SWBSS
2011 19 - 22 October
Limassol, Cyprus

Salt Weathering on Buildings and Stone Sculptures

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ISBN 978-9963-7355-1-8

Characterisation of salt combinations found at the 'Silk Tomb' (Petra, Jordan) and their possible source

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ABSTRACT

This paper presents the characterisation of salts found at the so-called 'Silk Tomb' one of the buildings that form part of the Royal Tombs assemblage at the Nabatean city of Petra (Jordan), with the purpose of creating a specific data base of salts for this tomb that will allow the use of portable non-destructive analytical techniques on it. The survey of efflorescences and subefflorescences in this building revealed the presence of a wide variety of salts such as halite (NaCl), sylvite (KCl), niter (KNO_3), gypsum ($CaSO_4{\cdot}2H_2O$), syngenite ($K_2Ca(SO_4)_2{\cdot}(H_2O)$), polyhalite ($K_2Ca_2Mg(SO_4)_4{\cdot}2(H_2O)$ and aphthitalite ($(K,Na)_3Na(SO_4)_2$ in different combinations that present a marked spatial distribution within a limited space. This reflects the variety of inputs generated by human activities and natural sources in contrast with other, more secluded, monuments in which the mineralogy found is simpler.

Keywords: Stone Decay, Salt Weathering, Archaeological Buildings, Petra, Rock-cut Façades

1 INTRODUCTION

The city of Petra is one of the most singular monumental sets in the world. It was an important Nabatean city in the crossroads of major commercial routes and it lived its heyday during the 1st centuries BC and AD. Petra was inscribed as a UNESCO World Heritage Site in 1985 and it is located in the southwest of Jordan, East of the Wadi Araba Valley in the northwest part of the Arabian Peninsula.

In Petra hundreds of monuments are carved in the mid and upper Cambrian Umm Ishrin Sandstone and the Ordovician Disi Sandstone (Jaser and Barjous 1992), also known as Nubian sandstones. The Umm Ishrin Sandstone Formation crops out in Saudi Arabia, Egypt, Jordan and Palestine and forms part of several very relevant archaeological structures in these countries, such as Madean Saleh in northern Saudi Arabia, and most of the monuments in Upper Egypt and Petra (Al-Naddaf 2009).

The conservation and management of such a large archaeological site is very challenging. Petra was included in 1998, 2000 and 2002 in the former World Monuments Fund list of the one hundred most endangered sites (now World Monuments Watch) (Heinrichs 2008). For this reason, in addition to its iconic character, there are many studies on the decay processes that operate in Petra and in recent years much work has been done locally towards a better management of the place, especially directing the conservation works towards preventive measures. Nonetheless, it is necessary to keep studying the weathering causes, so that strategies for preventive conservation become more efficient.

For example, one area still in development in the case of Petra is the use of data obtained from portable non-destructive analytical techniques, as they could allow detecting on site patterns of variability of salts, and permitting to make better-informed decisions based on a wide breadth of data, with the addition of not having to sample or damage any structure.

This paper presents data on the characterisation of salts found at the so-called ‘Silk Tomb’, one of the buildings that form part of the Royal Tombs assemblage at Petra, by means of laboratory analytical techniques. The focus of this paper is the detection of possible spatial patterns of salts, and how these might relate to different origins for the salts. This work was done as the foundation for further studies with portable Raman (Lopez-Arce et al 2011).

The Silk Tomb was selected as it was specifically cited before in relation to the variability of salts (Goudie and Viles 1997, Heinrichs 2008) and its highly weathered profile with less dust layers covering the stone surface in comparison to other tombs would facilitate the subsequent survey with portable Raman.

2 SALT WEATHERING IN PETRA

In the 90s of last century the first extensive studies on salts as a major decay agent in Petra were published internationally. Fitzner & Heinrichs (1994) cite halite (NaCl), gypsum ($CaSO_4{\cdot}2H_2O$), niter (KNO_3) and $MgSO_4$ as the most common salt types found. Goudie and Viles (1997) also recognize salts as the main weathering agent in these monuments and specifically mentioned the Silk Tomb as an example and conclude that the decayed rocks were loaded with large quantities of saline material.

