# Investigation of salt weathering on stone monuments – the 'petraSalt' research project

## Untersuchung der Salzverwitterung an Steinbauwerken – das Forschungsprojekt „petraSalt"

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## Abstract

Salt weathering is known as a major cause of damage on stone monuments. Despite many years of intensive research, processes of salt weathering still cannot be explained satisfactorily. The lack of knowledge impedes reliable damage prognosis as well as selection and implementation of appropriate and sustainable monument preservation measures. The overall aim of the "petraSalt" research project is to improve knowledge of salt weathering on stone monuments. The project aims at real-time/real-scale weathering models that depict characteristic interdependencies between stone properties, monument exposure regimes, environmental influences, salt loading, salt crystallization-dissolution behaviour and salt weathering damage. These models are expected to allow reliable rating and interpretation of aggressiveness and damage potential of salt weathering regimes considering their variability. The methodological approach combines assessment of weathering damage and monument exposure characteristics, laboratory analysis of salt loading and continuous monument environmental monitoring by use of the innovative wireless sensor network technology. In order to ensure findings of high transferability, the rock-cut monuments of Petra/Jordan were selected for studies, since stone type and spectra of monument exposure regimes, environmental influences, salt loading and weathering damage are very representative for a multitude of stone monuments worldwide. Methodological approach and results of the 'petraSalt' research project are presented.

**Keywords**: Stone monuments, salt weathering, weathering damage, 3D laser scanning, environmental monitoring, wireless sensor network

## Zusammenfassung

Langjahrige Erfahrungen haben das zerstörerische Potential der Salzverwitterung und ihren erheblichen Anteil an der Entstehung von Schäden an Steinbauwerken belegt. Trotz vieler Jahre intensiver Forschung sind die Vorgänge der Salzverwitterung jedoch noch wenig verstanden. Dieses Kenntnisdefizit erschwert zuverlässige Schadensdiagnosen und –prognosen sowie die Auswahl und Durchführung möglichst dauerhaft wirksamer Schutzmaßnahmen. Das übergeordnete Ziel des „petraSalt" Forschungsprojektes ist es, zu einem besseren Verständnis von Salzverwitterungsvorgängen an Steinbauten beizutragen. Hierbei werden zuverlässige Modellvorstellungen zu charakteristischen Wechselbeziehungen zwischen Gesteinsbeschaffenheit, Bauwerksexpositionsregimen, Umwelteinflüssen, Salzbelastung und Verwitterungsschäden angestrebt. Um Erkenntnisse hoher Übertragbarkeit zu erzielen, wurden die Felsmonumente Petras in Jordanien als Untersuchungsobjekte ausgewählt, da Gesteinstyp und Spektren von Bauwerksexposition, Umwelteinflüssen, Salzbelastung und Verwitterungsschäden repräsentativ für eine Vielzahl von Steinbauwerken weltweit sind.

**Schlüsselworte**: Steinbauwerke, Salzverwitterung, Verwitterungsschäden, 3D Laser-scanning, Umweltmonitoring, drahtloses Sensornetzwerk

## 1 Introduction

Stone monuments represent an important part of world cultural heritage. All stone monuments are affected by weathering. Findings obtained from in-situ investigation, laboratory experiments and weathering simulation during the last decades have revealed salt weathering as a major cause of damage on stone monuments worldwide. Despite long-time intensive research, processes and mechanisms of salt weathering are still rather poorly understood. This is due to the heterogeneity of the systems "stone", "salt" and "environmental influences" and the complexity of their dynamic interaction. Assessment of the dynamics of salt crystallization and dissolution processes has become an important focus of modern salt weathering research. From experts´ point of view, further systematic investigation of stone monuments affected by salt weathering is required for the improvement of knowledge on active salt weathering processes and controlling factors. Temporal and spatial high-resolution monitoring of environmental conditions at the stone monuments in combination with precise identification and quantification of salt loading is highly desirable. The research project 'petraSalt - Investigation of salt weathering on stone monuments by use of a modern wireless sensor network exemplified for the rock-cut monuments in Petra / Jordan' takes this approach. The rock monuments of Petra were selected for studies, since stone type (sandstone) and spectra of monument exposure scenarios, environmental influences, salt loading and weathering damage are very representative for a multitude of stone monuments worldwide. Petra is located in Southwest Jordan. In Petra many hundred monuments such as tombs, sanctuaries and places of worship were carved by the Nabataeans from sandstone about 2.000 years ago (Fig. 1). The Petra region is mainly composed of sedimentary rocks of Lower Paleozoic age. The relevant stratigraphic units with respect to the rock-cut monuments are the middle and upper part of the Cambrian Umm Ishrin Sandstone Formation and the Ordovician Disi Sandstone Formation (JASER & BARJOUS 1992). In 1985 UNESCO inscribed Petra on the list of World Heritage. All rock monuments show damage due to weathering. Salt weathering was identified as major cause of this damage (HEINRICHS 2008). The 'petraSalt' research project is funded by DFG - Deutsche Forschungsgemeinschaft (German Research Foundation). It is carried out in close cooperation with the Department of Antiquities of Jordan and with the Petra Development & Tourism Region Authority / Petra Archaeological Park & Cultural Heritage Commission.

