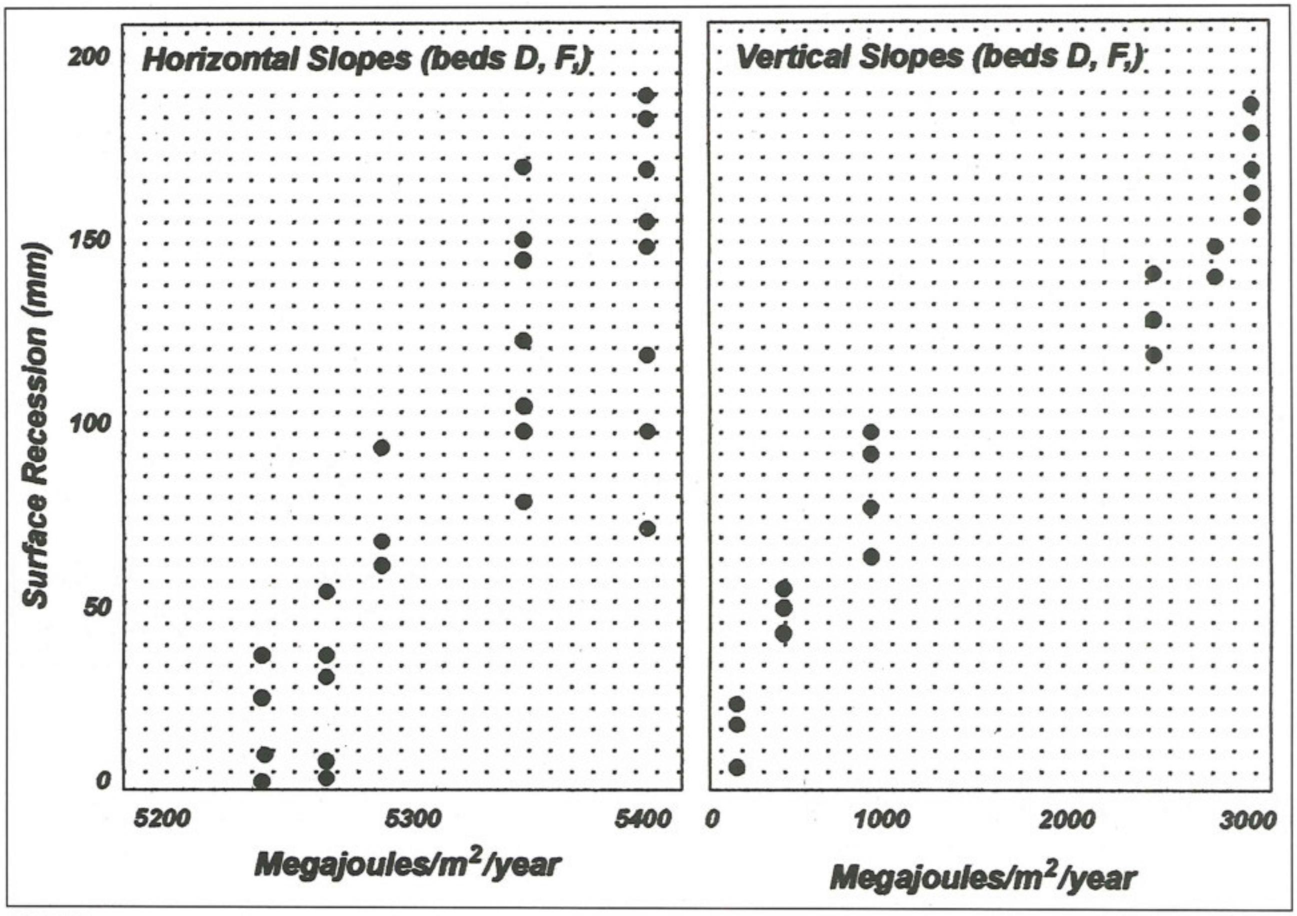
were converted to mirror the values from 000° to 180°. True south represented the highest value for statistical analysis, while both bilateral aspectual values descend toward true north. This permitted a greater level of explanation for analysis involving aspect since previous research has indicated the importance of solar flux to weathering (Paradise and Yin 1993; Paradise 1998).

