3D Digital Documentation, Assessment, and Damage Quantification of the Al-Deir Monument in the Ancient City of Petra, Jordan

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The rock-cut monuments in the ancient city of Petra in Jordan form an outstanding tangible heritage site. Unfortunately, this important part of the world’s cultural heritage is gradually being diminished due to weathering and erosion problems. In this research, an approach combining in situ surveying and laboratory analysis is applied in order to provide sufficient and comprehensive data regarding the documentation and evaluation of the status of the Al-Deir monument in Petra. The purpose was not only to quantify the damage, but also to make a first step towards creating a 3D monitoring programme of the deterioration rate. The approach presents a correlation study between the environmental condition and the surface weathering damage, using 2D mapping of the weathering form and accurate 3D realistic modelling from laser scanning and digital photogrammetry. The 2D mapping provides detailed weathering damage information for the entire stone surface of the monument, whereas the 3D modelling provides information on the spatial distribution and texture of the damage. Additionally, the 3D digital model can provide reference data as an exact guide to the restoration needed. In order to support the visual presentation of 3D surface details, a hybrid approach combining data from laser scanning and digital imagery was developed.

Studies of stone texture and spatial distribution of soluble salts were carried out at the monument in order to explain the mechanism of the weathering problem. Relative humidity, temperature, and wind are the main factors in the salt damage process. In order to study the effect of these conditions in the salt crystallization process a series of fieldwork
investigations and laboratory work were undertaken. The results show that visible zoning of weathering damage is correlated to different salt concentrations.

**KEYWORDS** damage assessment, 2D weathering form, 3D modelling, laser scanning, photogrammetry, salt content

**Introduction**

In 2007 the ancient city of Petra, the capital of the Nabataean empire from 400 BC to AD 106, was selected to represent one of the ‘New Seven Wonders of the World’. Petra’s temples, tombs, theatres, and other buildings, which are carved into rose-coloured sandstone cliffs are scattered over 400 square miles. In 1985 Petra was inscribed into the UNESCO list of world cultural heritage. However, the majority of its monuments have deteriorated at a fast pace over recent years (Bumbaru et al., 2000: 123). Due to this fact, in 1998 the World Monument Fund inscribed Petra into the list of the one hundred most endangered monument assemblies in the world. The city, located in south-western Jordan, suffers from weathering and erosion problems. Problems result from the mainly porous inorganic materials of the monuments and the uncontrolled environmental conditions around them. This weathering results in potential salt damage as the main force on the monument’s stone structure (Fitzner & Heinrichs, 2001: 12; Goudie & Viles, 1997; Eklund, 2008).

Reliable monitoring on weathering did not exist for most of the monuments in ancient Petra. This is due to the lack of referential archive documents on the state of weathering damage in the past (Heinrichs, 2008: 643; Kühlenthal & Fisher, 2000). Recently, a large number of digital investigation methods have been newly developed for reliable, easy, and fast surveying of large-scale monuments, including those that are difficult to access. The integration of these techniques with the laboratory analysis allows for a quantitative registration, documentation, and evaluation of complete monuments.

This study aims to present a combined documentation and evaluation approach that can be applied, in order to provide reliable information on the measurement and characteristics of the stone decay problem at Al-Deir monument in Petra. The work included a correlation study between the environmental conditions and surface weathering using 2D mapping of the weathering forms and 3D realistic modelling of both the geometry and radiometric properties of the surface details. The data could be used in future studies of conservation action at the site.

