

# PRESERVING PETRA THE CRUMBLING CITY OF STONE

by Tina Luton

The ancient city of Petra lies deep in a valley of Jordan surrounded by steep, impassable sandstone walls and winding, faulted gorges. Taken from the Latin word 'petrae', meaning 'rock', Petra's sandstone is the oldest in a series of formations underlain by pre-Cambrian granite with gneiss and schist. The sandstone consists of coarse- to medium-grained quartz clasts, shot through with an iron-and-manganese-rich matrix, and it varies in colour from red to yellow to chocolate.

Geologists have identified the formation as the remnant of a large, braided stream complex, buried by another white, friable sandstone formation – a limestone layer caps high points throughout the region.

Petra was 're-discovered' – Bedouins were living there – and consequently revealed to the Western world in 1812 by 25-year-old Swiss aristocrat-turned-explorer Johann Burckhardt, who had heard whispers of some interesting ruins in the Valley of Moses ('Ain Musa). After following a stream through an ever-narrowing gorge, he came across a towering mausoleum carved into the face of the sandstone cliff. Further investigation revealed a Roman-style theatre, the foundations of buildings, crumbled columns and paved streets – indications that a large city had once stood here.

Although archaeological evidence indicates occupation in the valley since 7000 BCE (before the common era), it was the indigenous Arab residents, the Nabataeans, and their Roman visitors who brought great power to the region. And it was their craftsmen who worked the red-brown and yellow sandstone walls of Petra into simple caves and elaborately-carved tombs and structures, many exceeding 50 metres in height.

The Romans took over the desert metropolis at around 100 CE and immediately set about installing a complex integrated system of hand-carved stone flumes (some lined with ceramic pipes), reservoirs and 200 cisterns capable of supplying as much as 46,000 litres of water a day to the settled valley. This intricate water management system helped protect the city against erosion.

A devastating earthquake in 551 CE all but brought the city to ruin. Approximately 800 carved cliff monuments survived, but the living city of Petra died – trade routes had shifted sometime in the previous century, and historians believe that the community lacked the wealth to rebuild its central town structures after their destruction.

Without any maintenance, Petra's water system crumbled. The Nabataean dams and canals no longer diverted water flow away from the tombs and town, making the sandstone that composes most of Petra's monuments and its Roman theatre once more susceptible to accelerated weathering.

University of Arkansas geosciences professor Tom Paradise works with the Petra National Trust, a Jordanian non-government organisation. He has spent more than a decade studying the deterioration of the sandstone and the architecture at Petra, seeking to determine the effects of sandstone composition, climate, sunlight and tourism on the disintegration of its structures.

Intrinsic (lithologic constituents, fractures) and extrinsic (climate, human contact) weathering influences on the sandstones, show that they are deteriorating at an accelerated rate due to natural and human-induced stone decay processes.

"In particular, the crowds of people visiting Petra each year have left unexpected marks on the ancient rocks and greatly accelerated the natural processes at work," he said.

## VISITOR IMPACT

In 1980, the number of annual visitors to Petra was 100,000. By 1989, largely thanks to Hollywood blockbuster *Indiana Jones and the Last Crusade*, this number increased three-fold to 350,000. By 2000 at least half a million people were traipsing all over the World Heritage site.

In January this year, the *Jordan Times* reported that political conflict in the region had dramatically affected tourism in Jordan in 2006, with the number of visitors to the ancient Nabataean city down by 8.6 per cent to 359,366.



The Roman theatre once seated up to 10,000 people but is now eroding under the soft, gripping soles of tourists.

Bad news for resources-poor Jordan which relies heavily on its tourism revenues – the largest drawcard of which is Petra – but good news for the now crumbling city of stone.

One of the most popular attractions at Petra is the grand Al-Khazneh tomb.

Elaborately carved with classical elements (pediment, columns, entablature, etc.), it consists of a large staircase, two small exterior flanking chambers and a primary chamber with three antechambers.