More recently Al-Saad & Abdel-Halim (2001), Wedekind & Ruedrich (2006), Bala’awi (2008), Eklund (2008) and Heinrichs (2008) also insisted in how salt crystallization is one of the most important factors that have contributed to the destruction of the buildings not only of the rock-cut facades but of the free-standing Qasr al-Bint monument and the nearby monastic building complex at Mount of Aaron, Habal Jaroun. These authors mention, in addition to the above-mentioned salts: magnesium chloride ($MgCl_2$) thenardite (Na_2SO_4), potassium sulphate (K_2SO_4), sodium carbonate ($NaCO_3$), magnesite ($MgCO_3$), kalicinite ($KHCO_3$) and potassium carbonate (KCO_3).

Many origins have been suggested for these salts; mainly the local soil for the halite and the sulphates (Fitzner & Heinrichs 1994). The soil would be enriched in carbonates and soluble salts, especially in the most arid parts (Singer & Amiel 1974), and in addition it would have inputs from sodium chloride used for food processing and sulphates as a result of past building activities (Fitzner & Heinrichs 1994). Dust and soil particles would be deposited on buildings thus resulting in constant loading in these salts. Rain chemicals are also considered a possible source for chlorides and sulphates (Heinrichs 2008). Domestic cattle are the main cause established by some authors for the origin of nitrates (Heinrichs 2008). In some cases, past restoration campaigns used cement mortar, from which salts migrated (Al-Saad and Abdel-Halim, 2001).

3 MATERIALS AND METHODS

3.1 The Silk Tomb

The so-called ‘Silk Tomb’ (Figure 1) is one of the buildings that form part of the Royal Tombs assemblage at the Nabatean city of Petra (Jordan). This building is formed by a large external façade of 200 m^2 that gives entrance to three relatively small chambers and it is believed it was conceived initially as a tomb. The name ‘Silk Tomb’ is given due to the multi-coloured façade which contrasts with the more homogeneous brownish colours the surface of surrounding tombs shows. The Silk Tomb is carved onto the Middle Umm Ishrin sandstone, which is a multi coloured medium to fine-grained quartz arenite with quartz syntaxial cements and different types of oxide cements coating the grains.

The Silk Tomb shows an intense damage throughout all the façade. In fact, the bright colours displayed are the result of the ongoing granular disaggregation which reveals the fresh surfaces of the rock without surface dust deposits or other coatings.

Figure 1. The Royal Tombs assemblage where the Silk Tomb (marked in the figure) is located. An area of intense breakdown of drainage channel is also marked.

The internal chambers of this building are relatively small (few meters side) in comparison to the external façade. The chambers do not show any type of decoration and they show evident remains of human habitation activity, such as bonfire traces (discolourations and soiling by ashes) and human and/or domestic animals excreta vestiges.

3.2. Analytical methods

Fourteen samples with efflorescences and subefflorescences were taken at the Silk Tomb in a field campaign carried out in July 2010 from loose and/or disaggregated fragments on the stone surface located as shown in Figure 2. Ion Chromatography (IC) and powder X-ray diffraction (XRD) were performed in these samples. In addition, although the detailed results are not included in this paper, further samples were taken from another, more secluded, façade (The ‘Monastery’) to establish comparisons between the salts present and the degree of habitation.

Some additional samples were taken of water coming from small springs related to bedding contacts nearby the ‘Monastery’ façade also carved onto Umm Ishrin sandstone. These samples were taken to discriminate what salts could come from the dissolution of components of this sandstone, and which would be likely to be originated by external inputs. Ion Chromatography was performed with a METROHM 761 COMPACT IC on dispersed sample solutions obtained from diluting 0.1g of sample in 10ml of ultrapure water. XRD patterns were acquired using a 0.02º step scan in the 2θ range 2-65º (CuKα radiation, graphite monochromator). Mineral phase identification was carried out with EVA Software V3.2.

