ANTHROPOGENIC INFLUENCES ON CHAMBER HUMIDITY IN PETRA, JORDAN

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Abstract

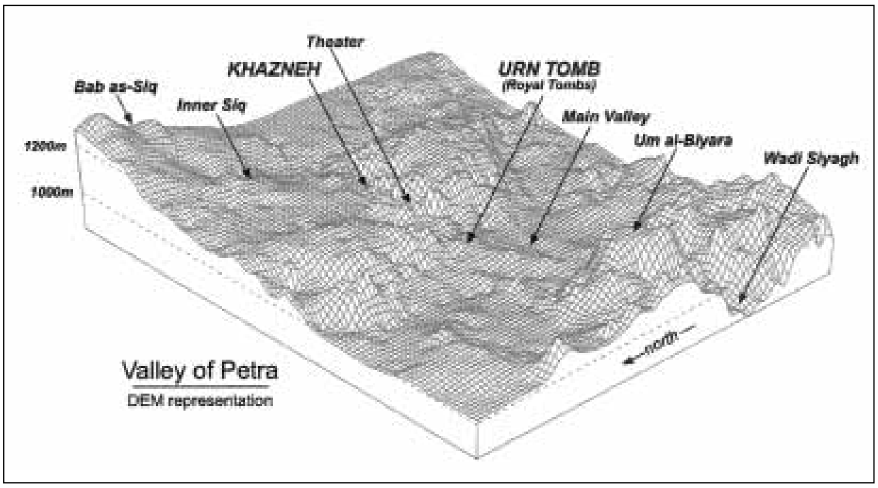
However seemingly eternal is the unique setting of Petra, Jordan, its hewn architecture is deteriorating from natural and induced influences. Weathering studies have shown that wetting and drying cycles accelerate weathering, however little is known about human-induced moisture changes affecting deterioration of stone architecture. So, comprehensive interior and exterior humidity measurements were made in Petra's most celebrated structures, al-Khazneh and Urn Tombs in conjunction with data on visitor numbers and frequency. This study found that small visitor groups entering the tomb chambers caused interior relative humidity increases of 5% to 15% -- a possible accelerating weathering influence on the sandstone walls. Statistical correlations of determination (r^2) were used to explain the relationships between visitors and humidity. It was found that that indeed strong relationships occurred between visitor contributions and chamber humidity, however, they were not simultaneous but after a lag time of fifteen minutes. Correlations increased dramatically when the tourist numbers were compared to relative humidity in the chambers both simultaneously (r^2=0.007, 0.136), and to fifteen minute delays (r^2=0.707, 0.895). Relationships were found for thirty minute delays, however they were not as strong ((r^2=0.149, 0.514). These relationships indicate that it takes ten to twenty minutes for human respiration and transpiration to contribute to relative humidity in chambers of this volume (2,000-3,600m^3) — an important finding regarding the possible anthropogenic acceleration of architectural deterioration.

Introduction

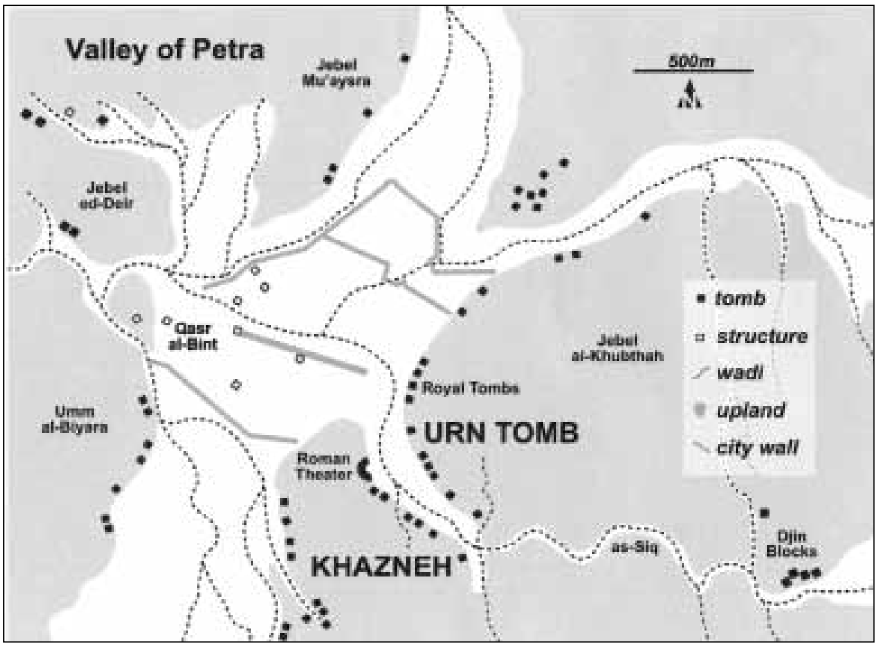
Petra is located in a deep valley surrounded by steep, nearly impassable sandstone cliffs and winding gorges in the arid environment of Jordan's southern desert. However, it is the beautiful, hewn classical architecture rather than its spectacular setting that has drawn worldwide attention and tourists since it was first 'discovered' and presented to the Western world in 1812. Although evidence indicates occupation in the area since 7,000 BC, it was its Nabataean residents, and Roman visitors that gave Petra notoriety then and now. The citizens of Petra worked the sandstone walls into elaborately carved tombs and spaces, hewn directly from the reddish-brown and yellowish sandstone cliffs, many exceeding fifty meters in height. Since its construction 2000 years ago, natural and anthropogenic forces have been working to ruin this friable architecture.

