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CULTURAL HERITAGE SITE UNDER RISK: A CASE STUDY FROM PETRA, JORDAN

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ABSTRACT

One of the major problems facing the World Heritage Site of Petra is of salt damage caused by weathering effect; this study examined and monitored the salt types and distribution within four different monuments at the site; these were the Treasury, Palace Tomb, Deir Tomb, and the Theatre. The study examined the interaction of both single salts and the salts in mixed solutions and their effect on each other's solubility, it also determined the 'safe' levels of relative humidity where salt damage in monuments or objects contaminated with these salts can be minimized.

KEYWORDS: Weathering effect, salt damage, thermodynamic analysis, Petra/ Jordan

1. INTRODUCTION

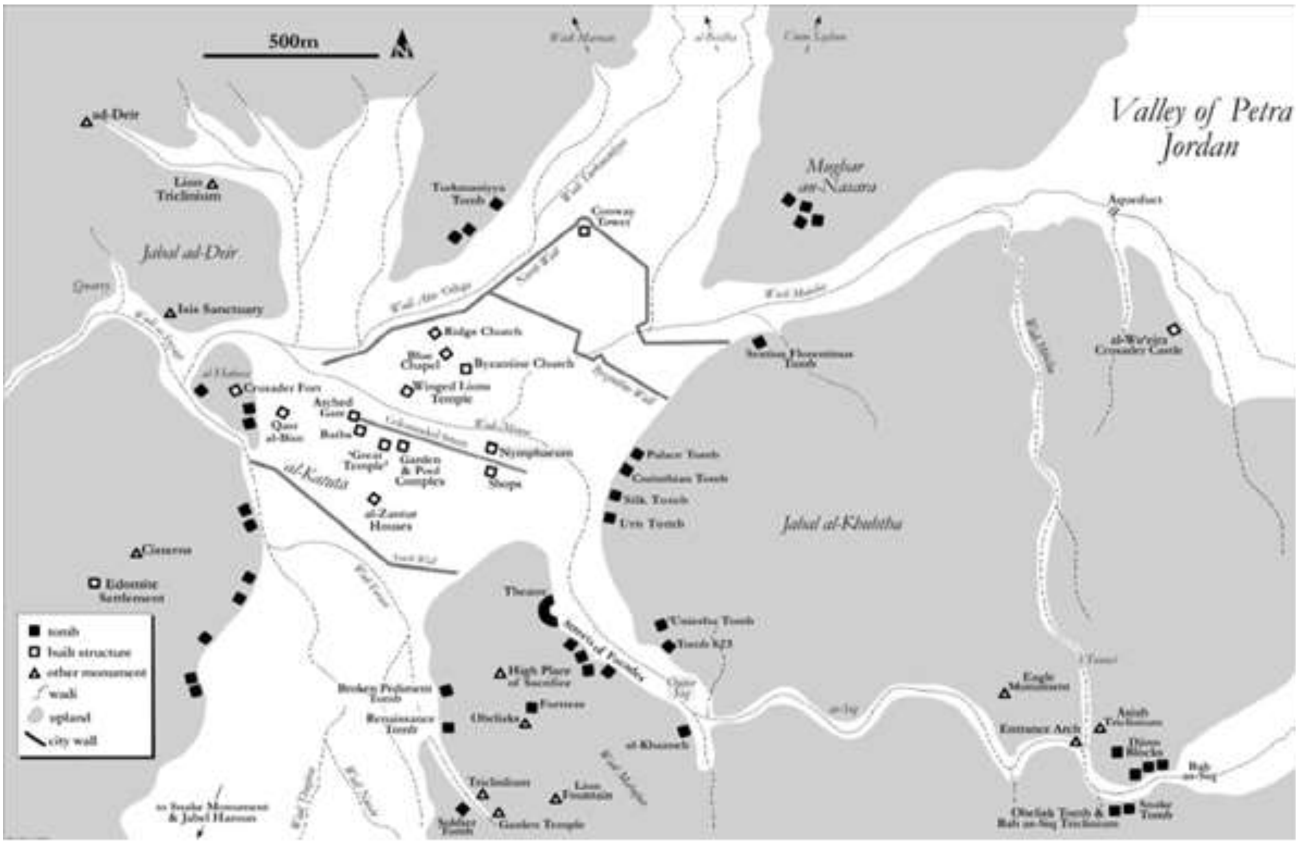
Petra was listed as a World Heritage Site in 1985; despite the great economic benefits gained by tourism to this heritage site, a great pressure and negative impacts caused by the increasing influxes of tourists made UNESCO consider it as an endangered site (UNESCO 1993). There are some potential economic, sociocultural and environmental negative impacts that are threatening the future of the site in the absence of a sustainable management plan for the site. For negative environmental impact taking place at Petra, these take many forms; one of them is damage caused by tourists' behaviour while navigating within the site. The random climbing and movement on site's rock-cut features is leaving drastic effects. According to Tom Paradise, a geomorphologist from the University of Arkansas at Fayetteville, the fact that people are wearing shoes with soles that grab on everything instead of the rubber-soled working boots or soft sneakers, is causing the quick disappearance and loss of rock carved features; moreover, parts of the façade of the Khazneh [the Treasury] had lost sand because that is where tour guides let people sit, he indicates that this caused the loss of half a cubic meter of sandstone over few years. Another threat facing Petra is the rising level of humidity resulted by the crowds of the tourists present at the site, which is an obstacle facing the preservation of sandstone. An indicator of deterioration is presence of the white deposits on the walls of carved tombs, mainly the Treasury; according to Paradise, tests showed that the deposits are to be of stearic acid, when people rest by leaning against the wall with sweating hands, they leave a scum of fat behind (Lubick 2004). Horse and camel rides are also causing a problem to the site since the dust raised by these animals becomes encrusted on the sides of the Siq. (UNESCO 1993). Some graffiti is also to be seen on the rock cut Siq and tombs of the city. Littering can be also noticed although of the littering cans placed throughout the site. In addition to the danger caused by tourists and tourism development, other natural factors are negatively affecting the site; one of these is the corrosion of lower sections of facades by the wind which carries sand particles from the crumbling sandstone rock. Also, the water that infiltrates into the rock by capillary action enables vegetation to grow in the interstices, consequently resulting in the fracture of rock, and in worse cases rock fall (UNESCO 1993). Not less important than all previous problems is the one of salt damage caused by weathering effect; this study will examine and monitor the salt types and distribution within the four different monuments in the world Heritage site of Petra. The case study monuments are the Treasury, Palace Tomb, Dier Tomb, and the Theatre.