Over the years, Tom and his students have monitored how people in the tour groups behave in the tomb, from where they put their hands to where they place their feet – and they compare this to what has disappeared.

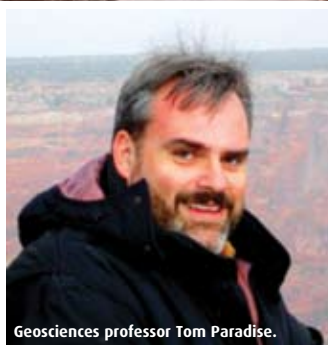
While the sandstone’s finely-hewn detailing along the jambs, pilasters, mantle and entablature remains relatively unaltered, most chamber interior detailing has deteriorated. The four interior walls exhibit original stone dressing marks. However, in the past decade many of these dressed grooves have rapidly deteriorated from 0.5 to 2.5 metres above the tomb floor.

Surface erosion was mapped in 1999 using laser levelling devices to create a virtual netted surface model. It was found that across the 4 × 3 metre tomb wall surface, as much as 40 mm of sandstone had eroded, in less than 50-100 years, as a result of visitors touching the stone.

“One whole chunk of wall of the Khazneh had lost half a cubic metre of stone over a few years, because that’s where tour guides let people sit while they talk about the history of the site,” Tom said.

“In fact, on the more than 100 occasions that Al-Khazneh was visited, local police, tourists and tour guides were found leaning, touching, rubbing and propping their feet against the chamber walls, producing small, loose sand piles at the base of the measured wall,” he added.

The appearance of strange white deposits on the walls inside the structure led Tom to take a sample. He assumed it was some kind of salt deposit growing in flower-like structures on the surface. Lab tests,



Geosciences professor Tom Paradise.



Petra attracts thousands of visitors each year.



Tourists inside Al-Khazneh dramatically increase relative humidity.

however, showed the deposits to be stearic acid – or beef fat, a component of cheap suntan oil once commonly available in the Middle East.

“People would rest by leaning against the wall with sweating hands. This is when you realise that what is happening at Petra is bad,” he said.

Increased humidity is one of the biggest problems. Environmental monitoring of the interior of Al-Khazneh (conducted repeatedly since 1998) has revealed a very strong relationship between large numbers of visitors and a subsequent rise in relative humidity. Increased moisture in restricted spaces can increase the production of efflorescence (surface salts) in-rock permeability and moisture wicking, and cause a general accelerated weathering and surface recession of sandstone due to particle disaggregation.

“The greatest increases in humidity occur when visitor groups exceeding 25–30 people remain within the tomb for more than five minutes. During peak tourism season, 35 or more people occupy Al-Khazneh almost all day,” said Tom.

“With more than 30 people entering the tomb the humidity jumps from 30 to 60 per cent, which is unacceptable in relation to preservation of the sandstone.”

Possible solutions to decrease interior humidity fluctuations may involve modification of interior microclimates (such as adding fans or

dehumidifiers) or the restriction of in-tomb visitor numbers at any one time, with sufficient gaps between groups to permit the tomb chambers to re-stabilise to a naturally lower humidity. In addition, a solution to decrease wall abrasion by visitor contact may be to simply restrict or prohibit direct access to the tomb interior walls.

**EROSION OF THE ROMAN THEATRE**

Al-Khazneh is not the only structure at Petra to have suffered under the weight of increasing tourism.

Tom has also conducted an extensive study on the Roman-style theatre, which may have seated up to 10,000 people.

Although it was carved before full Roman occupation in 106 CE, it was hewn out of the surrounding sandstone cliffs – according to the canon of the great Roman engineer Marcus Pollio Vitruvius – using the highest Roman engineering and construction standards of the period. These early requirements for theatre and building construction were so standardised that the level of the original surfaces can be estimated

from the current receded surfaces.