Statistical Examination

Statistical scattergrams revealed a number of strong relationships. In addition, study variables were examined through principle component analysis in an effort to determine a causal hierarchy. Using conventionally prescribed statistical methods for factor analysis (SYSTAT 5.02), correlation-type analysis was used with a chosen Eigen value of 1.00 and full varimax rotation. The following results were used to create a ranking of weathering influences.

Interestingly, over 75% of the variation in weathering of the Theater is explained by the variables measured, as evidenced by the accumulated total. When the variables of the greatest loading values are explained, they can be assembled into groups of general influence: intrinsic (lithology) and extrinsic (insolation). The first column that has a 25% explanation level, can be grouped as lithology since the variables all represent matrix attributes or constituents. Also, the inverse character of insolation affecting horizontal vs. vertical surfaces implies the vary nature of solar flux influencing the measured horizontal surface depths, and having a reverse (non-effect) effect on vertical surfaces where annual solar angles are oblique rather than direct.

Principle component analysis permitted the ranking of the variable groupings according to their percentage of total variance explained. This enabled the development of a causal hierarchy explaining 75% of the explained variation in the measured sandstone recess depths.



10. This scattergram shows the relationship of weathering surface measurements to accumulated annual insolation.

Table 1: Principle Component Analysis of the Petra Theater Values.

	horizontal surfaces				*vertical surfaces*			
aspect (0-180°N)				0.753				-0.707
solar flux (magejoules/m²)				0.842				-0.802
density (gram/cm³)			0.850				0.921	
matrix/clast ratio	-0.240							
alumina concentration (Al_2O_3)	-0.915				-0.860			
silica concentration (SiO_2)	-0.704				-0.936			
calcium concentration		0.637				0.634		
iron concentration	-0.402		0.847		-0.367		0.921	
explained variance by percent	*25%*	*20%*	*17%*	*12%*	*27%*	*19%*	*15%*	*13%*

The values represent the rotated loadings

primary influence: *general lithology*
secondary influence: *rock density (a function of iron concentration)*
tertiary influence: *solar flux*

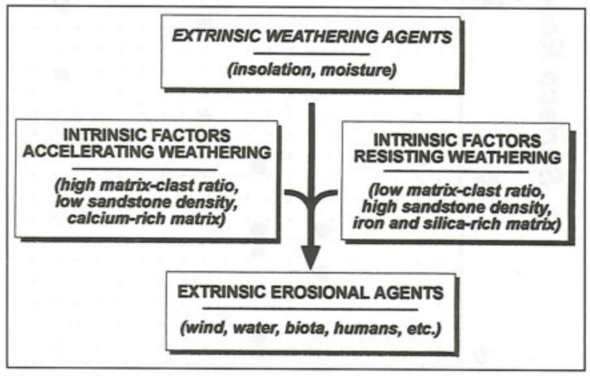
This weathering influence hierarchy is valuable in that it establishes the contributory importance of the influences and/or groups of effects to weathering – a previously unrecognized concept in architectural weathering studies.

Weathering Rates

This study also determined a number of weathering rates for the minor variations in sandstone lithology. Since the sandstone of the *Umm Ishrin* Formation shows little variation in clast size or composition, it was revealed that minute variations in matrix constituents greatly affected surface recession. Fluctuations in matrix alumina, silica, iron, and calcium were found to be important intrinsic agents that affected the speed at which the sandstone surfaces receded. Recession rates ranged from 7 mm per millennium on iron-rich, calcium-poor vertical surfaces (bed #B) to 66 mm per millennium on relatively iron-poor and alumina-poor horizontal surfaces (bed #E) (Fig. 11).