The first part of this paper presents a literature review for the main environmental conditions that affect the architecture of Petra. The second part discusses the different mapping methods used in the *in situ* surveying, including 2D mapping of the weathering forms and digital photogrammetric techniques. Section 3 presents the weathering mapping forms for Al-Deir. The methodology for the generation of accurate and realistic 3D models of the Al-Deir monument, combining photogrammetry and laser scanning, is presented in section 4. The environmental monitoring data and chemical analysis of the salt content of the samples collected from the monument are presented in section 5. In section 6 the results are discussed and concluded.
Literature review

Petra: weathering agents

Natural processes and human activities, as well as a lack of maintenance in the ancient city of Petra, are all involved in the weathering processes. Petra is located in a tectonically active region; Barjous and Jaser (1992) traced three major faults in the area. Due to the high seismic slip between these faults, the area has suffered from a series of serious destructive earthquakes since ancient times. Most of the Theatre was destroyed in AD 363, and another earthquake in AD 747 destroyed most of the monuments in the centre of the city. Generally, statistics showed that an earthquake with a magnitude above 6 on the Richter scale occurs every hundred years in the Petra area (UNESCO, 1992).

The annual rainfall in Petra is very low, but it falls in a very short period of time. Water erosion is, therefore, a very active agent in this environment. The Nabatean hydrological systems show that the Nabateans were very aware of water erosion as a problem in their area; they constructed ceramic pipes along the bedrock and the face of the monuments to protect them from flood water. Moreover, horizontal surfaces were covered with multiple mortar layers to minimize the effect of running water on these features (Shaer & Aslan, 2000: 89). Unfortunately, nowadays, the Nabatean water system is the main cause of water erosion at the site. Joints and cracks that were created by earthquakes, as well as the clogging of the Nabatean water channels, allow the Petra monuments to be eroded from within and without. In brief, the monuments of Petra had been affected by groundwater, running water, and rainwater through different mechanisms.

The American Centre of Oriental Research in Amman (ACOR, 1999) reported that the water table in Petra is actually much higher at the dawn of the twenty-first century than it was at the dawn of the last millennium. The rising of the water table in the area has had a major impact on many other deterioration mechanisms such as salt crystallization and the dissolution or leaching of materials (clay minerals, for example, since most of the Petra monuments were carved from sandstone with a high clay content). In short, water is a major factor in the deterioration process in the city of Petra through flood damage, rainwater, runoff water, and capillary action and their subsequent effects such as salt damage. Wind is another important weathering agent for the Petra monuments. Not only does it cause the destruction of monuments due to wind-blown sand (UNESCO, 1992), but it also enhances the effects of other weathering agents, such as salt crystallization. The effect of the wind-blown sand is mainly restricted to the lower parts of the monuments (1–2 m height), as these parts come into contact with sand particles (UNESCO, 1992).

Salt crystallization is another, if not the major, weathering agent for the Petra monuments (Eklund, 2008). Previous studies, such as Al Naddaf’s (2002), showed that drilled samples from the Petra monuments are rich in sodium chloride and calcium sulphate, while the scraped samples from the monuments’ surfaces were dominated by calcium sulphate.

Due to wide variations in temperature, both daily and seasonally, the monuments in Petra suffer from what is known as ‘thermal shock’. This kind of weathering is related to the fact that some minerals expand more than others at high temperatures.
and contract at low temperatures. A study of the temperature variations within a 24-hour cycle in Petra carried out by Fitzner & Heinrichs (1991: 908) showed a difference of 20ºC in the stone temperature and a difference of 21.1ºC in the air temperature. In another study of the effect of thermal shock, Paradise (1999: 353) concluded that, as a weathering agent, thermal shock was more destructive in calcite-cemented sandstones due to the fact that calcite expands $2.5 \times 10^{-6} \text{µm/°C m}^3 \text{calcite}$ parallel to the C-axis and contracts $4.9 \times 10^{-6} \text{µm/°C}$ normal to the same axis in temperatures between 18–50°C. The current paper does not discuss the thermal shock decay mechanism; however, it does present a detailed petrography of the case study monument, the Al-Deir tomb (below).

**Weathering form mapping and 3D modelling using photogrammetric techniques**

Precise classification and mapping of the damage phenomena are required for characterization, interpretation, and monitoring of the rate and types of weathering damage, which affects the stone monuments at Petra. Mapping of the weathering forms allows for a visual inspection of the surface damage, which is necessary for the recording of the type, intensity, and distribution of the weathering factors at the stone monuments (Fitzner et al., 2002: 315; Gillhuber et al., 2009; Siedel, 2008). Although the 2D mapping of weathering forms give us an idea about the distributions of the weathering processes, condition assessment of the structure using an accurate 3D modelling of the weathering damage is an important component of the remedial programme.