Petra, has also been called 'Sela' and 'Rekum' and was repeatedly mentioned in the Old Testament (i.e. 2 Kings 14:7, Isaiah 16:1, Judges 1:36), and in writings as early as Pliny the Elder (c. 79AD) and Josephus (c. 95AD). In his important Christian tome, *Ecclesiastical History* (326AD), Eusebius depicts 'Rekem' as an large city at vital crossroads in the region; a crucial hub for caravan routes since the 3rd century BC, known for its wealth and strategic location. It was first the ancient capital of Edom, to later become the capital of the Nabataeans. It is unknown when the Edomites and Nabateans merged or moved across the Jordan River and the Wādī 'Araba, however they migrated into Judea when the Jews were removed from the region, enslaved in Babylonia. This migration and expansion, also gave the Nabataeans control of the Gulf of 'Aqaba and the Red Sea (Agatharchides in Josephus c. 95AD) (**Figs. 1, 2**).

Since Johann Burckhardt 'discovery' of Pe-



1. *DEM representation of the Valley of Petra and its monuments, including al-Khazneh and the Urn Tomb.*



2. *Map of Petra highlighting the locations of al-Khazneh and the Urn Tomb.*

tra in 1812, Petra has become a popular tourist destination seeing as many as 5,000-8,000 visitors in one day. Visitors have increased from 100,000 in 1990, to 200,000 in 1994, to an astounding 800,000 in 2008 (JMT 2009); yearly totals exceeding one million visitors are forecast within the next few years. Despite regional conflict and instability, Petra's visitor numbers continue to rise, and from recent research on the anthropogenic influences on the deterioration of the architecture, Petra's decay is accelerating.

Petra however, represents an ideal outdoor laboratory for sandstone and limestone deterioration research — the structures have a known exposure, the sandstone lithology and conservation attempts have been documented, and Petra is situated in a region with little climate change since its construction 2,000 years ago (Paradise 2005). So, as tourism increases, it has been observed that in-tomb humidity is also increasing. Started in 1997, this long term project was undertaken to ascertain the fluctuations of moisture in these tombs as a function of entering tourists, as an indication of possible accelerated sandstone weathering, all in the hopes of slowing the decay of this magical, ruined city.

Weathering studies for sandstone architecture or landscapes in desert environments are relatively rare. Early observations on stone and architectural deterioration in the Near East and their often unusual features were made by Herodotus (c. 450BC), Strabo (c. CE10), Pliny (c. CE50), and R.F. Burton (c. 1850), however it is not until the 20th century that we begin to see the conceptual development of weathering studies (Turkington and Paradise 2005). Bryan (1928) and Blackwelder (1929) discussed many of the processes responsible for deterioration, in addition to the characteristics often distinctive to sandstone deterioration such as tafoni, honeycomb, and alveolae. Since Strabo, possible links have been suggested between moisture and weathering. Increased weathering in arid regions, and its subsequent surface recession and features (ie tafoni) have been observed near more humid areas (like in caves, alcoves, and overhangs), causing speculation that moisture accelerates weathering (Strabo CE10; Burton 1869). These were some of the first Western works that addressed sandstone weathering processes and not just the descriptions of weathering features.