This research is part of a project that aims at measuring and estimating the different impacts negatively affecting the archaeological sites in Jordan. This will be done by selecting some particular sites that are exposed to different kinds of problems that are causing their deterioration. Different scientific methods are used to measure such impacts; these sites are as follows with some of the problems they are facing: Petra: salt damage, wear and tear, humidity, air/wind, existence of animals in the site, wrong conservation actions and vegetation; Amman Citadel: waste, traffic congestion, fires, being close to residential areas, illegal excavations, wear and tear, and vegetation; Jerash: crowding, festivals, wrong conservation actions, managerial problems, wear and tear, and traffic close to site and Ghor es-Safi: agricultural activities and illegal excavations.

The results of the research will help in achieving the following implications: increasing awareness about problems facing these sites, it will help also in developing a set of procedures to decrease and mitigate different negative impacts, as well as in developing standards for implementation when planning for the tourism development of these sites, and in putting guidelines to conserve sites appropriately, also to minimize and avoid the negative impacts caused by extensive visitation to these sites.

2. ABOUT THE SITE

The archaeological city of Petra with its 2000 sandstone rock-cut façades was hewed into coloured sandstone and Limestone Mountains. The city of Petra lies hidden in the Desert Mountains in the southern part of Jordan (35° 25′ E - 35° 28′ E and 30° 19′ N - 30° 21′ N), it is 255 km far from Amman (the capital of Jordan). The city of Petra occupies an area of 15 km^2 and is 900 to 1500 m above sea level. The archaeological park which includes the ancient city is accessed through an outer Siq (path) in which significant features as Obelisk tombs and Djen Blocks can be seen, then a natural gorge known as Siq with a length of 1200 m with the water channels system is still existing, as well as niches and the two statutes of Dushara and al-Uzza gods. The Siq then widens upon the most magnificent of all Petra's monuments al-Khazneh (meaning Treasury in Arabic), which is carved out of solid rock with a height of 40 m. the Siq continues through the ancient city were different features can be observed; these include the Street of Facades, the Amphitheater which can accommodate more than 6000 spectators, the Royal tombs (Urn Tomb, silk tomb, Corinthian Tomb and Palace Tomb), also the Mausoleum of Sextus Florentinius; that is in addition to the colonnaded street leading to triple-arched Temenos Gateway which marked the entrance into the courtyard or "temenos" of Qasr al-Bint, one of the main Nabataean temples in the city. Other remains include Nymphaeum, the Great Temple Complex, Temple of the Winged Lions, Petra Church, Blue Church, a number of high places (with their platforms for the purposes of giving animal sacrifices), al-Deir (the Monastery) with its huge façade (50 meters wide and 45 meters high), a big number of tombs as the Lion tomb, Garden Tomb, Tomb of the Roman Soldier, Triclinium (Feast Hall), as well as many other features (Map 1). In general, the remains of the city are dated to different periods within Hellenistic Period (2nd century B.C.) to Late Byzantine Period (6th century A.D.) (Causle 2003; Teller 2006). Map 1 shows the most important carved monuments in the city. The monuments of Petra are unique in their architecture, structure and durability. The presentation of the monuments of Petra is beyond the scope of this research; however, four of the monuments will be presented here as case studies, where the samples and the microclimate data for this research project were collected.



Map 1: A map showing the locations of different archaeological features of Petra (Petra National Trust 2011)

3. THE SELECTED MONUMENTS

3.1 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). 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 façade is 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 (Ulama 1997; Khouri 1986). The upper story includes a central tholos surrounded by columns and flanked by two pavilions with a broken pediment 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

3.2 The Palace Tomb

The Palace Tomb is one of the three large façades at the eastern side of the city, known as Royal Tombs. It is so-called because it is a copy of the design of a Roman palace (Ulama 1997, Khouri 1986, Kennedy 1925). The lower part is a rock-cut façade, while the two upper parts are built as free-standing façades (Markoe 2003). Many writers such as Taylor (2001), Vivekanand (1995) and Maqsood (1994) have suggested that the Palace Tomb housed the last Nabatean kings (King Rabbel II, 75-106 AD). The Palace Tomb is one of the most impressive monuments in Petra, as it is located at the edge of a mountain cliff; it has a complicated architectural structure and an unusual appearance. Being at the edge of a mountain and in a very open area, as well as its highly deteriorated state, all are the main reasons for its selection as a sampling point.

