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DAMAGE ASSESSMENT AND DIGITAL 2D-3D DOCUMENTATION OF PETRA TREASURY

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ABSTRACT

The treasury is the icon monument of the world heritage site of ancient Petra city. Unfortunately, this important part of the world's cultural heritage is gradually being diminished due to weathering and erosion problems. This give rise to the need to have a comprehensive study and full documentation of the monument in order to evaluate its status. In this research a comprehensive approach utilizing 2D-3D documentation of the structure using laser scanner and photogrammetry is carried parallel with a laboratory analysis and a correlation study of the salt content and the surface weathering forms. In addition, the research extends to evaluate a set of chemical and physical properties of the case study monument. 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. Then a series of field work investigations and laboratory work were undertaken to study the effect of relative humidity, temperature, and wind are the main factors in the salt damage process. The 3D modelling provides accurate geometric and radiometric properties of the damage shape. In order to support the visual quality of 3D surface details and cracks, a hybrid approach combining data from the laser scanner and the digital imagery was developed. Based on the findings, salt damage appears to be one of the main problems at this monument. Although, the total soluble salt content are quite low, but the salts contamination is all over the tested samples in all seasons, with higher concentrations at deep intervals. The thermodynamic calculations carried out by this research have also shown that salt damage could be minimised by controlling the surrounding relative humidity conditions. This measure is undoubtedly the most challenging of all, and its application, if deemed feasible, should be carried out in parallel with other conservation measures.

KEYWORDS: Petra, Physical and Mechanical Properties, Decay, 2D-3D documentation, Salt, Environmental, Monitoring Programs, Thermodynamic.

1. INTRODUCTION

The role of documentation and damage quantification in the management of cultural heritage sites has long been recognised. They are indispensable, for the purpose of identification, interpretation and more importantly the conservation of the world cultural heritage treasures. One of the most unique World Heritage Site is the city of Petra in Jordan. Petra is the biggest tourist attraction in Jordan; however the city suffers from weathering and erosion problems, both natural and human in origin. 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). Nowdays, a large number of digital methods have been developed for reliable, easy, and fast surveying of large-scale monuments. Combined these techniques with the laboratory analysis allows for a quantitative, registration, documentation, and evaluation of complete monuments (Alshawabkeh et al., 2010).

The current paper aims to present detailed inventories to the icon monument of Petra city, the treasury, depicted in Figure 1. The study include an accurate and realistic 2D and 3D documentation of the structure and surface damage using laser scanning and photogrammetry, as well as a comprehensive physical and chemical evaluation of treasury monument. The main goal behind this study that despite the fact that the treasury is remarkably well-preserved, probably because the confined space in which it was built has protected it somewhat from the effects of erosion, the environmental conditions in the area are changing rapidly and lately a large number of decay serious features, especially salt damage decay features, started to appear in treasury façades. Moreover, the city of Petra was lately nominated as the second on the new world seven wonders, and since that the Treasury is first to greet the visitor arriving via the main natural entrance of the city, a new risk on the monument is came out from the large number of visitors, which could lead to serious damage in the city. In addition, a number of conservation works has been adopted in the monument with little or no document, which implies that a comprehensive inventory of such iconic monument is a must action.

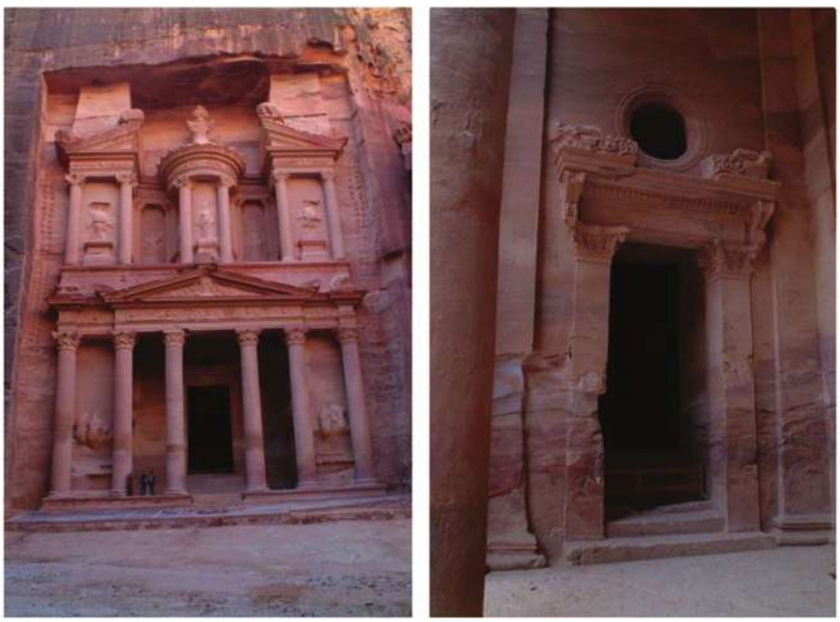

Figure 1. Petra treasury (Khazneh), the surface damage is clear in the inside right door of the treasury.

2. PETRA

The city of Petra lies hidden in the Desert Mountains in the southern part of Jordan, half way between the Dead Sea and the Gulf of Aqaba. It is 255 km away from Amman (the capital of Jordan) (Figure 1.). The international coordinates for the city are 35º 25′ E - 35º 28′ E and 30º 19′ N - 30º 21′ N. The archaeological city of Petra occupies about 15 km2 and is 900 to 1500 m above sea level (Bala'awi, 2006).

Petra monuments and ruins are unique in their architecture, distribution, and variety as well as their durability. The presentation of the monuments of Petra is beyond the scope of this research; however, it will present the case study of this paper, the treasury in detail.

2.1 The Treasury (Khazneh)

The best-known of the monuments at Petra, the treasury (*Khazneh*) is also the first to greet the visitor arriving via the Siq (The main entrance to archaeological site of Petra). It is one of the most beautiful, famous and amazing monument in Petra (Figure 2). The Khazneh is the Arabic name for the "Treasury"; it comes from the legend that it was used as a hiding place for treasure (Zayadine, 1992). It seems to be generally agreed now that the Khazneh was built as a tomb for one of the Nabateans kings (mainly Aretas III) in the first century BC. It is about 40 meters high and 28 meters wide. The Khazneh faces onto a large open space, floored with soft sand and surrounded by high walls.

The Khazneh façade has composed of two floors. The first floor, which has a gate leading to major hall with a small room in each side, is supported by six columns with carved statues between them representing the horsemen, sons of god Zeus (Lama, 1997; Koura, 1986). While the upper story include a central tholos surrounded by columns and flanked by two pavilions with a broken pediments on top (Khouri 1986). It is certainly true that the architectural models in the Khazneh monuments are really a fascinating feature, because they contain the Greek, Roman, and Egyptian styles as well as the Nabataean at the same time.

