Evaluation of desalination and restoration methods applied in Petra (Jordan)

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Abstract

One of the major causes for the deterioration of historical monuments made up of sandstones can be attributed to the circulation and evaporation of salt laden fluids percolating through the rock material, an aspect that has been either overlooked or neglected in previous restoration attempts, often with damaging consequences. Particularly the lack of consideration for the importance of a quantitative analysis of the salt content of the rock, has led to adverse effects in subsequent restoration attempts.

In the course of restoration of antique tombs no. 825 and 826 in the world heritage site of Petra the role of salt in the weathering process was fully taken into account and the restoration process executed accordingly.

With regard to the desalination two different methods were applied: the poultice method and the sprinkling method. The degree of desalination was in both cases intermittently measured until the concentration of the rock was evaluated to be low enough to initiate the restoration process with application of the selected restoration mortar. Its condition was then probed by long term successive inspections.

This study discusses the results and limits of both procedures and the techniques and methods applied in the course of the restoration of the two monuments.

Keywords: Petra, sandstone, salt weathering, desalination procedures, restoration mortar, restoration procedures, control of success

1. Introduction

The ancient city of Petra is situated south of the Dead Sea in the Kingdom of Jordan. It has gained international recognition when it was declared a UNESCO World Heritage Site in 1985 for its unique, approximately 650 relatively well preserved facades carved out of the sandstone bedrock. This magnificent monumental rock architecture, however, is in danger of severe and accelerating disintegration due to various forms weathering and neglect.

In order to halt or slow down the observable decay of these monumental structures and preserve them for future generations, a project was devised and executed aiming at establishing a Jordanian institution capable of independently handling all aspects of the restoration effort on a continuous and permanent basis. The result was the establishment of an institute that is now known as the "Conservation and Restoration Center in Petra (CARCIP)". The project was managed by one of the authors of this paper, funded by the German government and executed within the framework of the "German International Cooperation Agency (GIZ)" and the "Department of Antiquities (DOA) of the Jordanian government in the years 1993 to 2002. From its start the project furthermore secured the support of the "Bavarian State Conservation Office (BLfD). It was for most of its duration also under the patronage of His Roy-

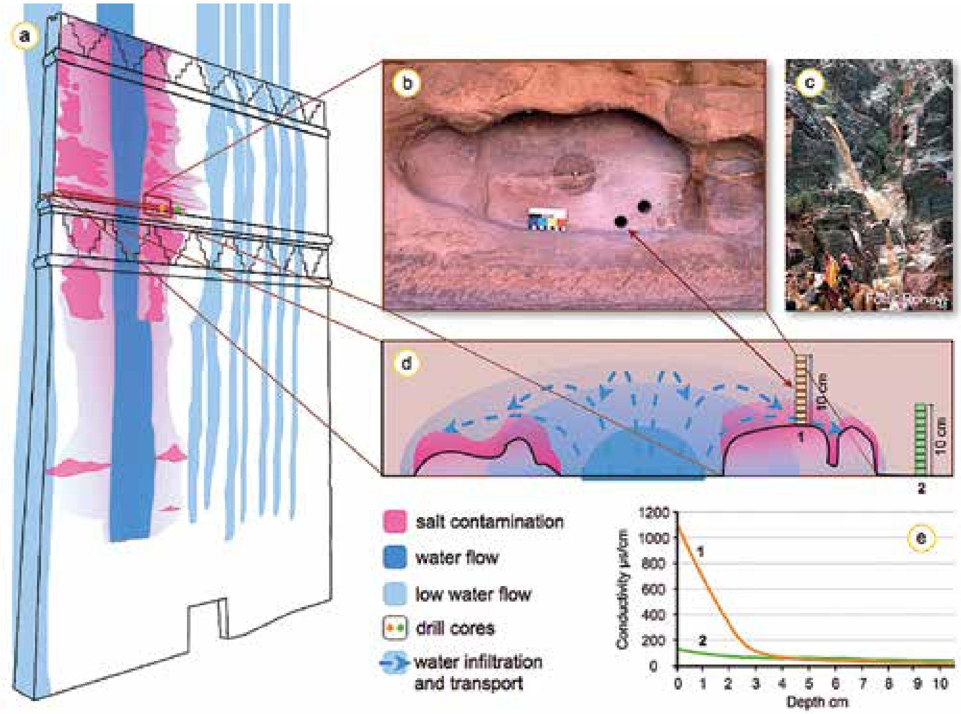

Figure 1: a) Distribution of alveolar weathering and traces where the rainwater drains at façade no. 826. b) Tafoni 3 with sampling point of the crust and drill core holes. c) Cascade-like water stains after a rainfall. d) Idealized cross section of the sampling area. e) Electrical conductivity at depth in the drill core samples.

al Highness Prince Hassan bin Talal, the then Crown Prince of the kingdom.