3.3 The Deir Tomb (The Monastery)

The Deir (meaning monastery in Arabic) received its name from the cave that is known as the Hermit's Cell. The journey to the Deir Tomb requires the climbing of 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 Nabataean capitals, the upper storey, which is better preserved, has eight columns with a conical central roof crowned with an urn. There is no actual dating for the Deir, however, many writers such as Bourbon (1999), Taylor (2001) and Khouri (1986) suggest the middle of the first century (44-70 A.D.). The monument's location on the edge of a high mountain and the presence of two different levels of stone decay are the main reasons for selecting this monument for sampling in the study.

3.4 The Theatre

Petra's theatre is typically Roman in its, Dr. Hammond in his excavations (1961-62) dated this feature to the first century A.D, possibly to the reign of Aretas IV, a time when Nabataean contact with Rome was strong (Browning1989). It has a seating capacity of 4000 people; it has a semi-circular orchestra measuring about 125 feet across its broadest and consists of 45 rows of seats that are divided horizontally by two diazomata. Above the cavea are numerous tomb facades, which were destroyed to make way for the theatre's upper tiers of seating. Petra's theater is cut in a solid rock that is badly deteriorated; the front side of the theatre (including most of the stage) was badly damaged by floods.

4. THE EFFECT OF SALT DAMAGE ON THE SITE

4.1 Methodology and Analysis

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 climatic data from the case study sites was an essential part of the current research. The study is based on detailed environmental monitoring programs for the microclimate condition within the site of Petra. The evaluation of microclimate data is carried out through the correlation between three microclimate monitoring programs; the first monitoring program involved detailed recording of the temperature and the relative humidity over a period of 18 months (August 2003- April 2005), using Gemini Tinytag Plus (TGP-1500) loggers (Balaawi 2006), the second monitoring program was during (April 2012- April 2014). Unfortunately, data loggers were not available for the recording of the wind speed and, therefore, spot readings were the basis for the evaluation of this environmental parameter. During each fieldwork visit to the case study locations, a group of detailed wind speed spot readings were taken, the wind speed was monitored for 12 hours using a Lutron hand anemometer (Am-4201).

4.1.1 First Monitoring Program

Generally, Petra microclimate data demonstrates the domination of the dry, hot and fluctuating wind speed conditions throughout the majority of the year. Besides, the high rate of fluctuation of the relative humidity and wind speed around the studied monuments was very obvious (see figure 1a & b). The data reveals a high fluctuation of these factors, not only between one period of the year and another, but even between one location and another within the same period. A considerable variation was also noted between readings that came from the same monument in different sampling points. Moreover, the wind speed figures showed that the Palace Tomb had the highest wind speed readings, also the highest rates of fluctuation in all the fieldwork visits, the wind speed fluctuation rates during daytime were higher than during night-time. By comparing and relating the spot readings for the three environmental factors (temperature, relative humidity and wind speed), the impact of the wind speed on relative humidity was evident. As the wind speed increased, the relative humidity dropped slightly, a condition that could be related to the dry nature of the wind in the area where Petra is located, the fall of the relative humidity was, in effect, accompanied by an increase in the temperature.

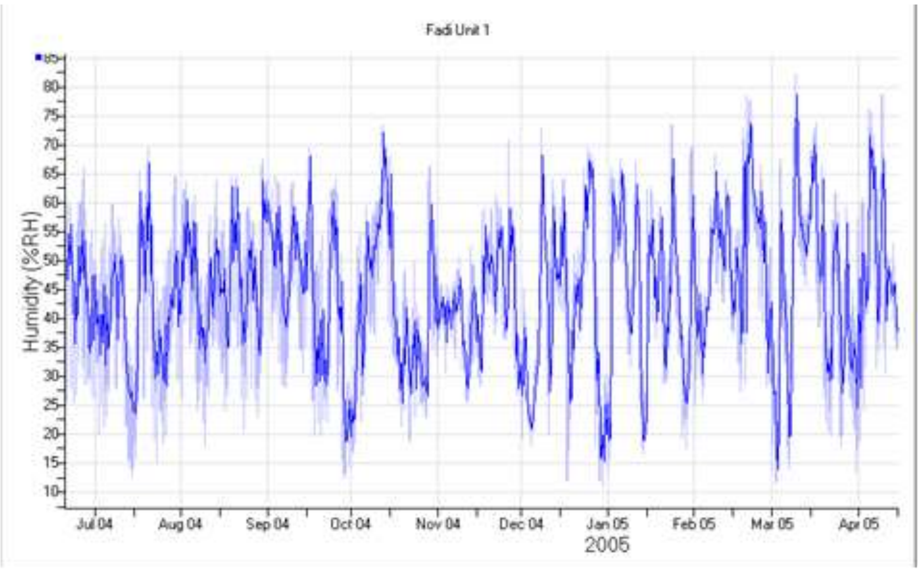


Figure 1a: The Relative humidity readings from the data logger, location: Deir Tomb.
(Recording Period: 20 June 2004-16 April 2005)