One of the earliest conservation projects in Petra is the repaired of the third pillar of the Treasury building in 1958. United State Agency for International development (USAID) founded this project. The project succeeds in restore and enhances the view of the most attractive monument in by reconstruct the third column of the monument (Fig. 4). However, it is hardly to notice this column from the others columns, especially if you did not know the conservation background of the site. Also, unfortunately, in the site there are no signs or boards that describe the conservation work in this site, or even just a brief mention of it. It is worthwhile to remember that the reconstitution of this column took place in 1958, which is before the Venice Charter 1964 or the Nara document on authenticity 1994. However, one can say that mentioned project did adhered the principles of Athens Charter for restoration of historical Monuments (1931), where its emphases were based in the aesthetic appearance of the monuments. From the authors point of view, the conserving of third column of the treasury is a part of the site history in these days and the project achievements should be appreciated, since the work had been simply documented and the its work carried out with highly accuracy. In contrast, the project did not take in consideration many modern conservation principles such as the minim intervention and the authenticity of the place. The procedure of a comprehensive inventory of the monument at this time could not only provide us in accurate reference date, but also in detecting the main threats to site and in the ways how to protect such unique heritage site.

2.2 The Geology of the site

In order to understand the mechanisms of stone deterioration at the Petra monuments, the geological and structural setting of the area should be considered.

2.3 *Lithostratigraphy*

Jasper and Bijous (1992), (Plunger, 1995) and (Heinrichs and Finer, 2000) have studied the geology of Petra. (Jasper and Bergius, 1992) outlined the main chronological sequences in Petra as follows (fig. 6.6), in increasing age order:

- Soil, soil cover over Pleistocene sediment (Age: Holocene - Recent)
- Alluvium and Wadi Sediments (Age: Holocene - Recent)
- Debris apron over ancient settlement (Age: Holocene - Recent)
- Pleistocene Gravel (Age: Pleistocene)
- Kurnub Sandstone Group (Age: Cretaceous Neocomian)
- Ram Sandstone Group, which includes three different formations: Disi Sandstone, Umm Ishrin Sandstone and Salib Arkosic Sandstone Formations. (Age: Cambrian-Ordovician).
- Al Bayda Porphyry Unit (Age: Pre-Cambrian).

As mentioned earlier, Petra lies in the southern part of Jordan, where Cambrian sediments are dominant. Most of the Petra monuments, including the case study monument (The treasury) were carved out of the late lower - middle Cambrian sandstone (Umm Ishrin Sandstone Formation) and the early Ordovician sandstone (Disi Sandstone) (figure 6).

3. PHYSICAL AND MECHANICAL PROPERTIES OF TREASURY SANDSTONE

The physical and mechanical properties of porous materials have a vital role in controlling their weathering mechanisms. Therefore, this section will address the main structural, physical and chemical properties of the main formations in Petra monuments (Umm Ishrin Sandstone Formation) where most of the city monuments including the case study monument (the Treasury) were carved out.

3.1 *Petrography*

A petrographic study of the main stone properties was carried out on two thin sections from the treasury monument. In order to avoid the destruction to iconic monuments, samples were taken from the surrounding rock cuts and not from the monument itself. The tested rocks were taken at 2 and 3 meter height from the surrounding rock cut area and not from the carved monument itself. The 30 μm thin section slides were prepared using a kerosene- based technique, in order to avoid any alteration to the physical properties of the stones, especially the Petra specimens, which contain soluble salts and clay minerals.

The petrographic study have showed that treasury sand stone thin section, depicted in figure 2, is composed of a multi-coloured, fine to medium grained, sub-angular to rounded, well sorted sandstone. The study revelled also that iron oxide (hematite) and clay minerals are the main cementing materials. Thin sections proved the high total porosity of tested stone material (approximately 18-20%) with medium (1-10 μm) to coarse pores (10-100 μm radii).

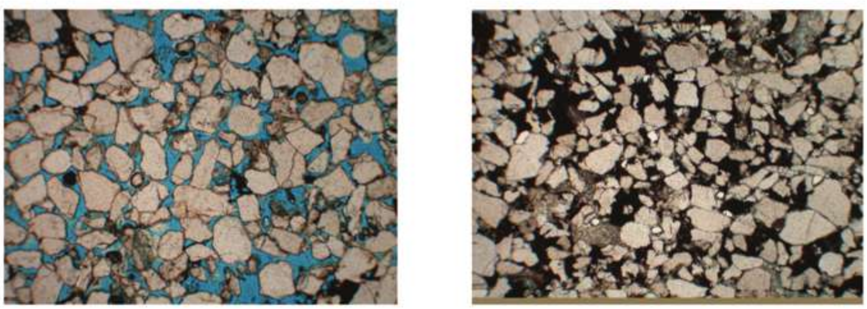

Figure 2. Photomicrographs of the petrological thin section of sandstone samples from the treasury monument . Field of view 2.5 mm. Magnification: 40x. (ppl).

3.2 Mineral composition

In addition to the petrographic studies, both XRF and XRD tests were carried out on the tested stones to verify the chemical composition of the specimens. The results (all expressed as weight percentage of the oxides) show that silicon is the main component of the 4 tested sandstone samples, as can be seen in Table 1. The samples were taken from 4 different heights (5, 105, 205 and 305 cm) from the rockcut façade near the monument (Figure 4). Aluminium is the second major component (approximately 7%); approximately 3 % hematite was found in the tested samples.

Due to the relatively high Aluminium content, XRD analysis was performed on the samples from the Treasury monument stone samples to identify the mineral phases and especially the clay mineral types, the results is shown in Figure 3. It was found that kaolinite was the main clay mineral in tested samples specimens. Hematite was identified in two of three tested samples.

Table 1: The main oxides in the tested samples from the treasury monument (for sample location please see Figure 4).

Sample Code	Sample Height (cm)	Na_2O %	MgO %	Al_2O_3 %	SiO_2 %	K2O %	CaO %	Fe_2O_3 %	TiO_2 %
T1	5	0.39	0.08	7.23	88.32	0.10	0.12	2.94	0.20
T2	105	0.36	0.02	6.87	89.01	0.11	0.16	2.91	0.18
T3	205	0.41	0.05	6.98	88.69	0.09	0.19	3.07	0.15
T4	305	0.0.36	0.02	7.04	87.97	0.11	0.17	2.86	0.19