Matrix Constituents

The relationships of surface recession to lithology were first examined. The predominant matrix constituents of Si, Ca, Al,

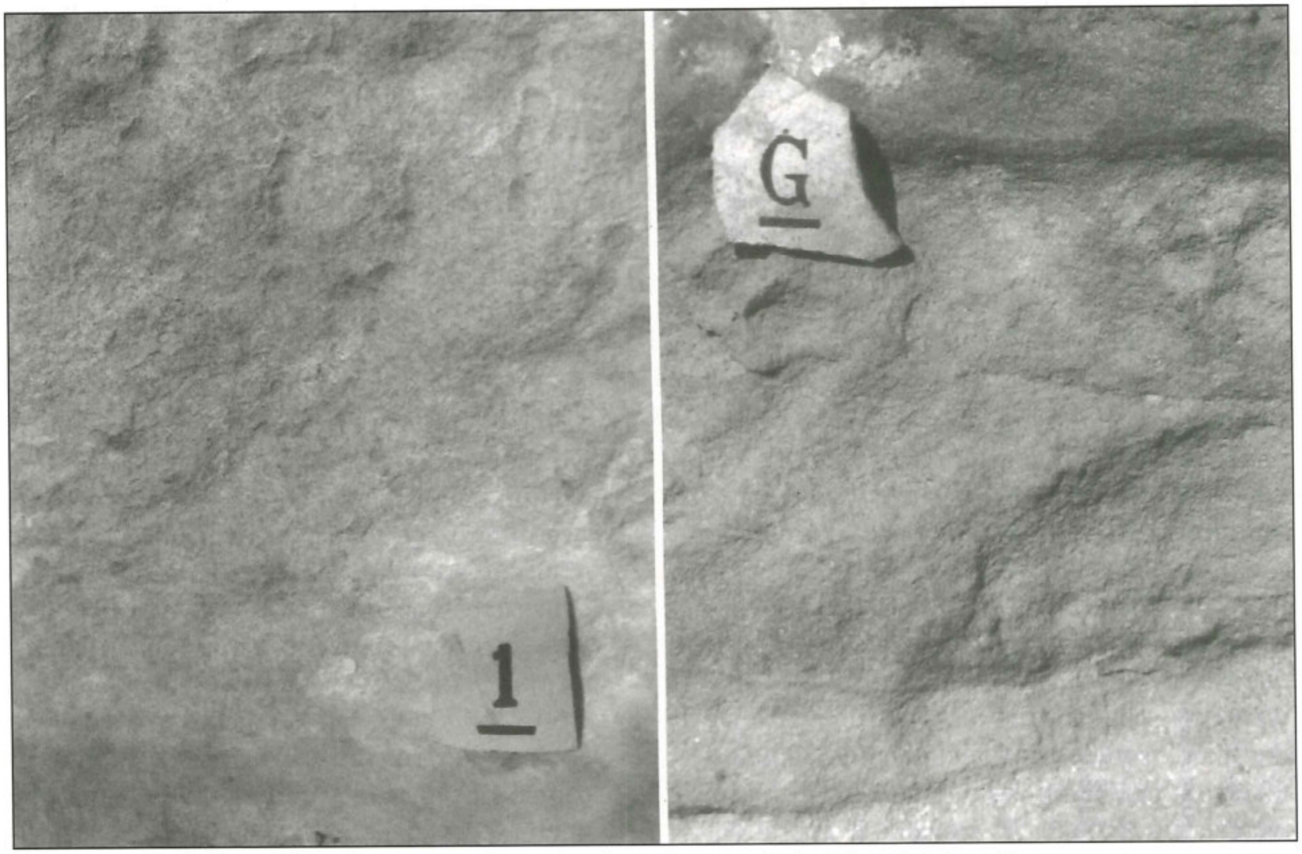


11. Basic weathering (deterioration) and erosion (removal) model for the sandstone of Petra's Roman Theater.

Table 2: Petra Sandstone Lithological Data and Weathering Rates.

