Stone Weathering in the Monastic Building Complex on Mountain of St Aaron in Petra, Jordan.

Susanna Eklund
University of Helsinki
Institute for Cultural Studies
Department of Archaeology
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1 Introduction

Since 1997 the Finnish Jabal Haroun Project (FJHP) has studied the ruins of the monastery and pilgrimage complex (Gr. oikos) of Aaron located on a plateau of the Mountain of Prophet Aaron, Jabal an-Nabi Harûn, ca. 5 km to the south-west of the UNESCO World Heritage site of Petra in Jordan. The project belongs to the research unit Ancient Greek Written Sources nominated by the Academy of Finland as a Center of Excellence in Research in 2000-2005 and in 2006-2011. Initially the project was funded by the Eemil Aaltonen Foundation, but at the time of writing it is funded mainly by the University of Helsinki. FJHP is directed by Professor Jaakko Frösen, University of Helsinki, with Dr. Zbigniew Fiema as chief archaeologist, Professor Mika Lavento as head of the survey team and Christina Danielli as senior conservator. The project is supported by the Department of Antiquities in Jordan.

Excavations have thus far revealed a large building complex, including a basilican church with an atrium and narthex, a chapel and several smaller rooms and auxiliary structures surrounding a central courtyard. The size of the entire site is ca. 2400m². It has suffered several earthquake-related destructions and the structures have been modified during each phase of rebuilding. The building complex served as a monastic/pilgrimage center in the Byzantine period, from the later 5th to the early 8th centuries A.D., possibly even later. Some structures at the site date back even further, to the Nabatean occupation of the area. (Fiema 2003.)

Unexcavated structures at the Jabal Haroun site are sheltered from outside climatic conditions. The surrounding soil offers support and a stable, moist environment. But when these structures are excavated, the conditions around them change suddenly.
Support of the soil is lost and the moisture in the structures evaporates rapidly causing e.g. salts to crystallize on and beneath the surface of the construction materials. As the structures dry, also the mud mortar that once held the stones in place loses cohesion. Many of the building stones are already weathered and fragile and as the supporting soil disappears, they may not be strong enough to support the weight of upper structures. These acute problems can be addressed by strengthening the structures with fresh jointing and by replacing weak stones with better ones. After this, however, the structures remain exposed to damaging outdoor climatic conditions. It is the responsibility of every research project in the archaeological park of Petra in southern Jordan, to plan and execute properly the long-term conservation of their excavation site (Petra Archaeological Park Operating Plan Draft 2000: 20/3).

The aim of this M.A. thesis is to observe the condition of the stone structures, especially the stone material, and to identify the damaging processes. Mortars and plasters are addressed in this work only briefly since they have already been researched by the projects’ senior conservator Christina Danielli and the results will be published in the upcoming FJHP publication (Fiema & Frösén, in press). As the site is very large and complex, damage assessment of the structures for this particular work needed to be restricted. The chapel was chosen as a case study since it represents the phases of occupation at the site while being small enough in size. Also the evaluation and study of the archaeological findings by the project is furthest with regard to the chapel and the church.

Potential damaging factors affecting the structures at the excavation site are examined in this thesis. One aim is to examine the climatic conditions affecting the ruins and also to find out if the climatic conditions on the mountain differ from the general conditions in the area. As Jabal Haroun is situated at a higher altitude\(^1\) than either Petra\(^2\) or Wadi Mousa, subzero temperatures are expected to occur more often up there. Also the relative humidity and amount of rainfall are expected to be higher than in the valley. For these reasons relative humidity and temperature were monitored and are set into local context. As salts are known to be an important factor in sandstone deterioration and

\(^1\) ca. 1250m above sea level (Frösén et al. 2002:25 )
\(^2\) ca. 900m above sea level (Barjous et al. 1992:1)
efflorescences have been observed on the structures also on Jabal Haroun, salt samples were taken for analysis. The aim is to find out what types of salts are present in the structures and to evaluate the possible threat they may pose in the context of the climatic conditions on the site. The paper pulp method developed by Ernesto Borelli (1994) was chosen for the extracting of the samples because of its nondestructive nature.

Methodology for the damage assessment on stone monuments in Petra has been developed by Bernd Fitzner and Kurt Heinrichs (1994, 2002, 2004) and the German-Jordanian Petra Stone Preservation Project, German Technical Cooperation Agency (GTZ) (Kühlenthal & Fisher 2000; Simon, Shaer & Kaiser 2004). It has been taken into account even though the documentation on Jabal Haroun follows rather the European Standard for Stone Damages (La Commissione Beni Culturali UNI-NorMal – 1/88). Weathering mechanisms and recession rates of sandstone in Petra have been studied by Thomas Paradise between 1990 and 2003 (e.g. 1995, 1998, 1999 and 2005). Geological studies of both natural formations and building stones in Petra have been published by Majdi Barjous and D. Jaser in 1992 (Geological Mapping Division), Friedrich Pflüger in 1995 and by Kurt Heinrichs and Bernd Fischer in 2000. These studies have been used as reference for the properties of the stone in the Jabal Haroun ruins, since the lithotypes in the structures correspond to the ones in Petra.

Andrew Goudie and Heather Viles (1997) present Petra as one case study in their marvelous book about the worldwide hazard of salt weathering. Although geographically somewhat farfetched from the point of view of Petra, the study by Thorborg von Konow (2002) of salt weathering in Suomenlinna fort in Finland provides valuable information about the properties and characteristics of certain salt compounds. Laboratory tests concerning the performance of sodium chlorides in the weathering of the local Umm Ishrin sandstone in Petra have been published by Lombardo et al. (2004). Climatic data from Petra has unfortunately not been published even though climatic monitoring has been done as part of the research projects mentioned above. Fortunately, with the kind assistance of Dr. Majdi Barjous, data concerning the year 2005 from the Wadi Musa weather station could be used in this thesis as reference and comparison.
My point of view in this thesis, as well as in the project, is that of both the conservator and the archaeologist as I have studied both fields and participated in the work of both teams. This kind of research is extremely multidisciplinary, as it is closely associated with chemistry, geology and physical geography. Some chemistry is fortunately included in the conservator’s schooling, but for a large part this work has opened new worlds to me and may be somewhat lacking in the eyes of an expert of any of these disciplines. In addition to the factors studied in this work, there are other factors (e.g. wind conditions, air pollution, earthquakes and tourism) threatening the Jabal Haroun ruins and stone structures in general, which should be considered when the protection and long-time conservation of the site are planned. This research offers a basis for the planning of long-term conservation and protection of the Jabal Haroun site and will hopefully be of use also for other research projects in the Petra area.

2 Background

2.1 Finnish Jabal Haroun Project

The Finnish Jabal Haroun Project (FJHP) is a multidisciplinary investigation project the goal of which is to study human occupation and adaptation in the Jabal Haroun area and its surroundings. Another goal is to study the significance of the area in a larger historical perspective. Teams consisting of archaeologists, surveyors, cartographers and conservators have worked on and around the mountain during eight seasons, the last excavation season being in 2007. The project acts also as a field school to train undergraduate and graduate students of archaeology, land survey and conservation from the Universities of Helsinki, Oulu and Turku, and the EVTEK Institute of Technology.

The archaeological survey team has aimed to study all evidence of past human activity in the surroundings of the mountain and to understand the role of the Jabal Haroun area in the regional context. Also the history of the extensive runoff cultivation system surrounding Jabal Haroun has been under investigation. The area surveyed between 1998 and 2005 covers ca. 6 km² including Jabal Haroun and its immediate surroundings. The multi-period survey has recorded numerous hydraulic installations, lithic scatters, building remains dating mainly from the Nabatean – Early Roman period,
Nabatean rock-cut graves, cultic installations and rock drawings, many of which are related to the pilgrimage up to Jabal Haroun. (Kouki 2006: 2, 23-25.)

Cartographers, working with both the survey and excavation teams, have carried out geodetic surveys and photogrammetric documentation. They have produced geographic reference data, consisting of a geodetic network and a three-dimensional digital elevation model (DEM), necessary for the field surveys. They have also developed new concepts of digital photogrammetric documentation to intensify the fieldwork of the survey team. It has been applied for example to terrestrial topographic surveys and 3-D recording of barrage systems and terrace walls. Cartographers have documented the building complex at the Jabal Haroun site, the proceeding of excavations and the finds by using geodetic, cartographic, photogrammetric, GIS, CAD modeling and virtual modeling techniques. (Koistinen 2002: 133; Lavento et al. 2006: 11, 19.)

Conservation of the ruins has thus far included mainly first-aid measures to ensure the stability of the structures after they have been exposed until long-term interventions and the site’s future will be planned. Testing of various conservation materials to find the right solution for this specific site has also been a part of the preservation work. (See more in Eklund & Pouta 2005.)
2.2 Petra and the Jabal Haroun Area in the Past

The ancient city of Petra in southern Jordan is characterized by its magnificently colored sandstone and rock cut tombs dating back to the Nabatean occupation of the area. It is situated at the crosspoint of major historical caravan routes, and it served as a trading center for centuries. Petra is supposedly the place where Moses struck water out of rock, and according to Jewish, Christian and Muslim traditions the mountain of Prophet Aaron (Jabal an-Nabi Harûn, Mt. Hor), located ca. 5 km to the south-west of Petra, is still considered the place of burial of Aaron, brother of Moses (Walmsley 2001: 522; Frösén et al. 2002b: 25.)

First evidence of human presence in the Jabal Haroun area are stray finds of bifaces (hand axes, almond-shaped stone tools) from the Lower Paleolithic period. Over 30 Middle Paleolithic Levallois points have been found which indicates that humans remained in the area for longer times, possibly searching raw material for making tools. The Upper Paleolithic is not well known. No sites belonging to this period have been found from the Jabal Haroun area and only a few from the Petra area, perhaps indicating that human populations lived in highly mobile hunter-gatherer groups. In the following Epipaleolithic period human populations living in the Petra area seem to have been very mobile foragers. This is evidenced by the small size of the sites and human skeletal remains found in the Wadi Mataha Epipaleolithic site in the Petra Basin. Few rock shelter sites have yielded also bones of hunted animals, including wild goats and gazelles. (Lavento et al. 2006: 21-22.)

The Early Neolithic period in southern Levant is considered to have been a time of developing agriculture, domestication of animals and of permanent settlement. These processes can be witnessed also in the Early Neolithic sites around Petra, but no sites are known in the immediate vicinity of Jabal Haroun. This may be explained by the fact that the closest villages were located 5-10km from the mountain. Jabal Haroun was easily accessed from these villages and thus there was no need to establish proper camps there. As the Jabal Haroun area was drier than the Petra valley, it is assumed that cultivation was not extended there. Instead the area would probably have been used for herding. Finds of axes in the Jabal Haroun area testify that the area was frequently
visited and that also wood cutting and working took place there. Wood was needed for construction and production of building materials, such as plaster, and as firewood for cooking and heating houses. (Lavento et al. 2006: 21-24.)

The shift from early Neolithic to late Neolithic period brought a collapse of the early Neolithic mega-village societies and traditions. Perhaps the available natural resources were affected by an increasingly arid climate and were exhausted as a result of population overgrowth. The reasons are not clear, but this collapse is visible also in the Petra area as small and few sites from this period, resulting most probably from increased mobility and seasonal occupation in the area. Seasonally occupied Early Bronze Age hamlets are known in Petra at a distance of ca. 5 km from Jabal Haroun. The Bronze Age sites suggest territorial distinction of areas took place in this period. (Jansson 2002: 40-41; Lavento et al. 2006: 24-25.)

The Edomite Kingdom flourished mainly from the 13th to 8th centuries B.C to the 6th century B.C. The Edomites occupied Petra and had a stronghold in Petra, the most famous site being a settlement on top of Umm al-Biyara (Arabic for “mother of cisterns”) mountain. Iron Age settlement of the Petra area developed and intensified by the late 8th century as a result of copper production in industrial scale and Arabian trade. Even though sites such as the one on Umm al-Biyara are characteristic during the Edomite presence, most Iron Age settlements around Petra seem to have been agricultural and domestic: open villages and farms. Jabal Haroun area was probably used for herding. (Jansson 2002: 41; Lavento et al. 2006: 24-25.)

After the fall of the Edomites, Petra was inhabited by nomads, mainly Nabatean Arabs, migrating from northeastern Arabia to southern Jordan. After a period of nomadic way of living the Nabateans adopted a more sedentary lifestyle and their material culture, characterized by monumentalization and social differentiation was strongly influenced by the Hellenistic world with which they were frequently in contact through trade. Petra developed into a well governed commercial and political center, with monumental architecture in the city center and a necropolis with tomb facades cut in the surrounding sandstone cliffs. (Schmidt 2001: 367-382) This development influenced also on the use of the Jabal Haroun area. In addition to a monumental building preceding the Byzantine
chuch on the mountain plateau (see Chapter 3.1), remains of several buildings have been found, many of which are probably related to the caravan route crossing the area on its way to the Wadi Arabah from Petra. Intensive farming was made possible by an extensive system of barrages and terrace walls. Petra city was supplied with water by an extensive and sophisticated network of water channels and an efficient drainage system protected it from winter flashfloods. Despite conflicts with its neighbors, the Nabatean kingdom remained independent until its annexation in A.D. 106 by Rome. (Lavento et al. 2006: 24-25.)

After the annexation former Nabatean territories belonged to the Roman province of Arabia and later, when the province of Arabia was partitioned, Petra was made capital of the new province of Palestina Salutaris (Freeman 2001: 434). The city continued to be involved in long-distance trade. Via Nova Traiana, the primary provincial road built around A.D. 111-112, connected Syria to the Red Sea via Petra. Major trade routes connected Petra to the Arabian Peninsula, to major eastern Mediterranean centers and to Egypt, but the Petra – Gaza road was the most important. The Romanized Petra flourished as a political and cultural center even in the 3rd century A.D., when the Roman empire witnessed violent times, for example the Persian wars. Petra was granted numerous honorifics, the sequence of which (Augustocolonia, Antoniana, Metrocolonia, Hadriana, Petra Metropolis) was used in official documents still in the 6th century. (Fiema 2002: 60-66.) However, the role as a major international trading center and the economical importance of the city came to an end during the 3rd century, as long-distance trade shifted to other routes (Freeman 2001: 448).

During the Byzantine period, Petra was slowly Christianized, although pagan temples still existed in the 4th century. It was believed that Petra was destroyed in an earthquake May 19th 363 A.D., that it never recovered to its former glory after the destruction and that final destruction came with the 551 earthquake. However, excavations in the center of the Petra in 1991-1993 revealed a basilican church built in the later 5th century by a wealthy congregation. The church had been destroyed by intense fire, and acts of vandalism had taken place immediately before the fire. In a side room (Room 1) an archive of charred papyri was found. The texts were dated between 513 and 592 and there was no mention of the 551 earthquake. Apparently it had not destroyed the city.
On the contrary, the texts showed that Petra still had wealthy landowners and clergy and a flourishing agriculture, which supported Petra as a cross point and place of maintenance for caravan routes. The papyri mentioned also a house (oikos) of Aaron, the high priest and brother of Moses, which refers to the monastery or pilgrimage center located on the mountain of Aaron. (Frösén 1999; Fiema 2001: 139; Frösén et al. 2002b: 25; Fiema 2002: 66-67.)

Both the Petra church building and the texts reveal a community led by the bishop of Petra, which proves that Christianity had a strong standing in the area. The names of the people in the texts showed that instead of disappearing the Nabateans had rebuilt Petra, converted to Christianity and adopted Greek as their official language. People in Petra owned land even in the west, near Jerusalem and by the Mediterranean coast near Gaza. The wealth of some upper class citizen, however, does not necessarily mean that the entire city was prosperous and there is no evidence of long-distance, international trade continuing through Petra. (Frösén 1999; Fiema 2002: 70.)

In the 7th century, during the Islamic period, the city seems to have been left in the political and financial shadow of its neighbors. The history of Petra as an urban center appears to end by the late 7th - early 8th century, yet in the early 12th century Wadi Musa, ancient Petra, is the most important object of Crusader military activity south of the Dead Sea. Latin sources describe Wadi Musa as a fertile valley having dense olive groves and mills on its streams. In 1100’s a Crusader military expedition discovered a thriving settlement in Wadi Musa and visited the still inhabited monastery of St Aaron on Jabal Haroun. The valley area was fortified by the Crusaders, but their occupation lasted only until 1189 when the last stronghold fell to the Ayyubids. In 1217 the Byzantine church on the summit of Jabal Haroun was still inhabited by two Greek monks, but the Petra valley was recorded to be empty and desolate in the 13th century. During the Ayyubid and Mamluk reconstruction of Jordan, directed especially towards restoring and improving the religious infrastructure, a Muslim shrine was built on the summit of Jabal Haroun, on the foundations of the earlier Byzantine church. (Peterman & Schick 1996: 477; Frösén 1999; Walmsley 2001: 518, 520, 533; Fiema 2002: 70, 72.)
After the rediscovery of Petra in 1812 by the Swiss Johann Burckhardt it has become a tourist attraction and site of archaeological investigation. The uniqueness of Petra has been recognized worldwide. It was inscribed on the UNESCO World Heritage List in 1985 on grounds that it represents a masterpiece of human creative genius and bears a unique or exceptional testimony to a cultural tradition or civilization which has disappeared. It is also an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates a significant stage in human history. (Frösén 2002: 15; UNESCO 2008a & 2008b.)