## 2 Methodological approach

The methodological approach combines:

- the assessment of monument exposure regimes (location, dimension and geometry of the monuments, original monument architecture, orientation of stone surfaces, rain-impact, water run-off situation, insolation condition),
- the assessment of weathering damage (type, extent and spatial distribution of apparent weathering phenomena, weathering progression, rating of damage),
- the assessment of salt loading regimes (type, concentration and spatial distribution of salts / salt mixtures, salt weathering profiles, salt uptake conditions),
- the continuous high-resolution environmental monitoring of the monuments (temperature, humidity, insolation, rain, wind),
- and the numerical analysis of potential salt crystallization / salt dissolution cycles according to frequency and depth, considering diurnal and seasonal variation.

In the course of the integral evaluation, all results get combined for overall comprehensive information on salt weathering and its effects on the Petra rock-cut monuments by means of weathering models that depict the characteristic interdependencies between stone type/stone properties, monument exposure regimes, environmental influences, salt loading, salt weathering processes and salt weathering damage. These models are expected to allow the reliable rating and interpretation of aggressiveness and damage potential of the salt weathering regimes considering their variability under range of lithology, monument exposure, macro-, meso- and micro-environmental conditions, state of weathering and time.

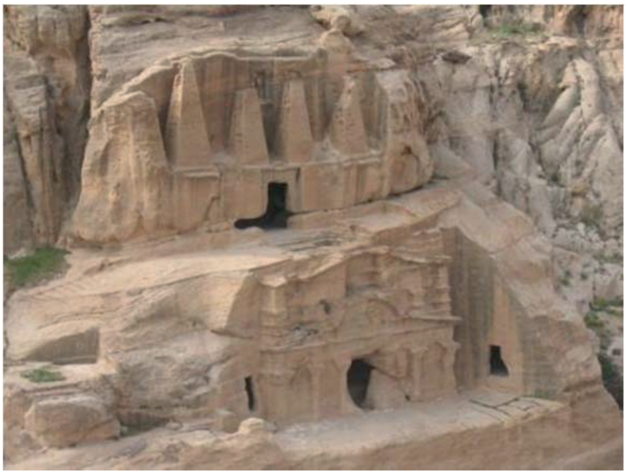

*Abb. 1: Barocktriklinium (unten) und Obeliskengrab (oben).*

*Fig. 1: Bab el-Siq Triclinium (bottom) and Obelisk Tomb (top).*

Achievement of the project´s aims requires high-resolution monitoring of environmental conditions affecting the monuments and acting as driving forces for salt weathering processes. An autonomously operating wireless sensor network - developed in cooperation with TTI GmbH - TGU Smartmote (Stuttgart, Germany) - is applied as an innovative technology that can make this contribution. The system comprises sensor nodes and gateways. With respect to sensor nodes, cylinders were equipped with six sets of sensors in depths from 1 cm to 18 cm (Figs. 2, 3).

