Salt-weathering, conservation techniques and strategies to protect the rock cut façades in Petra/Jordan

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ABSTRACT: The ancient city of Petra/Jordan has gained special recognition for its hundreds of rock façades carved out of the sandstone rock. Today, the existence of the unique rock architecture of these monuments is in danger due to decomposition, poor maintenance and lack of conservation. Within three years of on-site work and field research, findings about the geology and geomorphology of the cambric sandstone could be gathered. Acute safety repairs and restoration of stone façades were done and new techniques for conservation could be developed and employed. A new sprinkling method for desalinating natural stone was developed and first applied at Petra on monument no. 826. By desalinating monument no. 826 several hundred grams of halite could be extracted and by surveying at its distribution, conclusions about the local geomorphology could be drawn. Salt weathering tests and pore space analyses on three different sandstone types have been carried out. Especially the bimodal pore radii distribution and a partly pronounced hygric swelling of the investigated sandstones samples are probably responsible for their high sensitivity within the salt weathering tests.

1 INTRODUCTION

1.1 *Measures for the protection of the world cultural heritage of Petra/Jordan*

The ancient stone city of Petra is about 260 kilometers south of the capital Amman with an altitude of about 900-1500 meters. It is located in a semi-arid climatic zone with a mean annual rainfall of 190 mm (Goudi & Viles 1997). With its about 4000 individual monuments cut from rock, the site was added to the list of the world cultural monuments of the UNESCO (United Nations Educational, Scientific, and Cultural Organization) in 1995. The existence of most of the 2000-year old sandstone monuments of Petra is in danger due to progressive weathering (Wedekind 2005b). Today more than 50 % of the surfaces of the monuments are damaged by weathering phenomena. Nearly 12 % are totally destroyed by tafoni-weathering because of high contamination with rock salt (halite, NaCl). Therefore, a German-Jordan project for the establishment of a Conservation and Restoration Center in Petra (CARCIP) run by the German Technical Cooperation Society (GTZ) and the Department of Antiquities of Jordan (DOA) developed conservation and restoration methods to protect the sandstone monuments (Fig. 1) between 1993 and 2002 (Fischer & Kühlenthal 2000). Between 2000 and 2003 several scientific investigations, including study and diploma theses were performed by the Geoscience Center of the University Goettingen (GZG) and of the University of Applied Arts and Sciences of Hildesheim (HAWK), Germany.

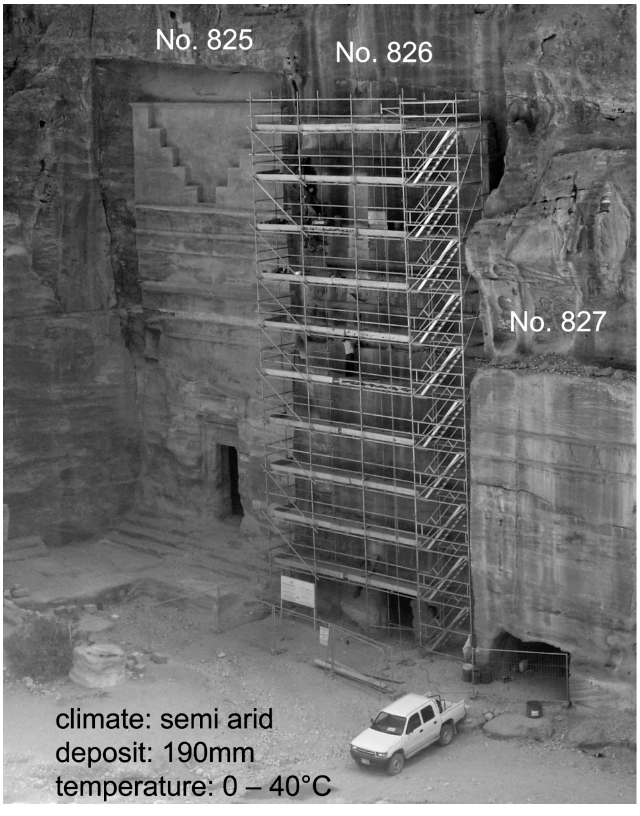

Figure 1: Investigated monuments of the ancient stone city of Petra/Jordan.