Although studies on chamber moisture and fresco, mosaic, and painting deterioration are relatively widespread, research on tomb humidity and stone architectural weathering is relatively rare. This research has been important for its contributions to theoretical backgrounds of landscape change, geomorphology, and rock weathering modeling and conservation studies (environmental and architectural), and in practical arenas and applications such as materials conservation. Early observations by J.L. Stephens (c.1830) postulated relationships between humidity and stone decay both on geologic and architectural surfaces. However it would be the catalog of Petra's tombs, monuments, façades, and structures by Brünnow and Von Domaszewski (1904: 125-428) that represents the earliest recorded descriptions of Petra's architecture and condition. Since then, few papers have addressed weathering relationships in Petra, sandstone and moisture fluctuations (Heinrichs and Fitzner 2000; Turkington and Paradise 2005).

Studies on tomb interior moisture and stone deterioration have been conducted in Egypt and in urban settings. It has been shown that repeated drying and wetting cycles, or regular moisture spikes in closed spaces (like tombs) will accelerate stone weathering. In some cases, decreases from nearly saturated states (95%-100%) will increase architectural decay and stone weathering (MCB 2007), however in arid landscapes, it is the increase in humidity that is often the culprit (Mustoe 1983). Emery (1960) discussed the visible effects of fluctuating humidity on the interior chambers in the Pyramids of Giza. Other studies (i.e. Winkler 1996, Wust and McLaneb 2000) explained how moisture changes caused warping and buckling in rock materials (like marble veneers or wall marls). When the tomb of Queen Nefertari was unearthed in 1904, was overrun with tourists until by 1940, the chamber walls exhibited such extensive plaster spalling and flaking from human-induced humidity, the tombs were closed. It was found that a relative humidity increase from 30% to 50% was accelerating chamber wall deterioration of the frescos and stone substrates — and only due to the presence of 17 visitors in the tomb for 20-30 minutes. Also in the Valley of the Kings, computer simulations in the tomb of Seti II were used to assess chamber humidity fluctuations. It was found that visitor groups exceeding 25 caused relative humidity increases from an ambient level of 30% to 75% (Khalil 2009). The increase was attributed to respiration, perspiration and transpiration; these results in Egypt are markedly similar to our findings in Petra and the thrust of this research.

Methodology

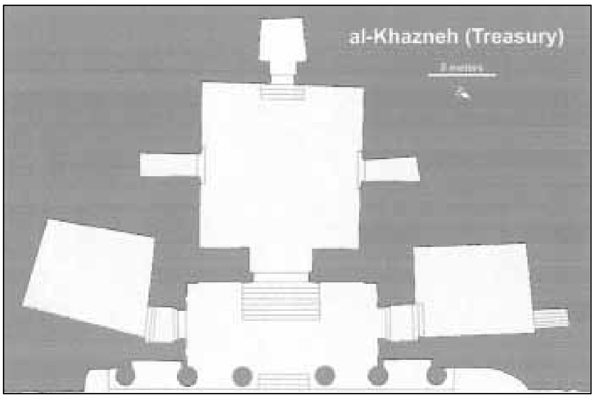
Daily tomb interior and exterior relative humidity measurements (RH) were taken and correlated to visitor numbers and times of entry and exit into the primary tombs of al-Khazneh and the Urn Tomb. Days were chosen for measurement when large bulk tickets sales were made in advance, and when tickets sales were high at the entrance into Petra. This would ensure variable sized tourist groups. Since tomb interiors in Petra are consistently higher (5-10%) than ambient relative humidity (RH) across the valley, it was important to link the spikes in RH to human respiration, transpiration, and perspiration. So, busy days were chosen for daytime measurements, usually taken from 10am-3pm when the tourists are wandering the valley and visiting the primary tombs. Since it takes roughly one hour for visitors to walk from the gatehouse to al-Khazneh — the most visited tomb — and the gate opens at 8am, measurements at the al-

Khazneh were not taken until 9am. Using an *EXTECH Humidity-Temperature Pen* (resolution of ±0.1% RH and 0.1°F/C), measurements were taken every fifteen minutes throughout the day. With each RH reading, the number of visitors in the tomb was also recorded, in addition to exterior RH and temperature.