Scientific investigation and research continued intermittently from the year 2000 to 2016 by the University of Goettingen (GZG), the University of Applied Arts and Sciences of Hildesheim (HAWK), and the private institution Applied Conservation Science (ACS). This work focused primarily on the role of salt (NaCl) in the weathering process, its impact on the behaviour of restoration mortars, as well as the development of efficient and safe desalination procedures.

Particularly on the basis of these continuing activities, new methods in the conservation effort, as well as new restoration materials were devised and implemented by the authors and presented in this paper.

2. Environmental conditions

2.1. Climate

Petra is located in a semiarid climatic zone with a mean annual rainfall of 190 mm.[1] Heavy rainfalls may occur during the winter months, whereas the winters are cold and wet. Due to the vicinity to the Mediterranean Sea lying some hundred kilometres to the west and winds blowing primarily from that direction a high load of soluble elements are contained in the rainwater.[2]

2.2. Rock material

The tomb facades of Petra were chiselled out of the reddish sandstones of the Cambrian Umm Ishrin Formation. In detail colours vary from reddish-brown to yellowish-brown, gray or white. The brown colour is attributed to the deposition of limonite ($FeO.OH.nH_2O$) in the pores during formation of the sandstones, while the reddish colours stem from the precipitation of hematite (Fe_2O_3) flakes in the pores. The different lithological layers of the sandstone are medium- to fine-grained and show porosities ranging from 4.2 % to 20.6 %. Average values are 13 %.[3] In contrast, the limonite rich varieties show a low porosity of 7%.[4]

3. Weathering processes and agents

3.1. Weathering in arid and semi-arid environments

Areas in arid or semi-arid climatic zones like Petra show an increasing amount of salt deposition.[5] Therefore, weathering due to salts plays a crucial role.

Weathering phenomena observed in the Cambrian sandstones in Petra are mainly caused by salt crystallization on the retreating surface of the rock, due to evaporation of percolating saline water reaching the surface. This process constitutes the most important factor for the destruction of built and rock-cut architecture in Petra.[6, 7, 8, 9, 10, 11]

The resulting formation of tafoni comprise locally limited, as well as completely deteriorated areas, their size ranging from more centimetres to of several meters in diameter *(Figure 1b)*. This kind of extreme deterioration is generally surrounded by mostly undamaged rock.

3.2.Weathering processes

Comparative examinations of the sandstone monuments of Petra have shown that two varieties of tafoni development can be distinguished. Damaged spots evolve either as horizontal or vertical tafoni *(Figure 2)*.

Horizontal tafoni are usually found above the microporous limonite layers which in turn are frequently observed parallel to sedimentation layers. This is to be expected due to the blocking and accumulation of seeping aquifer water above the less permeable limonite layers.

Vertical tafoni develop left and right of areas affected by rainwater flowing down

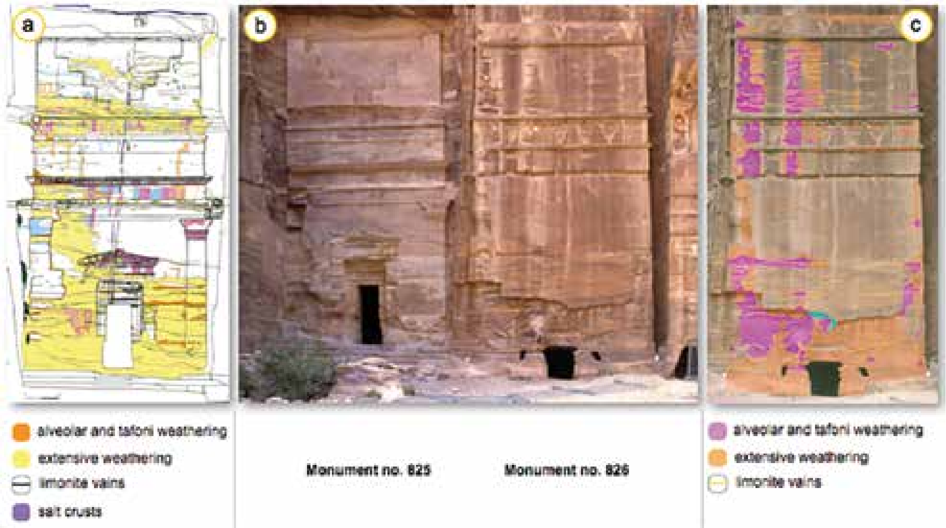

Figure 2: The treated monuments. a) Mapping by the CARCIP team. b) Monument no. 825 and 826 and c) mapping of monument no. 826.