1.2 *Petra, the capital of the Nabateans*

The ancient stone city was the capital for the Nabateans from about 400 BCE until the fourth century CE and housed 30,000-40,000 people during its heyday. The Arabic tribe of Nabateans achieved great wealth and political-economic significance through caravan trading on the Silk and Incense Routes. In 106 CE, the Nabatean kingdom lost its independence and was incorporated into the Roman Empire as Provincia Arabia. It was an earthquake in 363 CE that dealt a decisive blow to the still important and extremely wealthy city and Petra increasingly lost importance as a metropolis. As their territorial independence came to an end, the Nabateans lost the economic and political influence they once had. The Nabatean Era had come to an end. Although the majority of the residential city carved out of ashlar lies literally in ruins due to earthquakes, the nearly 800 façades chiseled in the rock leave a lasting impression of the wealth and importance of this former Arabic metropolis.

2 THE CAMBRIAN SANDSTONE OF THE UMM ISHRIN FORMATION

Geologically, the rocks are located at the end of the Arabian plate. It is part of the old African continental mass with the neighboring mountain range of Ethiopia, Eritrea and parts of Egypt (Nubia).

Most of the tomb façades of Petra were chiseled from the rock of the brown sandstone of the Middle Cambrian of the Umm Ishrin formation. In former days this sandstone had also been called Nubian sandstone. It is mostly reddish-brown, but also multi-colored yellowish-brown or with bright reddish-purple lines. It is medium to fine-grained and of medium porosity (Künne & Wanke 1997).

2.1 *Mineralogical components*

The detritical components of the sandstones from Petra are dominantly quartz and subordinated feldspar grains. The cementation of the rocks differs with regard to the mineralogical composition as well as in the concentration. Quartz and clay minerals are the main cementation components. Sometimes hematite or calcite can also be found.

The micro fabric of a sample from monument No. 826 is exemplarily shown in Figure 2. The thin section analyses exhibit that the detritical components are almost completely quartz grains. The sandstone shows a bimodal sorting with main grain sizes between 100 mm and 300 mm (Fig. 2a). The roundness of detritical grains is predominantly angular. The quartz grains often show mineralized micro cracks which represent fabric properties from the source area. Opened micro cracks are common and the result of a fragmentation during the diagenetic compaction of the sediment. The diagenetic cementation is characterized by intensively syntaxial quartz overgrowth on detritical grains (Fig. 2b). Hematite is also common and is found on the quartz cements.

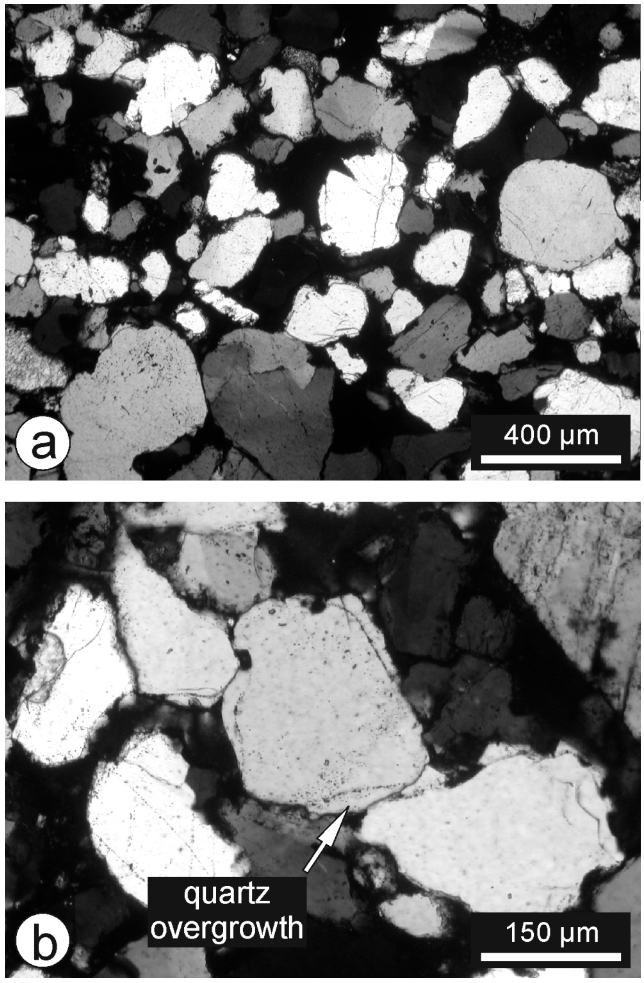

Figure 2: Photomicrographs (crossed polarisers) of a sandstone sample from monument No. 826: a) bimodal grain size distribution of detritical grains and b) syntaxial quartz overgrowth on detritical grains.