2.3 Environmental Setting of Petra and Jabal Haroun

The present day climate of the mountainous Petra region is semi-arid, with hot, dry summers and cool winters with periodical rains (Paradise 1998:152-153). The absolute minimum temperature measured at the Wadi Mousa weather station between 1984 and 1998 was -4.0 °C, while the absolute maximum temperature was 39.0°C (See Table 1).

Picture 3 The semi-arid environment of the Petra area.
Total annual rainfall between 1976 and 1998 was 179.3 mm with January being the rainiest month (40.0mm) and June - September having no rain. The majority (60% at 7a.m., 50% at 1p.m. and 90% at 7p.m.) of local winds in Petra are from the west/northwest (Paradise 1998:153). No precise data on wind velocities or directions at Jabal Haroun is available. However, personal experience shows that especially the gusty evening winds are usually strong enough to carry sand grains.

Table 1: Humidity, rainfall and temperature values from Wadi Mousa weather station. (Jordan Meteorological Department 2004.)

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>60.8</td>
<td>40.0</td>
<td>-4.0</td>
<td>24.0</td>
</tr>
<tr>
<td>February</td>
<td>57.1</td>
<td>37.5</td>
<td>-3.0</td>
<td>25.0</td>
</tr>
<tr>
<td>March</td>
<td>51.9</td>
<td>36.7</td>
<td>0.0</td>
<td>27.1</td>
</tr>
<tr>
<td>April</td>
<td>40.8</td>
<td>10.0</td>
<td>-3.0</td>
<td>34.0</td>
</tr>
<tr>
<td>May</td>
<td>38.3</td>
<td>4.2</td>
<td>4.5</td>
<td>37.1</td>
</tr>
<tr>
<td>June</td>
<td>39.0</td>
<td>0.0</td>
<td>9.0</td>
<td>37.1</td>
</tr>
<tr>
<td>July</td>
<td>40.9</td>
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<td>12.1</td>
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<td>August</td>
<td>46.3</td>
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<td>September</td>
<td>47.4</td>
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<td>10.0</td>
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<td>48.8</td>
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<td>6.5</td>
<td>33.0</td>
</tr>
<tr>
<td>November</td>
<td>53.0</td>
<td>13.1</td>
<td>0.5</td>
<td>27.5</td>
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<tr>
<td>December</td>
<td>61.3</td>
<td>34.2</td>
<td>-2.2</td>
<td>25.0</td>
</tr>
<tr>
<td>Annual</td>
<td>48.8</td>
<td>179.3</td>
<td>-4.0</td>
<td>39.0</td>
</tr>
</tbody>
</table>

Table 2 and Table 3 show climatic data from Wadi Mousa weather station in 2005. This data will be used later to find out how climatic measurements from Jabal Haroun relate to the surrounding area. Compared to the average rainfall values measured in 1976 - 1998, year 2005 in Wadi Musa was drier, while January 2005 received more rainfall than the average January. Temperatures in 2005 stayed within the limits of maximum and minimum temperature recorded in 1984 - 1998. Thus the year 2005 can be considered as a relatively normal year in terms of temperature and somewhat dry in terms of annual rainfall. Mean relative humidity was not calculated, as the data received from Wadi Mousa Station included relative humidity at 6am and 12pm (noon), which are not representative values for the whole twenty-four hours.
Table 2 Rainfall, Temperature and Evaporation at Wadi Mousa Weather Station in 2005.

<table>
<thead>
<tr>
<th></th>
<th>Total rainfall (mm)</th>
<th>Absolute min Air Temp. °C</th>
<th>Absolute max Air Temp. °C</th>
<th>Evaporation, Total (mm)</th>
<th>Evaporation, Mean (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>50,6</td>
<td>0,8</td>
<td>21,6</td>
<td>98,9</td>
<td>3,2</td>
</tr>
<tr>
<td>February</td>
<td>13,9</td>
<td>-1,6</td>
<td>23,0</td>
<td>97,5</td>
<td>3,5</td>
</tr>
<tr>
<td>March</td>
<td>19,3</td>
<td>1,8</td>
<td>26,6</td>
<td>182,1</td>
<td>5,9</td>
</tr>
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<td>April</td>
<td>7,5</td>
<td>2,6</td>
<td>32,4</td>
<td>278,3</td>
<td>9,3</td>
</tr>
<tr>
<td>May</td>
<td>2,1</td>
<td>6,2</td>
<td>31,4</td>
<td>307,8</td>
<td>9,9</td>
</tr>
<tr>
<td>June</td>
<td>0,3</td>
<td>12,6</td>
<td>32,8</td>
<td>340,5</td>
<td>11,4</td>
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<tr>
<td>July</td>
<td>0,0</td>
<td>13,8</td>
<td>33,0</td>
<td>355,0</td>
<td>11,5</td>
</tr>
<tr>
<td>August</td>
<td>0,0</td>
<td>15,2</td>
<td>33,2</td>
<td>350,4</td>
<td>11,3</td>
</tr>
<tr>
<td>September</td>
<td>0,0</td>
<td>14,0</td>
<td>31,0</td>
<td>273,2</td>
<td>9,1</td>
</tr>
<tr>
<td>October</td>
<td>0,2</td>
<td>7,8</td>
<td>29,6</td>
<td>216,6</td>
<td>7,0</td>
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<tr>
<td>November</td>
<td>0,4</td>
<td>4,8</td>
<td>25,6</td>
<td>146,6</td>
<td>4,9</td>
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<tr>
<td>December</td>
<td>2,2</td>
<td>1,0</td>
<td>26,8</td>
<td>176,7</td>
<td>5,7</td>
</tr>
<tr>
<td>Total annual</td>
<td>96,5</td>
<td>-1,6</td>
<td>33,2</td>
<td>2823,6</td>
<td>7,7</td>
</tr>
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</table>

Table 3 Rainfall at Wadi Mousa Weather Station in 2005.

<table>
<thead>
<tr>
<th></th>
<th>Number of rainy days per month</th>
<th>Total rainfall per month (mm)</th>
<th>Maximum rainfall per rainy day (mm)</th>
<th>Minimum rainfall per rainy day (≥0,1 mm)</th>
<th>Average rainfall per rainy day (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>9</td>
<td>50,6</td>
<td>37,3</td>
<td>0,2</td>
<td>5,6</td>
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<tr>
<td>February</td>
<td>5</td>
<td>13,9</td>
<td>5,4</td>
<td>0,1</td>
<td>2,78</td>
</tr>
<tr>
<td>March</td>
<td>2</td>
<td>19,3</td>
<td>17,5</td>
<td>1,8</td>
<td>9,65</td>
</tr>
<tr>
<td>April</td>
<td>2</td>
<td>7,5</td>
<td>7,0</td>
<td>0,5</td>
<td>3,75</td>
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<tr>
<td>May</td>
<td>1</td>
<td>2,1</td>
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<td>37,3</td>
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The climate of the Near East after 7000 B.C. is generally considered to have been quite like the present semi-arid climate. Fluctuations of more humid and increasingly arid conditions have taken place regularly, but always within the semi-arid range and the general trend being towards increasing aridity. (Kouki 2006: 36 - 39.) A dendrochronological sequence of Juniperus phoenicea revealed that the average interval of times of drought between AD 1600 and 1995 in southern Jordan was four years.
Most drought events lasted for one year and periods of drought exceeding the duration of five years proved unlikely in southern Jordan. (Touchan & Hughes 1999.) Latest arid periods have been dated to AD 1600-1850 in Wadi Faynan (Barker 2000: 80) and to the beginning of the 18th century, lasting until the present day, in the Negev desert (Bruins 1990: 96).

Sandstone in Petra belongs predominantly to the Cambrian to Ordovician Ram sandstone group. The upper plateau of Jabal Haroun and its surroundings in E- SE are mostly Umm Ishrin sandstone. Lower slopes of the mountain are formed of Abu-Kushayba Sandstone. Most of the monuments in central Petra have been carved in the Middle and Upper Umm Ishrin and Disi sandstone formations. Tectonic movement in the network of these fault zones has led to the formation of a complicated lithology in the Jabal Haroun area. Several earthquakes in the history of Petra and Jabal Haroun have caused severe destruction and phases of rebuilding. There are three major fault systems in the vicinity of Jabal Haroun and Petra. The Wadi ‘Arabah fault stretches from the northern part of the Gulf of Aqaba to the Dead Sea. It is still active, with annual movement of ca. 5 mm. No major earthquakes have occurred along the fault in the last 800-1000 years, but earthquakes during the time of occupation in Petra and Jabal Haroun might be related to movements of this fault. The NE – SW stretching Al-Quwayra fault zone is located ca. 4 km west of Petra, and east of it is the Wadi Mousa fault zone. (Kouki 2006: 42 - 45.)

3 The Jabal Haroun Excavation Site and Ruins

3.1 The Excavation Site and Phasing of the Church and Chapel

Fieldwork at Jabal Haroun has revealed a monastic building complex comprised of four wings around three courts. The central wing of the complex is a basilican church with an atrium and a narthex to its west and a chapel on its northern side. A courtyard north of the chapel is surrounded by 14 rooms on three sides. The appearance of the rooms and the general plan of this wing suggest that it served as a hostel for travelers or pilgrims (Fiema & Holmgren 2002: 101). The central court next to the narthex has a cistern cut in the bedrock with several water channels leading to it. To the west of this
court there is a north-south oriented structure that has several separate rooms. One of the rooms has been filled up intentionally and appears to have served as a platform or podium of some kind in a later phase of occupation (Fiema & Holmgren 2002: 102). The third court is situated between the southern wall of the church and the southernmost rooms of the monastic complex.

The most recent analysis of the monastic ruins at Jabal Haroun, in the form of Volume I of the FJHP publication, is in press at the time of writing of this M.A. thesis. The phasing below is a brief overview of the phasing of the church and chapel area by Erko Mikkola, Antti Lahelma, Zbigniew T. Fiema and Richard Holmgren, presented in detail in Chapter 6 (Mikkola et al. in press) of the coming book.
Pre-Byzantine occupation of the Jabal Haroun site by the Nabateans (Phase 1) is indicated most clearly by the NE-SW oriented Western building, the construction materials and techniques of which differ from the ones used elsewhere on the site, by the abundance of Nabatean pottery present everywhere at the site, and by reused fragments of architectural stone elements, originating from an unknown, monumental building. Also a characteristically Nabatean cistern at the foot of the summit of Jabal Haroun acts as evidence for Nabatean occupation. Based on finds from soundings below the church and the chapel, the phase is dated approximately to 1st century B.C. – mid-later 5th century A.D. Most active use of the site would have begun in the early 1st century A.D.

The construction of the basilican church and the early chapel (later 5th century) marks the beginning of Byzantine occupation of Jabal Haroun (Phase 2). Construction of the Byzantine shrine on top of the summit of the mountain possibly also took place at this time. Earlier structures were cleared from the construction site of the church and chapel.
or covered with a layer of large sandstone slabs, leveling the surface for the church walls. Walls were built directly on bedrock and partly on the leveled surface. The church was built with a rectangular plan, ca. 24.5 m long and 15.5 m wide, the maximum internal measurements of the church proper being 22.60 m x 13.60 m (ratio ca. 3:2), and the ratio of nave width to aisle width being ca. 2:1. Based on these dimensions, the church falls into the category of larger monoapsidal basilicas in the region.

Both the tripartite church and the chapel were originally longer than the church and chapel that can be seen today. The western wall of the early church extended to what is now the western wall of the atrium (Wall K) and had three entrances to the church – a wider main entrance and two side entrances. The two side aisles were divided from the nave by rows of seven columns. The columns probably supported clerestory walls and a pitched roof, but later rebuilding has destroyed all evidence of them. The east end of the church was occupied by a slightly horse-shoe shaped apse, with two pastophoria flanking it and a bema and synthronon in front. Approximately in the middle of the wall separating the church and chapel a doorway provided access between the two spaces.

The precise location of the early western wall of the chapel is not clear, but it is evident that the present wall (Wall OO) is not original. At the western end of the chapel there was a cruciform baptismal font and at the east end an apse with two cupboards on its flanks. The floor level was lower than that of the church. Apparently the buildings were intended for a wider audience than just the monastic community judging from the size and lavish decorations of these ecclesiastic structures. The entire floor of the church was paved with marble slabs and the semidome above the church apse was probably decorated with wall mosaic. The phase ended approximately in the mid - later 6th century in destruction (Phase 3), probably caused by seismic activity that affected the entire site and ended in an intense fire.

Following the devastation major reconstruction and remodeling of the buildings took place (Phase 4), but both the church and chapel were returned to their ecclesiastical function. The church was subdivided in two parts and the western part was turned into an atrium court. Also the new chapel was shorter than its predecessor. A new doorway
to the chapel was opened at the NW corner of the church. A narthex, or entrance porch, was added on the west side of the atrium. Later, the atrium was further remodeled and a mosaic floor was laid out in the narthex (Phase 5).

Some event (Phase 6), possibly of seismic nature, in the first half of the 7th century prompted the reconstruction and modification of the surviving structures of the complex (Phase 7). The roof support system in the church was remodeled and the interior of both the church and chapel was completely replastered. Neither interior had marble furnishings any longer, except for the original, repaired marble pavement in the church. New installations were built in the altar areas of the church and chapel, and a new baptismal font in the chapel replaced the old one. A masonry altar pedestal was built in the chapel, possibly to house relics from the Byzantine shrine, which may have been wrecked at this time. Iconoclastic damage to the mosaic in the narthex took place possible in early 8th century.

The third destruction (Phase 8) took place in mid 8th century, possibly due to the major earthquake in 18 January 749. It affected the southern part of the church most, causing the semidome and arches spanning the southern aisle and nave to collapse as well as the columns in the atrium. The semidome and badly damaged apse floor were never repaired, but the stone tumble was cleared away (Phase 9). Reusable building materials, e.g. tesserae were gathered and stored in several locations. The southern wall of the church (Wall J) tilted severely towards the south and a buttress was built to support it. A massive buttress was constructed also in the atrium against the southern part of the western wall of the church. The chapel on the other hand survived the destruction much better. The pavement, baptismal font and altar pedestal seem to have been left quite intact. While the church was partly repaired and modified for domestic occupation, the chapel remained in ecclesiastic use.

Following further destruction (Phase 10) sometime in the later 8th or early 9th century, the complex lost its ecclesiastical function but still remained occupied at least temporarily (Phase 11). The buildings were cleared of stone tumble and reusable material, such as glass, tesserae and fragments of marble, was collected into small piles. The chapel seems to have been used still by the monastic community as a shelter or
dormitory for pilgrims or for themselves. Small fireplaces, associated with flint and bone finds, were made directly on the floor surfaces and also outside in the open air. Simple charcoal drawings and Arabic graffiti on fragments of marble slabs were found in association with some fireplaces.

Final destruction (Phase 12) came with another earthquake in the very late 9th century or during the 10th century. The earthquake caused remaining structures to collapse and resulted in the final abandonment of the site. People still visited the ruins occasionally, in search of shelter or reusable material (Phase 13). A large amount of mosaic fragments and stone tesserae was collected from the ruins and stored in the apse of the church. Abandonment was followed by accumulation of sand in the ruins and natural decay of exposed parts of the structures until present day (Phase 14).

3.2 Construction Methods and Stone Material

Below, the methods of constructing the surviving wall structures will be addressed. The association of details of building technique in the Jabal Haroun ruins with certain phases of construction follows the analysis and phasing by Mikkola et al. (in press) presented in Chapter 6 of the FJHP publication Volume I mentioned above.

![Church apse](Picture 4 Church apse)
The walls of the church and chapel on Jabal Haroun have been founded on bedrock or ground leveled with large sandstone slabs, which has been a common practice for example in Judean desert monasteries and Palestinian dwelling masonry in the Byzantine period and up until recent times (Hirschfeld 1992: 95-96; 1995: 230.) The walls consist of two rows of stones laid with a thin layer of mortar and a filling of small stones, debris and mud mortar. Wall thicknesses are around 0.75 – 0.8 m. Lime and gypsum plaster (painted in some areas) was used to cover interior walls and masonry built benches (Danielli 2002: 158). Stucco decoration, attached to walls with bronze

Picture 6 The southern wall of the chapel.

Picture 5 The northern wall of the chapel with the later baptismal font between the columns.
nails, seems to have covered some walls of the original church and the Western Building. (Mikkola et al. in press.)

Most walls have been constructed using quarry stone and more or less hammered fieldstones of varying sizes, and special structures such as the apses, wall corners and pilasters have been built with special care using ashlars. It is sometimes difficult to know which of the building stones have originally been well dressed ashlars, since the stone material is very weathered. The method of building walls by laying two courses of hammered fieldstones with a filling of small fieldstones in between has been used for example in Jerusalem until the early Byzantine period (Hirschfeld 1995: 233). Walls built with this method would be 0.65-0.85 m thick and the courses would have smaller stones inserted between the hammered fieldstones so as to create a straight wall face.