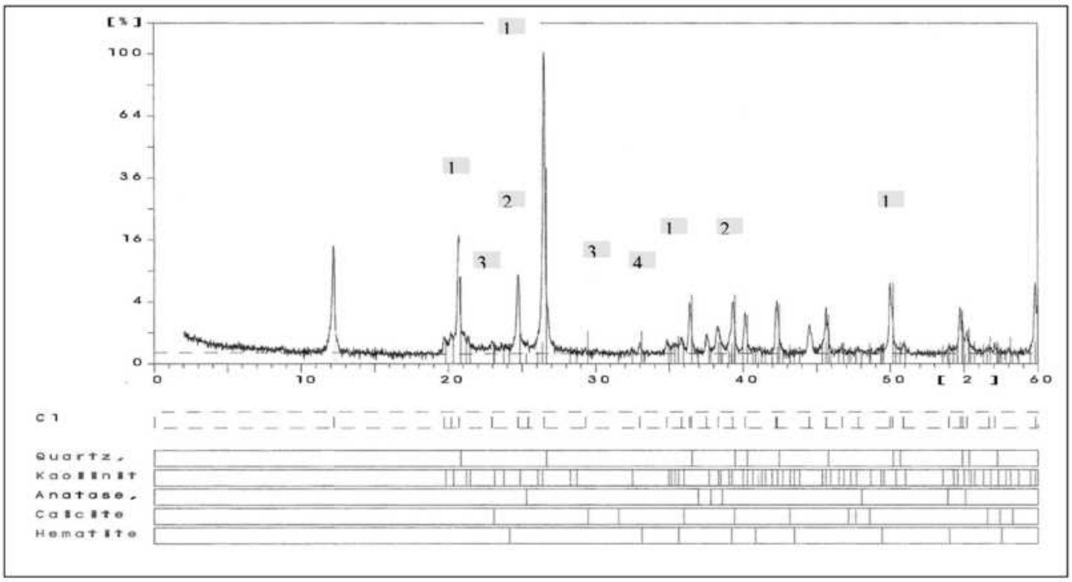

Figure 3. The X-ray diffraction pattern of on the tested samples from the treasury monument specimens. Analysis type: Non-preferred orientated sample. 1: Quartz, 2 Kaolinite, 3 Calcite and 4 Hematite are the major minerals as shown from the above peaks

4. DECAY AND DECAY FEATURES AT THE TREASURY

The identification, classification, documentation and evaluation of the stone weathering forms are crucial stages prior to the start of any remedial or preventive conservation work. The field survey is the starting point, where the weathering forms are identified. The classification and documentation of these forms are the second step. Due to the many forms of stone decay, various methods are used to classify and document the damage state of the stones.

Viles et al. (1997) presented a very basic scheme for the classification of the visible deterioration of historical stone monuments. The scheme has three different levels: microscale (cm or less), mesoscale (cm to m) and macroscale (whole façades, entire monuments).

According to Heinrichs and Fitzner (1999), the term "weathering form" is used for stone deterioration visible at the mesoscale. The Natural Stones and Weathering Group at Aachen University of Technology presented a comprehensive monument - mapping method for in situ studies of weathering damage on natural stone (Fitzner and Heinrichs, 2002). This mapping method offered a detailed documentation of all weathering forms, according to the exact type, intensity and distribution. It is based on a comprehensive classification scheme of stone weathering forms, which resulted from the detailed investigation of different monuments around the world (Fitzner, Heinrichs and Kownatzki, 1995).

The Treasury asperse to be one of the most well preserved monuments in Petra for many reasons. Firstly, it is located in a very well protected area, so it can be said that it is located in a shattered area, where the surrounding environment condition are quite stable. Moreover, the site is the icon monument of the arcahlogical city of Petra, so a number of conservation and cosmetic action were carried out at the site through the last few decays. In addition, recenatly and due to its touristic, the site is well monitored in regards to human damage, which emitted or minimizes the human damage at this monument. In other words, it is one of few well protected and guarded monuments in the archaeological site of Petra.

Despite all that, the detailed investigation of the Treasury did reveal a number alarming of decay feature (see Fig. 1); the monument is still recognized as a well preserved monument. This is mainly due to the low intensity of these decay features. A detailed investigation of the decay feature in the treasury will not only produce a detailed documentation of the actual monument status, but it will also play a major role in preventing the site from further deterioration through a comprehensive understanding of the decay mechanism within the monument.

The fieldwork investigations showed that scaling, flacking, Granular disintegration, efflorescence, back weathering, relief, washout, fractures and cracks are the main decay feature at the site; this is depicted in figure 4.

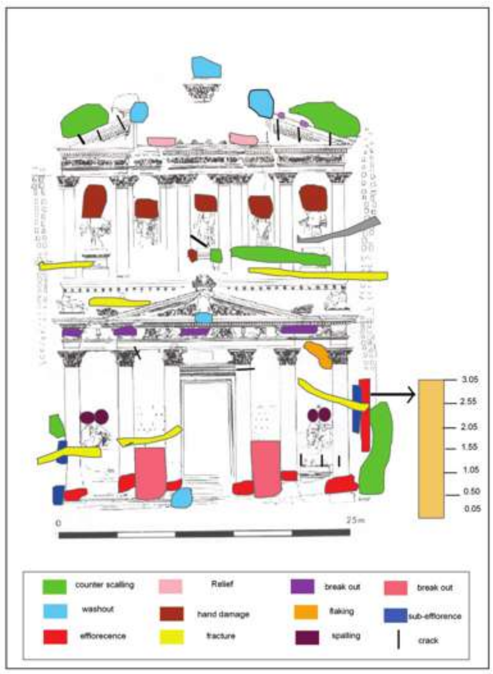

Figure 4. 2D mapping of the main weathering forms of the Treasury. The colours are hypothesised one and do not have any indications.

The clear observation of the decay features of the treasury shows that most of these features are mechanical features where salt and salt damage are mainly involved. Therefore, the current paper will investigate the salts and salt damage problem in this monument in a more details. In summary, it can be concluded that Treasury monument under a high risk.

5. SALT AND SALT DAMAGE

The deterioration of porous building materials due to crystallisation of salts within their pore structure is a widespread weathering process and the main cause of decay of many archaeological sites, including the World Heritage Site of Petra. Salt damage is one of the most common phenomena in archaeological sites, since salts can absorb moisture, dissolve, crystallise and recrystallise, and many of them can exist in both hydrous and anhydrous forms (Goudie and Viles, 1997). Despite the vast amount of research in the salt damage processes (see, for example, Correns, 1949, Winkler and Singer, 1972, Arnold and Zehnder, 1991, Steiger and Zeunert, 1996, Goudie and Viles, 1997, Rodriguez-Navarro and Doehne, 1999a & 1999b, Scherer, 1999 & 2000, Pender, 2000, Sawdy, 2001, Flatt, 2002), the overall understanding of this phenomenon is still open to question. This is due to its complexity, which is mainly related to the wide range of factors involved and the difficulty in monitoring the exact details of the entire process that occurs on a microscopic scale within the pore structure of porous materials .Since the beginning of the last century, the salt damage process in porous materials has been given more attention by researchers and has attracted scholars from many different fields including geomorphology, geology, chemistry, conservation, environmental and materials sciences. The current study will examine the salt types and distribution within the treasury monuments. The study will be combined of a detailed monitoring programme for the microclimate condition within the area. This includes 8 months monitoring program for temperature and relative humidity using a tinytag 2 plus 4500 loggers. Also it include six fieldwork monitoring visits for wind speed conditions in the site, each visit the wind were monitored for 12 hours using a Lutron hand anemometer model : AM-4201.