the surface during heavy rainfalls. *(Figures 2c, 6b)*

4. Description of the tombs no. 825 and 826

The tombs no. 825 and 826 are located beside each other along the southern tip of the so-called "Kings Wall" *(Figure 2 b)*.

Tomb no. 825 is on the left and is also known as the tomb of the 14 graves *(Figure 2 b)*. It was evidently built after the construction of the water pipes in the second century within the rock. It is 19 meters high and 9 meters wide.

Tomb no. 826 has a double tin frieze *(Figure 2b)*. It is of the Assyrian type and 21 m tall. The maximum width of the pedestal part is 12 meters, whereas the top part is 10 meters wide. The monument's actual ground level is invisible because of submersion in rubble.

4.1. The monuments in relation to encountered weathering processes

Tomb no. 825 is affected by seeping aquifer water moving through the massive rock, whereas tomb no. 826 is affected by run off water. Therefore, at tomb 825 horizontal oriented alveoles are created, whereas at monument no. 826 mainly vertical ones are observed *(Figure 2)*.

5. Evaluation of restoration methods and materials

5.1. The "Silica sol repair mortar"

The mortar chosen for restoration on monument 825 was a silica-sol mortar, based on good experiences made by the BLfD on several sites under restoration in Bavaria, where it was applied on sandstones. After promising results of its application in a Nabatean quarry the project decided to start its use on monument no. 825.

There, however, surprisingly it soon turned out to respond in a rather unexpected and unfavourable way. The material started to crumble, sometimes already a short time after application. Careful evaluation of the problem led to the conclusion that the rapid disintegration of the mortar was due to salt contamination of the rock onto which the mortar was applied.

This can also easily be explained by the fact, that Silica-sols are colloidal solutions of SiO_2 in water that are negatively charged.[12] The negative charges are balanced and stabilized with a defined amount of positively charged ions, namely Na^+. After application of the mortar, the Na-ions migrate from the rock into the mortar leading to a destabilization of the silica-sol binder. (Fig*ure 9b)*. Sometimes even salt efflorescence appeared on the surface of the freshly applied mortar. In consequence, collapsing of the mortar took place *(Figure 9 a)*. It thus turned out that salt reduction was of prime importance in any further attempt to apply the chosen mortar.

5.2. Salt extraction by application of poultices

The negative results experienced with the repair mortar on monument 825 stressed the necessity to devise a method to effectively desalinate the sandstone before its renewed application poultices. One method to reduce the salt load was to chisel off strongly salted areas.[13] The method chosen, however, was salt extraction by application of poultices. In first trials, clay based poultices were used. These turned out to be unsuitable as they clinged to the suface and upon removal would even sometimes destroy delicate Nabatean chisel marks. They were finally replaced by poultices developed by the