Stratum code	%Al_2O_3	%SiO_2	%FeO	%CaO	gm/cm³	Munsell	Density %Matrix	Weathering Rate /Millennium
								horizontal/vertical
1	7.6	11.1	4.1	2.1	2.38	10YR 8/2	35.3%	23mm/5mm
2	5.5	15.8	0.6	1.4	2.61	10R 8/2	24.4%	17mm/10mm
A	20.7	21.7	3.7	0.1	2.91	5R 4/2	15.7%	15mm/8mm
B	25.3	26.5	12.2	0.2	1.98	N4	37.5%	44mm/7mm
C	26.1	33.8	2.7	0.9	2.31	10YR 8/2	18.5%	13mm/9mm
D	12.3	11.0	11.5	11.2	2.43	5R 2/2	35.6%	26mm/18mm
E	11.9	22.1	5.3	0.0	4.06	5YR 2/1	17.3%	66mm/18mm
F	7.1	8.5	0.3	11.3	2.05	5YR 3/4	16.3%	27mm/14mm
G	18.7	21.7	1.6	5.2	3.09	5YR 6/1	16.7%	44mm/16mm

These constituent data represent the mean values for each lithological stratum determined through conventional petrological laboratory measurement and microprobe analysis. The mean weathering rates represent the level of recession since the Theater's construction during the first Century AD.



12. The two beds that exhibited extreme surface recession rates were strata 1-2 and stratum G.

and Fe were all compared to the surface measurements, although only the influence of iron and calcium concentrations to weathering displayed a significant correlation (see Figs. 7 and 12). Strata 1-2 displayed mean recession rates of 23 mm per millennia (horizontal surfaces) to 5 mm/millennia (vertical surfaces), compared to stratum G which displayed mean recession from 44 m/millennia (horizontal surfaces) to 16 mm/millennia (vertical surfaces). Differences in surface recession can be attributed to iron and calcium concentrations, where it was found in this study that matrix iron decreases weathering and surface recession, while matrix calcium accelerated it.

It was found that as iron concentrations approached 2%, the mean surface recessions quickly decreased, and weathering decreased to immeasurable limits when matrix concentrations exceeded 4% - an important principle in the understanding of surface recession of sandstone. As matrix concentrations of iron increase, surface recession decreases (weathering). Field observations corroborated the fact that the Theater's femic beds (blackish, dense) displayed a nearly unweathered/uneroded nature, showing numerous original tool dressing marks. This indicates that iron concentrations act as matrix integrating and indurating agents that lessens the overall sandstone weatherability. Since sandstone density is a function of matrix iron concentrations, it follows that there was a negative relationship for sandstone density and recession measurements. When the overall sandstone density exceeds ~2.2 grams/cm^3, the rate of weathering also decreases abruptly until no surface recession is measurable.

Various study influences may also act to counter-affect each other. For instance, an iron and calcium-rich matrix may exhibit weathering rates the same as those sandstone matrices containing no iron and calcium, since this study found iron constituents to decrease weathering while calcium components increased deterioration - a balanced pair of matrix constituents. In a similar manner that various lithological components can counteract each other's effects, some constituents may reinforce each other, possibly synergistically influencing the weathering rates.

Insolation Threshold

Since sunlight has had a questionable influence on weathering since the early works of Walter (1891), Schaffer (1932), and Blackwelder (1933), it has continued to perplex geomorphologists as to its direct and indirect influences on weathering. Griggs (1936) found that temperature fluctuations did not influence weathering until moisture was introduced. This landmark study discussed the greater consequence of moisture on weathering than insolation-induced heating. Greater levels of insolation were found to decrease weathering through the elevated evaporation and removal of moisture. Since Griggs' work, numerous studies have investigated the role of moisture in accelerating weathering processes such as wetting and drying cycles, slaking, and hydration expansion in accelerating weathering (i.e. Dragovich 1967; Winkler 1975; Mottershead 1988).