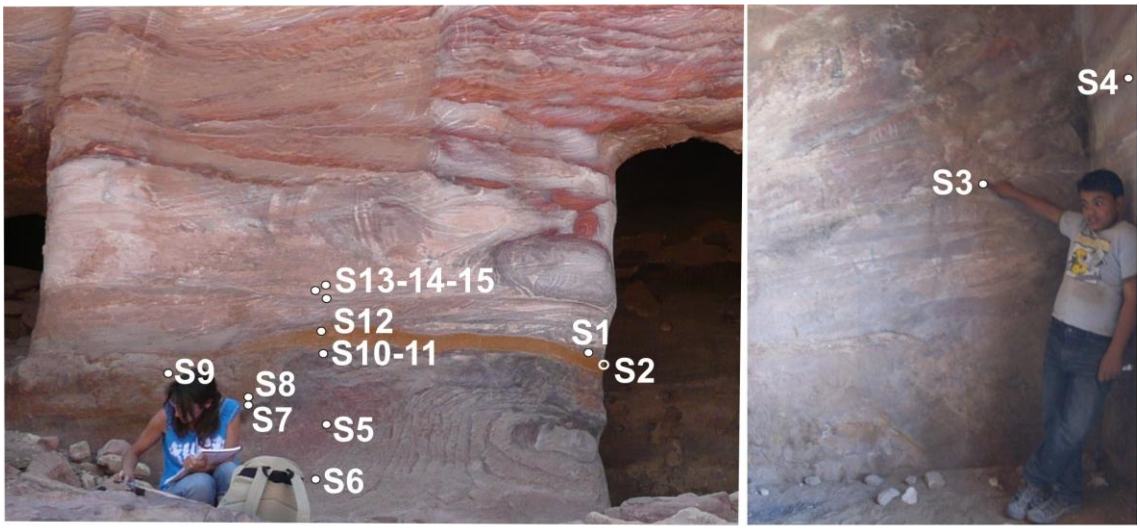

Figure 2. Sampling points in the external façade and the central internal chamber of the Silk Tomb.

A thermodynamic model was performed with RUNSALT software 1.9 based on the IC results obtained from water samples. This software is a version of ECOS software (Price 2000) that is based on the Pitzer theory of electrolyte solutions (Pitzer 1973) and calculates which mineral phases are present in equilibrium at a certain relative humidity and temperature. The prediction of gypsum crystallisation might cause problems, since the software is unable to calculate the crystallisation of other salts in its presence. For this reason it was removed from the system.

4 RESULTS AND DISCUSSION

Results from XRD patterns (Table 1) show a limited variety of salts in most of the analyzed samples from Silk Tomb, with halite (NaCl) and niter (KNO_3) being the most abundant salts overall. Sylvite (KCl) and gypsum ($CaSO_4 \cdot 2H_2O$) are also common, while only one sample from the internal chamber shows a higher variability of salts (S3) with syngenite ($K_2Ca(SO_4)_2 \cdot (H_2O)$), polyhalite ($K_2Ca_2Mg(SO_4)_4 \cdot 2(H_2O)$ and aphthitalite $(K,Na)_3Na(SO_4)_2$.

Thermodynamic simulations obtained from the water analyses (Table 2 and Figure 3) show that, at low relative humidity halite (NaCl) niter (KNO_3) and sylvite (KCl) are precisely the most stable salt phases that would crystallize from percolating water. This confirms that dissolution and re-precipitation of rock components due to both percolated water and surface runoff is the main source of the salts found at this façade. In the areas where intense runoff takes place, salt weathering is concentrated (mainly in the shape of taffoni and honeycomb weathering).

The limited diversity of salts found in the external façade contrasts with the higher variability of salts present in the internal chambers, where combinations of Na, K, Ca, Mg sulphates are found. In general, the higher amount of niter found at the Silk Tomb also contrasts with other more secluded monuments in which human activity has been less intensive. This is the case, for example, of 'The Monastery', where the predominant phase is gypsum, in addition to halite, while niter and sylvite are less abundant than in the Silk Tomb.

Table 1. Salts present as interpreted from XRD patterns of samples from Silk Tomb

Sample	Halite	Sylvite	Niter	Gypsum	Other salts present
ST-S1	X	X	X		
ST-S2	X	X	X		
ST-S3	X	X	X		Polyhalite, Syngenite, Aphthitalite
ST-S4	X				
ST-S5	X				
ST-S6	X		X		
ST-S7	X				
ST-S8	X		X	X	
ST-S9	X				
ST-S10	X				
ST-S11	X		X	X	
ST-S12	X	X	X	X	
ST-S13		X	X		
ST-S14			X	X	

Nitrates are related to human and animal activity, especially cattle and human excreta. Therefore the more accessible monuments, such as the Silk Tomb, present higher rates of these salts. In addition, other human activities that took place in the internal chambers of the monuments, such as fires, generate ashes rich in ions such as sulphur, nitrogen and potassium (Gomez-Heras et al. 2009) that add complexity to the array of salts found inside the tombs.