Al-Khazneh Tomb Chamber: Tourism, Weathering and Humidity

Current research in Petra is investigating changes in anthropogenic (human-caused) humidity and its effects on weathering rates. Previous research and a recent study at the 'Anjar quarry above Petra (Paradise 2005) indicate that moisture and temperature in tandem accelerate stone deterioration in arid regions like Jordan. However, studies are rare that address the direct effects of humans and small-space humidity changes in arid region tomb chambers like Petra's al-Khazneh (**Fig .3**).

This large temple/tomb rises 40m above the sediment-filled 'plaza' that lies at the T-intersection of the Inner Sīq and the Outer Sīq in Petra. It is elaborately faced with classical elements (pediment, columns, entablature, etc.) all carved directly out of a northeast-facing box canyon cliff face of the Umm 'Ishrīn Sandstone Formation (Paradise 2005). It consists of a primary chamber with three antechambers (interior volume of approximately 2,000m^3) with a façade aspect of 061ºN. As is typical of most Nabataean architecture, the intricately hewn façade was constructed with interior ante-chambers and halls that exhibit no or little surface decoration. Its original purpose is unknown but has been speculated as a tomb, shrine and/or worship site (Taylor 2005: 224). This hewn structure was made famous in Spielberg's 1987 film 'Indiana Jones and the Last Crusade'. Since 1998, environmental monitoring in the interior of al-Khazneh indicates that there is a strong relationship between large numbers of visitors in the tomb and a subsequent rise in relative humidity (and unrelated to outside climatic fluctuations). Preliminary measurements indicate that the greatest increases in humidity occur when visitor groups exceeding 25-30 persons remain within the tomb for more than five minutes. This is an important finding since many tour groups visiting al-Khazneh in Petra consist of at least 20 persons and remain more than 5 minutes in the inner chamber.



3. planimetric map of al-Khazneh (grey color represents the solid sandstone of the cliff face).

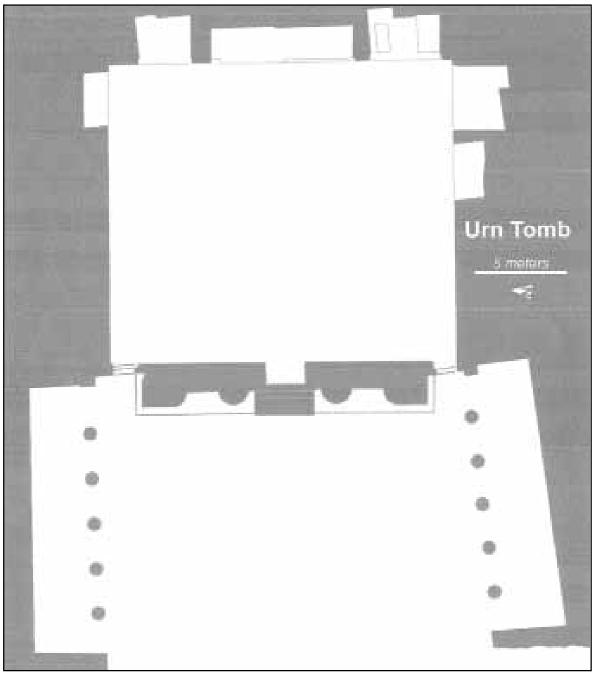
Prior studies have shown that increased moisture in restricted spaces can increase the production of surface salts (efflorescence), increase in-rock permeability, moisture wicking, and a general accelerated deterioration of sandstone from particle disaggregation (Price 1995; Paradise 1995, 1999). Extensive research in arid regions (i.e. Egypt, Arizona) suggests that drier structures exhibit slower deterioration rates than wetter ones (i.e. Emery 1960, Young 1987). Precisely how this increased moisture regime contributes to accelerated deterioration in Petra, however, needs further study. So, as tourist numbers increase in Petra's chambers or tombs, interior humidity increases will accelerate deterioration. Because Petra's visitors have increased from roughly 100,000 in 1990 to 900,00 in 2008, it is essential that we monitor all environmental variables (external and internal) in order to evaluate carrying capacities and accessibility in this UNESCO World Heritage Site.