The outside of walls V and D (Trench C1) in the S-E corner of the building complex has not been excavated, but the method of construction of the interior walls resembles a description by Hirschfeld (1992: 65 – 66; 1995: 233) of a popular method of building

Picture 7 Trench C1 in the S-E corner of the building complex.
both public and private buildings and for example auxiliary buildings in Judean desert monasteries, introduced in the Byzantine period. Typical walls were about 0.7 m thick and consisted of an outer face made from hewn stone or ashlars and an inner face constructed from fieldstones and cement. Unfortunately Hirschfeld (1992: 65-66) does not describe the composition of cement in the context of the new Byzantine building technique, but in a later study (Hirschfeld 1995: 223) uses the term for the mixture of clay mortar and lime. Such cement was used both for bonding in wall construction and as a base for plastering the walls and ceiling. The thicknesses of Walls V and D are 0.7 m (Wall V) and 0.82 m (Wall D), but contrary to the method described by Hirschfeld, they have been constructed using mud mortar without lime.

The practice of using recycled building material and a filling of earth mortar containing debris, such as sherds of pottery and glass lamps, animal bones etc., is evident on Jabal Haroun and has been documented in ancient and traditional Palestinian building practices (Hirschfeld 1995: 221). Recycled building material, originating from the preceding Nabatean monumental structure, has been used already for the early walls of the church and chapel.

The Nabatean Western Building has been built using two or three times larger well-dressed ashlars compared to the average stones used at the site and probably a lime-based mortar. Decorated architectural stones (limestone and sandstone), fragments of cornices have been found in reused positions in the church and chapel. Traces of Nabatean stucco decoration have been found in the Western building, apparently the exterior wall was covered with stucco plaster.

What remains of the roof support systems of the different phases is a variety of columns, column bases, pilasters and voussoirs discovered in the soil during excavations. Arches in the small pastophoria sprang directly from the walls while the arches covering longer distances in the church and chapel were supported by pilasters or columns. Most locations of the columns visible at the site originate from later phases of construction. The only exposed in situ Phase 2 column drums are to be found in the atrium. Some remains of the Phase 2 colonnade in the church were found in soundings made beneath the present marble floor. The column drums and capitals have been
reused and at least a number of capitals found associated with Phase 4 columns are Nabatean in origin. (Mikkola et al. in press.)

Rural masons, living in the towns and villages near the building site, seem to have influenced the Byzantine architecture in provincial areas most. Though the architectural designs of ecclesiastic buildings may have been adopted from the Aegean coastlands, the supervision of the building projects and the execution of the construction was usually done by local professional masons and was thus based on local tradition. In Byzantine Palestine desert monasteries resemble the mansions of wealthier families in the quality of masonry and in the plan and conception. Judean desert monasteries in this period had the resources to invest in the best materials and the finest construction especially when the common buildings, such as the church, were concerned. Living quarters and other auxiliary parts of monasteries were built in a simpler, practical way. (Krautheimer 1986:135; Hirschfeld 1992: 62, 68, 235 – 236; 1995: 227.)

The majority of building stone at the Jabal Haroun site is local Umm Ishrin sandstone, from the upper and middle horizons. Blocks of white sandstone can be either from the Disi formation (thick, homogeneous) or the Umm Ishrin formation; Kurnub sandstone is too soft to be used as building stone. Pieces of various types of recycled marble (ex. Carrara) from broken furniture can be found in later wall structures. Yellow marly limestone, coming from the Upper Cretaceous limestone formation, Ajlun group, has been used mostly in the church apse and its semidome, probably also in the semidome of the chapel apse. Also another yellow stone can be found in the wall structures, but this is very silty sandstone from the Middle Umm Ishrin member rather than limestone. This was tested with lemon juice, which should react with limestone (citric acid with calcium carbonate), but the silty stone did not show any reactions. (Majdi Barjous, pers. comm. 14 August 2005, 17 September 2005.)

The floors have been paved with Proconnesian marble, Nummulitic limestone from the Ma’an region, alabaster (in the chapel) and Umm Ishrin sandstone. Marble and limestone can be found in the main church area, while sandstone has been used also in the chapel, atrium and some auxiliary rooms on the site. Hydraulic mortar was used as

4 Damaging Factors Affecting the Condition of Stone Structures

4.1 Characteristics of Stone

Sandstone weathering studies at the Roman Theater in Petra established a hierarchy of weathering processes responsible for sandstone deterioration. The results of statistical analysis showed, that general rock composition was the most important single factor (25%). The influence of iron oxide concentrations were next (17%) and after that came climatic influences such as sunlight and moisture (12%). (Paradise 2005: 42.)

As was mentioned in Chapter 3.2, mainly sandstones from the upper and middle Umm Ishrin and Disi Sandstone Formations have been used for building at Jabal Haroun. Also Ma’an limestone, marley limestone from the Upper Cretaceous Formation and some marble are present in the structures. However, as there is an abundance of research available concerning the local sandstones in Petra, and while I managed to find none concerning the limestone, sandstone will be given preference in this chapter. It is after all the main building material at Jabal Haroun.

The way in which stone behaves with respect to weathering is determined by its compressive strength, specific gravity and porosity. The strength of stone depends largely on the bond between mineral grains (clast) and the cementing agent, also called matrix, comprising of minerals with grain sizes under 30μm. Often stones with fine grains are stronger than those with coarse grains. Also the quality of interlocking between crystals contributes to the strength of stone material. In areas prone to earthquakes, the elasticity of stone is important. Also hardness, or resistance to abrasion, is a quality that is needed in special structures, for example in steps and paving. (Dimes 1990:33-36; Shadmon 1996:15-20.)
The geochemical composition of stone along with characteristics of stone fabric, including grain size, cement types and larger scale features, affect the strength of the material and influence its vulnerability to salts. For example limestone, containing calcium carbonate, is susceptible to sulpha tion by air pollution, while siliceous rocks generally are not. Sedimentary rocks are more vulnerable to salt attack than igneous or metamorphic rocks. (Goudie & Viles 1997:93; 112-114.)

The resistance of rock to salt attack is related to the amount of water and salt it is able to absorb. Porosity affects the movement of water in the stone material and the location of major salt crystallization. More important than the total porosity of stone are the shape, size and nature of the pores. Especially the amount of micropores (pores with diameters less than 0.05mm) is important. Salts tend to crystallize first in the larger pores and after they have been filled, in the small ones. Limestone with high porosity, but large pores, can resist salt damage better than low porosity limestone with pores having a small diameter. This is more or less true also for sandstone. In sandstones where macropores interconnect microporous areas of the cement, granular disintegration of stone surfaces is caused by salt crystallizing in small pores of the cement (matrix), which results in the detachment of individual grains. The pore structure is important also in case of frost damage, where stone with coarse pores is more resistant. (Honeyborne 1990:154-155, 159; Shadmon 1996:16-17; Goudie & Viles 1997:91-93, 112-114.)

The extent in which sandstones are affected by air pollution depends on what the cementing agent is. Sandstones, in which quartz crystals are cemented by silica, can resist sulphuric acids very well, while calcareous sandstones (cemented by calcite) are very vulnerable. The ability of limestone to resist acid attack depends on the porosity of the stone: stone with coarse pores is most durable. Marbles undergo more or less the same chemical reactions as limestone. Due to a minimal amount of pores on the surface, marble is much more resistant than limestone. However, in the case of considerable temperature variations, marble deteriorates more rapidly because cycles of heating and cooling can result in the increase of porosity. (Honeyborne 1990:156-158)

According to the studies by Heinrichs & Fitzner (2000), both upper and middle Umm Ishrin Sandstone Formations contain a variety of sublithotypes with differing
petrographical properties. The stone types vary from medium/coarse–grained types to silty types. Some have a grain-supported fabric, while others have a matrix-supported fabric. The main mineral component is quartz, and kaolinite is the dominant matrix clay mineral. Hematite occurs as iron-oxide mineral, goethite and limonite as iron-hydroxide minerals. There are very quartz-rich stone types, and also very matrix-rich stone types, with the matrix being siliceous, clayish, ferritic or carbonatic. (Heinrichs & Fitzner 2000: 289, 307.)

Paradise (1998: 156, 159) has observed that the strata of stone, which have greater percentages of matrix calcium, are more vulnerable to weathering caused by high solar flux, whereas matrix iron slowed weathering. Thus the amount of iron and calcium in the sandstone matrix are of primary importance in influencing weathering in arid regions.

Stone from the upper Umm Ishrin Formation is hard and medium or coarse-grained. Multicolor banding is characteristic, with common colors including white, gray, yellow and red. Cavernous/honeycomb weathering, caused by the solution of matrix cement and subsequent granular disintegration, is characteristic. (Barjous & Jaser 1992: 29; 49; Heinrichs & Fitzner 2000: 285-288.)

Sandstone from the middle Umm Ishrin Formation on the other hand is mainly fine-grained, with multicolored (white, yellow-brown, grey, reddish brown and mauve/violet) color-banding being characteristic. It is friable and sensitive to moisture changes. Strong weathering is caused especially by the solution of ferruginous and manganiferous layers and cements. This results in the change of the face color from red-brown to yellow and grey. (Barjous & Jaser 1992: 29; 49; Heinrichs & Fitzner 2000: 285-288.)

The multicolored middle Umm Ishrin sandstones are matrix-rich, while upper Umm Ishrin sandstones have lower matrix-content and a higher proportion of large pores. The strength of the stone material relates rather to its grain fabric, especially the contacts between grains. Increasing grain size correlates with a decreasing proportion of cementing materials, while an increase in matrix means the fabric is increasingly
supported by the cementing materials. Increasing grain size also correlates with growing total porosity and an increasing proportion of coarse pores. According to the studies made by Barjous and Jaser (1992), a number of pore spaces are isolated by interlocking particles. As total porosity increases, also the median pore radius increases, while the pore surface decreases. (Barjous & Jaser 1992: 35-37, 50; Heinrichs & Fitzner 2000: 289, 307.)

Disi sandstone is white, pale-gray or yellowish gray in color. Compared to both upper and middle Umm Ishrin sandstones, Disi sandstone is coarser-grained, contains quartz pebbles and has the lowest matrix-content (mostly kaolinite and calcite). It is characterized at outcrop by white, rounded-weathering morphology. Disi sandstone is hard, relatively weak and quite poorly resistant to weathering. (Barjous & Jaser 1992: 29; Heinrichs & Fitzner 2000: 285-288, 292.) Building blocks such as column drums made of this stone have deteriorated much more than those made of iron rich Umm Ishrin sandstone (Paradise 1998: 156).
4.2 Influence of Humidity and Temperature

Water is an essential prerequisite for most damaging processes. It enables salt damage and biodeterioration and plays a part in air pollution and wind related weathering. Nourissier et al. (2002: 70) identify capillary rising of water as a major threat to stone walls in the Mediterranean region. Water rising from the ground and moving up in the wall corrodes the mortars and joints by dissolving the binders (earth or lime). Empty spaces are created within the walls, which can make the structures unstable. Capillary rising of water also moves salts in the structures until water evaporates and causes the salts to crystallize. Temperature, and especially rapid cyclic variation in temperature, is also an important damaging factor. High temperature speeds the loss of moisture from structures and causes thermal expansion of materials. Low ($\leq 0^\circ$C) temperatures combined with moisture cause frost damage to masonry.

Biodeterioration is associated with excess moisture in structures. Trees, ivy and shrub harm masonry mainly with their roots that grow into the mortar joints and faults in the stone blocks. A dense covering of leaves keeps structures moist. Decaying plants form humic acid when they combine with water. Water contaminated with this acid helps the dissolution of limestone (Paradise 1998:162). Algae colonize damp masonry and do not necessarily need anything organic to feed on. They are not harmful, but their green appearance is not considered to be very aesthetic. Fungi on the other hand need organic food to survive. On masonry this can be provided by algae, bacteria, decaying leaves or bird droppings. Fungi cause damage both chemically and by growing hyphae (food seeking threads) into stone. The chemical products of fungi (organic acids such as oxalic and citric acids) are especially damaging to limestone, because they dissolve calcium carbonate. (Honeyborne 1990: 167-168.)

Lichens are the product of the symbiotic relationship between fungi and algae, in which the hyphae of fungi provide water and salts, while algae produce organic food by photosynthesis. Honeyborne (1990:168) suspects that lichens are more damaging to limestone than either of the contributing organisms separately. Lichen living on calcareous stone may secrete oxalic acid, which forms calcium oxalate when it reacts with calcite (Goudie and Viles 1997: 77). Lichens have been witnessed to cause also decay of other stones, such as sandstone. Honeyborne suggests the damage in this case
is due to surface stresses induced by lichens shrinking while drying. On the other hand Paradise (1998:159) claims that lichens can protect stone from surface erosion. Lichens have been observed in Petra on the northern sides of column drums that have been only partly buried in soil. Lichen blankets have protected the stone material from surface recession by causing the stone material to have a cooler surface and less frequent wetting – drying cycles. Still, deterioration may take place under the lichen thalli. (Paradise 1998:159, 162.)

Bacteria do not change the appearance of masonry, but produce damaging chemicals. Some bacteria can for instance oxidize sulphur, producing sulphuric acid; others oxidize ammonia to form nitric acid. Both of these acids damage limestone. Some bacteria produce organic acids that dissolve silicates. However, there is very little evidence that shows either lichens or bacteria to be significant factors of deterioration as for example salts, freezing or air pollution. (Honeyborne 1990: 168-169.)

No trees grow at the Jabal Haroun site. Instead there are some shrubs mostly on top of the walls and on ground level. The roots of these plants may harm the upper parts of the structures. Since the Petra area has very sparse vegetation, the ground waters remain neutral or slightly alkaline and thus the ground is an ideal environment for the preservation of limestone (Paradise 1998:162). Due to the arid climate especially in the summer, algae and fungi do not seem like a serious threat. However, lichens are present especially on walls facing north (see Chapter 6.5).

Frost damage takes place only in those parts of stone structures that freeze while they are very wet. As with salts, the pore structure of stone is an important factor when determining the capability of stone to resist frost damage. Stones with fine pores are more vulnerable. If there are salts present, water freezes in lower temperatures. (Honeyborne 1990:161, 162; Steiger 2004:186.) January temperatures in Wadi Mousa may drop below 0°C during night time, but the mean temperatures vary from 6°C – 12°C (see Chapter 2.3, Table 1). Thus the potential for damage caused by the freeze-thaw cycle is minimal in the Petra area according to Paradise (1998:153). Due to the higher altitude of Jabal Haroun, it would seem natural that freezing temperatures would
occur there more often than in Petra or Wadi Musa. The climatic conditions were monitored on the mountain to find out if this was true.  

Wind is related to stone damage in several ways. In addition to high winds carrying polluted air from distant industrial areas, strong winds can cause more rapid evaporation of moisture from stone. This in turn results in enhanced salt crystallization. (Honeyborne 1990:164). In Petra, wind erosion takes place when strong winds carrying sand remove the outer surface of sandstone that has already disintegrated due to salt crystallization or other weathering processes. This process can be noticed especially at the lower parts of the monuments. (Barjous & Jaser 1992.)

### 4.3 Solar Radiation and High Surface Temperatures

The effects of solar radiation and matrix chemistry on sandstone weathering have been studied for example in the Roman theatre of Petra in the 1990’s. This study revealed that high solar flux accelerates sandstone weathering especially in strata of stone, which have greater percentages of matrix calcium. This is due to calcium and silica minerals expanding and contracting differently when exposed to high (>50°C) temperatures. Maximum surface temperatures measured at the theatre were between 30°C and 56°C (air temperature being 26°C – 44°C). As a result of this study, mean weathering rates for sandstone in arid regions were estimated. These rates range from ~5-20 mm/millennium on vertical surfaces to ~15-70 mm/millennium on horizontal surfaces. (Paradise 1998:157; 1999:353, 362-365.)

The orientation of a monument also influences the damaging processes. Fitzner and Heinrichs (1994:670) studied this by comparing monument facades carved in the same geological formation and Paradise (1998:157-158) by observing different aspects of Nabatean Djin Blocks and obelisks. Fitzner and Heinrichs observed that on northern aspects much of the stone was solid and that erosion of different intensities was the main form of damage, with sanding, flaking, scaling and their transitional forms occurring only in the most severely eroded areas. On eastern facades, severe eroding and intense forms of sanding, flaking and scaling are seen. These differences were

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3 Temperatures and relative humidity at Jabal Haroun will be discussed in Chapter 7.
attributed to the different microclimatic conditions of the orientations, mainly larger
daily variation of surface temperatures on eastern facades than on northern ones.
Observations by Paradise confirm this. Northern aspects were least weathered but
western and eastern aspects showed greatest surface recession instead of southern ones.
These faces had been subject to both high surface moisture (from morning dew and
rainfall) and high insolation exposure (half-day sunlight and heating, summer surface
temperatures exceeding 50°C), whereas the southern aspects received full-day sunlight,
but less surface moisture.