5.1 Microclimate Evaluation Programme

The activation of salt damage is highly controlled by the surrounding environmental conditions. Relative humidity, temperature, solar radiation and air speed are the main factors with a direct influence on the salt damage process. Therefore, the collection of

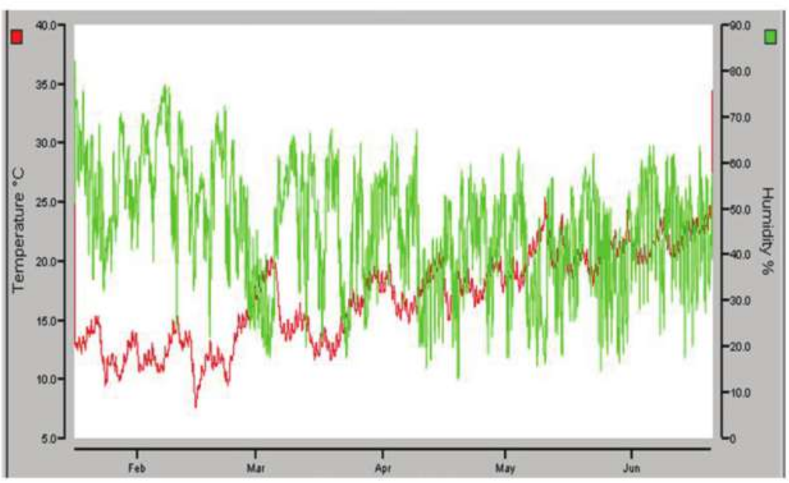

Figure 5. Diagram combining relative humidity and temperature readings from the data logger. Location: The Petra Treasury (Recorded period: 15 January 2010 till 14 June 2010).

climatic data from the case study sites was an essential part for evaluating the salt damage problem at the case study monument.

Based on the detailed monitoring program shown in figure 5, the microclimate conditions during summer periods could be summarised as very high temperature, very low relative humidity with slightly fluctuating wind speed values during day-time hours, and slightly lower temperature, slightly higher relative humidity and slightly stable wind speed rates during night-time hours. During winter period, the temperature readings were much more stable than the relative humidity ones, with January and February as the most humid months.

Due to the importance of the wind speed factor in the activation of salt damage problem, sets of wind speed spot readings were taken during each fieldwork visit. Unfortunately, there were no loggers or any other instrument available in order to record the wind speed over a long period as in the case of temperature and relative humidity. In order to get a clear indication about wind speed at the studied monument, wind speed spot readings were taken at different heights at the monument. The readings were taken at approximately 1m distance from the surface of the façade. A total of 20 sets of spot readings were taken at each sampling point as shown in Table 2, each of which consisted of five spot readings at approximately 1m distance from the sampling points (Figure 4). The wind speed was monitored for 4 days in each fieldwork visit. During winter fieldwork visit (January 2010), the wind speed varied slightly from one day to another and from one location to another and even from one sampling site to another at the same location.

Table.2: Wind speed spot readings. Location: The treasury Tomb, Petra Jordan. (12 January 2010)

Location	Date	Height (cm)	Time	Maximum wind speed (m/s)	Minimum wind speed (m/s	Average wind speed (m/s)
T1	12.1.2010	5	05.30	0.30	0.00	0.25
T1	12.1.2010	5	06.30	0.60	0.05	0.30
T1	12.1.2010	5	07.30	0.50	0.05	0.30
T1	12.1.2010	5	08.30	0.70	0.20	0.40
T1	12.1.2010	5	09.30	0.95	0.25	0.60
T1	12.1.2010	5	10.30	1.05	0.30	075
T1	12.1.2010	5	11.30	1.25	0.25	0.80
T1	12.1.2010	5	12.30	0.75	0.05	0.30
T1	12.1.2010	5	13.30	1.20	0.10	0.50
T1	12.1.2010	5	14.30	0.30	0.10	0.20
T1	12.1.2010	5	15.30	0.90	0.30	0.60
T1	12.1.2010	5	16.30	1.60	0.30	0.85
T1	12.1.2010	5	17.30	1.50	0.25	0.85
T1	12.1.2010	5	18.30	2.05	0.50	1.05
T1	12.1.2010	5	19.30	2.20	0. 45	1.14
T1	12.1.2010	5	20.30	2.05	0.25	0.89
T1	12.1.2010	5	21.30	1.85	0.35	1.10
T1	12.1.2010	5	22.30	2.62	0.35	1.32
T1	12.1.2010	5	23.30	3.08	0.45	1.89
T1	12.1.2010	5	00.30	3.12	0.42	1.97

5.2 Soluble salts

The determination of the salt types and their distribution in the treasury monument at Petra has a great importance in understanding and evaluating the weathering process at this iconic monument. The types of salts, their depth of accumulation, the pore structure and moisture regimes as well as the surrounding microclimate conditions are the main features controlling the decay of stone materials (Nicholson, 2001, Winkler, 1994, Doehne, 1994 and Rossi-Manaresi and Tucci, 1991).

5.2.1 Sampling and Sampling procedure

The soluble salts (TSSC) content of the treasury monument was tested by analysing 27 samples. The TSSC were measured at two fieldwork visits. The former were held on January 2010 and the second on August 2010. One could argue that the outcomes of these fieldwork data might not represent the actual phases of the soluble salts at the site, since phase transitions could happen in very short period of time. However, the author's argument is that the samples were collected during two different seasons when major climatic changes take place in the area and these samples were accompanied by spot readings for the major environmental conditions. By combining the salts content and the microclimate conditions from the same location, the salts distribution in the studied monument could be evaluated.

For authenticity reasons, Samples were taken from the rock cut area next to Treasury. (Figure 4). The tested profile was 5m high and nine sampling points were chosen. Three different depth intervals were taken from each sampling point (0-1, 1-3 and 3-5 cm). Samples were collected using a manual drill to avoid thermal effect on the samples. The salt content was determined by measuring the main cations and anions using the IC and ICP-AES techniques respectively. 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).

5.2.2 Salt soluble content

In the 27 analysed samples from the sampling profile at the Treasury monument taken during the first fieldwork visit (January 2010) sodium and calcium were the major cations, while magnesium, potassium, aluminium and iron were secondary components. On the other hand, chloride, nitrate and sulfate were the main anions. The total soluble salts content at the tested profile ranged between 0.32 and 2.40 % with an average of 1.04 %. By looking at the total soluble salts content from different heights and depths at this profile (Table 3), a general trend of salt distribution can be observed. The total soluble salts content in the three depth intervals (0-1, 1-3 and 3-5 cm) started very low at low height and increased gradually up to the height of around 255 cm, where it started to drop again. These figures support the theory that the groundwater is the main source of soluble salts in the area and that salts will rise up to a certain height and crystallise gradually according to each salt's solubility and reaction with the surrounding microclimate. Moreover, despite the fact that that total soluble salt content are quite low, but the salts contamination is all over the tested samples, with higher concentrations at deep intervals. These figures are very alarming since salts are higher at higher depth which means more potential damage at the monument.