The 3D modelling of the monuments by complete surveying and assessment is realized by the integration of 3D laser scanning and photogrammetry. By these means spatial data, as well as detailed structural data, can be obtained. The availability of a 3D realistic model easily allows multiple views and a virtual manipulation. The purpose of such visual information may serve as a tool for the identification of the nature, extent and severity of the deterioration (Gaiani et al., 2001: 86; Fuentes et al., 2007: 543). Mapping is required for characterization, interpretation, and monitoring of the rate and types of weathering damage affecting the stone monuments at Petra. The mapping of weathering forms presents a visual inspection of the surface damage, which is necessary for recording the type, intensity, and distribution of the weathering factors at the stone monuments. As an archive gathered over time, the 3D models provide valuable information when restoration is required. In the case of damaged monuments, the 3D digital model can provide reference data as an exact guide to the restoration needed and with detailed high-resolution 2D images, the texturing of 3D models can provide both stone texture and spatial distribution of weathering features on the monument.

Different contact-free techniques have been used for generating realistic 3D models of an object or building. Photogrammetry has a long history as a tool for efficient and accurate data acquisition, including cultural heritage applications (Grün et al., 2002: 363; El-Hakim et al., 2002: 58; Debevec, 1996). Photogrammetric measurement allows 3D data collection from multiple images (Figure 1). If a point is depicted in at least two images at different viewpoints, its corresponding 3D object coordinates can be determined.
In order to determine 3D point coordinates from measurements in overlapping images, information on the position and orientation of the camera at the time of exposure are required. In addition to what is termed the exterior orientation, the parameters of the interior orientation have to be provided: this describes the position of the image plane with respect to the centre of projection of the camera. Both exterior and interior orientations can be reconstructed if the object coordinates are available for a number of the control points. For the orientation of multiple overlapping images, tie points, i.e. corresponding image points are additionally used. If the parameters of the exterior and interior orientations are available, the object and image coordinates can be linked by the co-linearity equation. This equation mathematically formulates the theory that a point in the object space, the projective centre of the optics, and the corresponding point in image space, forms one straight line. Applying this principle, the 3D coordinates of all points can be determined by a spatial intersection of straight lines, if they are observed in at least two images. One of the main advantages of photogrammetry is the potential to simultaneously record both the geometry and the surface texture of the depicted objects. This is especially important when attempting to generate 3D virtual models of historical monuments or artefacts from archaeological excavations (Schindler et al., 2003: 463). On the other hand, image-based modelling alone is difficult or even impractical for the parts of surfaces where homogenous texture prevents the reliable measurement of point correspondences. Additionally, the identification, and manual or semi-automatic measurement of points, can be very labour intensive, especially if dealing with a complex structure that requires a considerable number of points to be captured.

Due to the disadvantages of close-range photogrammetry, laser scanning has become a standard tool for 3D data collection for cultural heritage sites and historic buildings (Boehler et al., 2001: 480). For 3D data collection almost all commercially available terrestrial laser scanners apply the so-called time-of-flight measurement principle. Within this approach distances to the respective object surface are derived from run-time measurements of reflected light pulses. Point clouds covering the visible

![Figure 1: Principle of photogrammetry for 3D object modelling.](image-url)
object surface can then be collected by scanning the respective area of interest. This results in a very effective and dense measurement of surface geometry. This is especially useful for the 3D reconstruction of geometrically complex objects that are typically encountered in cultural heritage applications. However, the achievable accuracy of time for a flight scanner is relatively low and commonly results in centimetre range. Another type of scanner is triangulation-based and consists of a transmitting device, sending a laser beam at a defined, incrementally changed angle from one end of a mechanical base. A CCD camera at the other end of the base detects the returned laser spot. They have better accuracy in terms of measurements, which depend on the triangle base relative to its height. Due to this it can only be used for relatively small objects and short distances (Boehler et al., 2001), an example is the Arius scanner.