3 FORMS OF WEATHERING

Especially in areas with arid or semi-arid climatic zones like Petra an increasing amount of salts accumulates. Therefore, weathering due to salts plays a crucial rule. These observations were also supported by laboratory examinations (Sperling & Cooke 1980). Even the specific visible marks of weathering on the Cambrian sandstone in Petra point to damage caused by extreme salt contamination. The typical development of alveolar and tafoni is obvious and completely covers the rocks. During the past centuries, it has also spread to the monuments. The tafoni comprise locally limited and completely deteriorated areas spanning several meters. This kind of extreme deterioration is surrounded by mostly undamaged rock.

3.1 *Alveolar and tafoni weathering*

Various theories account for alveolar weathering. Some authors assume that there is chemical weathering due to so-called core weathering (Abu-Safat 1988). Various mechanisms are assumed to be responsible for the physical forms of weathering as well. Some authors assume that alveolar weathering is caused by abrasion due to wind (Quayle 1992). Others consider the pressure induced by swelling clay minerals in combination with the effects of salts to be the major causes (Pye & Mottershead 1995).

However, the majority of the authors are convinced that salt weathering due to salt explosion is responsible for the development of tafoni (Kirchner 1995).

Recent research states that different drying processes in the affected zones cause tafoni weathering (Huinink et al. 2004). The largest amount of salt settles in zones in which the drying process is slow and therefore causes damage.

3.2 *Forms of damage*

Comparative examinations of the sandstone monuments of Petra have shown that two varieties of tafoni development can be distinguished. Damaged areas evolve either vertically or horizontally.

Horizontal alveolars usually run below and markedly above the limonite veins that often run through the rock massif towards the sedimentation. In contrast to the surrounding sandstone, the first milimeters of this clay-silicic limonite layer are very soft. On the outside, they deteriorate faster than sandstone. However, drill resistance measurements have proved that, in depth, these limonite layers have a high hardness and a higher density than sandstone. They are mechanically stronger than feldspar or arkosic sandstones. Apparently, the clay-containing yellowish deposits serve as water veins or are similar to a water-damming layer. After rainfalls and dampened rock, the water accumulates and is directed to the stone surface. Thereby, the water also brings the salt to the surface, which was observed on many examples in Petra after rainfalls. Heavy stone weathering is found at the outsets of the respective clay bench. The damage displays a similar picture to the damp seam mortar of raw stone masonry. Here, the seam mortar as well as the stone deteriorates from the edges inward.

Regarding the vertical variation, the development of tafoni takes place in the zones left and right of the water run off. This is where draining water influences tafoni development. Assumedly, during the process of vertical alveolar development, the salts deposited due to the stones' dampness are activated, or the water transports the salts from the higher massif. Due to the evaporation on the rock surface, a high concentration of salts accumulates in the areas close to the surface. The rare but annually occurring heavy rains in the winter and spring dampen all the vacant rocky areas and wash out the salt efflorescence. However, the water does not drain off the back walls of the alveolars, tafoni or semi caves, but merely seeps into these areas because of the radial expansion of the water. The seeping water and the dryness subsequent cause an increasingly high concentration of salt in those zones. After the rainfalls, the rocks and façades dry up again within only a few hours. The high concentration of salts on the surface results in blast off effects of the sand grain layers close to the surface – a physical process that has not yet been completely examined. The resulting loss of material leads to alveolars and subsequently to tafoni development. Those areas that are washed up periodically and freed of the salt deposits are in comparably good condition. This is also where most of the plaster and stucco remains of the formerly rich sculptural decoration on the tomb façades are best preserved. This was also noticeable on the tomb façade No. 826. Thus, the draining water does not lead to an extensive removal of the plaster remains or even the rock. Mainly, the rock is quartz-bound. In addition, the tafoni areas on monument No. 826 run parallel to the traces of the rainwater drains.

Based on the observations of the draining rainwater, it may be concluded that it is possible to dissolve the salt concentration by controllably rinsing the over-saliferous areas. The aim was to reverse the process of high salt concentration and to maintain the status quo.

The process of dissolving was supposed to be carried out with the greatest care with regard to the fragile and often sandy rock surfaces. Therefore, the sprinkling method for desalinating the tafoni zones was suggested.