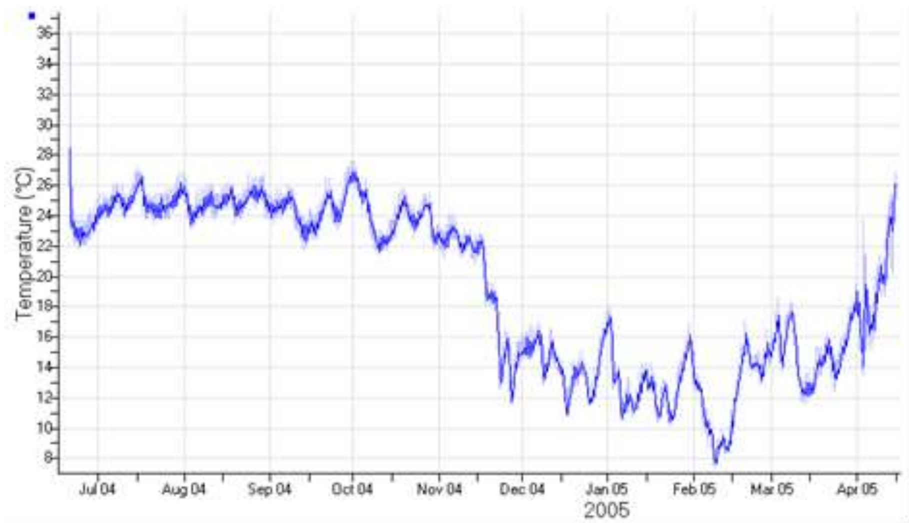


Figure 1b: Temperature readings from the data logger, location: Deir Tomb.
(Recording Period: 20 June 2004-16 April 2005)

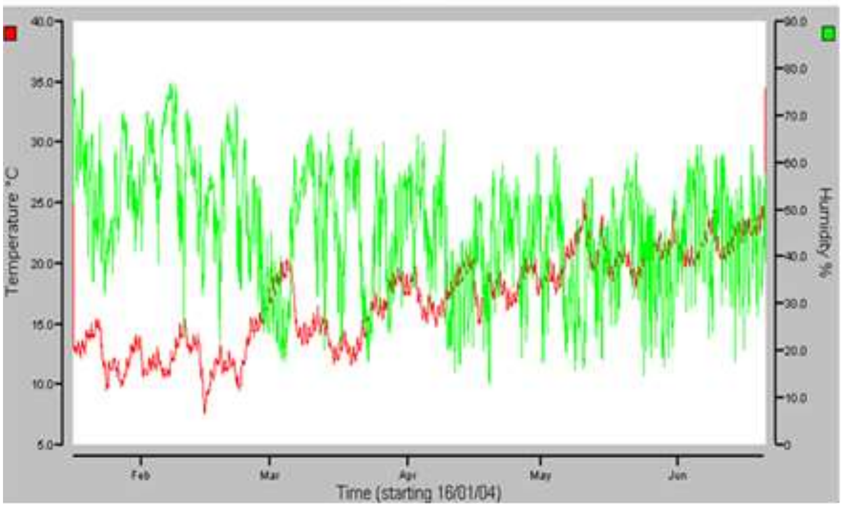


Figure 2: The temperature and humidity readings in Petra Area.
(Recording Period: 15 January 2013 -14 June 2013)

4.1.2 The Second Monitoring Program

Based on the detailed monitoring program, the microclimate conditions during summer periods could be summarized 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 relative humidity ones, with January and February as the most humid months.

4.1.3 Third Monitoring Program

It should be mentioned that the current study is continuing monitoring the environmental conditions using 2 tiny tag 2 plus 4500 loggers installed in a sheltered area, the first near the theatre and the other one is near the Palace Tomb. The monitoring program will be for 2 years (April 2012- April 2014) and the results from this program will be compared with the two previous monitoring programs, more upcoming research will reveal the results after finalizing measurement process, the overall microclimate conditions of the four studied monuments could be evaluated in great depth.

In order to get a clear indication about wind speed at the studied monuments, wind speed spot readings were taken at different heights at each monument. The readings were taken at approximately 1m distance from the surface of the façade or the structure. A total of 20 sets of spot readings were taken at each sampling point, each of which consisted of five spot readings. The wind speed was monitored for 4 days in each fieldwork visit. Till now, 2 fieldwork visits were made to the site, the first was in August 2012 and the second was in January 2013. During the first fieldwork visit (August 2012), wind speed spot readings were taken at five selected sampling locations in each case study monument. Generally, the airflow measurements have shown a wide fluctuation at the four locations; however, the same wind speed trend could be traced in all case study monuments, where slow wind speed readings were featured during the morning session (6am-10 am), slightly higher wind speed profiles between 10 am till 1 am and finally a slightly high wind speed profile between (1 pm till 6 pm). The data from the second fieldwork visit (January 2014), has shown that 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, this can be seen in Table I, which shows wind speed spot readings in the Treasury Tomb, Petra for the visit of January 2012.