Calculating the amount of surface recession of the Jabal Haroun structures since
construction would be difficult since the construction of the buildings follows no exact
standards like the Roman theatre in Petra. Most of the originally dressed ashlars have
no tool marks left on their surface and much of the building stone at the site was reused
already during the time of occupation. The weathering thresholds estimated by Paradise
can be applied to Jabal Haroun if the surface temperatures on the structures are first
monitored. This unfortunately could not be included in this thesis, but will hopefully be
included in future research.

4.4 Salts

"Salt weathering requires salts, sources of moisture, suitable environmental conditions
and susceptible material” (Goudie & Viles 1997:17).

Salts are ionic compounds consisting of cations and anions of acids. Common salt types
include sulphates, nitrates, chlorides and carbonates. Their ability to dissolve and
recrystallise makes them important agents of weathering in a wide range of
environments – from the polar regions to deserts and urban environments. (Goudie &
salts are one of the most important causes of stone decay. They affect all porous
building materials regardless of their chemical properties and may enhance the effects
of other deteriorating factors.
The role of salts in stone weathering has been recognized already in antiquity. Jewish sources mention “Walls that are filled with holes due to moving creatures within them or a wall that is decaying due to saline influences” (Sifre Zuta 15, cit. Hirschfeld 1995: 237) and outline cautionary guidelines to protect the walls against deterioration: “Piles of olives-refuse, manure, salt, lime or stones may not be kept within three handbreadths of his fellow’s wall and he must plaster it with lime. Seeds or a plough or urine may not be kept within three handbreadths of the wall” (M. Baba Bathra 2:1, cit. Hirschfeld 1995: 237).

Goudie and Viles (1997: 49, 79) identify four main sources of moisture for salt weathering: dew, fog, rain and groundwater. These can either provide a source of salts or a source of moisture to hydrate, mobilize and deposit salts in structures. Hygroscopic salts can take up water from air and in extreme cases they will dissolve in the water they have taken up. Observations of dew frequency in the Negev desert in Israel revealed that dew events took place on 8-26 nights/month, minimum being in April and maximum in September, the amount of dew hours being 2.5-5 hrs/night. Such frequent dew events provide sufficient conditions for salt hydration and for hygroscopic salts to take up moisture. Precipitating fog also adds moisture to rock surfaces and is a potential source of salts especially in coastal deserts. For example in the Central Namib desert of Namibia precipitating fog has been observed to occur on about 50-90 days in the year, with the precipitation values exceeding 180mm per year and annual rainfall being around 20mm. (Goudie and Viles 1997: 79-80.) Dew and fog frequencies for Jabal Haroun will be addressed in Chapter 7 along with other results obtained from environmental monitoring.

According to Goudie and Viles (1997: 82) the characteristics of rainfall in arid areas vary, depending on the location of the area. Rainfall events are not always of low frequency and high magnitude. Rather, deserts in higher latitudes tend to receive smaller amounts of rainfall per rainy day than those in lower latitudes. Rainfall chemistry close to seas differs from the chemistry of rainfall inland. Inland rain contains more sulphates and carbonates while rain near seas has more chlorides. Sea salt particles can be carried up to 900km inland by rainfall. (Goudie and Viles 1997:64-66.) Rainfall data from Wadi Mousa weather station shows that the amount of rainy days in 2005 was 26,
minimum 0 days being in July - September and maximum 9 days in January (see Chapter 2.3, Table 3). Both the highest amount of rainfall per month (50.6 mm) and highest amount of rainfall per rainy day (37.3 mm) were in January. The average rainfall per rainy day in 2005 was 3.71 mm. In comparison, average rainfall per rainy day in arid areas of North Africa was 3.82 mm over a timescale of 30 years according to Goudie and Viles (1997:83, Table 3.12.).

Various sources contribute to the salt content of stone structures. Seawater contains many types of salts with sodium chloride being the main constituent. Salts can be carried by wind not only from the sea, but also from the desert. Dust originating from the deflation of various susceptible surfaces may provide saline materials. For example dust of the Negev desert in Israel has been reported to contain up to 48% calcium carbonate and up to 3.1% soluble salts. Also rock weathering provides saline materials to the surroundings as most rocks contain salts or chemical elements that can participate in the formation of salts after being released by weathering. (Price 1996: 7; Goudie and Viles 1997: 64-69.)

Goudie and Viles (1997:16, 50) mention air pollution as having an increasing influence in salt accumulation, especially in urban environments where traffic and industry produce nitrogen oxide, sulphur dioxide and soot in the air. Air pollution is not a major threat for Jabal Haroun at the moment but as Thomas Paradise (1998:162) points out, the growing traffic and industry in southern Jordan may be a future threat to the monuments in Petra (including Jabal Haroun) as air pollution can be carried by fog, clouds or high winds from more polluted urban/industrial areas, also from more distant locations such as Israel, Egypt etc.

Some materials used for building and repairing, such as Portland cement or gypsum, bring salts to structures. Also human activity, e.g. storage or preparation of salty food over a long period of time, storage of manufacture of gunpowder, or the use of a building as a prison or toilet, can contribute to the salt content of structures as well. (von Konow 2002: 21-22.) This is where archaeological and historical investigation and chemical analysis can support each other. If the function of a space is known, certain sources and types of salts can be expected. If on the other hand the function of a space is
unclear, the analysis of salts present in the structures can help in the archaeological interpretation.

Goudie and Viles (1997: 118) identify two main categories of mechanisms of salt attack: physical changes, such as crystallization, hydration and thermal expansion, and chemical changes. Damage by crystallization can be caused by almost any salt, but hydration damage requires salts that are capable of being in several hydration states. Sodium sulphate is an example of such a salt. (Honeyborne 1990:154.) Salt solutions can cause damage chemically by causing etching and the transformation of minerals in stone. (Goudie & Viles 1997:49, 118.)

Crystallization and dissolution of salts are always accompanied by changes in volume. Subflorescence inflicts pressure on the walls of the pores. The pressure causes loss of strength of the material and eventually after several wetting-drying (or crystallizing – dissolving) cycles this will show as powdering on the surface of the masonry. Also changes in temperature may cause crystallizing and dissolving to occur. (Honeyborne 1990:154; Shadmon 1996:18; von Konow 2002:16) The pattern of water movement in walls influences the nature of salt efflorescence. Salts transported by the water are precipitated in a spatial sequence. Sulphates and carbonates are present in the lower zone as they are less soluble and less hygroscopic than chlorides and nitrates that are present in the upper zone. (Honeyborne 1990:154; Goudie and Viles 1997: 77.)

5 Methods Used in the Damage Diagnosis of the Jabal Haroun
Masonry Ruins

5.1 Damage Mapping

All structures at the Jabal Haroun ruins that have undergone conservation treatment have been mapped as part of the projects’ conservation documentation. As the conservation is mainly emergency conservation at the moment, the documentation concentrates on structural stability, including damage assessment of mortar joints and remaining wall plaster, and methods of conservation treatment. The damages on
individual stones have received less attention. The documentation presented in this M.A. thesis concentrates on the condition of the stone material. Detailed mapping and description of the state of conservation of all the Jabal Haroun structures would have been too great a task to be done for this M.A. thesis. Instead, the interior walls of the chapel were selected as an example to show the main damage categories visible at the whole site. The evaluation of damages was done visually. Damage symbols were drawn by hand on A4 size transparencies with printed digital photographs of the walls attached underneath as models. (See Appendix 1.)

Several standards or classification glossaries were available for damage mapping. The working group “Natural stones and weathering” of the geological Institute in Aachen University of Technology developed a damage mapping method for the monitoring of the rock-cut monuments in Petra (e.g. Fitzner & Heinrichs 1994). This classification system consists of a three leveled hierarchy of damage forms. The person doing the damage assessment can thus choose between a general or detailed mapping mode. The original classification system concentrated mainly on stone, but later, in the context of the German-Jordanian Petra Stone Preservation project, German Technical Cooperation Agency (GTZ), the classification system was complemented with damage categories for plaster by Shaki Aslan and May Shaer (2000). Later Fitzner and Heinrichs added a fourth level (differentiation of damage intensities) to the system, expanded the damage classification to an international scale, and presented it in the 2001 SWAPNET (Stone Weathering and Atmospheric Pollution Network) conference and its proceedings (Fitzner & Heinrichs 2002). This was followed by an online photo atlas of weathering forms on stone monuments (Fitzner & Heinrichs 2004).

The FJHP conservation documentation is based on the European Standard for Stone Damages (La Commissione Beni Culturali UNI-NorMal – 1/88), which includes damage categories for both stone and plasters. Lately the ICOMOS International Scientific Committee for Stone (ISCS) has worked to unify the terminology used in stone damage classification by developing the ICOMOS - ISCS glossary on stone deterioration patterns (ICOMOS 2008). This glossary combines the terminology of seven earlier glossaries and classification systems, including Fitzner & Heinrichs 2004 and the UNI-Normal 1/88. Damage mapping of the building stones in the chapel was
originally done according to the UNI-NorMal 1/88 but when the condition of stones will be described in Chapter 6, the terminology of the ICOMOS – ISCS glossary will be used because of its international nature.

5.2 Monitoring Temperature and Relative Humidity

Relative humidity (RH%) and temperature are the most important climatic agents influencing the condition and behavior of materials. Precipitation is generally also an important factor in sandstone weathering (Paradise 2005:40), but due to the arid climate of the Petra region its influence is reduced. Climatic data is available for Wadi Mousa by Jordan Meteorological Department. The German-Jordanian Petra Stone Preservation project, German Technical Cooperation Agency (GTZ) has monitored climatic conditions within caves in Petra in 2001 and 2002 (Stefan Simon et al. 2004: 963; Stefan Simon e-mail 27 June 2005), but this data was not available at the time this M.A. was written.

Experience from the Jabal Haroun site has shown that the conditions in the Petra valley differ from those on the mountain and thus the climatic data is not directly applicable to the mountain. For example chemicals such as ethyl silicate and acrylic resin used for conservation at the Petra Church have not worked properly on Jabal Haroun (Karakoski 2001:7-8). Relative humidity (RH%) and temperature have been briefly monitored at Jabal Haroun in 1999 with a Vaisala handheld humidity and temperature meter, primarily to see what chemicals could be used for conservation. The monitoring (25 August – 6 September) was done at one point in shade (in the office tent, where first-aid conservation of objects took place). Measurements were taken four times a day: at sunrise, noon, in the afternoon and at sunset. (Karakoski 2001:87).

<table>
<thead>
<tr>
<th>Time</th>
<th>Min/Max RH%</th>
<th>Mean RH%</th>
<th>Min/Max Temp. ºC</th>
<th>Mean Temp. ºC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunrise 6:30-7:30</td>
<td>52.0 – 83.0</td>
<td>68.0</td>
<td>13.1 – 17.5</td>
<td>15.8</td>
</tr>
<tr>
<td>Before noon 9:00-11:00</td>
<td>41.0 – 48.0</td>
<td>45.1</td>
<td>23.2 – 26.7</td>
<td>24.6</td>
</tr>
<tr>
<td>Afternoon 13:00-17:00</td>
<td>26.0 – 32.3</td>
<td>29.6</td>
<td>28.0 – 31.6</td>
<td>30.2</td>
</tr>
<tr>
<td>Sunset 19:30-21:00</td>
<td>40.0 – 53.3</td>
<td>47.2</td>
<td>21.5 – 25.8</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Table 4 Mean temperature and relative humidity at Jabal Haroun 25 August - 6 September 1999. (Karakoski 2001: 87)
For this M.A. thesis, relative humidity (RH%) and temperature were monitored more extensively in 2005-2006 with a HOBO Microstation Datalogger to observe the conditions to which the structures are exposed. The HOBO Microstation Datalogger was installed in the chapel and hidden in a plywood box sheltering an altar. Two humidity and temperature sensors were used, one of which was placed with the logger inside the altar box. The other sensor was placed in open air at the other end of the chapel. It was necessary to protect the sensor from direct sunlight and rain with a wooden shelter that allowed air to move freely within. The recording interval was set at two hours. Logging began in August 2005 and it ended in August 2007. The logger measured temperature (°C), relative humidity (RH%) and dew point (°C) for a full year, from 20 August 2005 to 15 September 2006.

5.3 Paper Pulp Method for Acquiring Salt Samples

“Qualitative analysis of soluble salts (from a stone ornjavascript:queryInspectedTermOrObservationOrStatement()ortar sample) furnishes information about the types of ions (sulphates, chlorides, etc.) present in the sample and gives an indication of the maximum quantity of single ions present. Such information provides some clues as to the type of deterioration in progress and its causes.” (Teutonico 1988:58.)

The paper pulp method created by Ernesto Borelli (1994) involves the extraction of soluble salts from a surface with a poultice of wet paper pulp, Arbocel BC 1000. The ideal weight proportion of pulp to water is between 1/6-1/8. The poultices are applied when wet and collected after they have dried completely. The samples should always be tested with the same amount of paper pulp in the same amount of water, so that results are reliable and comparable.

The method is a non-destructive method for finding out what soluble salt types are present near the surface of the material from which samples are taken. It does not reveal what salts or salt combinations are deeper inside the structure, nor does it show the non-soluble salts present. Also the form or crystal phase of the soluble salts may alter when they move from the stone material and recrystallise in/on the paper pulp.
A more detailed picture of the salt combinations, their location in the stone material and the crystal phases can be acquired by drilling samples but this method is more destructive. As the stone material in the structures, although mostly belonging to the same lithotype, is very heterogeneous in respect to quality and state of conservation, drill samples would only show the situation of the ashlars they were taken from. For now, the method causing no permanent damage was preferred for this research.

5.4 Methods for Analyzing Salt Samples

Merckoquant Salt Strips and HCl in Analyzing Salt Samples

Merckoquant salt strip tests determine the concentration of salts in sample solution semiquantitatively. The analytical test strip is immersed in the sample solution for one second and excess liquid is shaken from it. After one or two minutes, depending on the test at hand, the color pattern of the reaction zones is compared visually with the color scale of the strip package. Table 5 shows the measuring range and special requirements of the strips. The strip test shows which soluble salt anions (nitrates, chlorides, carbonates, or sulphates) are present in the samples but not salt cations, possible combinations of salts or the actual amount of salts in the structures.

<table>
<thead>
<tr>
<th>Salt Anions</th>
<th>Measuring range</th>
<th>pH range</th>
<th>Expiration date</th>
<th>Storing temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphates SO₄²⁻</td>
<td>&lt;200 0 &gt; 1600 mg/l</td>
<td>4-8</td>
<td>Jan06</td>
<td>15-20°C, dry</td>
</tr>
<tr>
<td>Nitrates NO₃⁻</td>
<td>0-500 mg/l</td>
<td>1-12</td>
<td>Feb06</td>
<td>Unopened in 2-8°C, opened in cool &amp; dry, not refrigerator!</td>
</tr>
<tr>
<td>Nitrites NO₂⁻</td>
<td>+/++</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorides Cl⁻</td>
<td>0 - ≥ 3000 mg/l</td>
<td>5-8</td>
<td>Jul07</td>
<td>2 - 8°C</td>
</tr>
<tr>
<td>Carbonates (hardness test)</td>
<td>0-24°d (0-4,32 mmol/l Ca²⁺ + Mg²⁺)</td>
<td>-</td>
<td>Feb08</td>
<td>15-25°C</td>
</tr>
</tbody>
</table>

Sulphate analysis by Merck strips is based on the reaction of sulphate ions with the red thorin-barium complex in the reaction zones of the strip. The analytical test strip is
immersed in the sample solution for one second and excess liquid is shaken from it. After two minutes the color pattern of the reaction zones is compared with color rows on the strip package label. In the presence of sulphate ions, the color of the equivalent reaction zone changes to that of the yellow thorin. (Merckoquant Test Cat. No. 1.10019.0001, Official informative label.)

The reaction of the nitrate/nitrite test is based on nitrate being reduced to nitrite by a reducing agent. The nitrite is then converted to nitrous acid in the presence of an acidic buffer. Nitrous acid diazotizes an aromatic amine, which couples with N-[1-naphthyl] ethylenediamine to form a red-violet azo dye. The test strip contains two reaction zones, one of which reacts only to nitrites and the other to both nitrites and nitrates. The zone reacting to nitrites serves as a warning zone, as the presence of nitrite interferes with the reaction. The analytical test strip is immersed in the sample solution for one second and excess liquid is shaken from it. After one minute the color pattern of the reaction zones is compared with the color scale of the strip package. (Merckoquant Test Cat. No. 1.10020.0001/1.10050.0001, Official informative label.)

The chloride test is based on chloride ions reacting with silver ions, resulting in the decolorization of red-brown silver chromate in the reaction zones of the test strip. The analytical test strip is immersed in the sample solution for one second and excess liquid is shaken from it. After one minute the color pattern of the reaction zones is compared with color rows on the strip package label. (Merckoquant Test Cat. No. 1.10079.0001, Official informative label.)