Possible solutions may be two-fold for the anthropogenic weathering in al-Khazneh. For humidity-induced deterioration, mitigation could involve modification of interior microclimate through the use of fans or dehumidifiers. This would stabilize human-induced shifts in interior ambient humidity. Another solution would be to simply restrict the in-tomb visitor numbers at any one time, with time spans between visitors long enough to permit the tomb chambers to re-stabilize to a naturally lower humidity. This policy has been imposed now since 2000-2001 and — so far — and only time can prove the effectiveness of the new policy.

Urn Tomb Chamber: Tourism and Humidity

Along the southwestern slopes of Petra's mountain barrier, Jabal Khubtha lies the hewn row of the Royal Tombs. The Royal Tombs include the Urn, Silk, Palace, and Corinthian tombs. The Urn Tomb was hewn and constructed high up on the cliff face and requires a number of stairs to visit. The original Nabataean access has been lost, but since its use as a Byzantine church in the 5-6th centuries, a series of vaulted flights lead up to the façade. Scholars have suggested that the Urn Tomb was the tomb of the Nabataean Kings Aretas IV (d. 40AD) or Malchus II (d. 70AD) (Mackenzie 2005). Inscriptions inside the church indicate that it was consecrated as a church or chapel in 447AD and was modified to act as a worship site, after its possible use as a tomb (**Fig. 4**).

The Urn Tomb façade faces directly east (090°N) — one of the few structures in Petra that exhibits any sort of exact cardinal or celestial alignment. The structure consists of a large chamber with seven niches (six to the rear, one near the front), and an even larger plaza (25x15m) with two flanking colonnades. Its interior chambers and main hall displace approximately 3,600 cubic meters of volume (or nearly double that of the Khazneh at 2,000m^3). This volume represents only the interior space and not the plaza that fronts the tomb-chapel.

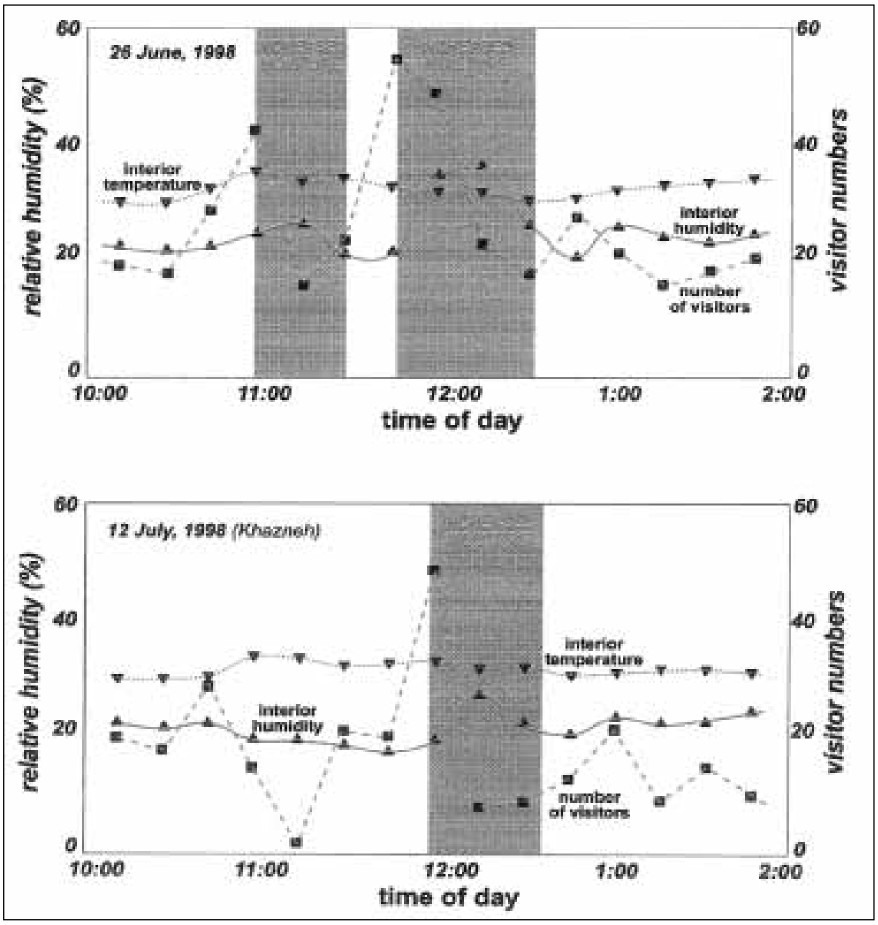


4. planimetric map of the Urn Tomb (grey color represents the solid sandstone of the cliff face).