Table. I: Wind speed spot readings. Location: The treasury Tomb, Petra/ Jordan. (12 January 2012)

Location	Date	Height (cm)	Time	Maximum wind speed (m/s)	Minimum wind speed (m/s)	Average wind speed (m/s)
T1	12.1.2012	5	05.00	0.30	0.00	0.25
T1	12.1.2012	5	06.00	0.60	0.05	0.30
T1	12.1.2012	5	07.00	0.50	0.05	0.30
T1	12.1.2012	5	08.00	0.70	0.20	0.40
T1	12.1.2012	5	09.00	0.95	0.25	0.60
T1	12.1.2012	5	10.00	1.05	0.30	075
T1	12.1.2012	5	11.00	1.25	0.25	0.80
T1	12.1.2012	5	12.00	0.75	0.05	0.30
T1	12.1.2012	5	13.00	1.20	0.10	0.50
T1	12.1.2012	5	14.00	0.30	0.10	0.20
T1	12.1.2012	5	15.00	0.90	0.30	0.60
T1	12.1.2012	5	16.00	1.60	0.30	0.85
T1	12.1.2012	5	17.00	1.50	0.25	0.85
T1	12.1.2012	5	18.00	2.05	0.50	1.05

The determination of the salt types and their distribution in the treasury monument at Petra has a great significance in understanding and evaluating the weathering process affecting case study monuments. 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; Rossi-Manaresi & Tucci 1991).

4.2 Sampling and Sampling procedure

The soluble salts content (TSSC) of the case study monuments was tested by analyzing 12 selected samples from each monument. The TSSC is being measured within four seasons: August 2012, January

2013, May 2013 and August 2013. 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 a very short period of time. However, the authors' argument is that the samples were collected during four different seasons when major climatic changes are taking place in the area, and that 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 case study area; expect the ones from the theatre where samples were taken from the structure itself. The tested profile was 6m high, six sampling points were chosen, three different depth intervals were taken from each sampling point (0-1 and1-3). 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 percentage of salt per weight unit of dried stone powder sample (0.2 g).

4.3 Salt soluble content from the first fieldwork visit

4.3.1 The Treasury location

The total soluble salts content at Treasury monument during the first fieldwork visit (August 2012) was generally low. The total soluble salts content at the tested profile ranged between 0. 27 and 0.42 % with an average of 0.36 %. All previous data suggested that due to the high evaporation rate during the summer visit, the salt mobility was low and therefore, the overall soluble salts were slightly low. Tables II & III show soluble salt content in the sample (%) of dry weight as well as the cations and anions for Treasury sample.

Table II: Soluble salt content in the sample (%) of dry weight in Treasury monument.

Sample Number	Height (cm)	Depth (cm)	Soluble salt content in the sample (%) of dry weight
T1	10	0-1	0.38
T2	10	1-3	0.37
T3	110	0-1	0.36
T4	110	1-3	0.39
T5	210	0-1	0.41
T6	210	1-3	0.41
T7	310	0-1	0.37
T8	310	1-3	0.42
T9	410	0-1	0.29
T10	410	1-3	0.36
T11	510	0-1	0.23
T12	510	1-3	0.27

Table III: Salt contents main cations and anions for Treasury sample

Sample Number	Height (cm)	Depth (cm)	Ca (ppm)	Na (ppm)	Mg (ppm)	K (ppm)	Cl (ppm)	NO_3 (ppm)	SO_4 (ppm)
T1	10	0-1	1.15	11.70	0.10	0.63	2.10	29.30	0.81
T2	10	1-3	0.80	10.87	0.14	0.55	3.14	24.30	0.23
T3	110	0-1	0.41	8.97	0.24	0.71	3.01	25.7	0.19
T4	110	1-3	0.39	9.14	0.41	0.55	7.11	24.14	0.09
T5	210	0-1	8.90	8.58	0.87	1.26	4.37	33.60	3.14
T6	210	1-3	8.83	8.67	0.84	1.22	5.01	32.78	3.44
T7	310	0-1	11.34	17.28	0.99	0.87	8.57	3.07	15.41
T8	310	1-3	10.47	15.74	1.02	0.77	9.01	3.03	13.54
T9	410	0-1	10.27	9.21	0.73	1.24	7.14	1.41	12.31
T10	410	1-3	9.57	12.41	0.63	1.14	8.74	2.10	11.99
T11	510	0-1	5.96	11.47	0.81	1.47	10.47	1.78	12.04
T12	510	1-3	5.87	10.99	0.77	1.23	9.87	2.02	11.85

4.3.1 The Palace Tomb location

The total soluble salts content at Palace Tomb location was much higher than the Treasury during the first fieldwork visit (August 2012). The total soluble salts content at the tested profile ranged between 0.68 and 2.14 % with an average of 1.31 %. The current high readings of soluble salts are in conjunction with the high wind speed readings at this location, since the highest wind speed measurement as well as the highest wind speed rates of fluctuation were recorded at the Palace Tomb location.

Table IV: Soluble salt content in the sample (%) of dry weight in Palace Tomb monument.