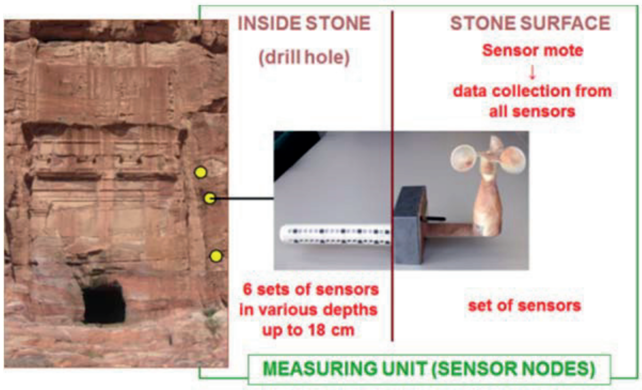


*Abb. 2: Konfiguration des drahtlosen Sensornetzwerkes. Sensorknoten.*

*Fig. 2: Configuration of the wireless sensor network. Sensor nodes.*

Each set includes sensors for the measurement of temperature, humidity and electrical impedance. The cylinders were tailored to insertion in drill holes. A special spreading technique ensures proper sealing of the six measuring chambers against each other as well as dense connection between cylinder and stone substrate. Exterior system components of the sensor nodes comprise sensor mote with rain-proof enclosure, long-life batteries, processor board, radio module and sensors for the measurement of air temperature, air humidity, stone surface temperature and light. In addition, several sensor nodes were equipped with wind and rain sensors. In this way, a sensor node can be equipped with 24 sensors at maximum. The sensor motes act as data collector and were programmed to collect data in intervals of 15 minutes.

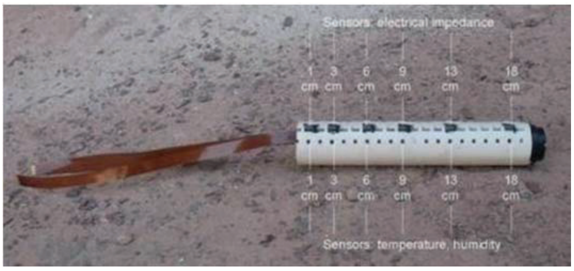


*Abb. 3: Säulensensor.*

*Fig. 3: Sensor cylinder.*

The sensor motes send the collected data to gateways in Petra (Fig. 4). These were equipped with a solar energy supply unit. The gateways relay the measurement data to a long-distance network (GSM) for remote access per internet. The possibility of remote access to the data allows their continuous evaluation. The data are stored in a MySQL database. In the course of installation, the investigation areas were scaffolded. Then dry core drilling of 37 mm in diameter was made carefully. The sensor cylinders were installed in the drill holes.

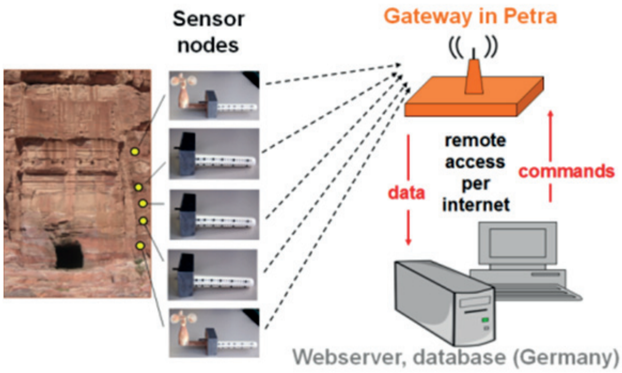


*Abb. 4: Konfiguration des drahtlosen Sensornetzwerkes. Datentransfer über Basisstationen.*

*Fig. 4: Configuration of the wireless sensor network. Data transfer via gateways.*

In the next step, the mote boxes were screwed on the sensor cylinders. Finally, the mote boxes were coated with sand of colour similar to that of the corresponding stone surface. In all 21 sensor nodes and three gateways were installed (Figs. 5, 6).

*Abb. 5: Installierter Sensorknoten.*

*Fig. 5: Installed sensor node.*

*Abb. 6: Basisstation.*

*Fig. 6: Gateway.*

## 3 First results

Five rock-cut monuments were selected for investigation. In the course of monument identification, description and documentation, high-resolution 3D terrestrial laser scanning (TLS) of these monuments was performed by use of an OPTECH ILRIS 3D laser scanner (Fig. 7) (Heinrichs & Nguyen 2011).