3.3 *The rock salt of Petra*

The rock salt of Petra primarily consists of halite (NaCl). Heinrichs & Fitzner (2000) identified the solid salt crust as halite. In areas behind the crusts, non-readily soluble calcium sulfate ($CaSO_4$), potassium, nitrates, and magnesium sulfate were also found. In fact, there is a salt mixture. Al-Naddaf (2002) also examined the destructive salt of Petra with similar findings. In addition to NaCl and $CaSO_4$ he found traces of $KHCO_3$, $CaCO_3$, KNO_3, and KCl. Drilling core examinations and drilling dust samples taken from the depth profile of monument No. 826 determined the contamination with salts. Whereas an invariably low amount of salt was found in the undamaged areas, the concentration of salts was high in the deteriorated tafoni areas up to 10.5 centimeters in depth (Fig. 3).

The analyses of drilling dust samples determined a salt concentration of up to10 mass percent (M%) in the first centimeter of the depth profile of heavily marked tafoni zones.

The main salts causing structural damage were halite (NaCl), some calcium sulfate ($CaSO_4$) and traces of phosphate (PO_4).

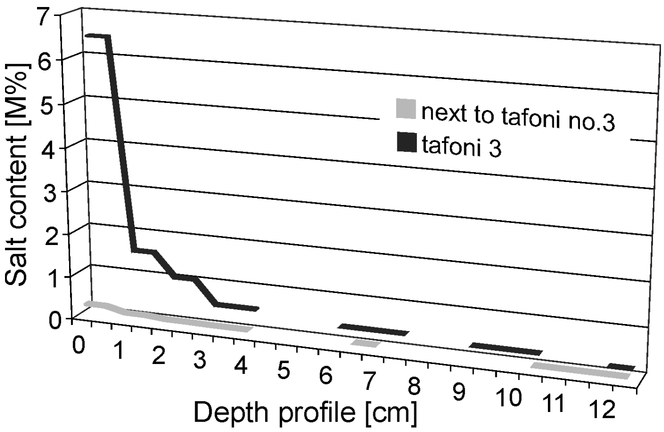

Figure 3: Salt content in drilling cores centered and next to tafoni No. 3 (for explanation see text).

4 DAMAGE MAPPING, PRELIMINARY EXAMINATIONS AND FINDINGS

4.1 *Description of tomb No. 826*

Tomb No. 826 is located on the so-called road of façades in the outer Sik. It is one of the last tomb façades preceding the monumental tombs in the Wadi Musa, the so-called King's Wall. On the left there is Tomb No. 825, which is also known as the tomb of the 14 Graves. It is a Hegr type and was built during or after the construction of the water pipes in the second century. The shape of tomb No. 826 is cubic and has a double tin frieze. It is dated into the second developmental stage (IB) of the Assyrian tomb types and was built during the first half of the first century. The outer shape of the tomb looks like a vertical rectangle. It is about 20.70 m tall. The maximum width of the pedestal part is 12 meters, whereas the top part is about 9.70 meters wide. Today, the monument's actual ground level is invisible because of a one-meter high coat of rubble and debris. The tomb protrudes from the nearby rock about 1.0-1.5 m.

4.2 *Damage mapping*

Only 76.0 % of the original form of the monument No. 826 is still conserved. Two-dimensional backweathering and the loss of tool traces as well as tafoni and alveolar weathering were distinguished. The latter had already destroyed 7.9 % of the façade surface. 15.2 % is lost by backweathering. 22.0 % were lost due to blasts during earthquakes. The mapping has shown that the two-dimensional deterioration corresponds to the tafoni weathering found. About 80 % of the weathering phenomena can be traced back to salt weathering.

All the investigated tafoni of monument No. 826 were given numbers. The biggest damage zones of the upper half of the left part of the façade present vertically marked damage features. They run along two parallel lines. Additional smaller areas spread over the entire façade surface.

4.3 *Surface temperature and relative humidity*

Comprehensive climatic monitoring of the façade of tomb No. 826 facing west done during the cold period in 2001/2002 has proved that the point of deliquescence for NaCl of 75 % had been exceeded on 35 days (Simon et al. 2004).

On a late summer day in September 2001 at an average temperature of 28 °C, the surface temperature of several monuments on the so-called road of façades was analyzed in connection with the relative humidity. In the afternoon during sunshine, the temperature of façade No. 828 near tomb No. 826 was up to 47 °C and dropped to 22 °C at night. The humidity varied between about 15 % during the day and 30 % at night.