Five hundred locations were examined across the theatre for intrinsic factors, such as variations in rock composition and particle size, and extrinsic influences including sunlight angle, lichen coverage, slope, and surface temperature.

*“From 13 years of field research in Petra’s Roman theatre, Anjar quarries and Al-Khazneh tomb, we are able to better understand the complex dynamics of sandstone decay in Petra and in arid regions and to develop conservation strategies that will successfully protect this unique architecture...”*

*Tom Paradise, geosciences professor.*

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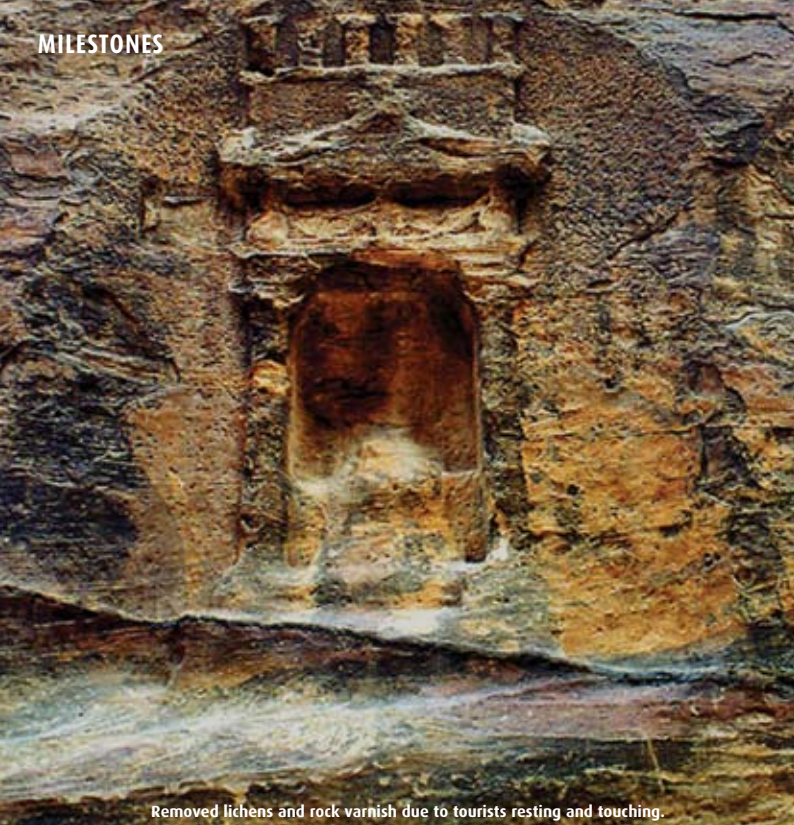


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Removed lichens and rock varnish due to tourists resting and touching.



Petra sandstones are banded in spectacular colours.

The research found that sandstone recession is accelerated by insolation (where temperatures exceed 50°C), by carbonate content, and by wide spacing of sandstone sand grains (high matrix-to-clast ratio). Rock properties could also be interpreted on the basis of sandstone colour, since paler calcium-rich and/or high-matrix sandstones are often softer and more friable than darker coloured, iron-rich sandstones. It also revealed that lithologic factors, such as iron oxides and silica in the sandstone matrix, dramatically decrease weathering.

Simple observations supported these findings where the original Roman stonemason tool marks were obvious atop iron-rich sandstone (dark reddish), while large, weathered cavities had developed on the rock areas that were iron poor (pinkish-beige to white).

It was also found that when matrix iron concentrations exceeded four per cent (by weight), dressing marks appeared so fresh and deep that little or no sandstone deterioration was apparent.

Inferential statistical analysis found that the iron and silica proportions of the sandstone matrix explained 50 per cent of all deterioration in the theatre.

The other 50 per cent could be put down to human traffic.