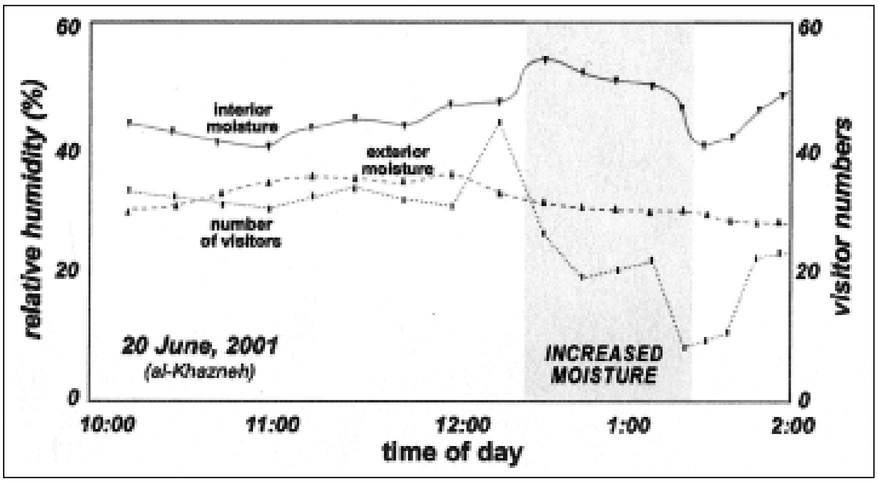
Second or third only in visitor numbers to the tombs (Salem 2003), the Urn Tomb is typically filled with tourist groups throughout the busiest months of April-May, and September-November. Groups of 20-30 visitors often visit the tomb in series with as many as 100-120 persons in the tomb during peak season, and peak times (10am-2pm). Since the Urn Tomb interior displaces a much larger volume than al-Khazneh, it follows that more moisture is needed to change the specific humidity (and relative humidity). When visitors inside the Urn Tomb increased from 11 to 17, the relative humidity was recorded to increase from 6% to 18%. While, in al-Khazneh humidity increased from 21% to 35% when 20 tourists jumped to 50 inside the chamber -- a significant change. Overall in the Urn Tomb, although it was twice the volume of the Khazeh, our readings recorded a faster humidity change than in al-Khazneh. This may be due to the air mixing that occurs with two large entrance portals, a more exposed façade, and its elevated location. Because of the two flanking doorways, a draft is often felt in the Urn Tomb, an uncommon phenomenon in al-Khazneh **(Figs. 5, 6 and 7)**.

Humidity Analysis: Urn Tomb vs. al-Khazneh

To explain the relationships between visitors, relative humidity and tomb chamber volumes, correlations of determination (r^2) were conducted for the data from both al-Khazneh and Urn Tomb. Correlations were done for both (a) visitor numbers to relative humidity (%), and (b) visitor numbers to delayed relative humidity (%) measurements: 15 minutes and 30 minutes. An analysis of lag-times was conducted to investigate any possible delayed relationship between tourism humidity introduction (respiration, perspiration, transpiration) and ambient air humidity changes; a relationship was discovered. When correlations were conducted for the Urn and Khazneh tombs, the strongest r^2 were found with a lag-time of 15 minutes, most notably for the smaller space of al-Khazneh. It would follow that smaller spaces (al-Khazneh) were affected faster, than larger volumes (Urn Tomb). Essentially, the greatest relationships were explained when tourist numbers were correlated to