Carbonate hardness is defined as that portion of calcium and magnesium ions present in one liter of water for which there is an equivalent amount of carbonate and hydrogen carbonate ions originating from dissolved carbonic acid. It is officially stated in terms of the concentration of the hardness ions $\text{Ca}^{2+} + \text{Mg}^{2+}$ in mmol/l. The carbonate and hydrogen carbonate ions react with acid. The reaction zones of the test strips contain a mixed indicator, the color of which depends on the pH value resulting from the reaction of the ions to the acid. Strong bases and other acid-consuming substances, such as phosphate, in the sample interfere with the test. (Merckoquant Test Cat. No. 1.10648.0001, Official informative label.)
After the removal of paper pulp and water from the samples, analysis with HCl reveals the presence of carbonates that have not dissolved in water. According to Teutonico (1988: 64) the presence of insoluble carbonates in a sample can be analyzed by adding 1 or 2 drops of concentrated hydrochloric acid (HCl) to the insoluble part of a sample. Bubbles of carbon dioxide CO$_2$ gas in the solution indicate the presence of carbonates (CO$_3^{2-}$).

\[
\text{CaCO}_3 + 2\text{HCl} \rightarrow \text{CaCl}_2 + \text{H}_2\text{O} + \text{CO}_2 \uparrow \quad \text{(gas)}
\]

**SEM/EDX and X-Ray Diffraction Methods**

SEM/EDX analysis is used to find out what elements are present in a sample. The sample is bombarded with electrons in an electron microscope. When an atom receives a high-energy beam of electrons, electrons from the inner shells of the atom may be released, leaving the atom in an excited (or ionized) state. The energy of the electron beam needed for exciting depends both on the atom and which electron shell the electrons are released from. The atom returns to its lowest energy state when an electron from an outer shell of the atom moves to the inner shell and fills the vacancy. Energy released in this shift can release as x-ray radiation, the energy of which is typical to each atom and each shift. The EDX detector collects the x-ray quanta thus formed and sorts them according to the energy. This gives an EDX spectrum that shows the intensity of the x-ray lines as a function of energy. (Friel 2003:5.)

The sample for EDX analysis should have an even surface and conduct electricity well enough. Uneven samples can also be analyzed but the results are not as accurate. The detectability limit of the EDX analysis is generally considered to be 1000 ppm (0.1 mass %). If the sample contains only a small amount of the element, it is not necessarily detected at all or the amount detected is not accurate. When small amounts are concerned, also the identification of elements can go wrong, especially if the spectrum shows x-ray lines of other elements in the same energy range. (Friel 2003:1-2; Marianna Kemell, pers. comm. 18 January 2008.)
X-ray diffraction (XRD) technique is used for characterizing crystalline material. It does not identify atoms directly, but gives order information on atomic positions from diffraction patterns. From diffraction peak intensities it is possible to identify individual crystalline phases and their relative amounts in polycrystalline samples. This is made possible by a data bank containing almost every phase of every known material. In addition to identifying phases and their structural properties, XRD is used for determining strain and particle size in thin films. The sensitivity of XRD depends on the material being analyzed. (Fitzpatrick et al. 1992: 193-194; Toney 1992: 198.)

6 State of Conservation of Masonry Walls in the Jabal Haroun Chapel

6.1 Southern Wall, Wall H

![Picture 9](Wall H after emergency conservation. The panorama is a combination of 5 photographs, thus the appearance of the pilasters is not necessarily truthful.)

The southern wall (W.H) has separated the chapel and the church since the construction of these buildings. It has two door openings, one in the middle of the wall (narrowed in Phase 4 and blocked in Phase 7, see Mikkola et al. in press) and the other in the western end. Three pilasters (loci I.11, I.07/Y.19 and Y.17) and two columns (loci Y.15 and C.13) have been built beside the wall and between them there are masonry built benches (loci I.22, Y.31, Y.37 and Y.33), width 0.38 – 0.5 m, height 0.3 - 0.35 m. The wall is 24.50 m long and 5-9 courses high. The wall has been built using dressed quarry stones
and possibly some ashlars, with only few small stones used for wedging. However, only few stones still show the original dressed surface. Small patches of plaster have survived on this wall, mainly at its bottom parts between pilasters I.11 & I.07/Y.19, and Y.19 & Y.17. The mortar inside the wall has lost cohesion, contributing thus to the poor state of preservation.

The condition of the stones varies greatly (see Appendix 1). The original dressed surface has survived on some stones, while many stones are in an extremely bad state of preservation. The most common form of weathering on the stones is erosion. Erosion is defined in the UniNormal 1/88 as “wearing away of the surface due to various causes” and in the ICOMOS – ISCS glossary as “loss of original surface, leading to smoothed shapes” (ICOMOS 2008, www –document). Erosion is affecting the surface of the stone with different intensities, depending on whether the sandstone is from the more resistant upper Umm Ishrin Formation or the middle Umm Ishrin Formation. Erosion shows mostly as the rounding of stone edges but also as relief formation caused by differential erosion.

The more severely weathered sandstones belong mainly to the middle Umm Ishrin sandstone formation. In addition to erosion, the stones are suffering from sanding, delamination/exfoliation and flaking/scaling. Sanding is defined in the ICOMOS – ISCS glossary (ICOMOS 2008, www –document) as “granular disintegration of sandstone”. It is a subtype of disintegration, the “detachment of single grains or aggregates of grains”. Disintegration is equivalent to terms such as "loss of cohesion", "friability", "disaggregation" and "pulverization". An eroded stone can have loose sand granules on its surface resulting from granular disintegration. However, in this mapping of weathering forms, sanding as a term was used only for those stones, whose surfaces still retained most of the disintegrated material, thus being so soft they could be carved with a fingernail.

Delamination is a detachment process affecting laminated stones (most sedimentary rocks). It is the physical separation of stone material into one or several layers following the bedding planes of the stone. The layers may be oriented in any direction with regards to the stone surface and their thickness and shape are variable. A subtype of
delamination is *exfoliation*, the detachment of multiple thin stone layers (cm scale) that are sub-parallel to the stone surface. Another form of detachment, *scaling*, differs from delamination and exfoliation by being totally independent of the stone structure. The plane of detachment of the scales is located near the stone surface. *Flaking* is a subtype of scaling and occurs in thin flat or curved scales of submillimetric to millimetric thickness. (ICOMOS 2008.)

Some individual stones have *cracks*, mainly in the area between pilasters Y.19 and Y.17. Most cracks are major *fractures*, crossing the stone completely. In this same area, one quarry stone is missing. Elsewhere, only smaller stones seem to be missing. Salt *efflorescence* is visible only on stones in the lower part (courses 2 and 3) of the wall east from column C.13. This part of the wall has been exposed for the longest period of time – from 1998. Biological colonization, in the form of *lichens*, can be seen on a few stones around the blocked doorway in the middle of Wall H and on pilaster I.11.

### 6.2 Eastern Wall, Wall S

Wall S (W.S) is the eastern wall of the entire monastic building complex (see Appendix 1). Its interior face in the chapel consists of the curved wall of the apse and two cupboards on its sides. It has been built using ashlars and quarry stone. The mortar has lost cohesion, thus contributing to the poor state of the wall. The surviving inside face of the wall is 5-6 courses high in the apse. The outer face of the wall had collapsed and was reconstructed after excavation to the height of the fourth interior course to stabilize the apse wall. Some plaster was still attached to the wall in the northern part of the apse when it was excavated in 2003, but by 2005 it had mostly fallen off. The cupboard shelves have

![Picture 10 Wall S in 2005. Compare with picture CH06 (taken in 2003) in Appendix 1.](image)
been made of large sandstone slabs integrated into the wall structure. Only the lower shelf in the southern cupboard is still entirely in place.

Wall S displays a wide variety of weathering forms and intensities. Especially stones at the protruding ends of the apse wall are severely eroded, perhaps as a result of wind abrasion. Several stones in the southern end of the apse have cracked, more or less along a vertical line, it seems. The interior of the apse is more sheltered and here the damaged stone surfaces are mainly exfoliating and scaling. A couple of stones in the southern part of the apse show a combination of damage forms: from pitting and/or small scale alveolization to scaling, and from delamination to flaking and scaling. Salt efflorescence is visible especially in the area where the remaining wall plaster used to be. Some lichen grows in the northern part of the apse.

6.3 North Wall, Wall GG

The northern wall (W.GG) is also an original wall of the chapel (see Appendix 1). It houses three cupboards, none of which were excavated due to the instability of the surrounding wall. Two columns (loci Y.04 and Y.14) and three pilasters (loci Y.18, I.09/Y.20 and I.06) have been built beside the wall. Between the pilasters and the western one of the two columns there are masonry built benches (loci Y.29, Y.30, I.20 and I.24). The space between the two columns is occupied by the later baptismal font (locus Y.26). Several large stone blocks have a dark surface and are very well preserved. This black crustification is iron oxide that has formed when the stone material has been exposed to the sun for a long period of time before being used for construction (Majdi Barjous, pers. comm. 14 August 2005).

The main damage type to be seen in the stones in Wall GG is erosion, the intensity of which is again influenced by type of stone. The middle Umm Ishrin sandstones are generally in a worse state and show rounding and differential erosion. The pilasters have not eroded as severely as the ends of the apse in Wall S. Compared to the other walls, Wall GG has a larger proportion of stones suffering from delamination, scaling and flaking. Also some stones are sanding severely. On the other hand, more plaster has survived on the wall, benches and one column. Cracks occur in some individual stones
both in the wall and in the pilasters. The only clear case of alveolization in the chapel can be seen in pilaster I.09/Y.20. The top portion of one of the stones still has its original dressed surface, but the bottom part is very rounded and has a single alveolar cavity in the middle. Stone material is detaching from its sides in the form of scales.

6.4 Western Wall, Wall OO

The western wall (W.OO) of the chapel we see today (see Appendix 1) is not the original western wall, but derives from Phase 4, when both the church and the chapel were shortened (see Chapter 3.1). It has suffered most destruction of all the chapel walls. A masonry built bench (locus I.19) runs alongside the whole length of the wall.

The damage types in this wall are the same ones as in the other three walls of the chapel. The stones are mostly more or less eroded. The surface of many stones is scaling and/or flaking and some stones are exfoliation. A couple of stones in the southern end of the wall have fractured.

![Wall OO in 2005.](image11)

**Picture 11** Wall OO in 2005.
6.5 Damaging Processes Contributing to the State of Conservation

During the course of history the site has faced several phases of destruction and reconstruction. Large scale structural destruction has mostly been caused by earthquakes, while damage to the building material is mainly due to weathering. The stone material was found already weathered when the structures were exposed by the FJHP excavations. This means that they have been exposed for long periods before sand has accumulated and covered them. Old building materials were reused when the buildings and structures were reconstructed and remodeled after the first destructions. The reused building blocks were sometimes already weathered. In later phases the structures have been more exposed to weathering as the fallen stones and debris has been cleared after destruction, but the spaces have been left open.

Generally the E-W running walls of the church and chapel are better preserved than N-S running ones, probably as a result of seismic E-W movement of the Wadi ‘Araba rift valley (Mikkola et al. in press). One reason for the overall poor preservation situation of the walls is that the mud mortar in the walls has lost cohesion throughout the structures. Most of the plaster that used to cover the walls has fallen during the phase of exposure before the walls were entirely buried.

The sandstone material in the walls is suffering from an ongoing process of deterioration. Many rates of weathering are visible in same blocks of stone due to cross beddings (Majdi Barjous, pers. comm. 14 August 2005). Stone from the middle Umm Ishrin Formation is most affected, while stone from the upper Umm Ishrin Formation has resisted weathering better. Of the different weathering forms in the chapel walls described above, erosion (rounding and differential erosion), scaling/flaking and delamination/exfoliation are the most common. Exfoliation is characteristic especially for stone coming from the middle Umm Ishrin formation (Majdi Barjous, pers. comm. 14 August 2005). Sometimes it is difficult to differentiate between different forms of weathering because stones may display intermediate deterioration patterns and some blocks exhibit more than one form of deterioration. Sanding is also common while pitting and alveolar weathering are quite rare. Cracks in the stones are mostly fractures, caused either by weathering, flaws in the stone, static problems or vibrations caused by earth tremors. Also fire and frost may cause cracking.
In the course of damage mapping the Jabal Haroun chapel walls, such a clear distinction between aspects as has been noted in Petra (Fitzner and Heinrichs 1994:670; Paradise 1998: 157, 159) was not noticed. The northern aspect showed erosion, scaling, exfoliation, granular disintegration, and salt efflorescence in same intensities as the southern aspect. The main difference was, that most lichen growth occurred on the wall facing north, which is consistent with observations made in Petra, and the only case of clear alveolar weathering was seen on a pilaster facing south. Salt efflorescence was not observed on the south facing wall at the time of damage mapping, while there were some noticeable efflorescences on the northern aspect. The north facing southern wall in the Jabal Haroun chapel is exposed on both sides, while the wall facing south has soil on the other side.

The curved wall of the apse facing west is more complex and has surfaces facing various directions. The area is more sheltered except for the protruding parts of the apse, which show severe differentiated erosion, likely the cause of wind abrasion. Certain damage types in the apse occurred actually on opposite directions compared to the other walls. Lichen growth was observed on a southern aspect, while a transitional form of alveolization and pitting was found on the northern aspect. The wall facing east is not very well preserved, so it is difficult to compare it with other walls. Most stones are, however, very damaged, suffering mostly from erosion, delamination and scaling.

Erosion can be caused by chemical, physical or biological processes (ICOMOS 2008) and be a result of other forms of weathering. For example sanding and scaling/flaking take place at first and then wind abrasion removes the loose surface. Strong winds carry sand, but also speed the drying of the surface and thus speed up for example salt crystallization. Surface temperatures exceeding 50°C are also a cause for enhanced surface recession of sandstone (Paradise 2005: 40). Rapid changes in relative humidity RH% cause sandstone erosion by enhancing the salt crystallization and dissolution cycles which lead to the detachment of the stone surface.

Since sandstone comprises of granules in a binding matrix, granular disintegration is a typical result of its weathering. Either the sandy clast fractures or dissolves and falls out
or the binding matrix fractures or dissolves and releases the clast (Paradise 1998:155). Either way the end result is loose sand as the weathering product and a variety of weathering forms on the stone material. Surface features such as alveolization or rounding are the result of partial or selective granular disintegration (ICOMOS 2008). Humidity cycles lead to the flaking and granular disintegration of Umm Ishrin Sandstone when it contains salt (NaCl) (Lombardo et al. 2004: 203). Granular disintegration may be induced also by temperature cycles, especially in sandstones with matrix calcium exceeding 10%. High surface temperatures may cause the clast to expand and contract, leading to the development of small fractures between the clast and matrix and subsequent granular disintegration (Paradise 1998: 156).

7 Temperature and Relative Humidity at Jabal Haroun in 2005 – 2006

7.1 Monthly and Annual Observations

Climatic conditions vary annually and thus the data acquired in the monitoring on Jabal Haroun does not give a comprehensive picture of the overall climate on the mountain. It is rather a sample of the conditions during one year, and gives an idea of what the masonry ruins are standing up against. The observations presented below are based on the visual examination of the graphs in Appendix 2 and calculations made from the numeric data.

In September 2005 (see Appendix 2 | 1) daily temperatures ranged usually between 20° C and 30° C, with night time temperatures often dropping slightly below 20° C. Maximum temperature was 31,93° C and minimum 15,62° C. Daily variation of relative humidity was great. The most rapid rise of RH% took place on the 11th when RH% rose 51,16% (from 22,09 - 73,25%) in 2 hours. The most rapid fall occurred on the 14th when RH% fell 56,09% (from 74,74 - 18,66%) in 4 hours. If compared to the beginning of September 2006 it can be noticed that September 2005 is somewhat dryer. No dew events occurred in 2005 while in the beginning of September 2006 three dew events took place.
October 2005 (see Appendix 2 | 1) witnessed longer periods of warm, relatively dry days and cooler, more humid days. Changes in RH% were not as abrupt as in September. During the warm days temperatures stayed between 20°C and 30°C, and RH% dropped below 20%. On cooler days temperatures varied between 10°C and 20°C, while relative humidity varied mostly between 40% and 90%. The biggest change in RH% (56.5%) occurred on the 3rd when relative humidity rose from 17.75% to 74.25% in 12 hours.

Temperature in November 2005 (see Appendix 2 | 2) stayed mostly around 10°C (±5°C) with slightly warmer days in the middle of the month and a clearly warmer period in the end of the month, during which the temperature stayed around 20°C. RH% varied mostly between 40% and 90%. During the warmer periods RH% dropped to 30-40% in the middle of the month and 20-40% in the end.

The first half of December 2005 (see Appendix 2 | 2) was quite dry (4.75% - 55.25%, RH mostly between 10% and 20%) and the temperature varied around 20°C (±5°C). In the latter half of the month, temperature dropped to 0-15°C and humidity varied between 30% and 95.75%. Towards the end of the month the temperature rose again to 10-20°C and RH% dropped to 20-30%.