Table 2. IC analysis (mg/l) of water sample used for thermodynamic simulation

Sample	F^-	Cl^-	NO_2^-	NO_3^-	PO_4^{2-}	SO_4^{2-}	$C_2O_4^{2-}$	Na+	K+	Ca2+	Mg 2+
Mo-b	0.399	15.552	0	0.856	0	14.535	0	10.75	3.258	25.89	2.897

These results confirm previous findings and point to surface runoff and human activity as the main sources for the salt loading of the façades and therefore the main agents to act on in any management plan for the Archaeological Park of Petra.

The most intense surface runoff at the Royal Tombs assemblage is, in many cases, related to breakdowns of drainage channels carved above the tombs and designed by the Nabateans both to better exploit the water resources of the area (to conduct and store rain waters to be used for agriculture and consumption) and to prevent structural damage of the buildings. However, as pointed out by Wedekind (2005), most of these drainage channels are, nowadays, lack of maintenance and have either filled up or are partly destroyed. The 'Silk Tomb' is a fine example of this (Figure 1), as the noticeably higher weathering rates of this façade (in comparison to the surrounding tombs in the Royal Tombs assemblage) are caused by leakage and surface runoff from one of these damaged channels

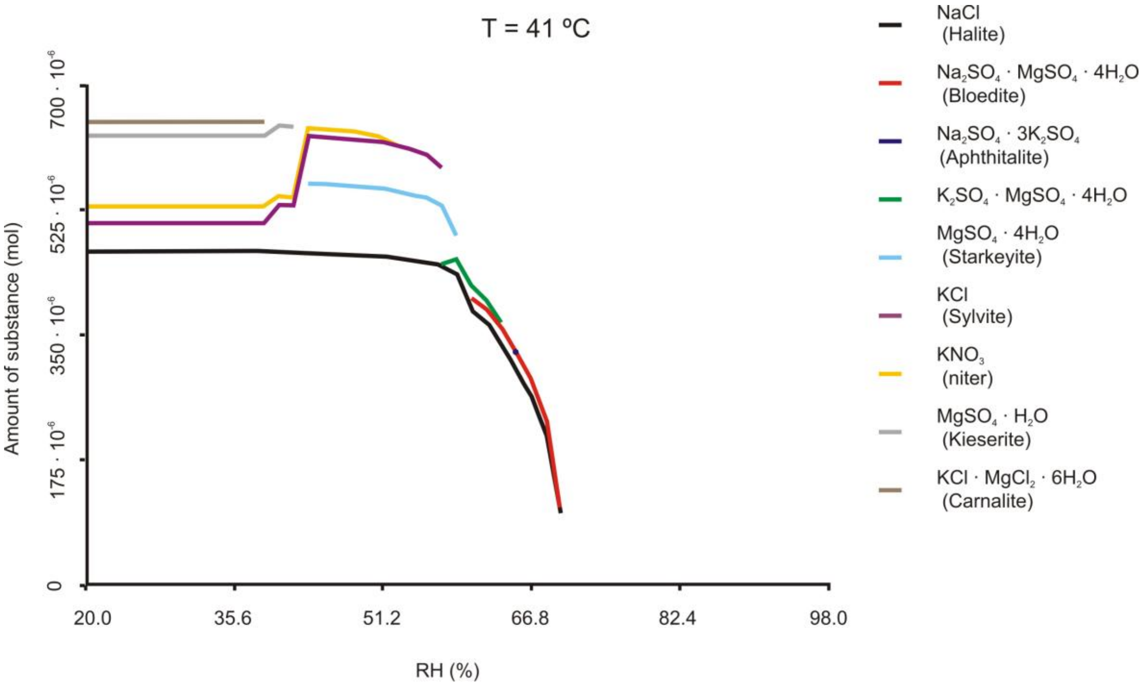

Figure 3. RUNSALT thermodynamic simulation for the water samples analyzed at 41ºC.

In relation to human activity, the tombs are not inhabited any more as they were in the past, however, the chambers are still partially used to keep animals, and often used as improvised ‘toilets’, in part due to the lack of facilities associated to the tourist track.

5 CONCLUSIONS

Salts are one of the most important weathering agents in the Royal Tomb assemblage at Petra, as it has been long stated. Moreover, the ‘Silk Tomb’ is the most damaged tomb of this assemblage in relation to salts. In fact, the name given to this façade relates to the variety of colours it displays, which is really the reflection of an intensely weathered surface due to ongoing granular disaggregation.