This research, however, suggests a strong relationship between solar flux and sandstone weathering in strata containing relatively greater percentages of matrix calcium. Where calcium levels were determined to be greater than 11% (strata D, E), scattergrams indicate that weathering drastically increased when an accumulated annual solar flux exceeded approximately 5300 megajoules/m^2 (an amount that represents an exposed southern aspect). The reason for this increased weathering in calcium-rich sandstone strata may be explained by recent petroleum petrology research. Somerton's (1992) findings indicate that when calcite ($CaCO_3$) is raised in temperature from 50° to 100°C, it expands 1.9% normal to the C-axis and contracts 0.4% parallel to the C-axis. This irregular effect is contrary to quartz crystals which expand 1.4% and 0.8% respectively - an important concept since the primary matrix constituent of the *Umm Ishrin* sandstone is silica (chalcedony). This differential expansion and contraction between the calcium and silica minerals disrupts the interface between the matrix and the clasts, leading to clast-matrix separation and particle disaggregation, a commonly attributed influence on sandstone weathering (Kerr *et al.* 1984; McGreevy 1985). This finding implies that sustained summertime warming may be all that is needed to cause matrix disruption, subsequent disaggregation and sandstone deterioration. It was found that the maximum sandstone surface temperatures of the Theater to range from 30° to 56°C (26°- 44°C air temperature) by using Omega® thermistors. This is hot enough to support Somerton's findings (1992) that the increased weatherability and related threshold of the calcium-rich matrices may be caused or influenced by the heat-induced expansion and contraction of calcite and the expansion of quartz. These are meaningful findings since the importance of thermally-induced weathering of architecture (for exposure and/or aspect) has been relatively discarded in recent years (Price 1996).

Summary

During this study, it was found that sandstone weathering in Petra's Roman Theater is due to variations in rock matrix chemistry (i.e. iron, calcium, silica, alumina), and, aspect and its related annual solar flux (i.e. southern, exposed faces vs. protected northern faces). It was found that with sandstone densities greater than 2.2 gram/cm^3 (from matrix iron concentrations), the rate of weathering diminished to levels too low to measure. This was also found for matrix iron concentrations exceeding 2% whereby the weathering rate was found to abruptly decrease until levels of weatherability were too

small to measure beyond a 4% matrix iron constituency. Field observations in Petra confirmed this finding because local sandstone strata containing matrix iron concentrations (exhibiting a darker reddish-brown color) exceeding this level exhibited numerous original and nearly unchanged stone-mason marks dressed two thousand years ago – the most remarkably preserved stratum surfaces of the Theater. However, the rate of weathering in sandstone beds with densities less than the 2.2 grams/cm^3 displayed increasingly weathered surfaces as the matrix iron concentrations neared zero (see Table 2).

It was also found that insolation not only had an accelerating effect on sandstone weatherability, but also required a minimal level of accumulated annual insolation receipt to be an effective weathering agent. When annual insolation exceeded approximately 5200 megajoules/m^2 (representative of an exposed, southern aspect) on sandstone strata containing at least 11% matrix calcium, then there is a positive relationship between insolation and surface recession. This may be due to the fact that calcite exhibits irregular crystalline expansion and contraction when exposed to high temperatures (>50°C, similar to sandstone surface temperatures in Petra). This causes clast-to-matrix micro-fracturing, disruption, subsequent disaggregation and surface recession. In addition, below this extrinsic threshold of 5200 megajoules/m^2 little correlation was found between insolation and weathering, whereas above this amount, weathering was found to increase in association with solar flux. Statistical analyses using principal component analysis confirmed that the most influential factors in sandstone deterioration are lithology (matrix iron, calcium and silica) and aspect (annual solar flux amounts), on both horizontal and vertical surfaces (see Table 1).

Weathering influence and rate studies, such as this one in Petra are important for a number of reasons. Current conservation studies, earth sciences, weathering research, and material science are all lacking in quantified studies that have determined causes, effects, and rates of rock weathering and architectural deterioration. These studies in Petra are filling an important niche in the field. This study contributes to the applications of monument conservation and architectural preservation, in addition to the theoretical framework of landscape change, sediment supply, and rock weathering - an important direction in international and multi-disciplinary research.

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