January 2006 (see Appendix 2 | 2) was overall a very humid month,

Picture 12 Location of the open air sensor in the S-W corner of the chapel. The sensor has been placed inside a well-ventilated shelter.
with RH% being over 60% for much of the time. Dew point values rose over temperature values 9 times during the month, which means as many dew events with moisture condensing on surfaces. This can be seen also in the RH% curve as values of 100%. The values recorded by the datalogger were actually over 100% during the dew events, which can be explained by condensation on the sensor head. Since relative humidity values cannot be over 100% the values exceeding it were converted. The temperatures were mostly between 0˚C and 10˚C. There were a couple of warmer periods, with the temperature being 10-20˚C. During these periods the relative humidity varied between 8,63% and 78,25%.

February 2006 (see Appendix 2 | 3) was also a cold and humid month. The annual minimum temperature 0,29˚C occurred during a dew event which lasted for three days. Altogether 3 dew events were recorded with a minimum duration of ca. 2 hours and total duration of ca. 82 hours. Generally the relative humidity stayed between 20% and 70% and the daily variation was not as severe as during several other months. Maximum temperatures of the month were slightly over 20˚C. Usually the temperature varied between 0˚C and 20˚C.

Rapid variation of relative humidity took place in March 2006 (see Appendix 2 | 3). Dew events and 100 RH% occurred six times while minimum RH% was 5,25. The time between the maximum and minimum values was 58 hours. There were four periods of warmer temperatures during which relative humidity values stayed mostly under 30%. The temperature stayed usually between 10˚C and 20˚C, but dropped under 10˚C during the dew events.

Daytime temperatures in April 2006 (see Appendix 2 | 3) reached ca. 30˚C during four warm periods lasting 2-4 days each. Night temperatures during these periods were around 20˚C and relative humidity mostly between 10% and 30%. More humid and cold periods between the warm days had temperatures around 10˚C and RH% generally varying from ca. 40% to 100%. Dew events occurred 12 times with the total amount of dew hours being ca. 79.
May 2006 (see Appendix 2 | 4) had temperatures varying between 10°C and 34°C. This month was drier compared to the previous ones as relative humidity stayed mostly under 70%, the maximum value was 88.75%. During the warmer days relative humidity fell below 10%.

Temperature in June 2006 (see Appendix 2 | 4) stayed mostly between ca. 20°C and 35°C, with night time temperatures dropping below 20°C in the middle of the month during a more humid period. During this period RH% varied from ca. 10% to ca. 70%. In the first third of the month humidity variation was relatively small, with values staying between 15% and ca. 40%. The last third was as warm as the beginning of the month, but more humid. The RH% values ranged from 10% to 55%.

Table 6 Maximum, minimum and average temperature and relative humidity on Jabal Haroun between September 2005 and August 2006.

<table>
<thead>
<tr>
<th>Open Air</th>
<th>Temperature ºC</th>
<th>Relative Humidity RH%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Max</td>
</tr>
<tr>
<td>September 2005</td>
<td>22,34</td>
<td>31,93</td>
</tr>
<tr>
<td>October 2005</td>
<td>18,31</td>
<td>29,10</td>
</tr>
<tr>
<td>November 2005</td>
<td>12,84</td>
<td>24,40</td>
</tr>
<tr>
<td>December 2005</td>
<td>12,76</td>
<td>24,40</td>
</tr>
<tr>
<td>January 2006</td>
<td>7,93</td>
<td>19,42</td>
</tr>
<tr>
<td>February 2006</td>
<td>9,94</td>
<td>22,48</td>
</tr>
<tr>
<td>March 2006</td>
<td>12,74</td>
<td>25,56</td>
</tr>
<tr>
<td>April 2006</td>
<td>16,08</td>
<td>29,50</td>
</tr>
<tr>
<td>May 2006</td>
<td>21,66</td>
<td>34,01</td>
</tr>
<tr>
<td>July 2006</td>
<td>24,80</td>
<td>34,85</td>
</tr>
<tr>
<td>August 2006</td>
<td>26,60</td>
<td>35,70</td>
</tr>
<tr>
<td>Annual</td>
<td>17,59</td>
<td>35,70</td>
</tr>
</tbody>
</table>

July 2006 (see Appendix 2 | 4) was more humid than June, but the temperatures were generally the same, mostly between ca. 20°C and 35°C. Relative humidity showed constant daily variation between ca. 20% and 60-80% in the second half if the month. A period of three days in the middle of the month showed relatively small variation of lower RH% values (range 13 - 37%). This period was followed by a sudden jump of
relative humidity to 100%, the only dew event of this month, and the period of greater variation in the latter part of the month.

Daily variation of temperature in August 2006 (see Appendix 2 | 5) was ca. 10°C, ranging between ca. 20°C and 36°C. Relative humidity varied from ca. 10% to ca. 80% staying usually between 20% and 60%. The second quarter of the month was more humid than the rest of the month, but in comparison with the other months, August was quite dry and warm. The annual maximum temperature 35,70°C was measured in August.

Generally the Middle Eastern year is divided into three seasons with summer extending from mid-June to mid-September, the cooler rainy season from mid-October to mid-April and the months in between constituting the transitional seasons (MacDonald 2001:595). On Jabal Haroun May, June, July and August 2006 were the less humid and warmest months, while the most humid months were November, January and February. September, March and April were months of intense fluctuation between warm, dry periods and cooler, more humid periods. Based on the average values presented in Table 6, August and June were the warmest months and January and February were the coldest. The lowest temperature 0,29°C occurred in February and the highest 35,70°C in August. Average relative humidity was highest in January and lowest in June.

Maximum RH% values (100%) were reached in January, February, March, April and July, while the lowest RH% value (4,75%) occurred in December. Dew events took place 0-12 times per month, the duration of the events varying from approximately 1 hour to 70 hours. The biggest difference (94,75%) between highest and lowest relative humidity was in March. On a monthly scale more humid periods usually correlate with periods of lower temperatures and warmer periods coincided with lower RH%. Relative humidity values of over 90% usually occurred when temperature dropped below 10°C. Lowest daily temperatures occurred usually between 12am and 8 am and highest occurred between 12pm and 6 pm. Looking at the measurements, it is obvious that such large and frequent cycles of humidity and temperature must have a serious effect on the preservation of exposed stone material.
7.2 Temperature and Relative Humidity in the Sheltered Chapel Altar

Some structures, such as the plastered Phase 7 altar and baptismal font in the chapel, have been protected by covering them with geotextile and well-ventilated plywood boxes. The bottom parts of the boxes were left entirely open and the side parts equipped with air holes at the top to ensure sufficient movement of air inside. The top parts of the boxes were covered with plastic to protect the plywood from rain and condensing water.

The problem with building the shelters was how to make them resistant enough to survive strong winds, rain, condensing water and the burning sun. Also the local availability of building materials and equipment limited the possibilities. Plywood was the only available material at the time for building the boxes for the altar and baptismal font. The second sensor was placed inside the altar to monitor how much the conditions would differ from those in open air. Table 7 shows the average, maximum and minimum values inside the altar and can be compared and Table 6 shows the same values for open air.

Table 7 Maximum, minimum and average temperature and relative humidity between September 2005 and August 2006 on Jabal Haroun in the recess of the sheltered chapel altar.

<table>
<thead>
<tr>
<th>Inside Altar</th>
<th>Temperature ºC</th>
<th>Relative Humidity RH%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Max</td>
</tr>
<tr>
<td>September 2005</td>
<td>22,78</td>
<td>26,73</td>
</tr>
<tr>
<td>October 2005</td>
<td>18,93</td>
<td>24,40</td>
</tr>
<tr>
<td>November 2005</td>
<td>12,79</td>
<td>19,04</td>
</tr>
<tr>
<td>December 2005</td>
<td>12,59</td>
<td>19,81</td>
</tr>
<tr>
<td>January 2006</td>
<td>8,11</td>
<td>15,62</td>
</tr>
<tr>
<td>February 2006</td>
<td>9,12</td>
<td>17,52</td>
</tr>
<tr>
<td>March 2006</td>
<td>13,03</td>
<td>21,33</td>
</tr>
<tr>
<td>April 2006</td>
<td>15,45</td>
<td>23,24</td>
</tr>
<tr>
<td>May 2006</td>
<td>21,09</td>
<td>27,91</td>
</tr>
<tr>
<td>June 2006</td>
<td>24,71</td>
<td>29,50</td>
</tr>
<tr>
<td>July 2006</td>
<td>24,57</td>
<td>28,31</td>
</tr>
<tr>
<td>August 2006</td>
<td>26,62</td>
<td>30,31</td>
</tr>
<tr>
<td>Annual</td>
<td>17,48</td>
<td>30,31</td>
</tr>
</tbody>
</table>

Average temperature was not drastically different between the sheltered altar and the open air. Maximum variation was 0,82°C. Average relative humidity in the altar was ca. 0,38 - 4,5°C lower during the year with the exception of February, when average RH%
was ca. 1.70% higher than in open air. Maximum temperature was 3.8 - 6.54°C lower in the altar box throughout the year, especially during the summer months April-August. Minimum temperatures in the altar did not drop as low as in the open air, but stayed 2.14 – 4.24°C higher. Maximum relative humidity values were reduced by 19 – 43.25% in the altar and minimum values stayed 5.5 – 20% above the values in open air. Overall the shelter stabilizes the conditions by reducing the extremity of temperature and humidity variation (see Appendix 2 | 1, 3, 4 and 6).

7.3 Jabal Haroun Temperature and Relative Humidity in a Wider Context

The Jabal Haroun temperature values can be compared with simultaneous measurements (see Table 8) and measurements over longer periods of time from the nearest weather station in Wadi Musa. It would also have been useful to compare the JH measurements with data from Petra. Unfortunately data from Petra and Wadi Musa (2006) was not available at the time this comparison was made. Thus comparable simultaneous measurements are only for four months from September to December 2005. Therefore this is but a sample; the results would probably have looked different if an entire year could have been compared. The Jabal Haroun dew conditions were compared with results of a research made in the Negev Desert by Zangvil 1996 (cit. Goudie & Viles 1997:79).

Table 8 Comparison of temperature values in Wadi Musa and on Jabal Haroun.

<table>
<thead>
<tr>
<th>Year</th>
<th>Wadi Musa</th>
<th>Jabal Haroun</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Absolute max °C</td>
<td>Absolute min °C</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>31.0</td>
</tr>
<tr>
<td></td>
<td>October</td>
<td>29.6</td>
</tr>
<tr>
<td></td>
<td>November</td>
<td>25.6</td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>26.8</td>
</tr>
</tbody>
</table>
During the four months minimum temperatures reached somewhat lower values in Wadi Musa than on Jabal Haroun. Maximum temperatures were higher in Wadi Musa from October to December. The differences range between 0.6°C and 2.4°C. Average values or monthly relative humidity could not be calculated reliably as the data received from Wadi Musa contained only daily measurements at 6 am and 12 pm in addition to daily values of rainfall, min and max temperature and evaporation.

Comparison of the 2005 September to December values of temperature and RH% in Wadi Musa and on Jabal Haroun at 6 am and 12 pm (see Appendix 2 | 6) shows that the mornings were ca. 2°C colder on the mountain, while average noon temperatures did not differ much. Absolute maximum and minimum temperatures occurred on the mountain. Humidity conditions at 6 am were not as clearly divided. According to the average values, both morning and noon in Wadi Musa were generally more humid. It should, however, be kept in mind that highest and lowest daily values did not always occur at these given times as the measurements on Jabal Haroun showed.

Table 9 shows how the monitored months on Jabal Haroun relate to the long-term data from Wadi Musa, measured in 1984 - 1998. Average relative humidity values were mostly lower on Jabal Haroun than in Wadi Musa with the exception of January 2006 and April 2006 being more humid. Neither minimum nor maximum temperatures on Jabal Haroun reached the corresponding values in Wadi Musa. This comparison indicates that the 12 months measured were by no means extreme with regard to temperature and generally drier than average with regard to average relative humidity.

Dew and fog water are two important sources of moisture for stone weathering caused for example by salts. In the Negev Desert dew events were observed 8-26 days per month, minimum in April, maximum in September, with an average 2.5 – 5 dew hours per night (Zangvil 1996, cit. Goudie & Viles 1997:79). The observations on Jabal Haroun in 2005-2006 revealed that at least during these 12 months dew events were not as plentiful as in the Negev desert. As already was mentioned above, dew events on Jabal Haroun took place 1-12 days per month in January, February, March, April (max) and July (min) and the duration of the events varied from approximately 1 hour to 70 hours. Most of the dew events occurred at night time and lasted for max. 12 hours.
exception of this was in January, when three dew events took place just before or at noon. Two periods of longer lasting condensating conditions took place in February and April. The period in February lasted for three days and nights, 70 hours total and the period in April lasted 34 hours. During these events a cloud has probably surrounded the mountain for several days.

Table 9 Comparison of humidity and temperature values from Jabal Haroun to long-time values from Wadi Mousa weather station.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>September (2005)</td>
<td>47.4</td>
<td>43.30</td>
<td>10.0</td>
<td>15.62</td>
<td>36.5</td>
<td>31.93</td>
</tr>
<tr>
<td>October (2005)</td>
<td>48.8</td>
<td>47.67</td>
<td>6.5</td>
<td>9.03</td>
<td>33.0</td>
<td>29.10</td>
</tr>
<tr>
<td>November (2005)</td>
<td>53.0</td>
<td>52.33</td>
<td>0.5</td>
<td>6.62</td>
<td>27.5</td>
<td>24.40</td>
</tr>
<tr>
<td>December (2005)</td>
<td>61.3</td>
<td>40.95</td>
<td>-2.2</td>
<td>1.60</td>
<td>25.0</td>
<td>24.40</td>
</tr>
<tr>
<td>January (2006)</td>
<td>60.8</td>
<td>61.60</td>
<td>-4.0</td>
<td>1.17</td>
<td>24.0</td>
<td>19.42</td>
</tr>
<tr>
<td>February (2006)</td>
<td>57.1</td>
<td>55.12</td>
<td>-3.0</td>
<td>0.29</td>
<td>25.0</td>
<td>22.48</td>
</tr>
<tr>
<td>March (2006)</td>
<td>51.9</td>
<td>42.91</td>
<td>0.0</td>
<td>2.89</td>
<td>27.1</td>
<td>25.56</td>
</tr>
<tr>
<td>April (2006)</td>
<td>40.8</td>
<td>51.56</td>
<td>-3.0</td>
<td>6.22</td>
<td>34.0</td>
<td>29.50</td>
</tr>
<tr>
<td>May (2006)</td>
<td>38.3</td>
<td>33.29</td>
<td>4.5</td>
<td>10.99</td>
<td>37.1</td>
<td>34.01</td>
</tr>
<tr>
<td>June (2006)</td>
<td>39.0</td>
<td>31.86</td>
<td>9.0</td>
<td>16.38</td>
<td>37.1</td>
<td>35.27</td>
</tr>
<tr>
<td>July (2006)</td>
<td>40.9</td>
<td>39.28</td>
<td>12.1</td>
<td>17.14</td>
<td>38.0</td>
<td>34.85</td>
</tr>
<tr>
<td>August (2006)</td>
<td>46.3</td>
<td>34.34</td>
<td>13.5</td>
<td>19.42</td>
<td>39.0</td>
<td>35.70</td>
</tr>
<tr>
<td>Annual</td>
<td>48.8</td>
<td>44.52</td>
<td>-4.0</td>
<td>0.29</td>
<td>39.0</td>
<td>35.70</td>
</tr>
</tbody>
</table>
8 Salts at the Jabal Haroun Site

8.1 Acquiring Salt Samples

Salt is transferred to the pores of stone as a solution in water. The sandy soil on Jabal Haroun facilitates the evaporation of water up to 1 m in depth. The salts in the soil are able to move through the sand and so they do not penetrate in the stone. Below the level of 1 m, the soil is more compressed and especially in the presence of stone tumble the sand is mixed with clay from the mud mortar in the walls, which retains the water. Thus the water is left standing and salts have the opportunity to penetrate the stone more deeply. It is in this area, where there is the most chance of crystallization and subsequent damage. (Christina Danielli, pers. comm. 26 April 2008, 28 April 2008.) Thus most of the samples were taken from ≥1m below the level where the soil surface was before excavation.

Six salt samples were taken from five locations: samples 1 and 2 from inside the chapel altar, sample 3 from the eastern wall (Wall U) of the northern aisle of the church, sample 4 from Wall I facing East in the atrium (over the bench), sample 5 from Wall J facing North in the atrium (over the bench) and sample 6 from Wall EEE facing East in Trench A1 (See Map 2). These locations were selected because each displayed visible and large amounts of salt spikes and/or crystals. The different locations have been exposed for different lengths of time.

Samples 1 and 2 were scraped off the cupboard surface with a scalpel, while samples 3 - 6 were taken with paper pulp. Thus samples 1 and 2 are not quantitatively comparable with samples 3 - 6. The paper pulp was prepared by mixing Arbocel BC1000 cellulose fibre with deionised water. A layer of paper pulp (dimensions around 100x150x5mm) was applied on the walls in the afternoon. The samples were covered with thin plastic foil and left to dry over night. The samples were collected next day at noon by scraping the dry cellulose fibre with a spatula into plastic bags.
Map 2 Locations of salt samples 1-6 in the excavation site. Original map provided by FJHP.