Sample Number	Height (cm)	Depth (cm)	Soluble salt content in the sample (%) of dry weight
P1	10	0-1	1.74
P2	10	1-3	1.88
P3	110	0-1	1.24
P4	110	1-3	1.27
P5	210	0-1	2.14
P6	210	1-3	2.09
P7	310	0-1	1.34
P8	310	1-3	1.37
P9	410	0-1	0.68
P10	410	1-3	0.64
P11	510	0-1	0.71
P12	510	1-3	0.73

Table V: Salt contents main cations and anions for Palace Tomb sample

Sample Number	Height (cm)	Depth (cm)	Ca (ppm)	Na (ppm)	Mg (ppm)	K (ppm)	Cl (ppm)	NO_3 (ppm)	SO_4 (ppm)
P1	10	0-1	40.10	11.03	1.29	8.78	11.78	35.10	200.10
P2	10	1-3	36.41	10.58	1.21	8.14	11.33	37.80	187.30
P3	110	0-1	122.36	16.79	4.02	8.98	15.40	74.69	0.87
P4	110	1-3	119.36	17.04	5.01	9.01	16.74	77.36	0.88
P5	210	0-1	65.65	17.27	1.69	16.03	28.01	5.64	239.70
P6	210	1-3	70.31	18.10	1.66	17.07	30.14	6.07	240.36
P7	310	0-1	47.16	41.00	5.45	3.16	92.60	64.38	1.24
P8	310	1-3	48.02	44.30	5.07	2.89	95.21	66.64	1.20
P9	410	0-1	35.00	23.74	5.78	2.80	34.21	33.01	1.00
P10	410	1-3	34.14	23.07	5.09	2.74	33.54	34.78	0.97
P11	510	0-1	28.68	17.90	3.35	1.66	38.98	29.21	0.81
P12	510	1-3	26.14	18.01	3.09	1.74	40.01	29.87	0.77

4.3.3 The Dier Tomb location

The total soluble salts content in the location were the lowest between all locations. The total soluble salts content at the tested profile ranged between 0.21 and 0.48 % with an average of 0.35 %. The noticed feature in this profile is that all samples have shown a very close range of total soluble salt content compared to previously tested locations where considerable variations were noticed between the tested samples at each profile. This could be related directly to slow wind speed conditions at this location since the microclimate monitoring program revealed that the Dier location had the slowest and the most steady wind speed readings between all profiles. Calcium and sodium were the main cations while sulphate and chloride were the main anions. However, the sodium and chloride ions showed a clear increasing trend towards the upper part of the sampling profile, while calcium ions decreased slightly towards the upper end of the profile.

Table VI: Soluble salt content in the sample (%) of dry weight in Deir monument

Sample Number	Height (cm)	Depth (cm)	Soluble salt content in the sample (%) of dry weight
D1	10	0-1	0.21
D2	10	1-3	0.23
D3	110	0-1	0.27
D4	110	1-3	0.34
D5	210	0-1	0.35
D6	210	1-3	0.33
D7	310	0-1	0.37
D8	310	1-3	0.41
D9	410	0-1	0.40
D10	410	1-3	0.43
D11	510	0-1	0.45
D12	510	1-3	0.48

Table VII: Salt contents main cations and anions for Deir sample

Sample Number	Height (cm)	Depth (cm)	Ca (ppm)	Na (ppm)	Mg (ppm)	K (ppm)	Cl (ppm)	NO_3 (ppm)	SO_4 (ppm)
D1	10	0-1	5.25	16.90	0.58	1.44	9.40	5.64	0.88
D2	10	1-3	5.64	17.22	0.54	1.26	10.32	5.61	0.87
D3	110	0-1	10.09	10.50	1.26	0.98	10.33	6.78	8.24
D4	110	1-3	9.87	11.24	1.21	1.23	11.69	5.87	6.14
D5	210	0-1	7.04	8.14	0.85	0.55	7.14	33.47	6.04
D6	210	1-3	6.87	8.54	0.79	0.49	8.14	30.14	5.14
D7	310	0-1	6.54	9.01	0.85	0.51	8.88	27.89	5.01
D8	310	1-3	6.02	10.21	1.01	0.64	11.05	26.14	5.04
D9	410	0-1	5.69	13.59	1.24	1.22	16.39	36.12	5.30
D10	410	1-3	5.51	14.63	1.40	1.28	17.30	33.01	4.01
D11	510	0-1	5.02	15.55	1.39	1.33	17.98	34.10	4.11
D12	510	1-3	5.08	15.01	1.44	1.40	18.01	34.34	4.05

Table VIII: Soluble salt content in the sample (%) of dry weight in Nabataean Theater

Sample Number	Height (cm)	Depth (cm)	Soluble salt content in the sample (%) of dry weight
NT1	First Left row	0-1	0.31
NT2	10th Left row	0-1	0.44
NT3	20th Left row	0-1	0.47
NT4	30th Left row	0-1	0.62
NT5	45th Left row	0-1	0.63
NT6	First middle row	0-1	0.33
NT7	10th middle row	0-1	0.33
NT8	20th middle row	0-1	0.61
NT9	30th middle row	0-1	0.74
NT10	45th middle row	0-1	0.77
NT11	First right row	0-1	0.40
NT12	10th right row	0-1	0.41
NT13	20th right row	0-1	0.50
NT14	30th right row	0-1	0.63
NT15	45th right row	0-1	0.66