*Abb. 7: 3D-Laserscanning, Palastgrab.*

*Fig. 7: 3D laser scanning, Palace Tomb.*

The evaluation of the TLS data has provided precise information on dimension of the monuments and orientation of their surface (Figs. 8, 9). Furthermore, the 3D models of the monuments served as an important basis for the assessment of their original architecture (Fig. 10). This step of evaluation makes an important contribution to assessment of weathering damage – especially loss of stone material – and development of monument exposure characteristics over time. In addition, the 3D models of the monuments and their surrounding were used for the calculation of rock mass removed for monument creation. Considering the huge masses of removed rock material, unweathered condition of the monuments´ rocks can be postulated for their initial phase of exposure. Thus, active salt weathering processes can be limited to about 2 000 years.

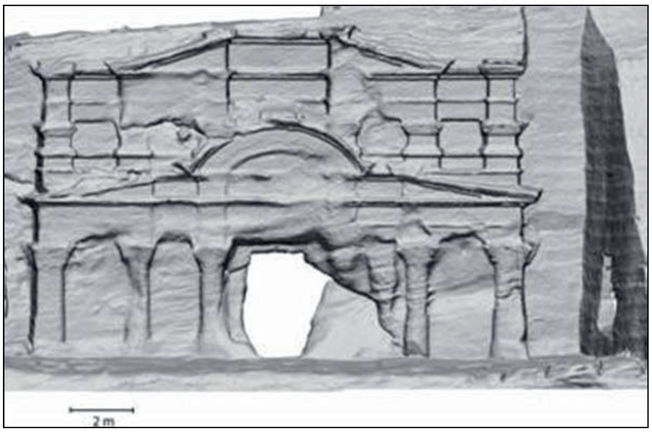


*Abb. 8: 3D-Modell, Barocktriklinium (vgl. Abb. 1).*

*Fig. 8: 3D model, Bab el-Siq Triclinium (see Fig. 1).*

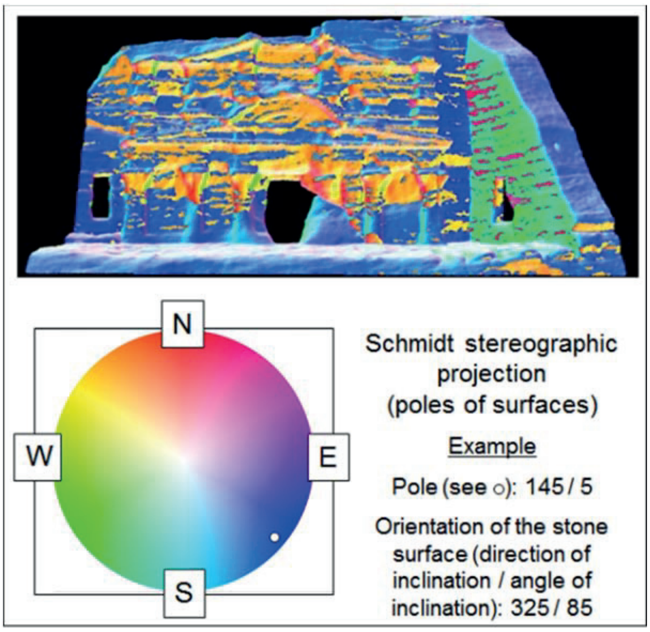


*Abb. 9: 3D-Modell des Barocktrikliniums mit Darstellung der Gesteinsoberflächenorientierung.*

*Fig. 9: 3D model of the Bab el-Siq Triclinium with illustration of stone surface orientation.*

A next step of investigation addressed water run-off and rainfall at the monuments, considering rain as an important source of salt loading. Those parts of the monuments affected by water run-off during or after rain were mapped in detail, considering short and long rainfall, light and heavy rainfall respectively (Fig. 11). The studies on rainfall have provided a statistical value in terms of direction and inclination of rainfall. This allowed the calculation of rain water input at the monuments in dependence on surface orientation. Based on scanning of the 3D monument models with the statistical rain linear, areas exposed to rain were precisely identified (Fig. 12). Measurements by means of infrared-thermography were performed for assessment of the heating-cooling behavior of the monument surfaces in dependence on their orientation and architectonic composition (Figs. 13, 14).