Location 1: Chapel Altar Pedestal, Samples 1&2

The masonry altar pedestal in the chapel is associated with Phase 7 of the church and chapel complex. Sample 1 is from the weathered sandstone surface of the cupboard ceiling in the altar. Sample 2 on the other hand consists of hard salt spikes and crust from the vertical plaster-covered surfaces of the cupboard. The altar has been excavated during two seasons: the southern part was exposed in 1998 (Trench C, locus C.16) and the northern part in 2003 (Trench Y, locus Y.07). The data logger and one sensor and were located here.
Location 2: Northern Aisle of Church, Sample 3

The sample was taken from the western side of Wall U, built in Phase 2. Distance of the sample from the top of the wall was ~1m. The eastern side of Wall U (locus E.9) was exposed in 1999 when trench E was excavated. The western side of Wall U (locus U.6) was exposed four years later in 2003 when Trench U was excavated.

Picture 14 Chapel altar and the weathered ceiling of the cupboard, location of samples 1 and 2.

Picture 15 Location of paper pulp sample 3 on the western side of Wall U next to the doorway of the northern pastophorion.
Location 3: Atrium, Sample 4

Sample 4 was taken from the western side of the Phase 4 wall (Wall I, locus G.2) in the atrium over a bench (locus L.15). The height of the sample from the bottom of the trench is ca. 50 cm. Wall I (the western wall of the church nave) is exposed on both sides. Trench G on the east side of the wall was excavated in 1999, while Trench L on the west side was excavated in 2000.
Location 4: Atrium, Sample 5

Sample 5 was taken from Wall J (locus B.3) above the bench (locus B.10), running along the southern wall of the atrium. The wall was the southern wall of the original Phase 2 church and the atrium built later in Phase 4. Trench B was excavated in 1998 and Wall J was exposed only on one side.

Picture 18 Location of paper pulp sample 5 on the south side of the atrium.

Picture 19 Paper pulp sample 5.
Location 5: Trench A1, Sample 6

The sample was taken from the surface of Wall EEE (locus A1.4) in the Western building, south from a pilaster (locus A1.13). Trench A1 was excavated in 2005. The height of the sample from the bottom of trench is ~50cm. The wall was exposed only on one side, surface of earth on the other side was ~2m above the sample. The height of the wall is ca. 2.65m. The room may have been associated with food production, storing and/or consuming. The association of this room to a certain phase of occupation at the site is unclear at the moment.
8.2 Analysis of Salt Samples with Merck Salt Strips and Hydrochloric Acid (HCl)

One third of each sample was dissolved in 200ml of deionised water. After the paper pulp had descended to the bottom of the flasks, the pH of each sample was measured with an electronic pH meter and the salt strip tests were performed with Merckoquant salt test strips. After this the water and paper pulp were poured away and the insoluble particles remaining on the bottom of the flasks were analyzed for insoluble carbonates by adding a few drops of hydrochloric acid according to Teutonico’s (1988: 64) instructions.

Table 10-11 show the results of the analysis. All paper pulp samples, as well as the deionised and distilled water samples, showed the same amount of sulphates, while samples 1 and 2 showed a smaller presence of sulphates. Sample 2 was slightly over the sulphate pH limit (pH 4-8) with a pH of 8.34. The general pH levels at the excavation site are: soil 7, sand 6.5, distilled water 6 (Christina Danielli, pers. comm. 21 Aug 2003). None of the samples showed traces of nitrates. The paper pulp samples did not contain chlorides, while sample 1 showed clear signs of them and also sample 2 may contain traces of chlorides. The carbonate hardness strips showed a possible small presence of carbonates in samples 3-6, no presence in sample 1 and some carbonates in sample 2. However, analysis of sample 2 with hydrochloric acid (HCl) showed a strong reaction, which indicates that it consists almost entirely of carbonates. The other samples showed no reaction with the acid.

The results raised questions. How could both the plain distilled and deionised waters show more sulphates than Samples 1 and 2? If all the samples had shown the same amount of sulphates as the plain water, it could have been explained by the samples being too dilute. While the carbonate and chloride strips were just purchased, the sulphate and nitrate strips were just about to expire. As the storage conditions for them had not always been as recommended by the producer, it is possible that the strips were not good any longer.
Table 10 Salt crystal samples 1 - 2 with Merck Strips and hydrochloric acid 3 February 2006.

<table>
<thead>
<tr>
<th></th>
<th>Deionized water filter reading 3.5 μS/cm</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount (~ g)</td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Water (ml)</td>
<td></td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>5.26</td>
<td>6.77</td>
</tr>
<tr>
<td>Sulphates SO₄²⁻</td>
<td>400-800</td>
<td>200-400</td>
<td>200-400</td>
</tr>
<tr>
<td>Nitrates NO₃</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nitrites NO₂</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Chlorides Cl⁻</td>
<td>0</td>
<td>1000</td>
<td>0 (-100)</td>
</tr>
<tr>
<td>Carbonates (strip)</td>
<td>0</td>
<td>0</td>
<td>0-4</td>
</tr>
<tr>
<td>Carbonates (HCl)</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

Table 11 Salt sample analysis with Merck Salt Strips 16 January 2006: paper pulp samples 3 - 6.

<table>
<thead>
<tr>
<th></th>
<th>Sample 3</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
<th>Deionized water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount (g)</td>
<td>7</td>
<td>9</td>
<td>7</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Water (ml)</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>5.65</td>
<td>6.23</td>
<td>7.6</td>
<td>6.33</td>
<td>5.5</td>
</tr>
<tr>
<td>Sulphates SO₄²⁻</td>
<td>400-800</td>
<td>400-800</td>
<td>400-800</td>
<td>400-800</td>
<td>400-800</td>
</tr>
<tr>
<td>Nitrates NO₃</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nitrites NO₂</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Chlorides Cl⁻</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Carbonates</td>
<td>0 (-4)</td>
<td>0 (-4)</td>
<td>0 (-4)</td>
<td>0 (-4)</td>
<td>0 (-4)</td>
</tr>
</tbody>
</table>

Table 12 Distilled water with Merck Strips 14 March 2006.

<table>
<thead>
<tr>
<th></th>
<th>Distilled water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphates SO₄²⁻</td>
<td>&gt;400⁴</td>
</tr>
<tr>
<td>Nitrates NO₃</td>
<td>0</td>
</tr>
<tr>
<td>Nitrites NO₂</td>
<td>-</td>
</tr>
<tr>
<td>Chlorides Cl⁻</td>
<td>0</td>
</tr>
<tr>
<td>Carbonates (strip)</td>
<td>0</td>
</tr>
</tbody>
</table>
* lowest part clearly lighter than other parts
Another problem was that interpretation of the strips was subjective. After the sulphate strips were immersed in water, no apparent change occurred - except for becoming wet - but still the closest resemblance in the color code was that of 400-800. Only samples 1 and 2 showed a slight change that was close to the 200-400 area. So it may well be that the strips were misinterpreted and that there were no sulphates in the other samples. If this were the case then there were no sulphates, no nitrates, no chlorides and no carbonates in the paper pulp samples. However, every location had visible salt efflorescence when the samples were taken. It seems the most probable explanation to these problems would be that the sulphate strips were misinterpreted and the sample solutions were too dilute. Even if the solutions had not been too dilute, the results would not have been reliable since the proportion of sample to water was not constant as it should have been. As for testing the presence of carbonates in the samples with HCl – the remains of the samples should probably have been dried after removing the paper pulp and water. This way even a small amount of carbonates might have shown a reaction. Now only the large salt spikes in sample 2 showed a clear reaction. Considering all the uncertainties, it was best to send the samples to professional laboratories for analysis.

8.3 SEM/EDX and X-ray Diffraction (XRD) Analysis of Samples 1 and 2

The SEM/EDX analysis was performed at the Helsinki University Laboratory of Inorganic Chemistry by Ph.D. Marianna Kemell 14 December 2007. The XRD analysis was done by M.Sc. Mikko Heikkilä 25 January 2008. Samples 1 and 2 were chosen to be analyzed with these methods because the results would not depend on the solubility of materials in water and because the powdery nature of the samples was well suited for the analysis. The SEM/EDX and XRD analysis methods complement each other and give more accurate results when used together – thus both of them were used. SEM/EDX shows which elements the sample contains and in what proportions. This information helps the interpretation of the XRD results. Together the methods give accurate information about the compounds and their proportions in the samples.

The equipment used for the SEM/EDX analysis included a Hitachi S-4800 Field emission scanning electron microscope (FESEM) and an Oxford INCA 350 Energy
dispersive X-ray microanalysis system (EDX). The EDX measurements were done with
ergy of 20 keV, which is enough to excite at least one x-ray line from almost all
elements. The analysis volume (depth) depends on the density of the material and the
energy of the electron beam. With energy of 20 keV the depth of analysis is typically
about 1-2 micrometers. (Marianna Kemell, pers. comm. 18 January 2008.)

The problem with samples 1 and 2 was, that they were very heterogeneous compared to
the scale in which the measurements were done. If the samples would have consisted of
only one compound, only one measurement site would have been enough. With these
samples, 8-11 sites were measured. The selection was done visually – based on which
particles looked most interesting and likely to be a salt compound.

Next the samples were analyzed with XRD. Sample 1 was powdery by nature, while
salt spikes selected from Sample 2 needed to be ground into fine powder. The analysis
showed that Sample 1 consists mostly of quartz SiO₂ and kaolinite Al₂SiO₅(OH)₄, with
also some halite NaCl. Sample 2 consists mostly of gypsum CaSO₄ x 2H₂O and calcite
CaCO₃ with some quartz SiO₂ present. (Marianna Kemell, pers. comm. 25 January
2008.) Thus Sample 1, taken from the weathered sandstone surface of the altar cupboard ceiling, mostly contained disintegrated sandstone and the visible salt efflorescence was halite NaCl. The salt spikes of Sample 2, taken from the plaster surface of the altar cupboard, seem to be calcite, calcium carbonate, with the plaster possibly consisting of lime and gypsum, with quartz aggregate.

8.4 Chemical Analysis of Samples 2 - 6 by Novalab Oy

Samples 2-6 were sent to Novalab Oy for analysis. Originally only samples 3 – 6 were intended to be sent to the laboratory, but for the sake of curiosity regarding what different methods of analysis would reveal, also sample 2 was included. However it was not tested for carbonates as the previous analysis with SEM/EDX and X-ray diffraction methods had already established the carbonate content. There should have been a sample of pure Arbocel BC1000 fiber for reference so any remains of salts could be checked. Unfortunately all of the fiber had been left at the mountain. According to Borelli (1994:164), Arbocel BC 1000 contains the following amounts of salt ions: 86 mg/kg chlorides, 28mg/kg nitrates and 57mg/kg sulphates.

The samples were first leached in water and chloride contents were analyzed with an electrode. NO₃ content was analyzed with the liquid chromatography method and carbonates with the titric method. Al, B-, Ca-, Cu, Fe-, K-, Mg-, Mn-, Na-, P-, S-, and Zn- contents were analyzed with a plasma emission spectrometer after dissolving in nitric acid. (See research report in Appendix 3.)

The analysis showed that all samples had a significant content of carbonates (2150 – 5680 mg/kg) and chlorides (1430 – 4860 mg/kg). The content of sulphur, indicating sulphates, was significant only in samples 4 and 6. Only small amounts of nitrates were recorded, the highest content being in sample 2 (312 mg/kg). The same applies to phosphorus (phosphates), with the content in sample 2 being (620 mg/kg). Sodium and magnesium were the most common cations present; some kalium was also present in all samples (130 – 1500 mg/kg). According to Matti Mäkelä (e-mail message, 6 March 2008), probable chlorides could include MgCl₂, halite NaCl, sylvite KCl and AlCl₃. Because crystal water of the salts in these samples cannot be examined, it is not possible
to know the hydration state of the salts. Detailed results of the analysis can be seen in the research report in Appendix 3.

Sample 2 contained chlorides (4860 mg/kg), some phosphorus and some nitrates. The very small content (47 mg/kg) of sulphur means sulphate content is not significant. Highest cation contents in sample 2 were those of Mg-, Na-, K-, and Al-. This sample was the only sample with a moderate content of iron, calcium and boron. Possible soluble salts in sample 2 are halite NaCl, sylvite KCl, AlCl3, carnallite KMgCl3·6H2O, some phosphates and nitrates, e.g. potassium nitrate KNO3, and perhaps salt combinations containing iron Fe, e.g. Rinneite NaK3FeCl6.

Sample 3 contained mostly carbonates and chlorides, with sodium being the most abundant cation. Some magnesium, kalium and sulphur were present. There was also a low content of aluminum and phosphates. Possible soluble salts in sample 3 are sodium carbonates NaCO3, magnesite MgCO3 and kalicinite KHCO3, halite NaCl, magnesium chloride MgCl2, thernardite Na2SO4 and potassium sulphate K2SO4.

Sample 4 showed carbonates, chlorides and sulphates, with sodium being the most abundant cation. Magnesium content was quite high (880 mg/kg) and some kalium was present. The content of aluminum, zinc, phosphorus and nitrate was low. Thus possible soluble salts in sample 4 include sodium carbonates NaCO3, magnesite MgCO3 and kalicinite KHCO3, halite NaCl, magnesium chloride MgCl2, thernardite Na2SO4, MgSO4 and potassium sulphate K2SO4.

Cations in sample 5 included magnesium (1100 mg/kg), sodium (930 mg/kg) and some kalium and aluminum. Anions were mainly carbonates and chlorides, but also some sulphates were present. Phosphate and nitrate levels were low. Possible soluble salts in sample 5 are sodium carbonates NaCO3, magnesite MgCO3 and kalicinite KHCO3, magnesium chloride MgCl2, magnesium sulphate MgSO4, halite NaCl, thernardite Na2SO4 and potassium sulphate K2SO4.
Table 13 The main salt content of each salt sample. The possible salt combinations in samples 2-6 were estimated according to the type and proportion of anions and cations found in them. There are several possibilities of hydration state.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Carbonates</th>
<th>Chlorides</th>
<th>Sulphates</th>
<th>Nitrates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>halite NaCl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample 2</td>
<td>calcite CaCO₃</td>
<td>halite NaCl</td>
<td>gypsum CaSO₄</td>
<td>potassium nitrate, niter (nitrokalite) KNO₃</td>
</tr>
<tr>
<td></td>
<td>possibly: sylvite KCl, AlCl₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>carnallite KMgCl₂·6H₂O</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rinneite NaK₃FeCl₆ ?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample 3</td>
<td>sodium carbonates NaCO₃</td>
<td>halite NaCl magnesium chloride MgCl₂</td>
<td>thermandite Na₂SO₄ magnesium sulphates MgSO₄ potassium sulphate K₂SO₄</td>
<td></td>
</tr>
<tr>
<td></td>
<td>magnesite MgCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>kalicinite KHCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>potassium carbonate KCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample 4</td>
<td>sodium carbonates NaCO₃</td>
<td>halite NaCl magnesium chloride MgCl₂</td>
<td>thermandite Na₂SO₄ magnesium sulphates MgSO₄ potassium sulphate K₂SO₄</td>
<td></td>
</tr>
<tr>
<td></td>
<td>magnesite MgCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>kalicinite KHCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>potassium carbonate KCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample 5</td>
<td>sodium carbonates NaCO₃</td>
<td>halite NaCl magnesium chloride MgCl₂</td>
<td>thermandite Na₂SO₄ magnesium sulphates MgSO₄ potassium sulphate K₂SO₄</td>
<td></td>
</tr>
<tr>
<td></td>
<td>magnesite MgCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>kalicinite KHCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>potassium carbonate KCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample 6</td>
<td>sodium carbonates NaCO₃</td>
<td>halite NaCl</td>
<td>thermandite Na₂SO₄ magnesium sulphates MgSO₄ potassium sulphate K₂SO₄</td>
<td></td>
</tr>
<tr>
<td></td>
<td>magnesite MgCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>kalicinite KHCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>potassium carbonate KCO₃</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sample 6 differs from the rest of the samples by having a higher content of sulphates (2900 mg/kg) than chlorides (2130 mg/kg). Carbonate content of the sample is even higher, 3310 mg/kg. Again, nitrate and phosphate levels were low. Sodium content was 860 mg/kg while magnesium and kalium were present in much smaller amounts. Sample 6 seems to contain mainly sodium carbonates NaCO₃, magnesite MgCO₃ and kalicinite KHCO₃, thernardite Na₂SO₄, potassium sulphate K₂SO₄ and halite NaCl.

8.5 Discussion on the results of the salt analysis

Carbonates in samples 3 – 6 probably include sodium carbonates NaCO₃, magnesite MgCO₃, kalicinite KHCO₃ and perhaps potassium carbonate KCO₃. Sodium carbonates are hydrating salts, meaning that as the relative humidity rises, the salt molecules take up water and change into other hydration forms. Pure sodium carbonate forms thermonatrite (Na₂CO₃·H₂O) at 66 RH% (20°C), heptahydrate (Na₂CO₃·7H₂O) at 73 RH% and natron (Na₂CO₃·10H₂O) at 90 RH%. When the humidity level falls, salt solutions become more concentrated and eventually the salts precipitate on the surface of the material. Sodium carbonates have been observed to grow out of the wall surface as whiskers or needles in sheltered surroundings and cause less damage than salts that are not directly visible on the surface (von Konow 2002: 23-25).