“Deterioration of the sandstone of the Roman theatre has recently accelerated. When it was first examined for this research in 1990, at least 15–20 per cent of the theatre displayed original stonemason dressing marks made 2000 years ago. In 2001, only 5–10 per cent of the marks were still evident,” explained Tom.

As such a dramatic change in the rate of decay could not be attributed to intrinsic or climate changes, Tom surmised that it must be the result of changes in tourism – not only to increased numbers but also to changing fashion.

“Erosion has been enhanced by shoes with soft, gripping soles that increase the relative friction between the visitors’ feet and the sandstone. The accelerated surface recession is especially evident near the orchestra, praecincterae (concentric walkways) and itinerae; parts of the theatre most commonly visited by tourists and tour group operators,” he said.

“Therefore, however sensitive visitors may be in their interaction with monuments and landscape, visitor-accelerated weathering in Petra will

only decrease when tourism decreases, when shoe soles become less abrasive, and/or when visitor access is restricted.”

Naturally, any kind of footwear that presses residue particles of sandstone against the substrate will create additional abrasion.

One recommendation is to limit access to the orchestra and walkways, with minimal access given to the main theatre where tourists – often encouraged by tour guides – scramble across the sandstone seats to the top of the theatre for a great view of Petra.

### THE HIERARCHY OF WEATHERING

While weathering studies of sandstone architecture in arid environments are relatively rare, research indicates that sandstone principally weathers in two ways.

Since it is comprised of clasts (particles) within a matrix (binder), either the clast fractures or dissolves and then falls out, or the matrix fractures or dissolves to release the clast.

Both weathering types represent the processes of disaggregation that produce loose sand as the by-product of sandstone deterioration, the source of many of the sand dunes throughout the Near East and North Africa.

Tom’s study established a previously unknown hierarchy of weathering processes responsible for sandstone decay.

It was found that general rock composition (measured through backscatter scanning electron microscope) was the most important single influence (25 per cent), followed by the effects of iron concentration (17 per cent) and climatic influences, such as sunlight and moisture (12 per cent).

“These findings emphasise the importance of lithology in understanding and predicting stone decay rates in arid regions, specifically in Petra. Such a hierarchy is vital in grasping the comparative controls on sandstone deterioration and the possible priorities needed in conservation applications and research,” said Tom.

Other studies examined topography, aspect and moisture availability as surrogates for insolation-induced weathering. These studies have explained the importance of aspect, heating-cooling cycles, and moisture availability in the acceleration of surface erosion and/or



Photographs of the hewn finial on al-Deir (the monastery) shot in 1928 (left) and 2005, show little natural deterioration in the sandstone over the past 75 years.

weathering feature development, reinforcing the notion that received solar radiation is important in the acceleration of weathering.

Among the sandstone cliffs of Petra are ancient Nabataean quarries, including those high above at Anjar where the Petra sandstone was sourced, and a number of unique carved cubic sculptures called the Djin Blocks.

The surfaces of the Anjar quarry and the blocks were studied as many of these hewn surfaces face different aspects, making them ideal for observing the effects of sunlight on stone deterioration.

The Nabataeans prepared the quarry surfaces by chiselling and dressing them into distinctive herringbone patterns, a style not used by Roman stonemasons.

At Anjar, the largest recession features were found on south-west and south-east faces, supporting the importance of the tandem role of heating/cooling and wetting/drying cycles.

Weathering features (i.e. tafoni, cavities) on the dressed quarry faces were measured, and a number of relationships were divulged.

Northern-facing surfaces showed the least erosion with 90 per cent of the original stone-dressing visible and no recessional features exceeding two centimetres in any dimension. The discrete and measured features were then mapped where their dimensional values (width, depth) were related to the quarry wall aspects.

The relatively minor weathering observed on northern faces can be attributed to decreased weathering from lichen overgrowth, since lichens are rarely found on other surfaces, and to the fact that less sunlight produces fewer wetting and drying cycles.