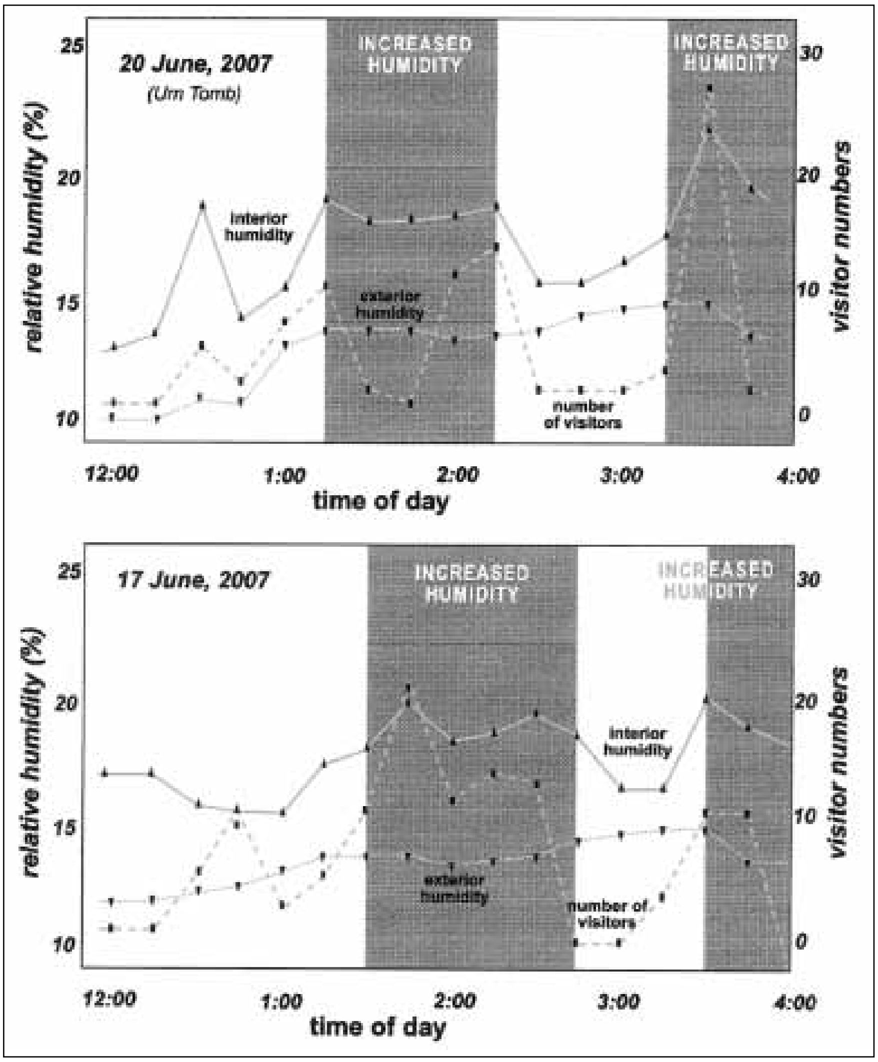
5. *graphs representing the relationships between visitor numbers in al-Khazneh and the changes in relative humidity.*



6. *graphs representing the relationships between visitor numbers in al-Khazneh and the changes in relative humidity.*

the relative humidity recorded fifteen minutes later. Since measurements were taken at fifteen-minute intervals, the only lag relationships possible were at 15 and 30 minute intervals.

Correlations were strong in both structures with values as high as 0.895 (Khazneh) and 0.814 (Urn Tomb). This implies that more than 80% of the humidity change is dependent upon the number of tourists in the chamber. In al-Khazneh, relationships jumped dramatically from 0.005 to 0.707 when the recorded humidity was correlated 15 minutes later, indicating that the greatest influence on in-tomb moisture occurs after 10-20 minutes and not simultaneous to the production of moisture through respiration (moisture release through the exhalation air



7. graphs representing the relationships between visitor numbers in the Urn Tomb and the changes in relative humidity.

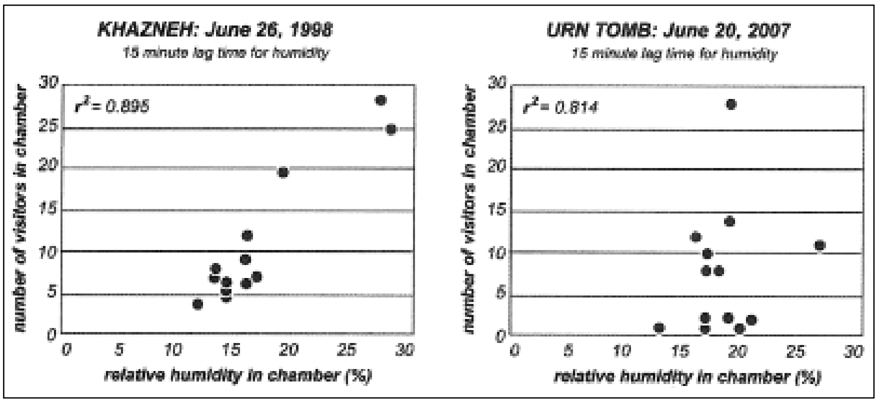
in exchange oxygen-carbon dioxide exchange), and transpiration (cell-level moisture release through tissue, pores) **Table 1**.