In addition to geometric data collection produced by a laser scanner, texture mapping is particularly important in the area of cultural heritage to help create more complete documentation. Photo-realistic texturing can, for example, add information about the structure’s condition, such as decay of the material, which is not present in the 3D model. The interpretation of 3D point clouds from laser scanning can be simplified considerably, if high-resolution imagery from digital cameras is available (Balis et al., 2004; Alshawabkeh et al., 2004: 424; Abdelhafiz, 2009). Some commercial 3D systems already provide model-registered colour texture by capturing the RGB values of each LIDAR point using a camera already integrated in the system. These images are frequently used for scan registration but are not sufficient for high quality texturing. High image quality is especially required to provide sufficient visual quality of 3D surface details such as decay forms and cracks as required for documentation. The collection of such images presumes suitable lighting, which frequently require camera stations that are different from the actual scanner position. Thus the use of independent cameras that are aligned with a suitable mathematical approach is an appropriate solution.

Mapping of weathering forms for the Al-Deir tomb (the monastery)

Al-Deir, meaning monastery in Arabic, received its name from the cave that is known as the Hermit’s Cell. The journey to the Al-Deir Tomb, depicted in Figure 2, requires climbing more than 2000 steps carved into the mountain. It is the largest and most impressive façade in Petra. The façade is about 50 m wide and 45 m high (Khouri, 1986). It is divided into two storeys; the lower one has a simple doorway (8 m high) with six columns topped by Nabatean capitals, the upper storey, which is better preserved, has eight columns with a conical central roof crowned with an urn. The main chamber in Al-Deir is huge (11.5 m by 10 m). A small part of it was used as a meeting room (symposium), whereas the main part was a mausoleum for the king. A huge area in front of the monument was levelled, and seems to have been used for great congregations of people. There is no actual dating for Al-Deir, however, many writers such as Bourbon (1999), Taylor (2001), and Khouri (1986) suggest the middle of the first century (AD 44–70). The monument’s location on the edge of a high mountain and the presence of different levels of stone decay are the main reasons for selecting this monument for sampling. The main weathering forms in Al-Deir tomb are shown in Table 1, while the main weathering groups, weathering forms,
and individual weathering forms at the Al-Deir Tomb, and their distribution across the surface of the monument, are shown in Figure 3.

### 3D modelling using photogrammetry and laser scanning techniques

**Sensors applied and 3D surface modelling**

A laser scanning system GS100, manufactured by Mensi S.A., France, was used to collect 3D point data. It has a $360 \times 60$ degree field of view. The maximum captured range for this scanner is $100$ m with a linear error of less than $6$ mm. The system is
able to capture 5000 points per second. During data collection a calibrated video snapshot of $768 \times 576$ pixel resolution is additionally captured, which is automatically mapped on to the corresponding point measurements. An example of the coloured collected point clouds is presented in Figure 4. In addition to the laser data, digital images were captured for photogrammetric processing using a calibrated Nikon D2x camera, which provides a resolution of $4288 \times 2848$ pixels with a focal length of 20 mm. These images were collected at almost the same time in order to have the same lighting conditions, which results in similar radiometric properties as needed for high quality colouring of the laser data. A single laser scan is usually not sufficient to cover a full structure. The number of scans necessary depends on the shape of the object, the amount of self-occlusion and obstacles hindering the object’s visibility from respective sensor stations, and the object size compared to the sensor range. During the data collection at the Al-Deir tomb, scans from five different viewpoints were done to resolve the occlusions. The mountainous environment surrounding Al-Deir restricted the choice of suitable viewpoint positions. In total, the five scans resulted in almost 3 million collected points.