At places that are in the shade most of the time and only about 100 m away from tomb No. 826, a measured 74 % during the early morning hours is close to the point of deliquescence. The surface temperature remained between 21 °C and 25 °C. The examinations illustrate that the relative humidity and the surface temperature vary strongly depending on the alignment and location of the façades. The same is true for the hydrological condition of the weathering zones. All the affected areas of monument No. 826 were dry, whereas the tafoni lines on tomb No. 74 on the road of façades stay damp all year round.

On the one hand, these observations indicate that there is hygroscopic moisture because of salt contamination. On the other hand, destruction results from hygric dilatation due to the cyclic change in phases of the saline, which was also discovered on numerous monuments in Egypt (Abd El-Hady 2000, Pinińska & Attia 2003). Regarding monument No. 826, however, crystallization processes have to be assumed as a reason for destruction.

5 LABORATORY EXAMINATIONS OF SANDSTONE SAMPLES

In order to gather more information on the characteristics of the sandstone weathering in Petra samples were taken from four different sandstone varieties of Petra and salt resistance tests were carried out. For the salt tests, three sandstone types were used: a homogenous brownish-red sample (Type I), a cloudy reddish sample (Type II) and a closely layeredreddish purple sample (Type III).

An important research question was how to judge the interplay of relative humidity, water, salt, and temperature with respect to weathering. The crystallization process based on sodium sulfate (Na_2SO_4) was used as a guideline for the test. However, equal to the predominant stone salt of Petra, 99 % pure sodium chloride (NaCl) was applied. The objects of the crystallization tests were five sample cubes (1-5) 4x4 cm in size. Two test variants were carried out.

A trial series was conducted according to the testing procedures VDI 3797 and DIN 52111. The samples were soaked in a 10 % NaCl solution at 20 °C. Then, the samples were dried for 16 hours in a preheated 60 °C drying closet with circulating air. After the stones cooled off, the samples were weighed.

In a different trial series, the same amount of the same stone variety samples was tested under differing testing conditions. After soaking them the sandstone samples were dried for 24 hours at room temperature (20-25 °C). Whether or not and how the temperature affects the weathering process was to be determined by comparing the results.

Concluding from the tests, the susceptibility of the particular stones to the salt resistance varies according to the conditions mentioned. Apart from the lined fraction the trial series that had dried under regular temperature circumstances did not show any loss of substance. In addition, the formation of a salt crust was limited. The absorption of the salt took place in a comparably even manner and leveled out in correspondence to the pore volume.

The influence of heat is a considerable determinant in connection with destruction by salt explosion. The samples dried in the drying closet developed a distinct salt crust formation. However, they varied in shape. Evidently, the formation of a salt crust depends on the drying process. The pore volume of certain stratum layers also seems to have an impact on the formation of salt crusts.

None of the damaged stone samples showed a loss of substance in those zones, in which the salt crust formation occurred, but rather in those areas that had been covered with the solvent during the drying process. Consequently, the loss of substance took place at the soaking stage rather than the drying stage.

The different weathering resistance of the investigated rocks is possibly attributed to their varying pore space distribution. Therefore we performed a quantitative determination of pore size distribution using mercury porosimetry (cf. Brakel et al. 1981). The results are exemplarily shown for three of the investigated samples in Figure 4. The specimens are characterised by a wide spaced pore radii distribution. For the samples Type I and II, a bimodal distribution can be observed, but the details of the spectrum are different. Whereas Type I has its maximum between 10.00 µm and 25.12 µm, the majority of pores of Type II specimen is between 2.51 µm and 6.31 µm. In contrast, Type III shows a broad spaced distribution of pore sizes. The maximum is between 0.10 µm and 2.51 µm. For all investigated samples, a relativly high content of smaller capillary and micro pores is observable. Thus, the samples should be particularly vulnerable against salt attack (cf. Fitzner & Snethlage 1982). The bimodal distribution of Type I and II is caused by two different preferred detritical quartz and feldspar grain sizes and a high amount of quartz cements. This is possibly the reason for the good resistance within the salt test. In contrast, the high amount of smaller pores in Type III results from a high amount of clay minerals. Within the salt resistance test, the latter sample is the most damageable material. Thus, it can be assumed that the high amount of clay minerals in combination with the existence of small capillary and micro pores is responsible for its sensibility against salt weathering.