The Silk Tomb shows a marked spatial distribution of salts. Halite (NaCl), niter (KNO_3) and gypsum ($CaSO_4 \cdot 2H_2O$) are the most common salts found in the external façades, while the internal chambers show in some cases a much more complex array of salts, including sylvite (KCl), syngenite ($K_2Ca(SO_4)_2 \cdot (H_2O)$), polyhalite ($K_2Ca_2Mg(SO_4)_4 \cdot 2(H_2O)$) and aphthitalite ($(K,Na)_3Na(SO_4)_2$). This reflects the variety of inputs generated by human activities and natural sources in contrast with other, more secluded, monuments in which the mineralogy found is simpler.

Results confirm previous findings and point to surface runoff and human activity as the main sources for the salts found in these buildings. This highlights the importance of taking into consideration repairs and maintenance of the drainage channels and management of people and animals as a preventive’ conservation strategy and a priority for of any conservation and management actuation at the World Heritage Site of Petra.

6 ACKNOWLEDGEMENTS

This research was supported by the Spanish Agency for International Cooperation AECID (PCI-AECID A/025170/09). We are indebted to Petra Archaeological Park Management, in particular Dr. Emad Hijazeen and Eng. Tahani Salhi for their support during the fieldwork. The President and Vicepresident of the Hachemite University are also acknowledged for their support.

REFERENCES

AL-NADDAF, M. 2009. The effect of salts on thermal and hydric dilatation of porous building stone. *Archaeometry* 51, 495-505.

AL-SAAD, Z., ABDEL-HALIM, M.A.H. 2001. Laboratory evaluation of various types of mortars for the conservation of Qasr al-Bint monument, Petra-Jordan, *Engineering Structures,* 23, 926-933.

BALA'AWI, F., 2008. Wind speed and salt simulation tests: Towards a more comprehensive approach. In: Salt Weathering on Buildings and Stone Sculptures. pp. 41-52

EKLUND, S., 2008. *Stone weathering in the monastic building complex on Mountain of St Aaron in Petra, Jordan.* Master of Arts Thesis. University of Helsinki.

FITZNER, B & HEINRICHS, K. 1994. Damage diagnosis at monuments carved from bedrock in Petra, Jordan. In III International Symposium on the Conservation of Monuments in the Mediterranean Basin. 22-25 June 1994. Fassina, V., Ott, H. & Zezza, F. (eds.). Venice.

GOMEZ-HERAS, M., MCCABE, S., SMITH, B.J., FORT, R., 2009. Impacts of fire on stone-built heritage: an overview. *Journal of Architectural Conservation* 15 (2), pp. 47-58.

GOUDIE, A. & VILES, H., 1997, *Salt weathering hazards,* John Wiley & Sons, Chichester.

HEINRICHS, K., 2008. Diagnosis of weathering damage on rock-cut monuments in Petra, Jordan. *Environmental Geology,* 56, 643-675.

JASER, D. & BARJOUS, M.O. 1992. Geotechnical studies and geological mapping of Ancient Petra City. Natural Resources Authority, Amman.

LÓPEZ-ARCE, P., ZORNOZA-INDART, A., VÁZQUEZ-CALVO, C., GOMEZ-HERAS, M. ÁLVAREZ DE BUERGO, M. & FORT, R., (In press). Evaluation of portable Raman for the characterization of salt efflorescences at Petra, Jordan. Spectroscopy Letters.

PITZER K.S., 1973. Thermodynamics of electrolytes. I. Theoretical basis and general equations. J Phys Chem 77(2):268–277

PRICE, CA., 2000 An expert chemical model for determining the environmental conditions needed to prevent salt damage in porous materials. European Commision. Protection and Conservation of European Cultural Heritage. Research Report 11. Archetype, London

SINGER, A., AMIEL, A.J., 1974. Characteristics of Nubian sandstone-derived soils. *Journal of Soil Science*, 25(3), 310–319.

WEDEKIND, W., 2005. Jordan - Petra. In M. Truscott, M. Petzet & J. Ziesemer, Heritage at Risk – ICOMOS World Report 2004/2005 on Monuments and Sites in Danger, Munich 2005, 151 – 156.

WEDEKIND, W. & RUEDRICH, J., 2006. Salt-weathering, conservation techniques and strategies to protect the rock cut facades in Petra/Jordan in ed. R. Fort, M. Alvarez de Buergo, M. Gomez-Heras, & C. Vazquez-Calvo. Heritage, Weathering and Conservation, Madrid. pp. 261-268.