The total soluble salts content at Treasury monument during the second fieldwork visit (August 2010) was lower than in the winter fieldwork visit, table 4. The total soluble salts content at the tested profile ranged between 0.18 and 0.71 % with an average of 0.37 %. All previous data suggested that the evaporation rate during the summer visit was higher than in the winter. Consequently, the salt mobility was lower in the summer

Table 3. The total soluble sat content in the tested samples at the Treasury moment (January 2010). Note: All samples were taken from the rockcut near the monument (see figure 4).

Sample Number	Height (cm)	Depth (cm)	Soluble salt content in the sample (%) of dry weight
T1	5	0-1	0.41
T2	5	1-3	0.43
T3	5	3-5	0.49
T4	55	0-1	0.53
T5	55	1-3	0.52
T6	55	3-5	0.54
T7	105	0-1	0.31
T8	105	1-3	0.34
T9	105	3-5	0.32
T10	155	0-1	0.61
T11	155	1-3	0.54
T12	155	3-5	0.55
T13	205	0-1	0.67
T14	205	1-3	1.95
T15	205	3-5	1.88
T16	255	0-1	2.31
T17	255	1-3	2.40
T18	255	3-5	2.35
T19	305	0-1	1.69
T20	305	1-3	1.92
T21	305	3-5	0.91
T22	405	0-1	1.61
T23	405	1-3	1.71
T24	405	3-5	1.86
T25	505	0-1	0.42
T26	505	1-3	0.45
T27	505	3-5	0.51

than in the winter and, therefore, the overall soluble salts levels were lower.

5.2.3 Thermodynamic Consideration of the Soluble Salts ECOS program

Despite the fact that the analysis of cations and anions of samples collected from the sampling profile at different depths and heights has revealed very useful information about the salts content and distribution at the treasury monument, the understanding of the dynamics of these soluble salts was limited. In other words, the relationship between soluble salts content, types and distribution and the surrounding environmental conditions was not adequately explained. Therefore, a more specific study of the thermodynamic behaviour of the soluble salts in relation to the surrounding environmental conditions is needed.

The determination of the hygrothermal conditions that control the behaviour of

Table 4. The total soluble sat content in the tested samples at the Treasury moment (August 2010)

Sample Number	Height (cm)	Depth (cm)	Soluble salt content in the sample (%) of dry weight
T1	5	0-1	0.31
T2	5	1-3	0.33
T3	5	3-5	0.34
T4	55	0-1	0.29
T5	55	1-3	0.34
T6	55	3-5	0.35
T7	105	0-1	0.36
T8	105	1-3	0.34
T9	105	3-5	0.31
T10	155	0-1	0.41
T11	155	1-3	0.41
T12	155	3-5	0.44
T13	205	0-1	0.39
T14	205	1-3	0.41
T15	205	3-5	0.40
T16	255	0-1	0.61
T17	255	1-3	0.64
T18	255	3-5	0.71
T19	305	0-1	0.34
T20	305	1-3	0.31
T21	305	3-5	0.29
T22	405	0-1	0.27
T23	405	1-3	0.29
T24	405	3-5	0.38
T25	505	0-1	0.18
T26	505	1-3	0.26
T27	505	3-5	0.25

single salts is a straightforward process. Each single salt has its specific equilibrium relative humidity (ERH) at a certain temperature and remains in solution when the surrounding relative humidity is higher than this ERH, but crystallises when the surrounding relative humidity is lower than this ERH.

Following these observations, it might be assumed that salt damage could be avoided in a very straightforward way by controlling the surrounding relative humidity and temperature. Unfortunately, the reality is more complicated, mainly because contamination with single salts in porous materials is rare (Price 2000), while predicting the behaviour of a salt mixture is much more complicated. Many models have been presented in the attempt to understand the behaviour of mixed salt solutions. Pitzer's thermodynamic model (1973) is one of the most widely accepted and applied models in many areas in the chemistry of the natural environment (Clegg and Whitfield, 1991). (Price and

Brimblecombe, 1994) used a new version of Pitzer's model, PITZ93, (Clegg, 1993) to predict the behaviour of two salt solutions that are commonly found in cultural heritage monuments and objects (the sodium nitrate - sodium chloride solution and the calcium sulfate - sodium chloride solution). The study examined the interaction of the salts in these solutions and their effect on each other's solubility. The study also determined the 'safe' levels of relative humidity, where salt damage in monuments or objects contaminated with these salts can be minimised.

The use of the Pitzer model in preventive conservation studies (Steiger and Dannecker, 1995 and Steiger and Zeunet, 1996) led to the creation of an expert chemical model (ECOS) for determining the environmental conditions needed to prevent salt damage in porous materials (Price, 2000). The runsalt program, which is a graphical user interface to the ECOS thermodynamic model, will be used to study the salt composition and behaviour of selected sampling samples from the studied monuments in Petra.

The two cations and anions results of the sampling points 5, 205 and 505 cm in each fieldwork visits were chosen to evaluate the thermodynamic of the soluble salts at the treasury monument. The selection of this sampling point was based on the fact that they represent different heights and could reveal a good indication of soluble salt behaviour at the studied monument.

The runsalt program requires the input of three types of data, an action and anion content with the average of one environmental parameter (temperature or relative humidity) and the range of fluctuation of the other parameter (temperature or relative humidity). Also, the literature review of the Runsalt applications showed that temperature did not significantly affect the salt solution's behaviour, while relative humidity had the greatest impact. Therefore, the current research has used Runsalt with the average temperature of each sampling period as the fixed parameter, and with the entire available range of relative humidity (15-98 %). The overall temperatures were 35 ºC and 20 ºC for the late summer and winter sampling campaigns respectively.

6. FIRST FIELDWORK VISIT: WINTER CAMPAIGN RESULTS

It was found that, due to the high content of calcium and sulfate together in these samples, the Runsalt program could not operate. However, after removing the gypsum from the solution, the program operated normally. The removal of gypsum was indicated and performed by the program itself. Removing the gypsum from the samples does not affect the thermodynamic behaviour of the salt solution substantially, since gypsum is a sparingly soluble salt and leaves the salt system at early stages. Removing the gypsum from the samples does not affect the thermodynamic behaviour of the salt solution substantially, since gypsum is a sparingly soluble salt and leaves the salt system at early stages.