6 SALT REDUCTION ON MONUMENTS

During the restoration of tomb façade No. 825 from 1997 to 2001 the salt crusts were mechanically

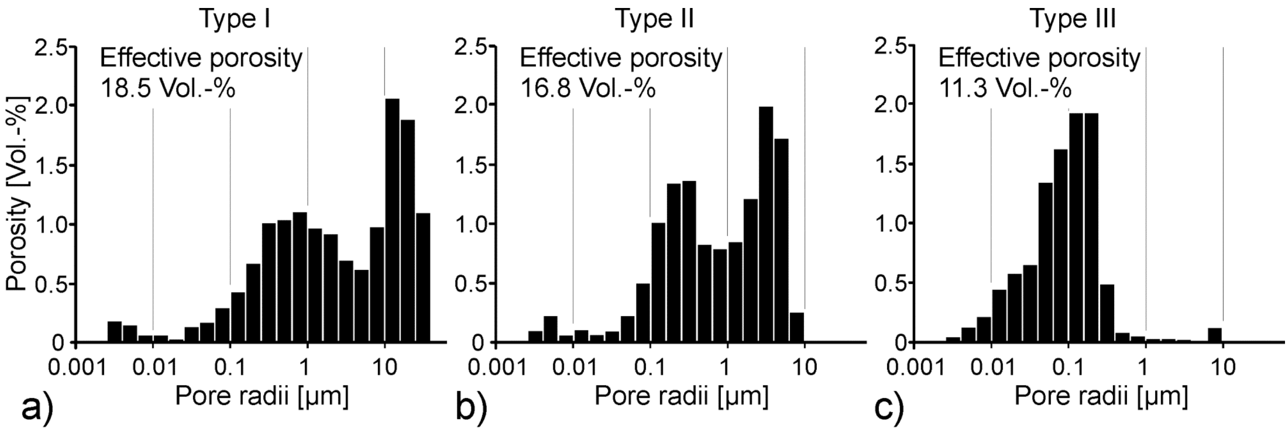

Figure 4: Pore radii distribution and porosity data of the investigated sandstone samples used for the salt deterioration test.

removed and the salt was reduced using compresses. Compresses made from long-fibrous cellulose and washed sand proved to be suitable. The common compress method for desalination was not adequate.

After up to 20 compress applications, heavy salt damage repeatedly occurred on the spare mortar, which could not harden because of the high salt concentration and virtually disintegrated.

Like most of the monuments of Petra, tomb façade No. 826 also had a drainage pipe in the roof part. It was freed uncovered from plants, emptied out and cleaned in order to allow the water to drain.

Before the actual salt reduction was completed, the extreme crusts in the tafoni areas were diluted by hand. In addition, two compress applications reduced the salt content of the surface. The reason for the first two compress applications was to prevent the salt from settling into the deeper structure during the rinsing process.

These first salt reducing steps were taken to remove the greatest part of the near-surface salt. By taking samples from the crust zones and the first two compresses, it was possible to draw some conclusions regarding the intensity of the salt contamination.

The first two compress applications proved that in tafoni 1 and 4, there was only little salt contamination. The largest load with a very high salt contamination was found in tafoni 6, followed by tafoni 9, 13, 7, 12, 2, 8, 3, 5, 14 and 11.

6.1 *The sprinkling method*

Low pressure pushes the water through a hose system (Fig. 5). Then, it runs through several nozzles and is sprayed onto the affected façade parts. This method is somewhat similar to the trickling method used for cleaning limestone. Then, a wall of clay was set up in the lower part. A hole was worked into the deepest spot of the clay wall, through which the washing water drained off. The nozzles were arranged in a way the spray could reach the deep parts because, evidently, these parts have the highest salt concentration.

The water is sprayed onto the stone surface through the nozzles at each end of the hoses. Immediately, it was absorbed into the porous stone surface. Depending on the sprinkling duration, little or a lot of water seeps into the stone and the depth reaction can be adjusted accordingly. The water not absorbed by the stone runs off the façade and can be collected at the bottom. Then, the electric conductivity of each liter was measured with respect to the dissolved substances. The mechanical spray pressure that is applied to the stone during the sprinkling process is very low. In addition, this method accomodated the prevailing climate because the drying process was rapid. Because of the heat in Petra, the water diffuses on the surface within just one day. It was assumed that for each subsequent washing a lower content of salt is brought to the surface. Step by step, the salt concentration would eventually decrease to almost zero.

Figure 5: On site implementation of the sprinkling method.