Table IX: Salt contents main cations and anions for Nabataean Theater

Sample Number	Height (cm)	Depth (cm)	Ca (ppm)	Na (ppm)	Mg (ppm)	K (ppm)	Cl (ppm)	NO_3 (ppm)	SO_4 (ppm)
NT1	First Left row	0-1	10.76	21.44	1.40	1.60	1.60	4.45	9.44
NT2	10th Left row	0-1	17.13	10.64	1.51	3.03	3.08	5.01	12.25
NT3	20th Left row	0-1	10.11	12.06	1.43	1.23	16.13	18.69	6.19
NT4	30th Left row	0-1	12.00	16.11	2.02	1.69	23.03	47.36	4.12
NT5	45th Left row	0-1	11.25	17.25	2.04	1.66	24.69	45.45	4.03
NT6	First middle row	0-1	11.59	19.69	2.20	1.80	3.01	5.69	8.87
NT7	10th middle row	0-1	15.69	13.69	1.55	2.25	4.58	5.04	10.36
NT8	20th middle row	0-1	11.07	23.01	1.44	1.29	18.67	19.87	6.89
NT9	30th middle row	0-1	15.58	27.89	2.70	2.45	40.10	30.14	5.89
NT10	45th middle row	0-1	15.04	29.66	2.80	2.52	44.36	31.16	5.88
NT11	First right row	0-1	13.01	18.74	2.25	1.74	3.09	6.41	9.14
NT12	10th right row	0-1	12.69	19.21	2.22	1.74	4.04	6.13	8.66
NT13	20th right row	0-1	11.99	26.81	2.80	2.09	9.01	8.58	7.58
NT14	30th right row	0-1	11.20	24.69	1.60	2.39	29.14	11.89	6.66
NT15	45th right row	0-1	10.87	27.51	1.75	2.45	30.18	12.04	6.08

4.3.4 The Nabataean Theatre

Due to the importance of this location as one of the few carved theatres worldwide, only surface samples were taken to evaluate the soluble salt content on the theatre. The total soluble salts content was slightly high at theatre surface samples especially for the middle section samples. The second highest sampling profile was in the right section, with the left section of the theatre recording the lowest salt content figures. In general, and in all sections, the total soluble salts increased with height. This wind speed measurement figures showed that the wind speed showed similar trend to the soluble salt content, which could indicate that the highest wind speed location recorded the highest soluble salt content. The results of the fifteen samples taken from the Nabataean Theatre during the first fieldwork visit revealed that sodium and calcium were the major cations, while magnesium and potassium were found in much lower concentrations. Sulphate and chloride were the major anions. Nitrate and phosphate existed in very low concentrations.

5. THERMODYNAMIC CONSIDERATION OF THE SOLUBLE SALTS ECOS PROGRAM (RESULTS AND CONCLUSIONS)

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 behavior of the soluble salts in relation to the surrounding environmental conditions is needed.

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 run-salt program, which is a graphical user interface to the ECOS thermodynamic model, will be used to study the salt composition and behavior 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 behavior at the studied monument. The run-salt 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 run-salt applications showed that temperature did not significantly affect the salt solution's behavior, while relative humidity had the greatest impact. Therefore, the current research has used run-salt 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 temperature for the first fieldwork visit was 32 ^{o}C.

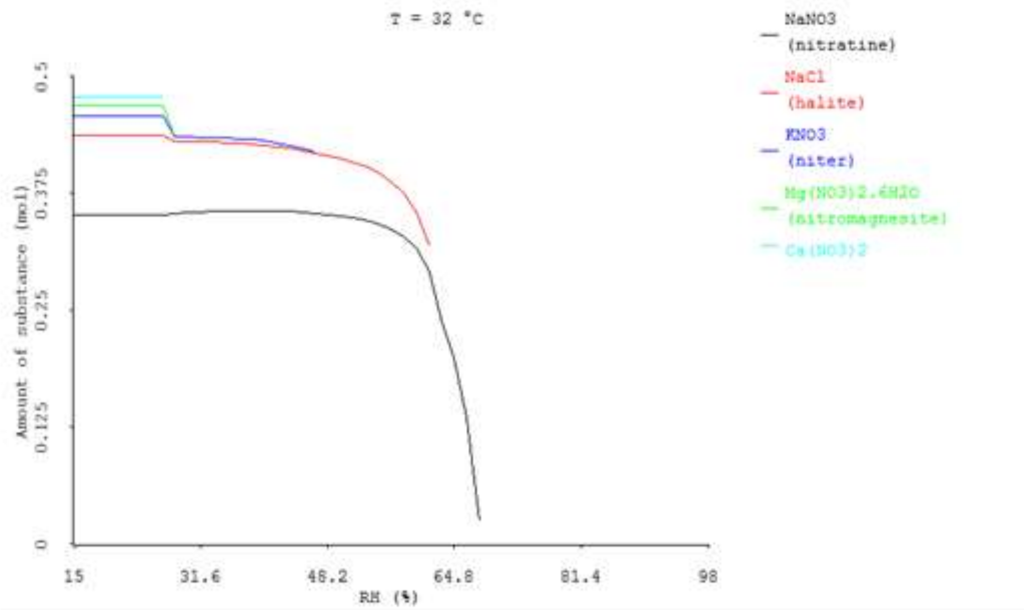


Fig. 3 Thermodynamic analysis using ECOS. Crystallization sequence of soluble salts: relative humidity against amount of substance (mol). Sampling number (T1). First fieldwork visit August 2012. Location: The Treasury Tomb (T3). (After the removal of Gypsum).