All the 3D models have been processed using Innovmetric Software, PolyWorks, and Mensi Real Work Survey Software. In general, the whole process for generating the 3D model can be subdivided into three main steps: registration, meshing or triangulation, and merging. For objects with a complex shape, a series of scans must be undertaken. In this case each scan has its own local coordinate system. The reconstruction of the 3D model of the surveyed object requires the registration of the scans in a single local reference system. This phase can be performed in an interactive
FIGURE 4  Al-Deir façade recorded by terrestrial laser scanning: a) Overview b) Detailed view of collected point cloud.
environment through the identification of the homologous points in adjacent and overlapping scans. Once the corresponding points are collected (of which there must be at least three), the spatial transformation between the scans’ six-parameter transformation can be estimated and all the corresponding points can be transferred into the coordinate system that has been selected as the reference system. Figure 5 shows the registration of two different scans used to cover the complete geometry of the Monastery. The main aim of the triangulation (meshing) process is to convert the point-based data into a visually more intuitive representation. Once the points are collected in a single coordinate system, a triangulation algorithm is used to connect the points to the meshes which represent the respective patches of the object surface. Finally, in areas of overlapping scans redundant point measurements are eliminated to reduce the size of the model, for the purposes of visualization or for further post-processing. Figure 6 shows the 3D meshed model of the Al-Deir tomb.

A combined approach for realistic colouring of the laser data

Although the 3D model produced by the laser scanner contains a large number of 3D data, which represent the object’s surface, it can still be difficult to recognize and localize the outlines of the surface features. This is illustrated by comparison of Figures 2 and 6: surface features such as structural cracks and edge outlines which are clearly visible in Figure 2 are not discernible in the corresponding 3D meshed model shown in Figure 6, as they are beyond the resolution of the available laser data. In order to support the visual quality of such details, a hybrid approach combining data from the laser scanner and the digital imagery was developed. Images from a calibrated camera, and the high quality of the registration process of both data sets, are crucial factors for achieving a realistic-looking model. This requires accurate

![Figure 5](image_url) Registration of two different scans in one coordinate system.
determination of the camera’s interior and exterior orientation parameters. For our investigations, the camera calibration parameters were computed using Australis software. These parameters were used to eliminate geometric image distortions. Corresponding coordinates between image and laser scanner were then measured using the Photomodeler software, which was also applied to calculate the camera position and orientation in the coordinate system of the geometric model. After the position and orientation parameters are computed for the sensor stations, the co-linearity equations, shown below, are then applied to calculate the image coordinate for each point of the laser scanner point cloud. The implementation was realized on a standard PC with an Intel 4, 3GHz Processor, and 1GB RAM using the C++ language.

\[
\begin{align*}
  x_a &= -c \left[ r_{11} (X_o - X_A) + r_{12} (Y_o - Y_A) + r_{13} (Z_o - Z_A) \right] \\
  y_a &= -c \left[ r_{21} (X_o - X_A) + r_{22} (Y_o - Y_A) + r_{23} (Z_o - Z_A) \right] \\
  z_a &= -c \left[ r_{31} (X_o - X_A) + r_{32} (Y_o - Y_A) + r_{33} (Z_o - Z_A) \right]
\end{align*}
\]

In these equations:
- \( x_a, y_a \): an object A’s image coordinates.
- \( X_A, Y_A, Z_A \): the object’s coordinates in object space.
- \( X_o, Y_o, Z_o \): the object space coordinates of the camera position.
- \( r_{11} - r_{33} \): the coefficients of the orthogonal transformation between the image plane orientation and the object space orientation, and are functions of the rotation angles.
- \( c \): camera focal length.

**Figure 6** 3D meshed Model for Al-Deir Tomb.
As it can be seen in Figure 7, the different acquisition time of the images collected from the laser scanner camera results in considerable differences in brightness and colour, which changes the appearance of the textured 3D model. By contrast, the proposed method for mapping high resolution digital images onto the geometry gives a highly realistic appearance to the model and offers a descriptive view of the scene which can be used for measuring and monitoring purposes, as depicted in Figure 8.

The measured point density for describing the surface of the monument was 2 cm at the object; this is due to the nature of the used laser scanner which features 6 mm accuracy. An example of a 3D model of a representative area of damage is given in Figures 9 and 10. As can be seen, the mapping of close and detailed high resolution images to the 3D model allows a good visual inspection of the surface damage, which is necessary for recording of the weathering factors at the stone monument according to type, intensity and spatial distribution.