In practice, this assumption proved to be accurate. The sprinkling method showed the expected results. The highest concentration of solvent substances was found in the first liters of the washing water, while gradually decreasing (Fig. 6). The concentration leveled out at a certain amount. In most cases that level was still above the level of the solvent substances of the washing water. Even when the sprinkling was repeated after short interruptions, the concentration of solvent substances increased. However, this increase in concentration did not reach the starting level of the respective washing day. Evidently, the salt solution had already been accumulated on the surface during these short breaks. At the end of the working day, a compress was put on the treated tafoni.

After repeated sprinkling, drying off and removal of the compress, the first liters again contained a much higher concentration of solvent substances. Still, this concentration was below the starting level of each sprinkling cycle. Depending on the salt concentration in the stone and the size of the rinsed area, the concentration decreased more quickly and fewer or more washing steps were necessary. The sprinkling was stopped after the concentration had repeatedly leveled out around the value of the washing water. Then a test was conducted in which repair mortar was applied. If the mortar was able to set and harden, the desalination was considered successfully completed. The ions of the salt disturbed the ion system of the silica sol mortar and, thereby, the setting process. Due to this, the mortar often could not cling to the highly salt-contaminated ground nor harden when applied according to the older compress method.

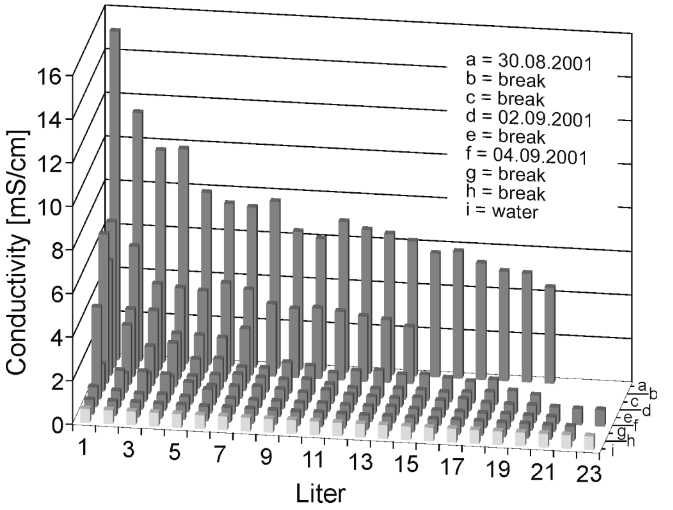

Figure 6: Results of the sprinkling method of tafoni No. 7 per liter rinsing solution dependent on the cyclic treatment.

6.1.1 *The sampling of the compresses*

Samples were taken from selected areas of the compresses and lab-tested. A watery solvent was used tu extract the salt of the samples. Then, its electric conductivity was gauged. In addition, a wet chemical analysis was done of the concentration of other ions, of which only traces were detectible. This was done on the basis of a simple indicator test analysis.

The wet chemical analyses of the half-quantity determination of various ions resulted in some findings that were true for all the samples. Neither nitrite, sulfite or solved iron was detected in the samples. The pH-factor of all the samples was neutral, at pH 7. In almost all the compress samples, there were very high rates of chloride. Most of the time, the values were >3000 mg/l.

6.2 *The calculation of the extracted amount of salt*

In the washing water from the sprinkling method there was a total amount of 1137 g of pure salt extracted from the tafoni areas measured by TDS (g/l) function of the conductivity meter (calibrated on NaCl).

Based on the extracted amount of salt, it was examined how the salt concentration of the deteriorated areas of the inner tafoni structure had spread over the monument. (Fig. 7) The result was that the salt concentration in the tafoni zones increased in line with the flow of the water from top to bottom. Further, the right tafoni area (No. 8 and 9) was more salt-contaminated than the left one. The highest contamination rate was found in tafoni No. 8, 13 and 9 following by No. 2, 3, 6, 7 and 10 between 0.04 and 0.09 g/cm^2. Tafoni No. 12 and 5 only have had a contamination rate of 0.016 and 0.014 g/cm^2, 14 and 11 only 0.004 and 0.005 g/cm^2.