The result of the lower sampling point (5 cm) is depicted in figure 6. After the removal of gypsum, the results showed nitratine was the first salt to precipitate out of the system at approximately 61 % relative humidity, while above this point all salts were in solution. Ca (NO3)2 was the next salt to leave the system at a relative humidity of approximately 37.6 %. Halite precipitated next at 30.1 % which is considerably lower than its equilibrium relative humidity as a single salt at a similar temperature (75 %) (Arnold and Zehnder 1990. Nitre (KNO3) left the solution at a relative humidity of 26.60 %, which is much lower than its ERH as a single salt (92.3 %) (Arnold and Zehnder, 1990).

Based on Runsalt results, the safest relative humidity condition is above 65%, and the

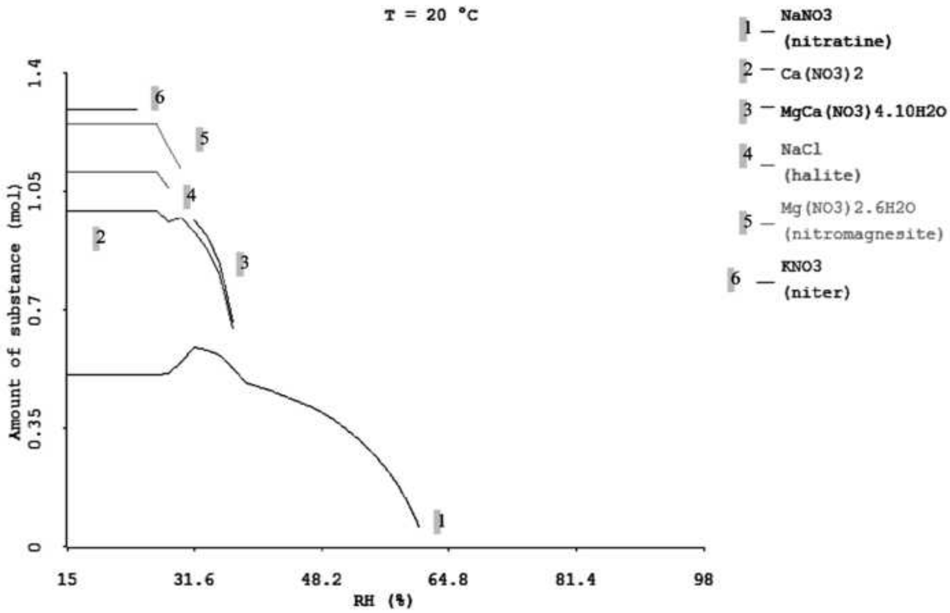

Figure 6: Thermodynamic analysis using Runsalt. Crystallisation sequence of soluble salts: relative humidity against amount of substance (mol). (Sampling height: 5 cm, sampling depth interval: 0-1 cm). First fieldwork visit.

second safest ranges are between 15and 30%.

After removing the gypsum from its content, the surface sample (0-1 cm) from the sampling point at 205 cm height (middle part) showed that Bloedite ($Na_2SO_4.MgSO_4.4H_2O$), an evaporite mineral which is usually formed in arid regions by the evaporation of water was the first salt to predicated out of the solution at 76.30, depicted in figure 7. Halite was the next salt solution to leave the system at 68.6%, which is also lower than its

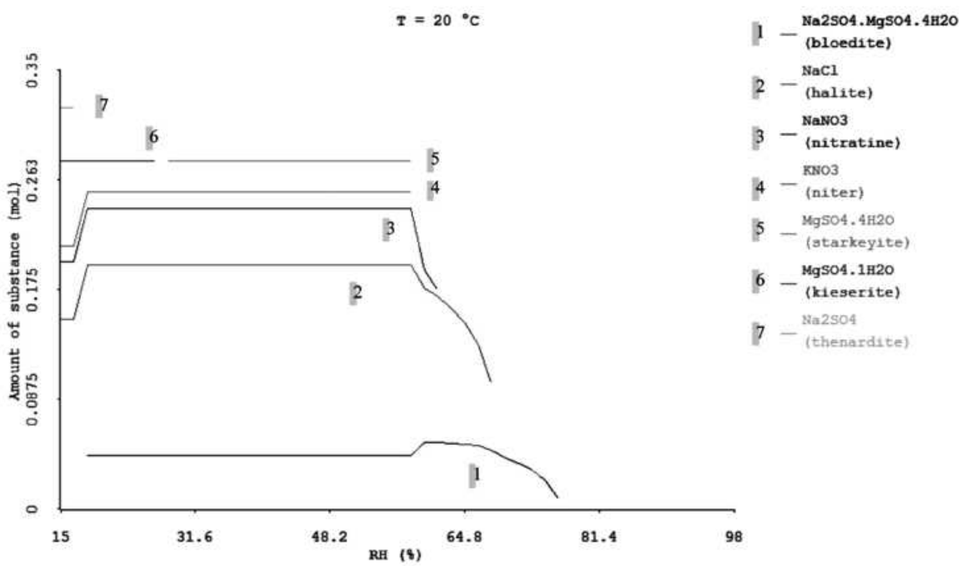

Figure 7. Thermodynamic analysis using Runsalt. Crystallisation sequence of soluble salts: relative humidity against amount of substance (mol). (Sampling height: 205 cm, sampling depth interval: 1-3cm). First fieldwork visit.

equilibrium relative humidity as a single salt at a similar temperature (75 %) (Arnold and Zehnder, 1990).

At the 1-3 cm depth interval from the same sampling point (205 cm), the ideal situation is to keep the relative humidity either above 77 %. Despite the fact that these two levels is quite difficult to achieve, minimising the salt damage is still possible by keeping the relative humidity between 33-60%, which is quite a 'stable' range where all salts will be in solid states and away from their transition zone, while calcium nitrate will remain in solution.

The Runsalt thermodynamic calculations from the cation and anion content at the surface sample (0-1cm) from the 505 cm sampling point (height) is depicted in figure 8. After removing the gypsum from its content, the results show precipitation of nitratine at 58 %RH, followed by Ca $(NO_3)_2$ at 36.5 %RH. Halite precipitated at 35% %RH. Based on these figures, the safest solution to keep the realtive humdity ranges