**Environmental monitoring and salt analysis**

The activation of salt damage is highly controlled by the surrounding environmental conditions. Relative humidity, air temperature, solar radiation, wind direction, and wind speed are known as important factors that directly influence the salt damage process (Lubelli, 2006; Price, 2000; Steiger & Zeunert, 1996: 353; Price & Brimblecombe, 1994: 90; Arnold & Zehnder, 1991: 103). Therefore, the collection of climatic data from the case study site was an essential part of the current research. The methodology for evaluating the role of environmental conditions on salt damage behaviour in cultural and historical heritage sites varies significantly. Some scholars,
FIGURE 8  3D textured model of Al-Deir Tomb using images of Nikon D2x camera (4288 × 2848 pixels).

FIGURE 9  3D textured model (using close detailed high-resolution images).

FIGURE 10  3D model corresponding to Figure 9.
such as Tricio and Viloria (2002: 67) and Camuffo and Bernardi (1995: 7) have undertaken a very detailed microclimate investigation in evaluating the effects of environmental parameters on historic buildings, while others, such as Al Naddaf (2002), prefer a basic monitoring programme to evaluate stone-weathering behaviour. A series of fieldwork investigations and laboratory work was undertaken in order to study the effect of these parameters on the salt crystallization process. The detailed monitoring approach was considered more appropriate for the current research because it would provide a more systematic way of evaluating the salt damage processes at different locations by comparing the microclimate data of each location with its salt content. This included an eighteen-month programme of microclimate monitoring for relative humidity, air temperature, and wind speed at the case study location, accompanied by four sampling periods for the determination of the salt content at the case study location. For the temperature and relative humidity measurements, Gemini Tinytag Plus (TGP-1500) loggers were used, and were placed near the gateway of the tomb. In addition, a Lutron hand anemometer (Am-4201) was used to measure the wind speed at the case study monument.

**Recorded environmental conditions**

The temperature readings were much more stable than the relative humidity readings (Figure 11). For example, in January the temperature readings ranged between 9.6
and 25.1°C with an average of 12.5°C. The daily fluctuation range was less than 2°C during this month. Even though the relative humidity overall monthly averages did not differ greatly, the individual relative humidity readings varied significantly. For instance, during January the relative humidity reached its maximum (82.1%) and dropped to 54% toward the end of the same month. May, June, July, September, and October were moderately dry and hot, while November and December had similar humidity averages but were colder. January and February were slightly humid and quite cold months. In March and April both temperature and relative humidity were unstable with overall humid and rather cold conditions.

Generally, the Petra microclimate data is typified by the domination of dry, hot conditions and fluctuating wind speeds throughout the majority of the year. In addition, the high rate of fluctuation of the relative humidity and wind speed around the studied monuments was very obvious. A considerable variation was also noted between readings that came from the same monument and at the same time, but from different sampling points.

**Petrography of the AL-Deir stone**

The Al-Deir Tomb is carved out of Upper Umm Ishrin sandstone, which is multicoloured sandstone from the subarkosic Umm Ishrin formation of the middle to late Cambrian age. The thin section of this stone (depicted in Figure 12) shows multicoloured, fine to medium, sub-angular to sub-rounded grained sandstone. Iron oxides and kaolinite are the main matrix. Quartz grains make up over 80% of the stone content. Porosity is moderate, with total porosity around 15% and mainly medium (1–10 µm) to coarse pores (10–100 µm radii).

**Salt types and distributions**

The determination of the salt types and their distribution in the Al-Deir tomb at Petra has great importance for understanding and evaluating the weathering processes at the monument. The types of salts, their depth of accumulation, the pore structure and moisture regimes, as well as the surrounding microclimate conditions, are key features controlling the decay of stone materials (Nicholson, 2001: 819; Rodriguez-Navarro et al., 1999: 1250; Winkler, 1994; Doehne, 1994: 143; Rossi-Manaresi & Tucci, 1991: 53).