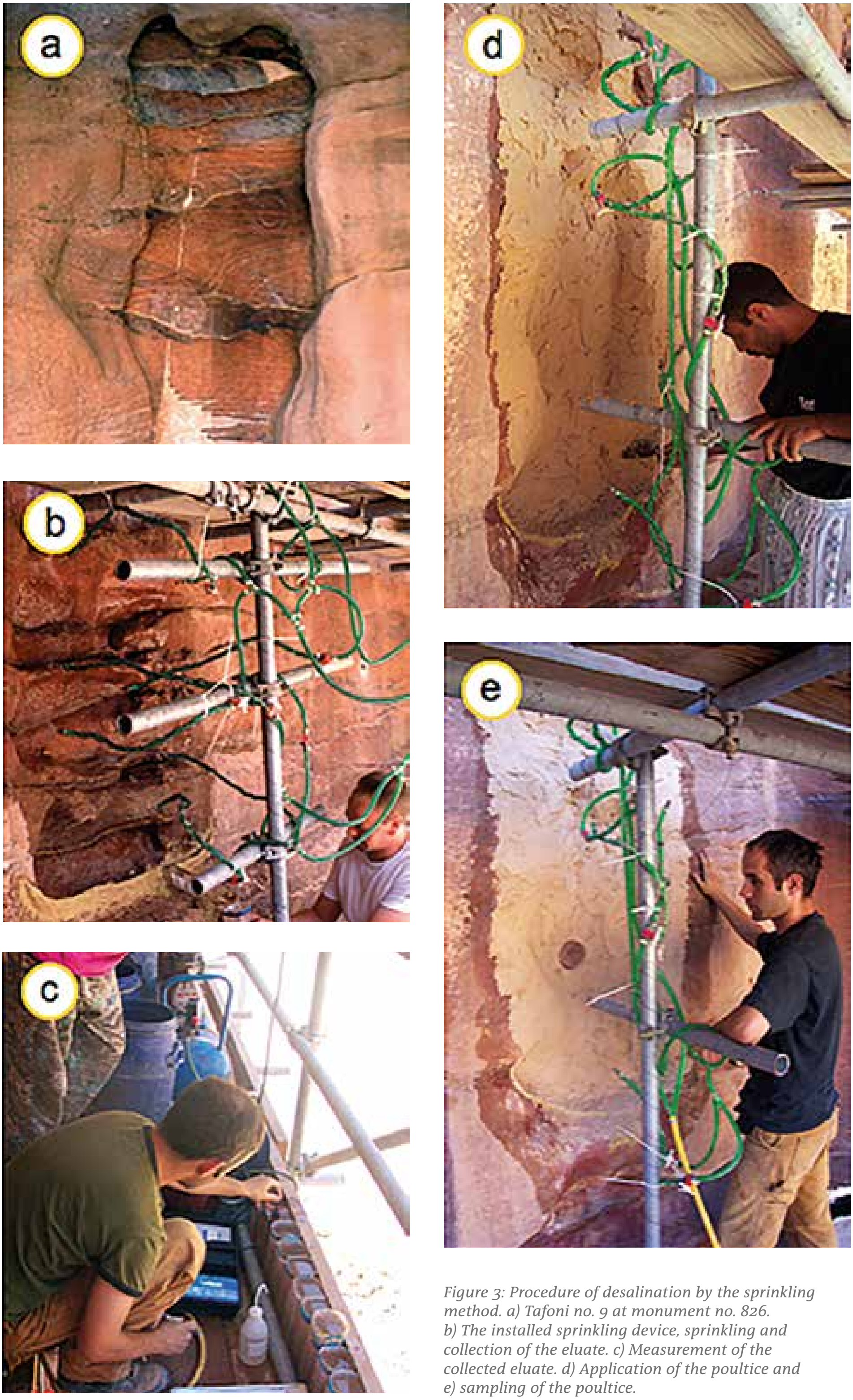

Figure 3: Procedure of desalination by the sprinkling method. a) Tafoni no. 9 at monument no. 826. b) The installed sprinkling device, sprinkling and collection of the eluate. c) Measurement of the collected eluate. d) Application of the poultice and e) sampling of the poultice.

conservator Egon Kaiser and one of the authors. These consisted of a wet mixture of cellulose and washed sand in a proportion of 1:5, and in general, showed a good workability as well as promising results in the beginning. The moist poultices were applied in square patches on the salt contaminated areas and were removed after drying *(see Figure 4d)*.

However, even after the application of several cycles of poultice application salt reduction turned out to still be insufficient, as the silica sol repair mortar would not bind as expected in some alveolar areas *(Figure 9b)*.

Obviously the efficiency of the desalination process needed to be further improved. In order to find a proper solution, a systematic quantitative analysis of the progress of desalination after each individual cycle of poultice application was undertaken in defined sample areas. Thus samples from the poultices were taken after each cycle, dissolved in distilled water and their relative salt content measured by electrical conductivity *(Figure 6a)*. But even after up to 17 cycles of poultice application an adequate improvement of the behaviour of the silica sol mortar could not be observed. The results thus indicated that the chosen method of salt extraction was unfeasible, not only with respect of its efficiency but also for the sheer enormity of the restoration effort, considering the size of the monuments. The poultice application method thus might work well on smaller, isolated objects, that are cut off from the water cycle encountered in objects that exposed to geological processes.