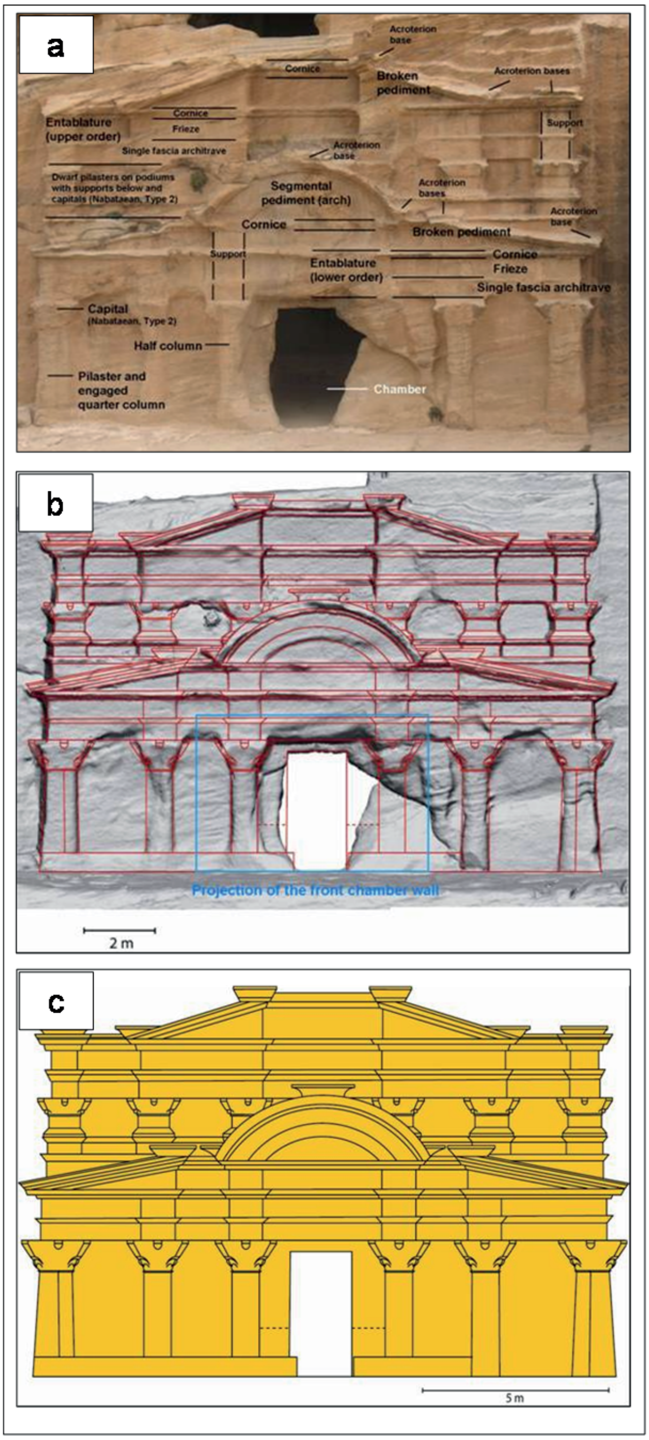


*Abb. 10: Barocktriklinium. Rekonstruktion der originalen Bauwerksarchitektur. a - Identifizierung der architektonischen Elemente, b - 3D Modell mit Rekonstruktion der Bauwerksarchitektur und Projektion der vorderen Grabkammerwand, c - Plan des Bauwerks im Ausgangszustand. Ca. 700 m³ Gesteinsmaterial wurden zur Schaffung der Bauwerksfassade abgetragen.*

*Fig. 10: Bab el-Siq Triclinium. Reconstruction of the original monument architecture. a - identification of architectonic elements, b - 3D model with reconstruction of the monument architecture and projection of the front chamber wall, c - monument plan, original architecture. Appr. 700 m³ rock material were removed for creation of the monument façade.*