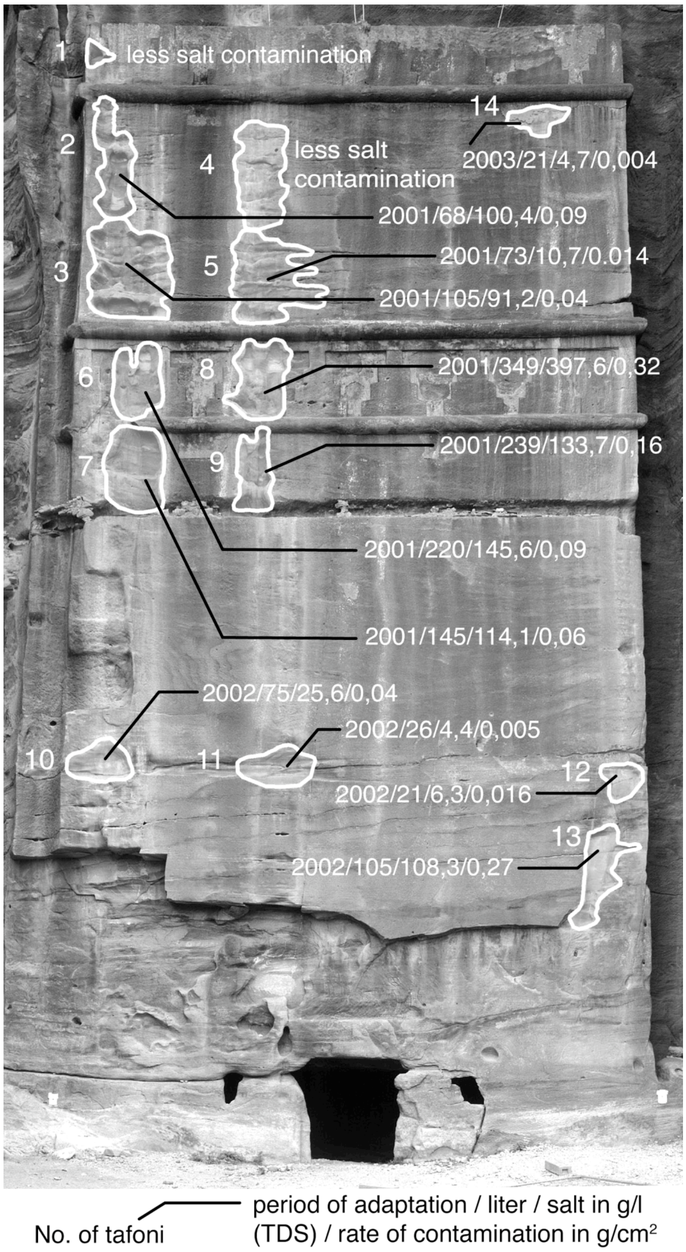

Figure 7: Desalted areas of monument No. 826 using the sprinkling method (photo T. Urban).

Depth profile measurements in tafoni zones proved a salt reduction from 60 up to 90 % compared to the value measured prior to the sprinkling. In one back-up measurement there was still 1 % left, which means that the damaging potential has not been totally averted. However it is to be expected that the process will slow down. In all, these are the preconditions for the durability of the silica sol mortar.

7 CLOSING REMARKS AND PROSPECTS

The presented sprinkling method for desalinating natural stone proved to be a tool that can reduce the salt of the affected problem areas significantly and easily, while permanently the quantity being checked. This procedure reduces the working load, material and time. At the same time, it backs up the quality of the sample findings in terms of the quantitative control as well as the overall aim: the desalination itself.

In addition, the quantitative analysis provides insights into the weathering processes of the individual building. Repeated application to further monuments could contribute a geo-morphological perspective in the process of understanding the damage development in Petra.

Taking into account the particular circumstances of Petra, the sprinkling method for desalination has proved to be the appropriate one. Four years after the mentioned measures, the applied silica sol mortar is still solid now.

In conclusion, it can be stated that particularly the combination of salt, water, and heat cause damage to the sandstones. Even though the laboratory tests may not be generally applicable to the situation in Petra, they do point out the necessity to protect the monuments from openly draining water and settling dampness.

8 STRATEGIES FOR THE SUSTAINING PROTECTION OF THE FAÇADES

Further investigations in the field dealt with the ancient drainage systems, repairs, and their reactivation (Wedekind 2005a). In ancient times, more than 50 % of the tomb façades had been supplied with drainage systems. Resulting from these observations and examinations a "Conservation Action Plan" based on the reactivation of the ancient drainage systems was developed that should contribute to the lasting protection of the tomb façades of Petra.

9 ACKNOWLEDGEMENTS

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