Nevertheless, the restoration of monument 825 was finalized and considered a success, keeping in mind that on large restored areas of its surface the salt load was rather small, no damage was done to the monument and that all in all the final result was satisfactory, though at a very high price that stood in no relation to the success. At least it can be said that it was a valuable learning experience. It should also be stressed in this connection that the main focus of the project was to train local Jordanian staff in its ability to manage and master a wide range of techniques employed in the conservation and restoration effort, in accordance with the highest international standards, including aspects such as planning, documentation, assessment procedures, site preparation, the use of heavy and specialized equipment, as well as the mastering of very specialized skills like surveying, core drilling or the use of analytical tools.

Towards the end of the project, however, the authors concluded that a new method for the efficient desalination of the monuments in Petra had to be developed and that the approach chosen so far and still supported by the project advisor [14]. Though possible alternative methods had already been suggested by the authors, these had been outright rejected by the project advisors.

5.3. The sprinkling method

After finalizing restoration monument 825, work was shifted to the adjacent monument no. 826, which showed rather different types of degradation and thus presented new challenges. Like before the different weathering forms were mapped, quantified and documented with other relevant observations. Additionally electrical conductivity measurements were carried out on selected surface areas using a portable measuring device (type: protimeter). Thereupon a number of samples were taken from defined areas in selected alveolae. First samples of crust material, then samples of poultices applied to the very same areas *(Figure 4e)*. Finally two drill cores were taken from these areas and also investigated *(Figures 2a, d, e)*. Different ions within the stone material of the drill cores were identified in different sections by ion-chromatography.

The totally new approach in the restoration effort here, however, rests in the introduction desalination method devised and implemented by the authors. This approach was inspired by previous observations on the development of vertical tafoni only adjacent to the areas that were marked by run off water, a process that had also been observed on some rare occasions of heavy rainfall. This clearly indicated that rainwater washes out salt accumulations on and under the rock surface. This observation then led to the development of a method, that mimicked the natural process of desalination. Thus a device was put into operation that would sprinkle water under controlled conditions onto the surface of the salt affected surfaces. This procedure was then labelled the sprinkling method.

By this method water is sprayed onto the stone wall surface through fine nozzles *(Figure 3b)*. At the start of this procedure water is predominantly absorbed by the porous stone surface through capillary forces. Water absorption is dependent upon the transport properties of the rock and these are essentially controlled by the pore space properties, like porosity and pore radii distribution and are a time-dependent process.[15]

The excess water not absorbed by the stone runs off the treatment area and is collected at the bottom in 1l containers *(Figure 3c)*. Electrical conductivity of the eluate of each sample container is then measured thus giving an indication of the amount and concentration of the dissolved substances *(Figure 3c)*. After the sprinkling a poultice of the same composition as used in previous applications was applied onto the treated area *(Figure 3d)* in order to detect if additional salt would be extracted that way. A sample taken therefrom *(Figure 3e)* was dissolved and tested by electrical conductivity, indicating no significant further salt extraction.

The spray pressure applied to the stone during the sprinkling process is very low. In addition, this is a particularly suitable method in situations where the prevailing climate is very warm due to the rapid evaporation rates there. Thus in Petra the water soaked up by the sandstones normally evaporates within a few days. After each subsequent washing cycle the amount of salt extracted from the surface was, as expected, observed to continuously decrease. Eventually salt concentrations decrease to a value, where mortars can be safely applied.

Measurements on the drill cores taken before and after desalination give a quantitative indication of the amount of salt dissolved from the rock.

It should be mentioned in this connection, however, that in spite of the fact, that salt contamination is efficiently reduced in areas treated by this method, side effects could be observed in some instances in the immediate vicinity to the not treated adjacent areas. Obviously some of the salty solutions would migrate towards the fringe of the treated are, a side effect that was actually observed. Though the effects are minor, we are aware that they are of concern. It must be stated here, however, that such effects cannot be precluded in situations, where the treated rock is part of a huge geological entity.

It may be added here, that similar side effects were also encountered at the fringes of poultices that were used in the early stages of the project for salt extraction.