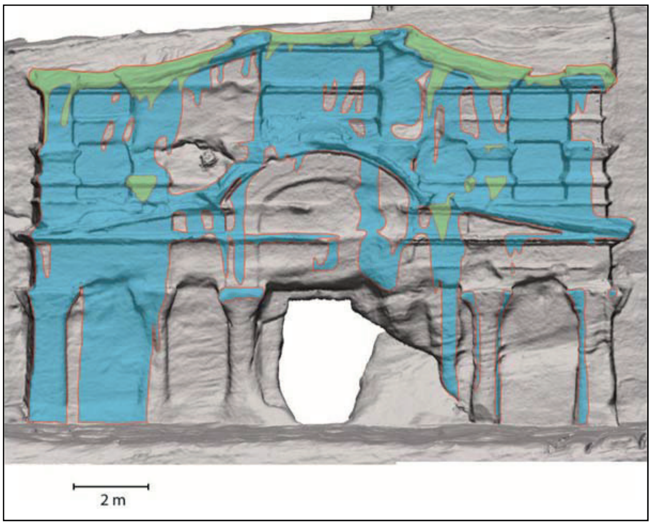


*Abb. 11: Barocktriklinium.3D Modell mit Wasserablaufbereichen nach kurzem, bzw. leichtem Regen (grün) und langem bzw. starkem Regen (blau).*

*Fig. 11: Bab el-Siq Triclinium. 3D model with water run-off areas after short / light rain (green) and long / heavy rain (blue).*

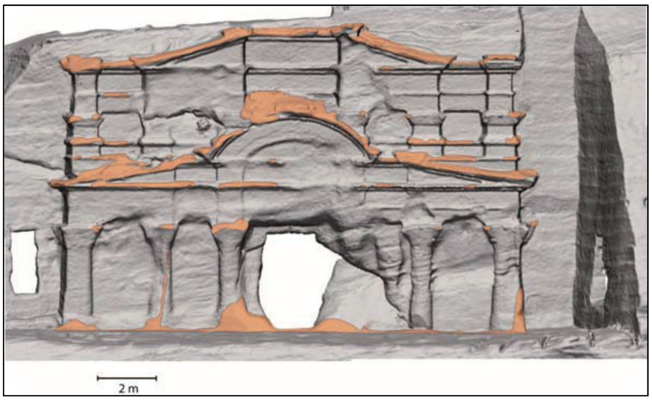


*Abb. 12: Barocktriklinium.3D Modell mit beregneten Bereichen (orange).*

*Fig. 12: Bab el-Siq Triclinium. 3D model with areas exposed to rain (orange).*

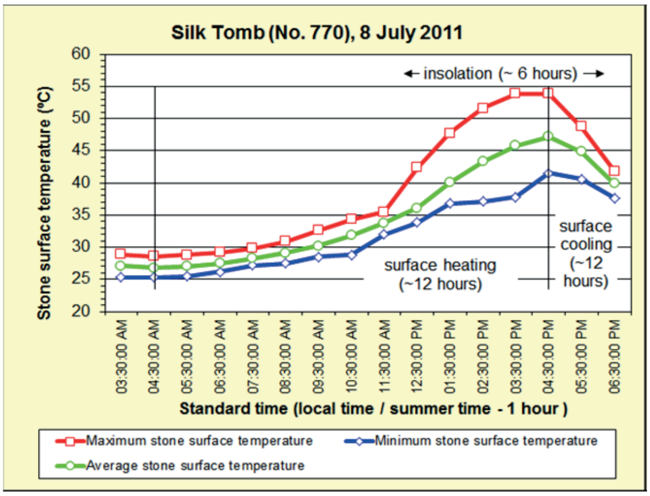


*Abb. 13: Buntes Grab, westexponierte Bauwerksfassade. Gesteinsoberflächentemperaturen im Hochsommer (Beispiel).*

*Fig. 13: Silk Tomb, façade exposed to west. Stone surface temperatures in high summer (example).*

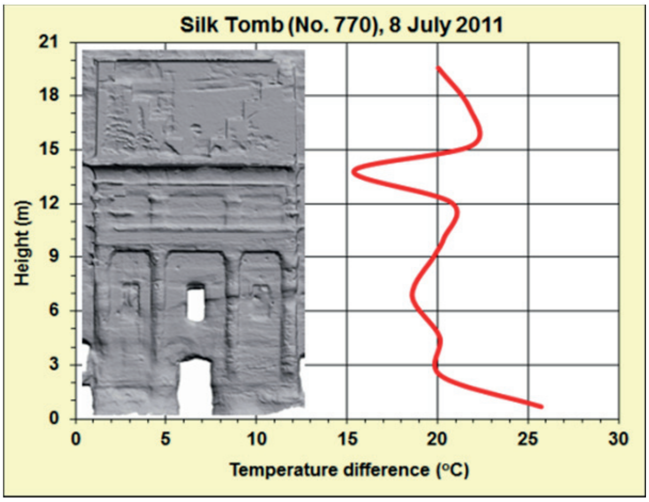


*Abb. 14: Buntes Grab. Differenz der Gesteinsoberflächentemperaturen im Tagesgang (Vertikalprofil, Hochsommer).*