**FIGURE 12** Photomicrograph of the petrological thin section of the Upper Umm Ishrin sandstone specimen. Field of view 2.5 mm. Magnification: $40 \times$ (ppl).
The Al-Deir Tomb is located on the edge of a high mountain and it has two different levels of stone decay between its two storeys. The lower part of the Al-Dier monument, as seen in Figure 8, had a wide range of stone decay features that are mainly linked to salt damage, such as scaling. The latter feature was the main reason for evaluating the salt distribution in order to match the weathering form on this monument and the salt distribution.

**Sampling profiles**
Two sampling profiles were taken from the Al-Deir Tomb, D1 and D2, as depicted in Figure 13; to minimize the level of intervention neither was from the carved façade. These two profiles were selected after a geological correlation with the tomb rocks, and the heights of the profiles where chosen at levels where a high salt content was expected due to the stone decay features at the tomb. Thirty-two samples were collected from this area during the first fieldwork visit using a manual drill. At profile D1, samples were collected from three different depths (0–1, 1–3, and 3–5 cm), whilst at D2 samples were collected from only two different depths (0–1 and 1–3 cm). The current study applied sampling techniques that could not get further into the rocks due to their hardness, especially in profile D2. For the rest of the fieldwork visits, between 22–26 samples were collected and the sampling depths were reduced to two intervals only (0–1 and 1–3 cm), due to the low content of the salt damage at the 3–5 cm interval.

**Cation and anion content analysis**
In order to identify the total salt content in each of the samples collected from each monument at the four sampling fieldwork visits, the cation and anion content of these
samples was measured. Before carrying out the analysis, the samples were diluted with distilled water. A sample of \(0.2 \pm 0.0005\) g was diluted with \(10 \pm 0.05\) ml of distilled water. The samples were filtered in order to avoid any metal debris from the drills affecting the results. The cation analysis was carried out using an Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES). This machine was capable of measuring the following cations: calcium, sodium, iron, aluminium, magnesium, potassium, titanium, and zinc. The machine was calibrated automatically every tenth sample. The anion content was measured using Ion Chromatography (IC). The experiment was carried out with the same diluted samples that were used for the ICP-AES in order to maintain homogeneous results. The samples were diluted further when the anion concentration exceeded the capacity of the machine reading. The cation content was measured using an Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES), while the anion content was measured using Ion chromatography (IC). The total soluble content in all analyses was expressed as the weight % of salt per weight unit of dried stone powder sample (0.2 g).

**Results and discussion**

The total soluble salts content at the Al-Deir Tomb was generally low (Table 2). During the first sampling season (August 2003), calcium and sodium were the main cations, while sulphate, chloride, and nitrate were the main anions. Potassium and phosphate were minor components. There was an obvious general trend of the total content of soluble salts in the three sampling depth intervals. The salt content started very low at 5 cm and increased gradually until it reached its maximum at 105 cm, after which it started to decline again at 155 cm. Thereafter, the salt content increased gradually with height. The significant increase of the total soluble salt content at 105 cm is mainly related to the presence of a small terrace (40 cm wide \(\times\) 250 cm long) at the height of about 95 cm. This terrace could be the main source of water accumulation and, therefore, an additional source of soluble salts. The increase of the total soluble salt content was accompanied by a noticeable increase of bromide content in the samples. The origin of the bromide is unknown. It should be noticed here that these readings are from one fieldwork session, and not for the whole monitoring period.

During the winter season, sodium and calcium were the main cations, while potassium and magnesium were present in low concentrations. Sulphate and chloride were the main anions. A high concentration of nitrate was found in a few samples that came mainly from the lowest level of the sampling profile (5 cm height). During the early summer fieldwork visit (June 2004), the total soluble salt content at the Al-Deir Tomb was slightly higher than in the previous two visits, with a more uniform distribution of the salts throughout the profile. Generally, the higher evaporation rates during this period resulted in higher soluble salt content in the deeper intervals, creating a more uniform distribution of the soluble salts between the surface and the deeper intervals (0–1 and 1–3 cm).