6. Results

It was realized already at an early stage of application of the sprinkling method, that it was far more efficient, economical and less time consuming than the me-

Tafoni	Salt content of the crust (g)	Salt content in the first two poultices (g)	Salt content in the eluate by sprinkling (g)	Number of collected litres
1	0.33	0.43	-	-
2	0.04	19.5	100.4	68
3	0.25	13.3	91.3	105
4	0.36	0.4	-	-
5	0.47	17	10.7	73
6	2.81	25	145.6	220
7	0.89	20.5	114.1	145
8	0.37	18.3	396.7	349
9	0.17	20.7	133.7	145

Table 1: Evaluation of the near-surface salt contamination and desalination at monument no. 826

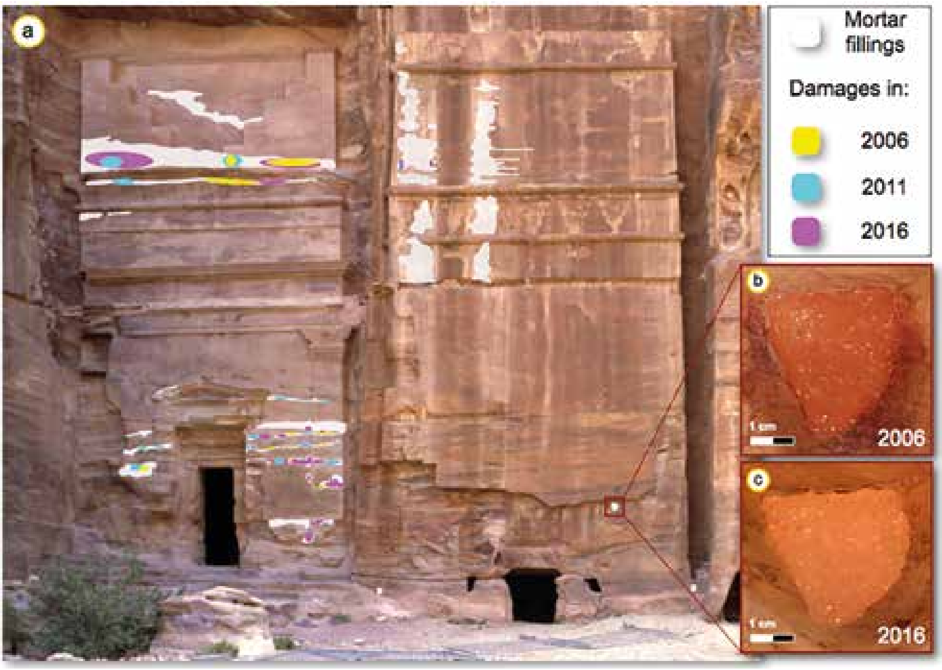

Figure 4: a) Ongoing damage progress of restored areas treated with silica-sol mortars during a period of 15 years on monument 825. b) Sample of a dry-slaked lime mortar just after application in 2006 and c) after 10 years.

thods previously employed.

In order to demonstrate the effectiveness of desalination by use of the sprinkling method, data collected from monument 826 are shown as an example in *Table 1*.

The table indicates that the highest degree of desalination by the sprinkling method was encountered in tafoni 8, the lowest one in tafoni 5. In total around 1000 g of solvent material was extracted from all tafoni areas by sprinkling. Tafoni 1 and 4 only show a very low salt content within the first two poultices, and therefore were not treated by sprinkling. However, from tafoni 2, 3, 6, 7 and 9 an amount of solvent material of around 100 g to 150 g were extracted.

While five years after restoration only a few damages in the restored areas could be observed on both monuments, around 10 years later almost all mortar applications were affected by crumbling on monument 825 *(Figure 4a)*.

As can be seen on monument no. 826, only very slight signs of degradation could be observed 10 years after the conservation treatment. *(Figure 4a)*.

Interestingly, a lime mortar newly devised by one of the authors also exhibits no signs of alteration after 10 years *(Figures 4b and c)*, indicating that there is also room for the development of alternative the repair mortars. Results of this potentially also far more economic effort will be presented in a separate paper.

7. Summary and conclusions

The sprinkling method for desalinating natural stone in Petra proved to be a tool that can effectively and easily reduce the salt load of areas affected by salt contamination, while the quantity of salt extracted can be continuously monitored at the same time. Quantitative analysis of the degree of desalination also provides better insights into the weathering processes of the individual buildings.

Taking into account the particular conditions encountered in Petra, where e.g. the extended presence of a scaffold structure in front of a monument can be an issue, the use of the more efficient and faster sprinkling method for desalination constitutes an additional advantage. Fifteen years after the application of silica-sol-mortar in areas treated this way, the mortars can still be seen to exhibit almost no sign of degradation, in contrast to the observations made on monument 825 treated with the previous method as shown in *Figure 4*.

A faster degradation of the repair mortar is clearly visible on monument no. 825, as compared to monument 826.

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