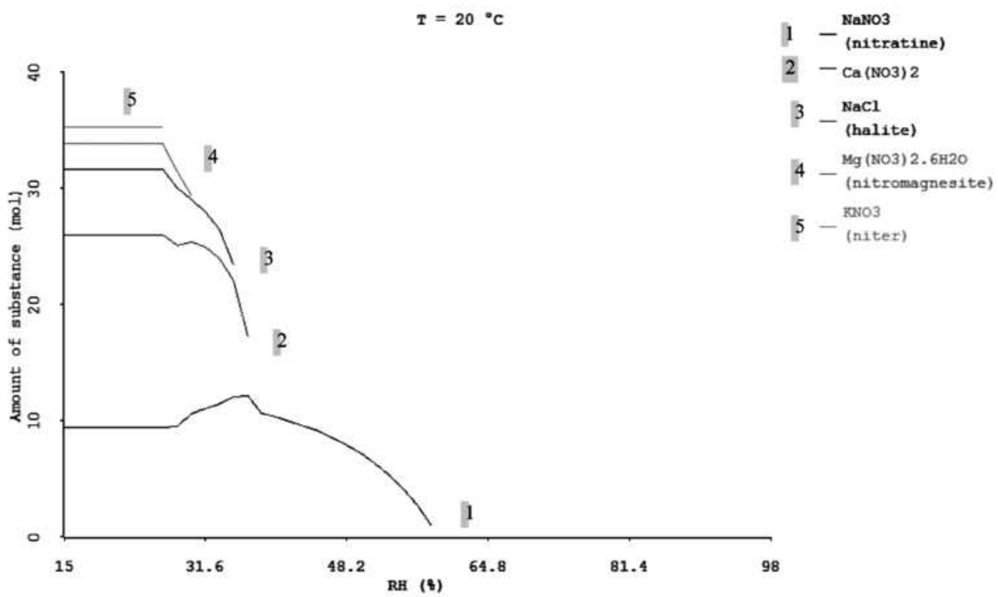

Figure 8: Thermodynamic analysis using Runsalt. Crystallisation sequence of soluble salts: relative humidity against amount of substance (mol). (Sampling height: 505 cm, sampling depth interval: 1-3cm). First fieldwork visit.

above, 58%, which not far from Petra condition at this time of the year.

By taking into account the recorded environmental conditions during winter around the period of sampling, it seems quite impossible to reach the required relative humidity levels to prevent salt damage. However, the relative humidity range between 30-35% could be considered to be a 'stable' condition. The relative humidity range of 40-65 % is the most 'dangerous' and should be avoided in order to minimise salt damage at this location.

7. SECOND FIELDWORK VISIT: SUMMER CAMPAIGN RESULTS

As stated early, the total soluble salt content of the summer fieldwork visit was much lower that winter fieldwork visit as depicted in Fig. 9. With the consideration of microclimate conditions during the sampling period, when the relative humidity fluctuated between 22 % and 60 %, Runsalts results of the same sampling points

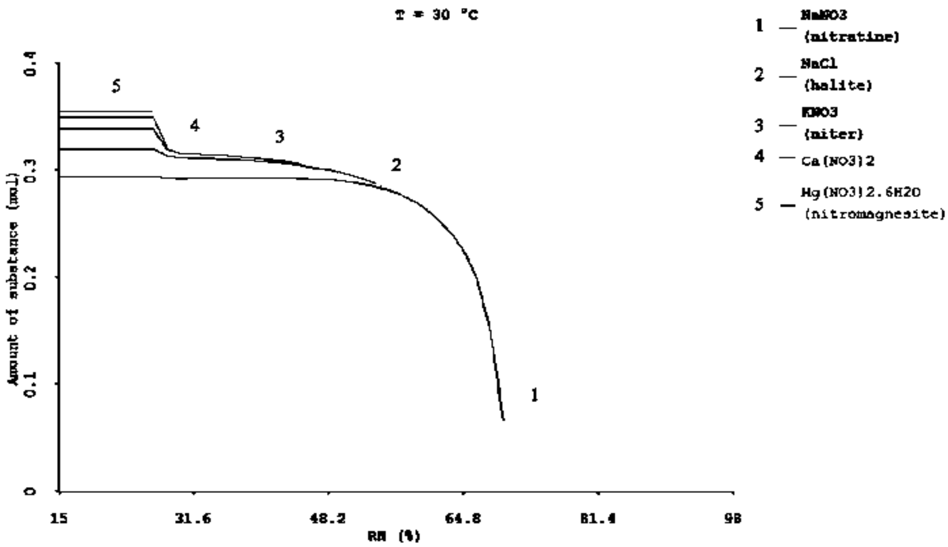

Figure 9: Thermodynamic analysis using Runsalt. Crystallisation sequence of soluble salts: relative humidity against amount of substance (mol). (Sampling height: 5 cm, sampling depth interval: 1-3cm). Second fieldwork visit.

of the winter visits showed that at such conditions (20-59 %RH) are dangerous for the treasury monument since most salts crystallise within these readings. From a preventive conservation point of view, these results indicate that the surrounding relative humidity should be kept either below 25 % or above 70 % in order to prevent the damage from such salt mixtures. Controlling the relative humidity to between 27-45 % or between 15-26 % could also provide relatively 'safe' environments, where salt damage can be contained, since with relative humidity between these two ranges no transition or salt volume change took place in this sample.

The correlation of Runsalt results from different sampling intervals at the same sampling point shows that the summer samples had the highest variations in salts behaviour. The high rate of evaporation during summer, accompanied with considerably higher rates of fluctuation in the relative humidity could be the main reason for such variations. However, the crystallisation sequence of common salts in the different sampling intervals did not vary significantly. Moreover, the Runsalts thermodynamic calculations confirmed the observations from the cation and anions analysis, where the more soluble salts crystallised at higher levels of the profile than the less soluble ones.

All in all, the Runsalts results from selected samples at the treasury revealed the importance of including the thermodynamic considerations in the evaluation of the salt composition and behaviour of a certain salt solution. Therefore, the evaluation of the salt composition and behaviour should consider not only the types of cations and anions but also the interaction between different anions as well as their interaction with the surrounding conditions. In addition, the variations in salt composition and behaviour from one sampling point to another and from one sampling season to another, showed how important it is to apply the calculations to as many samples as possible for a site the size of Petra. Further research is needed in order to study and compare the thermodynamic behaviour of salts at different seasons at this monument.

8. USING PHOTOGRAMMETRIC TECHNIQUES FOR 3D MODELLING AND 2D ORTHOPHOTOGENERATION.

8.1 Data Collection Using Laser Scanner

In our field investigation, laser scanning system GS100, manufactured by Mensi S.A., France was used to collect 3D point data. The scanner has a 360 by 60 degree field of view with maximum captured range of 100 meters with a linear error of less than 6 mm. The system is able to capture 5000 points per second and has calibrated video that take snapshot of 768x576 pixel resolution which is automatically mapped on to the corresponding point measurements. These images are used for scan registration and they are not sufficient for high quality texture mapping. 3D meshed model is generated using using Innovmetric Software, PolyWorks and Mensi Real Work Survey Software as shown in the Figure 10.