The cation and anion analysis of the samples from the first profile (D1) at the Al-Deir Tomb during the spring sampling fieldwork visit showed the lowest overall soluble salt content from all fieldwork visits (Table 3). The excess of cation charges compared to anion charges in these samples was one of the main features in these
results. This excess was noticed in most of the samples from the previous fieldwork visits, but was higher in the samples from the spring and winter fieldwork visits. The winter and spring seasons were the most humid ones compared to the early and late summer periods, causing higher groundwater levels inside the monuments. This situation strongly supports the authors’ arguments regarding the presence of carbonate or bicarbonate anions in the samples from the Al-Deir Tomb that originated mainly from groundwater inside the monument. However, despite the non-proportional distribution of the cations and anions, a correspondence of calcium and sulphate and of sodium and chloride ions existed throughout the profile.

It is worth mentioning that the current research had tested the moisture content in few samples from the Al-Deir area and the results showed a clear indication that groundwater is the main source of moisture in the tested section. The evaluation of salt distribution has shown that it is noticeably higher at the lower levels of this monument compared to the higher ones. The groundwater may have a direct influence on the salt distribution since it is the main source of these salts. Thus, the

\begin{table}
\centering
\caption{The soluble salt content from drilled samples, Al-Deir Tomb, location (D1). First fieldwork visit: August 2003.}
\begin{tabular}{cccc}
\hline
Sample number & Location & Height (cm) & Depth (cm) & Soluble salt content in the sample (%) of dry weight \\
\hline
79 & D1 & 5 & surface & 0.25 \\
80 & D1 & 5 & 1 & 0.12 \\
81 & D1 & 5 & 1–3 & 0.13 \\
82 & D1 & 5 & 3–5 & 0.17 \\
83 & D1 & 55 & 0–1 & 0.22 \\
84 & D1 & 55 & 1–3 & 0.13 \\
85 & D1 & 55 & 3–5 & 0.11 \\
86 & D1 & 105 & 0–1 & 0.41 \\
87 & D1 & 105 & 1–3 & 0.24 \\
88 & D1 & 105 & 3–5 & 0.44 \\
89 & D1 & 155 & Surface & 0.36 \\
90 & D1 & 155 & 0–1 & 0.40 \\
91 & D1 & 155 & 1–3 & 0.15 \\
92 & D1 & 155 & 3–5 & 0.10 \\
93 & D1 & 205 & Surface & 0.21 \\
94 & D1 & 205 & 0–1 & 0.35 \\
95 & D1 & 205 & 1–3 & 0.09 \\
96 & D1 & 205 & 3–5 & 0.18 \\
97 & D1 & 255 & 0–1 & 0.44 \\
98 & D1 & 255 & 1–3 & 0.16 \\
99 & D1 & 255 & 3–5 & 0.19 \\
\hline
\end{tabular}
\end{table}
main decay line at this monument is directly linked to the salt damage problem, since the highest salt accumulations were along this line.

Conclusions

Uncontrolled environmental conditions and salt content represent the main damage processes for the Al-Deir monument in the ancient city of Petra in Jordan. This gave rise to the need to have a comprehensive study and full documentation of the monument in order to evaluate its status. This research applied a comprehensive approach utilizing 2D weathering form mapping and 3D modelling using laser scanning and photogrammetry. 3D laser scanner technology was one of the important technical methods used to acquire spatial data of the monument. The data collected can be used to evaluate what restoration is required. In the case of damaged areas, the detailed high-resolution 2D images and the texturing 3D models of the monument will give both stone texture and spatial distribution of the weathering features and will help to explain the mechanism and rate of the weathering problem.

The present study also included laboratory analysis and a correlation study of the salt content and the surface weathering damage, which are the main damage processes at work on the stone at the monument, allowing an understanding of the deterioration mechanisms and causes. The evaluation of the salt distribution has shown that the visible zoning of weathering damage correlates to different salt concentrations.

Bibliography


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