Based on the evaluation of the thermodynamic figures at the four locations, the dangerous ranges, safe ranges and relatively safe ranges of relative humidity readings are listed in Tables X-XIII.

Table X: Ranges of safety and danger for humidity reading in Treasury Monument

Sample Number	Dangerous relative humidity ranges (%)	Safe relative humidity ranges (%)	Relatively Safe relative humidity ranges (%)
T1	61-68 26-32	Above 68	33-60 15-25
T2	61-68 26-32	Above 68	31-60 15-26
T3	61-68 26-28	Above 69	15-26 40-28
T4	62-63 26-36	Above 63.5	37-61 15-25
T5	26- 38 55-56	Above 57	15-25 37-54
T6	26-36	Above 60	15-25 48-58
T7	58-70	Above 78.5	15-19 23-57
T8	54-71	Above 72	34-53 15-20
T9	56-70 27-35	Above 71.5	31-55 15-27
T10	54- 70 31-36	Above 71.5	15-30 37-53
T11	54-70 34-36	Above 71.5	15-20 37-35
T12	26-42	Above 71.5	15-26 41-71

Table XI: Ranges of safety and danger for humidity reading in the Palace Tomb Monument

Sample Number	Dangerous relative humidity ranges (%)	Safe relative humidity ranges (%)	Relatively Safe relative humidity ranges (%)
P1	19-21 58-77	Above 78	20-57 15-19
P2	40-48 58-70	Above 85	22-40 49-57
P3	27-38	Above 38.5	15-27
P4	23-39.5	Above 40	15-23.5
P5	31-33 59-72	Above 87.5	33.5-58 15-31
P6	50-65	Above 65.5	20-48
P7	17-31 64.5-65	Above 67	31.5-64 15-17
P8	19-33 64-64.5	Above 65	15-18.5 33-63
P9	19-33 64-64.5	Above 65	33-36 15-18.5
P10	18.5-31 63-63.5	Above 64	33-63 15.18.5
P11	17-31 6.35-64	Above 63	15-17 32-62
P12	17-31 63.5-64	Above 65	15-17 32-63

Table XII: Ranges of safety and danger for humidity reading in Deir Monument

Sample Number	Dangerous relative humidity ranges (%)	Safe relative humidity ranges (%)	Relatively Safe relative humidity ranges (%)
D1	24-33 69-69.5	Above 70	15-24 35-68
D2	25-34.5 68-69	Above 70	15-28 35-68
D3	22-32 67-67.5	Above 68	15-21.5 33-67
D4	19-31 67.5-68	Above 68.5	15-19 32-67.5
D5	26-37 56-61	Above 62	15-25.5 37-55
D6	26.5-36.5 58-59.5	Above 60	15-26 37-57
D7	26.5-36.5 59-59.5	Above 60	15-26 37-38
D8	26.5-34.8 59-63	Above 63.5	15-25 35.5-59
D9	26-33 59.5-62.8	Above 63	15-25 34-59
D10	26-33 59.8-64.8	Above 65	15-25 33-58
D11	26-33.5 59.8-65	Above 65.5	15-26 32.5-59
D12	25.8-33.5 59.8-64.8	Above 65	15-26 33-58

Table XIII: Ranges of safety and danger for humidity reading in Nabataean Theater Monument

Sample Number	Dangerous relative humidity ranges (%)	Safe relative humidity ranges (%)	Relatively Safe relative humidity ranges (%)
NT1	19-21 41-43 57.5-77.5	Above 78	15-19 21.8-40 43.57
NT2	31-37 54-64.5	Above 65	15-30 37.5-54
NT3	24-35 63.5-64	Above 65	15-24 34-64
NT4	26-34 54.5-61	Above 61.5	15-25.5 37-53
NT5	26-35 56.8-62.5	Above 63	15-26 35-55
NT6	32.5-36.5 54.6-71	Above 71.5	15-31 37-53
NT7	31-37 53-67.5	Above 68	15-30 37.5-52
NT8	26.5-35 57.8-67.8	Above 68	15-26 35-57
NT9	22.5-34 67.5-68	Above 68.5	15-22 35-68
NT10	22.75-34.70 67-67.5	Above 68	15-23 34.567
NT11	9.7-21.6 35.15-36.6 54-69.7	Above 70	15-19 22-34 37-53
NT12	31-37 53-66.3	Above 66.5	15-30 37-55
NT13	26.7-46.5 61-67.8	Above 68	15-26 32-45
NT14	18-18.5 29.8-31.5	Above 70	15-17 32-69
NT15	27-29 68-69.5	Above 70	15-27 30-69

What makes the case here complicated is because contamination with single salts in porous materials is rare (Price 2000), while predicting the behavior of a salt mixture is much more complicated. Many models have been presented in the attempt to understand the behavior 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 behavior 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). Then dealing with single salts becomes a priority; the determination of the hygrothermal conditions that control the behavior of 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 it crystallizes 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 straight forward way by controlling the surrounding relative humidity and temperature, which should be carefully planned since monuments of Petra are all located in an open area. Care is vital preventing further risky effects (e.g. Shadi & Bashar, 2015).

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