“Even though it has been widely accepted that lichen attachment can accelerate substrate weathering through rhizinal penetration and oxalic acid production, in Petra it was found that lichen overgrowth acts as a sandstone surface-consolidating agent, which decreases overall surface recession,” revealed Tom.

Southern faces displayed 40 per cent of the original dressing with few recessional features larger than 15 cm in any dimension. Western to south-western and eastern to south-eastern faces, however, displayed the greatest amount of deterioration and recession, with less than 10 per cent of the original Nabataean stone dressing remaining and cavities exceeding 20 cm across.

This may be attributed to the optimal daily and yearly climatic regime experienced by these quarry faces, where temperatures are hot enough to expand the sandstone, causing disaggregation, and repeatedly moist

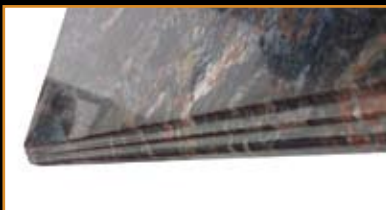
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conditions cycle the rock between hot and cool, thawed and frozen, wet and dry – cycles known to accelerate rock weathering.

A similar distribution of tafoni related to aspect was observed on the Djin Blocks. These discoveries reinforce the conventional notion that the deterioration of sandstone is greatly accelerated from increased heating and cooling or wetting and drying cycles. However, it is now believed to be faster and more destructive than previously understood.

“In Petra, this research demonstrates the delicate balance of weathering between climate and lichen overgrowth on stone architecture,” observed Tom.

In many countries, such as Italy, that actively work to protect their architectural masterpieces, conservationists once peeled off the lichen growing on historic buildings but they now recognise that in some settings lichens act as a natural seal that can protect rocks from erosion and weathering.

Methods of preserving architectural treasures have certainly changed over the past century, as archaeologists, geoscientists and historians adjust their approach to conservation and restoration, but in Petra one proposed method to preserve the rock faces would have actually destroyed them.

“Researchers wanted to apply a type of silica gel to the rocks,” explained Tom. “It’s a great product for statues, which can be dipped into the sealant and allowed to soak it up over days. If it’s done perfectly and every pore is sealed, it works great, but if it has one little crack in it, it concentrates moisture, which accelerates weathering in the long run and may cause spalling (where outer rock layers peel after freezing and thawing),” he said.

After more than 100 years of continual excavation at Petra, only a small percentage of the city has been revealed. Despite this, hundreds of thousands of tourists continue to flock to the site each year. Unfortunately, they bring with them a legacy that threatens to reduce the ancient city of stone to the shifting desert sand that surrounds it.

Something that Tom, who is returning to Petra in May to continue his weathering research and people-watching, finds disturbing – although he is optimistic.

“From 13 years of field research in Petra’s Roman theatre, Anjar quarries and Al-Khazneh tomb, we are able to better understand the complex dynamics of sandstone decay in Petra and in arid regions and to develop conservation strategies that will successfully protect this unique architecture from accelerated deterioration due to increasing regional and global tourism,” said Tom.

As an interesting footnote, Tom’s current research also indicates that a large flood, or series of flash floods, shut down the main colonnaded street of Petra and its ‘shopping mall’ in the third century. Evidence of flooding includes deep deposits throughout the interiors of the Roman street shops excavated in the mid-1990s.

“Flood deposits of up to one foot (about 30 cm) in depth were excavated in the 1990s a good 10-15 feet (four metres) above the main stream channel of Wadi Musa. These would have been disastrous waves and since the depositional particles were sands and not silts, this implies a high-energy rushing water state. Also, the sand was blond in colour not like the Umm Ishrin sandstone in the valley floor, but from the Disi sandstone outside the valley. These floods had to be catastrophic and when we return to Petra in May we will collect more data. When we prove it – and I am confident that we will – it will add a new chapter to Petra history,” Tom concluded. ☺



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