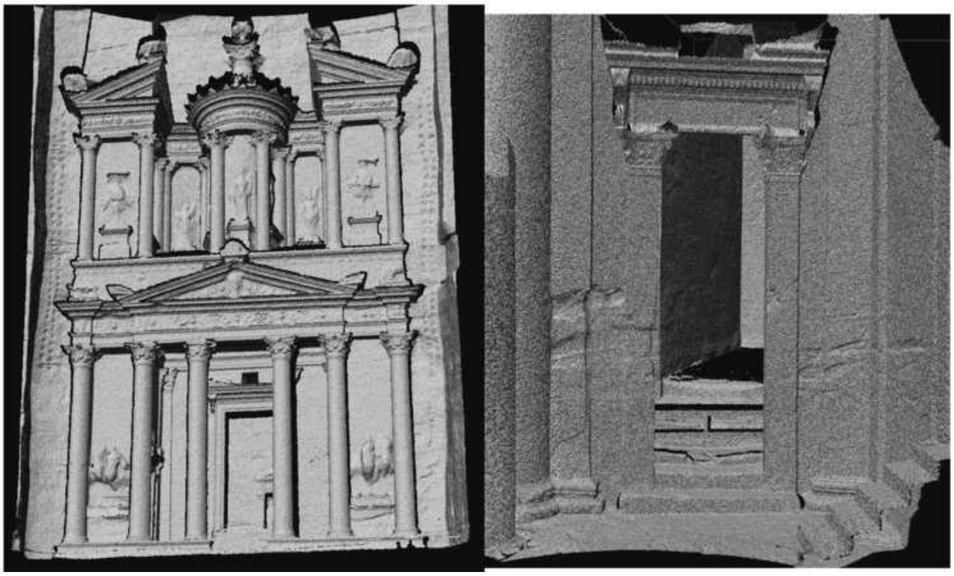

Figure 10. 3D meshed Model for Al-khasneh; outer façade and the right interior room

6.2 Integration Laser Data with Photogrammetry for Texture Mapping

Laser scanner model has a large number of 3D data represent the surface, but it can still be difficult to recognize and localize the outlines of the surface features such as the deterioration and cracks outlines which are clearly visible in the colored image, example the deterioration shown in figure 1. Such features are not discernible in the corresponding 3D meshed model shown in figure 10. For this reason, in addition to the laser data, digital images were captured for photogrammetric processing using a calibrated a Fuji S1 Pro camera, which provides a resolution of 1536x2034 pixels with a focal length of 20 mm. These images needed for high quality colouring of the 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 developed by (Alshawabkeh et al, 2005) is used. We have developed and adjust the illumination parameters of the algorithm in order to have highly realistic appearance to the model and offer a descriptive view of the scene. An example 3D model of a representative area of damage is given in figure 11 and 12. As it is visible, 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 registration of the weathering factors at the stone monument according to type, intensity and spatial distribution.

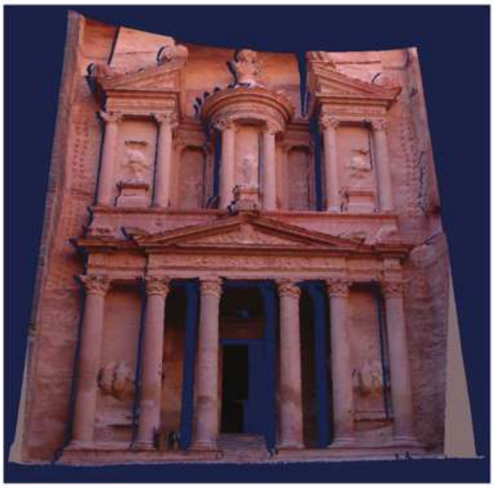

Figure 11: 3D textured model of Al-khasneh monument using image depicted in figure two

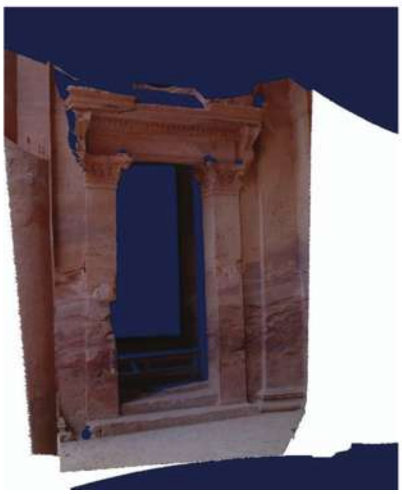

Figure 12: 3D textured model of interior right door of Al-khasneh monument using image depicted in figure two

6.3 Orthophoto Generation

Automatic detection and quantification of the cracks in historical structure using digital true orthophoto is another product of photogrammetry that could be used for accurate surveying and recoding in cultural heritage. The generated true orthophoto consists of a powerful textured representation combining geometric accuracy with a rich detail of the damaged area. In our application, the algorithm presented by (alshawabkeh et al, 2010) is applied for production of the true orthophoto of the right door of Alkhsneh. The algorithm uses precise 3D surface representations derived from laser scanning and digital images that cover the area of interest. Using two millimetre object size resolution of the required true orthophoto. The algorithm used the depth image generated from laser data to project every orthophoto pixel onto the original images with the collinearity equations. Then, an affine transformation is performed in order to find the exact location of the point in the colored image. Figure 13 shows the final product of the proposed algorithm.

Extraction of cracks from the image is conducted using digital image processing. The segmentation algorithms developed for image have been discussed extensively in the literatures (Palmer, 1996). The algorithms now can apply a real time segmentation of the intensity images; a widely used example is canny operator (Canny, 1986). The algorithms rely on differences in gray values of digital images. Cracks would be darker than the surrounding surface and could be easily extracted. Using an efficient edge segmentation operator for detecting deterioration and cracks outlines in the scaled orthophoto offers efficient approach for direct quantification and continuous record of the extent of damage in the whole affected area. In our application canny filter has been applied on the generated trueorthophotos for edge extraction. The segmentation result overlaid the trueorthopho is depicted in Figure 14.

Figure 13. True orthophoto of the right door of Alkhsneh with two millimetre object size resolution.

7. CONCLUSION

The current research has shown that iconic monument of Petra is under a huge potential risk. The results of the current research did not only provide us with a comprehensive documentation of the current status of this valuable monument, but it also extended to provide indication of the main threats at the no-renewable heritage site. A number of decay features, despite of their low intensity, are widespread at this monument. Salt damage appears to be one of the main problems at this monument. Although, the total soluble salt content are quite low, but the salts contamination is all over the tested samples in all seasons, with higher concentrations at deep intervals. These figures are very alarming since salts are higher at higher depth which means more potential damage at the monument could happen in the near future. Based on the findings that fluctuation of wind speed normally accelerates the salt crystallisation process and, thereby, the potential for higher stone decay rates, compared to the steady flow of

Figure 14. Image left, feature detection sing canny operator convolved the true orthophoto. Image right, the segmentation results projected over the trueorthophoto.

high or low wind speed, it is clear that fluctuation of this factor should be contained in order to minimise salt damage at Petra monuments. The study concluded that any intervention in the site should take in consideration a full thermodynamic calculation for the salt movement since a noticeable variation were noted from one season to another.

Both preventive and remedial conservation actions are needed to protect the icon of world Heritage site of Petra.

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