Interestingly, one would speculate that the

Table 1: table of the correlations of determination (r^2) explaining the relationships between visitor numbers in the chambers and relative humidity trends. Strongest relationships can be seen for fifteen minute lag times between peak visitor numbers and peak relative humidity.

		simultaneous	*15-minute lag*	*30-minute lag*
Urn Tomb	June 17, 2007	0.216	**0.501**	**0.518**
	June 20, 2007	0.704	**0.814**	**0.814**
al-Khazneh	June 26, 1998	0.136	**0.895**	0.149
	July 12, 1998	0.005	**0.707**	0.008
	June 20, 2001	-0.059	**0.253**	0.229

* correlations of determinations (r^2) represent 0.99 confidence



8. scattergrams representing the distribution of visitor numbers in the chambers and relative humidity trends. These figures represent the strongest relationships found for fifteen minute lag times between peak visitor entry into the chamber and peak relative humidity.

smaller chamber of al-Khazneh would show the biggest relationships between visitor number (and consequent moisture production), and increases in chamber relative humidity. This was indeed the case when 90% of the relationship (0.8950) can be attributed within fifteen minutes. However, the relationships in the Urn Tomb were nearly as strong accounting for up to 81%, because the Urn Tomb displaces twice the volume of air, it follows that the relationship would be weaker. Overall, this is an important relationship that not only links the number of in-chamber visitors to humidity changes, but also links those changes to space volumes (**Fig. 8**).

Conclusion and Implications

Nearly one million visitors entered the narrow Sīq to walk the short mile into the Valley of Petra in 2008 and 2009, to visit the more than 800 carved tombs, temples and structures across the famous Valley of Petra (JMT 2010). This is an increase of 40% over 2007's visitors, and with its recent vote as one the new Wonders of the World (by 22 million votes), it seems likely that Petra's wonders will be seen by more and more visitors.

While global tourism has surpassed one billion international arrivals each year (Steele-Prohaska 1996), the second Palestinian *intifaḍa* only briefly slowed Petra's visitation in the early 2000s. However, the Jordanian government and regional Petra tourism council have developed plans to continually increase visitation across the Valley. Therefore, in popular and susceptible tourist destinations like Petra, research that investigates natural and anthropogenic influences on architectural decay and environmental degradation are essential before it is too late and irreversible changes have occurred in these vulnerable sites. As tourism increases, the unique architecture of Petra deteriorates at rates often faster than conservation efforts are able to halt or decrease this decay.

It is known that tourism can accelerate rock decay simply through touching, climbing, and treading (Amorosa and Fassina 1983), however in this research it was found that even small visitor numbers can elevate moisture in chambers that can accelerate stone weathering through the mobilization of matrix salts, and matrix argillaceous and/or matrix carbonate expansion and contraction (Price 1995).

Possibly the most ubiquitous, and invisible influence on weathering is the visitor-induced humidity recorded in both tomb chambers in Petra. With as few as five tourists entering a chamber, relative humidity was found to spike 5% to 15% in chamber volumes ranging from 2,000 m^3 (Khazneh) to 3,600 m^3 (Urn Tomb) — an amount found in prior studies to accelerate rock disaggregation when cycling from drier to wetter and back.

Moreover, it was also found that chamber humidity was influenced within fifteen minutes by visitors entering the chamber. Through statistical correlations of determination (r^2), maximum increases were identified through the largest correlation, which occurred between ten and twenty minutes after entry. Differences were dramatically significant between the correlation of simultaneous visitor numbers and relative humidity and those with a lag time of fifteen minutes between the visitor entry and the correlated humidity. Striking increases were found from 0.136 to 0.895, and from 0.005 to 0.707 when the time variable was simply shifted fifteen minutes.

Measurements of human-induced humidity in al-Khazneh and the Urn Tomb are bringing new attention to the potential effect of tourism on the accelerated stone deterioration in vulnerable settings like Petra, Jordan. We are only now beginning to understand the complex and delicate nature of sandstone architectural deterioration and possible solutions that can help conserve, and preserve it for years to come*.

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