*Fig. 14: Silk Tomb. Diurnal stone surface temperature difference (vertical profile) in high summer.*

Since its installation, the wireless sensor network permanently has collected and transmitted environmental data. In this way, the sensor system provides an extraordinary information output regarding environmental conditions at the Petra monuments considering diurnal, seasonal and depth-dependent variation. Continuously the data get exported from the database for further evaluation. Examples are presented in Figs. 15-20.

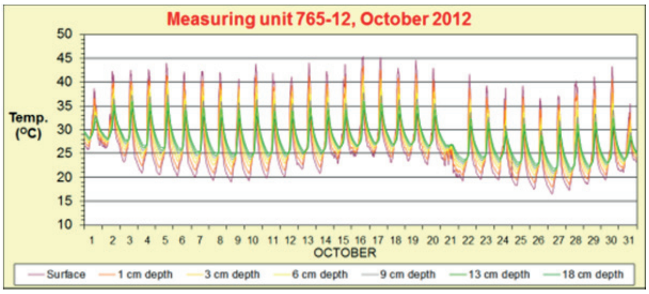


*Abb. 15: Palastgrab, Sensorknoten 12, kambrischer Sandstein. Gang der Gesteins-temperaturen im Oktober 2012. Abnahme der Schwankungen mit der Tiefe.*

*Fig. 15: Palace Tomb, sensor node 12, Cambrian sandstone. Run of stone temperature in October 2012. Decrease of variation with depth.*

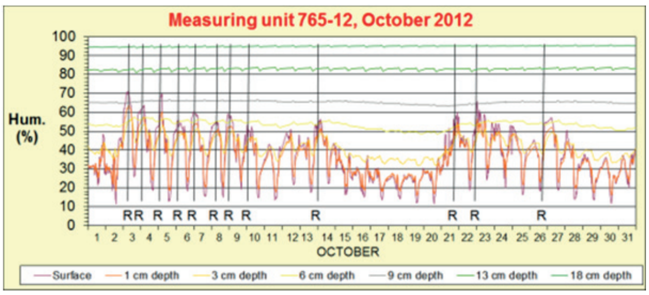


*Abb. 16: Palastgrab, Sensorknoten 12. Gang der Gesteinsfeuchte im Oktober 2012. Deutliche Abnahme der Schwankungen mit der Tiefe. R = Regenereignisse.*

*Fig. 16: Palace Tomb, sensor node 12. Run of stone humidity in October 2012. Considerable decrease of variation with depth. R = rain events.*

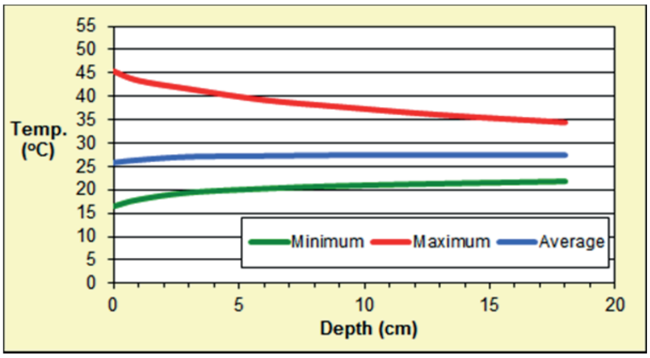


*Abb. 17: Palastgrab, Sensorknoten 12. Bandbreite der Gesteinstemperaturen im Oktober 2012 (Tiefenprofil).*

*Fig. 17: Palace Tomb, sensor node 12. Range of stone temperature in October 2012 (depth profile).*

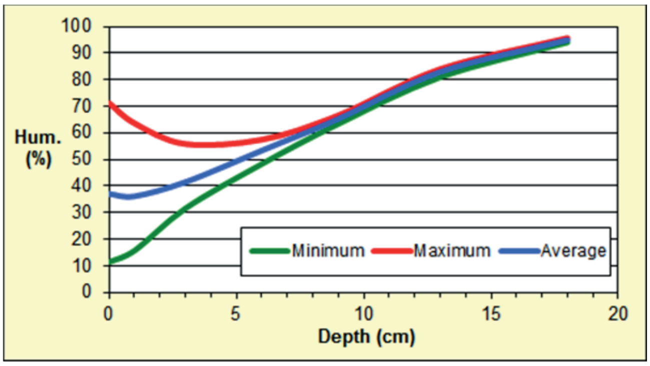


*Abb. 18: Palastgrab, Sensorknoten 12. Bandbreite der Gesteinsfeuchten im Oktober 2012 (Tiefenprofil).*

*Fig. 18: Palace Tomb, sensor node 12. Range of stone humidity in October 2012 (depth profile).*

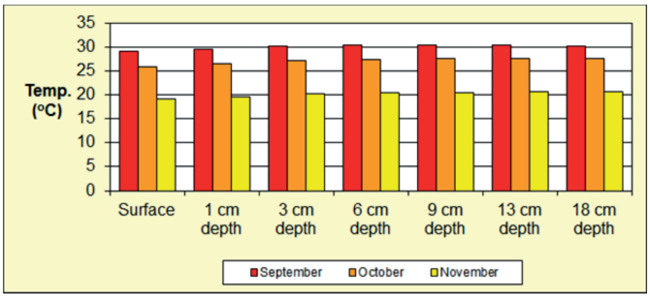


*Abb. 19: Palastgrab, Sensorknoten 12. Durchschnittliche Gesteinstemperaturen im Spätsommer 2012.*

*Fig. 19: Palace Tomb, sensor node 12. Average stone temperature in late summer 2012.*

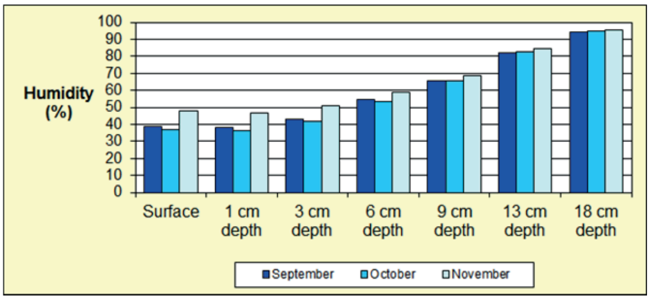


*Abb. 20: Palastgrab, Sensorknoten 12. Durchschnittliche Gesteinsfeuchten im Spätsommer 2012.*

*Fig. 20: Palace Tomb, sensor node 12. Average stone humidity in late summer 2012.*

The results already reveal a great diversity of micro-environmental regimes at the rock-cut monuments in dependence on lithology (different sandstone types with different petrographic properties), monument exposure characteristics and state of weathering.

The stone samples obtained from dry core drilling in the course of the sensor network installation are taken for segment-wise ionic analysis of soluble salts. The ECOS program is used via RUNSALT as thermodynamic model for the prediction of the salt crystallization behavior under changing climate conditions (BIONDA 2002-2005, PRICE 2000). On daily base, the climatic data provided by the wireless sensor network are attributed then to the corresponding salt crystallization models. This evaluation is made for total salt and, in addition, individually for each salt phase (e.g. halite, gypsum, sylvite, niter etc.) This will allow a differentiated, depth-dependent numerical analysis of salt crystallization – dissolution processes in dependence on lithology, monument exposure regimes, salt loading and state of weathering, considering diurnal and seasonal variation.

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## Acknowledgements

The authors give their thanks to DFG – Deutsche Forschungsgemeinschaft (German Research Foundation) for project funding. Furthermore, the authors would like to express their gratitude to the representatives of the Department of Antiquities of Jordan (DOA) and the Petra Development & Tourism Region Authority / Petra Archaeological Park & Cultural Heritage Office (PDTRA / PAP) for cooperation, discussion, advice and all support of the research project in Petra.