Salt spikes in sample 2 were confirmed to be calcite CaCO₃. This result was expected as the spikes were scraped from the surface of lime plaster. Although calcium carbonate is sparingly soluble in water, it can be a product of deterioration and appear as a surface crust under certain conditions. These conditions involve a high concentration of carbon dioxide and a humid wall. Carbon dioxide dissolves in water forming carbonic acid H₂CO₃, which reacts with calcium carbonate. The soluble bicarbonate salts formed in the reaction migrate to the surface of the wall and as the wall dries calcium carbonate is formed and deposited on the surface. (Teutonicco 1988: 58, 60.) The southern half of the altar, where the spikes were found, was exposed in 1999 and then covered under bags of sand for five years. Excavation allowed air and humidity to reach the plaster surface in the cupboard and the sand bags then made the movement of these elements more difficult, creating an environment in which the salts could crystallize freely. Had the
surface been in contact with the sandy soil, the salts would have been at least partially absorbed in it. (Christina Danielli, e-mail message, 26 April 2008.)

The easily soluble sodium chloride NaCl is an important salt in stone deterioration and has been observed also in Petra, on the surface of stone monuments especially in the area with rising damp (Honeyborne 1990:155; Fitzner & Heinrichs 1994: 670). Sodium chloride absorbs humidity from the air, its solubility does not depend very much on temperature and it moves easily into the masonry as an aqueous solution (Honeyborne 1990:155; Goudie & Viles 1997: 108.) Usually chlorides originate from sea spray carried inland by fog or winds, or sand used in mortars and plasters (Teutonico 1988: 60; Goudie & Viles 1997: 87). Jabal Haroun is not in a coastal region and even though sea salt can be carried inland for several hundred kilometers, there are other sources of salt available locally. The most probable origin of halite NaCl in the walls is the local soil, which has been used for plasters and mortars, which has surrounded them prior to excavation and which is carried to the vicinity of the structures by strong winds and gusts. If the room in the Western building from which sample 6 was taken was used for food processing, sodium chlorides in the sample may originate from long time storage of barrels of salt or of food preserved in/with NaCl. However the relatively smaller proportion of the components of NaCl in the sample as opposed to sulphates and carbonates is not in favor of this theory.

Sulphates in the Jabal Haroun walls most probably include sodium sulphates (ex. thernardite Na₂SO₄ or mirabilite Na₂SO₄·10H₂O), magnesium sulphate MgSO₄ (or epsomite MgSO₄·7H₂O) and possibly potassium sulphate K₂SO₄. Especially sodium sulphates are common in stone walls (Goudie & Viles 1997: 71). Laboratory tests (Goudie & Viles 1997: 102, 104) have found sodium sulphates to be very effective damaging agents especially in environmental conditions resembling those on Jabal Haroun. Magnesium sulphate has been found in Petra (Fitzner & Heinrichs 1994: 670) though not in the scale as halite or gypsum. On the rock cut monuments in Petra gypsum CaSO₄ has been observed especially in zones of detaching scales. The paper pulp samples contained very little calcium and thus gypsum, but this may be explained by the lesser solubility of gypsum with regard to other salt compounds in the samples and the fact that the paper pulp method favors the more soluble salts. The most probable
source of sulphates is the surrounding sand and soil which have been used in building and are still carried by wind to the structures. Also other materials used in mortars and plasters (ex. gypsum) may contain sulphates or compounds that participate in the formation of sulphates.

Potassium nitrate KNO₃ (niter, nitrokalite, saltpeter) has been observed in Petra by Fitzner & Heinrichs (1994:670) and is probably the nitrate found in sample 2. Saltpeter can be obtained from decomposing plants and has been used in the production of gun powder along with charcoal and sulphur (von Konow 2002: 22-23). Sodium nitrate NaNO₃ may be another possibility. It is highly soluble in water and crystallizes only in relatively high ambient temperatures (Goudie & Viles 1997:108). According to Teutonico (1988: 60-61) the decomposition of nitrogenous organic material, for example near old burial sites or where there is infiltration of sewage water, is a source of both nitrites and nitrates. Nitrates can also originate from agricultural land.

Temporary occupation after abandonment of the site may also have added to the salt content of the structures via bodily waste of animals and humans. In Shobak, a castle some distance away from Petra and a popular tourist attraction, the more sheltered rooms are being used even today as toilets by tourists and the people living close by. This might become a problem in the future also at Jabal Haroun if the site is not properly guarded.

9 Damaging Processes on Jabal Haroun

Discussion on the results of analysis in the three main areas of interest, namely damage types, climate conditions and salt types, has already been included in the corresponding chapters. In this part of the work the three areas will be combined to see what effect they have on each other and to form a more complete picture of what is going on in the structures of the Jabal Haroun excavation site.
A genetic sequence of damage forms has been established by Fitzner & Heinrichs (1994: 670). According to this model the first phase of damage in the area of rising damp is the formation of compact scales from the original surface of the stone. The thickness of the scales can vary, and salt efflorescences can be noted in the zone of detachment. After the loss of the initial scales more scales are generated, but the size and thickness is smaller than that of the first ones. Salts occur both at the back of and within these scales. The scales frequently exhibit a loosened grain bond. After the loss of scales, further back-weathering occurs as a result of flaking and granular disintegration still associated with salt efflorescences. These processes result in the formation of relief (differential erosion) or rounding erosion. With the progress of these processes, the stone surfaces become increasingly sensitive to wind abrasion. Overall Fitzner and Heinrichs (1994:670) state, that scaling in lower parts of monuments is caused mainly by salt crystallization processes, while scaling in upper parts are associated with various mechanisms. These include stress relief, thermal tensions, and frequent changes in wetting and drying. Whether Fitzner and Heinrichs mean frequent

**Picture 23** Transitional damage forms; delamination – scaling – flaking – granular disintegration / sanding. Picture taken from the wall if the chapel apse.
changes in wetting and drying cause damage by resulting in cycles of salt crystallization, hydration and dissolution or the solution of the matrix of the stone material was not clear. Salt on the surface of stone in the area of rising damp is mostly NaCl while the less soluble gypsum occurs mostly in the detaching zone of scales.

The most important source of salts in the structures is the soil that surrounded them prior to excavation. Analysis of Jabal Haroun soil with Merck salt strips by Christina Danielli (pers.com.) in August 2003 showed that it contained sulphates, carbonates and some nitrates. Efflorescences and intense granular disintegration in the walls of the Jabal Haroun chapel are taking place mostly under the level of 1 m from where the soil surface was prior to excavation. Other forms of damage occur quite evenly, though the greatest intensities of e.g. erosion are seen in the lower parts of the walls. The parts of the stones which had salt efflorescence suffered from granular disintegration of the surface. Otherwise the salts associated with different forms of damage were not analyzed. This might be one interesting subject to study in the future.

Salt weathering is recognized to be a problem especially in areas with large and frequent cycling of temperature and humidity or strong evaporation (Goudie & Viles 1997: 89-90). These conditions are relevant for Jabal Haroun, as has been seen in this work. Even the open air values on Jabal Haroun show how extreme the variation of temperatures on the site can be, not to mention how large the variation on the surfaces must have been. As strong wind can cause the surface temperatures to fall as much as 5°C (Thorborg von Konow, pers. comm. 27 November 2007) it is possible that the surfaces reach subzero temperatures in winter even though the air temperature would stay above 0°C (see Table 14). Surface temperatures exceeding 50°C have been noted to enhance surface recession of sandstone (Paradise 2005: 40). Maximum surface temperatures in Petra have been observed to be between 30°C and 56°C when air temperatures are 26°C – 44°C (Paradise 1999: 353, 362-365). Especially in direct sunlight the difference may reach even 20°C (Fitzner & Heinrichs 1994: 668). If corresponding air and surface temperatures between the values given by Paradise are estimated by assuming that the difference grows in a linear fashion, the air temperature would have to be approximately 40°C, for the surfaces to reach a temperature of 50°C. The highest surface temperature on Jabal Haroun would have been ca. 44 ºC in August 2006. This is, however, merely a
hypothetical estimation and should not be taken too seriously. Instead, surface temperatures and wind conditions should be monitored.

Table 14 A hypothetical estimation of possible surface temperatures on Jabal Haroun in 2005-2006.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>September (2005)</td>
<td>10,62</td>
<td>15,62</td>
<td>38,5</td>
</tr>
<tr>
<td>October (2005)</td>
<td>4,03</td>
<td>9,03</td>
<td>34,5</td>
</tr>
<tr>
<td>November (2005)</td>
<td>1,62</td>
<td>6,62</td>
<td>28,0</td>
</tr>
<tr>
<td>December (2005)</td>
<td>-3,4</td>
<td>1,60</td>
<td>28,0</td>
</tr>
<tr>
<td>January (2006)</td>
<td>-3,83</td>
<td>1,17</td>
<td>20,5</td>
</tr>
<tr>
<td>February (2006)</td>
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Laboratory experiments on how salts and Umm Ishrin sandstone react to humidity cycles have been done in the Getty Conservation Institute, USA. Normally the sandstone responds to increase in humidity by expanding, which is typical behavior for most stones. The experiments revealed that contamination of the stone with NaCl resulted in an opposite response: expansion during drying and contraction during humidity increase. This response was caused by the crystallization (and resulting increase in volume) of NaCl during drying. The speed of the humidity variations was very important for the crystallization kinetics. (Lombardo et al. 2004: 203, 209.)

Another reason, why the large and frequent variations of temperature and humidity are so important in salt weathering, is that all salts have an equilibrium relative humidity (EQRH) in which they crystallize or dissolve in water. For example NaCl takes water from air when the RH is 70-80%, depending on the temperature (Goudie & Viles 1997:155). Usually the EQRH% levels rise when temperatures fall. Salt content also influences the temperature in which water freezes and the pressure that is inflicted on
the pores as the water crystallizes (Steiger 2004: 179). In Table 15 there are the EQRH levels of some simple common salts at a temperature of about 25°C.

Table 15 Equilibrium relative humidity (EQRH) levels of some simple common salts at a temperature of about 25°C. The salts are in an order of increasing aggressiveness. (Honeyborne 1990:154)

<table>
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<th>Name of salt</th>
<th>Chemical formula</th>
<th>EQRH (%)</th>
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<tr>
<td>Potassium sulphate</td>
<td>K₂SO₄</td>
<td>98</td>
</tr>
<tr>
<td>Sodium carbonate hydrate (natron)</td>
<td>Na₂CO₃·10H₂O</td>
<td>90</td>
</tr>
<tr>
<td>Sodium sulphate hydrate (mirabilite)</td>
<td>Na₂SO₄·10H₂O</td>
<td>89</td>
</tr>
<tr>
<td>Potassium chloride (sylvite)</td>
<td>KCl</td>
<td>85</td>
</tr>
<tr>
<td>Sodium chloride (cooking salt, halite)</td>
<td>NaCl</td>
<td>76</td>
</tr>
<tr>
<td>Sodium nitrate</td>
<td>NaNO₃</td>
<td>75</td>
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<tr>
<td>Potassium carbonate hydrate</td>
<td>KCO₃ · 2H₂O</td>
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<tr>
<td>Magnesium chloride hydrate</td>
<td>MgCl₂·6H₂O</td>
<td>33</td>
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</table>

All salt compounds mentioned in table 14, with the exception of sodium nitrate, may be present in the Jabal Haroun structures. If the temperature at the site would stay constantly at 25%, it would be quite straightforward to point out the relative humidity levels that enable the salts to crystallize or to dissolve and to see how many times these thresholds are crossed. For example during the 12 months of monitoring in September 2005 – August 2006, 108 cycles of the relative humidity exceeding 75% took place, which means the threshold of 75RH% was crossed 216 times. However, as it became evident when the temperature and relative humidity on Jabal Haroun were discussed, the conditions are at a constant state of change. As such, the relative humidity threshold of each salt is changing with the temperature. Also when masonry structures are contaminated with a mixture of salts, the behavior of the salts is difficult to predict because the cations and anions can combine in a variety of ways to form different salts. In cases like this the equilibrium relative humidity of each salt is affected by the presence of the other salts. Mixtures of salts are often more aggressive than either of the salts alone and thus the aggressiveness of salt mixtures are difficult to predict. The behavior of the salts could be modeled by using a thermodynamic model of ECOS. The ECOS system is capable of predicting the behavior of aqueous solutions in porous materials. This system, accompanied with a user friendly interface developed by Davide
Bionda, has been used in modeling the behavior of salts in Suomenlinna. (See more in Bionda & Storemyre 2002.)

When long-term conservation methods are planned, it will become necessary to study the threat posed by salts in a more accurate manner. It will be necessary also to study the changes of moisture and temperature inside the structures and on their surface. The salts inside stones could be analyzes with x-ray from stone samples. This would give exact information about the amount, composition, crystal structure and crystal water of the salts. It might shed light on what salts are a natural part of the stones and which have emerged as a result of the changes caused by unearthing. It would also reveal the various phases of crystallizing or hydrating salts in different depths on the wall. These are questions that are not answered by the paper pulp method. (Thorborg von Konow, pers.com. 27 November 2007.)

Four plans for the management of Petra archaeological park have been prepared: the US National Parks Service Master Plan for the Protection & Use of the Petra National Park (1968), the UNESCO Petra National Park Management Plan (1994), the US/ICOMOS Management Analysis & Recommendations for the Petra World Heritage Site (1996) and the US National Parks Service Operational Plan (2000). Unfortunately none of these have been implemented properly. (Petra National Trust 2008.) Methods of monitoring the state of conservation of the structures on Jabal Haroun should follow the guidelines and methods requested in these plans (see also Kühlenthal & Fischer 2000: 84-88, 149-183). Prior to anything else the current documentation of the site should be supplemented with detailed documentation of all wall facades and their state of conservation, including architectural drawings (both photogrammetric and hand-drawn details, such as has been made already of the floors and plan of the building complex as part of archeological documentation) and systematic photographing. Especially diagnostic features, such as different masonry building techniques and possible remaining tool marks on stones, should be documented. The condition of the structures should be monitored by repeating the documentation procedure at regular intervals and by comparing the documents to earlier ones.
10 Conclusions

This M.A. thesis set out to observe the state of preservation of the sandstone structures at the Jabal Haroun excavation site, to study the conditions surrounding them and the main damaging processes affecting them. The salt analysis confirmed that the structures contain a variety of salts and that potential salt combinations include ones which have been found to be very aggressive by earlier research. The climate measurements confirmed that variation of temperature and humidity is large and frequent enough to enable severe damaging processes caused by salts, especially in stones whose lithological properties make them sensitive to the salt weathering. The comparison of the measurements on Jabal Haroun to long-term (1984 - 1998) values in Wadi Musa indicated that the 12 months measured were not extreme with regard to temperature and generally drier than average with regard to average relative humidity. Monthly minimum temperatures during September 2005 - December 2005 were generally lower in Wadi Musa and maximum temperatures higher than on Jabal Haroun. Absolute maximum and minimum temperatures occurred, however, on the mountain. Mornings were colder on the mountain, while noon temperatures were very close to each other. According to the average values, both morning and noon in Wadi Musa were generally more humid. It should, however, be kept in mind that highest and lowest daily values did not always occur at these given times (6 am, 12pm) as the measurements on Jabal Haroun showed.

Based on the results of monitoring, salt tests and the current state of conservation, it is obvious that the structures will deteriorate rapidly if left unattended. Climatic values cannot be controlled in an open space such as the Jabal Haroun site. Thus backfilling is the most effective way to protect the structures. If some part of the site, e.g. the chapel, is to be left exposed and/or sheltered, the structures and their state of conservation should be documented and monitored regularly. The quality and behavior of salts in this area should be examined in more detail to find out the safest climatic conditions. The microclimate inside the shelter should be created as stable as possible. The comparison between open air climate and the microclimate inside the altar box showed that sheltering can stabilize the conditions, as long as adequate ventilation is taken care of. Also other things should be considered, e.g. the wind conditions should be monitored to help structural planning. An important point of view is the aesthetic one – how well the
shelter fits in the landscape and how well it supports the historical characteristics and values associated with the site. The impact of visitors or seismic events was not addressed in this thesis, but they should be considered as well.

As this work is an academic thesis, I feel it is proper to end it by discussing some of the problems I encountered, mistakes I made, and what I learned from them. During the time of mapping in the field, I had a black and white copy of the UniNormal 1/88, the pictures of which were not good. As I begun to write the chapter and analyze the mapping data and photographs, and when I compared the damages to those in the ICOMOS ISCS glossary, I realized that I had misinterpreted some of the damage types, namely scaling/flaking and delamination/exfoliation. Also some damages, e.g. missing stones, had not been noted. Most of the problems were solved by changing the meaning of the symbols used, but some mistakes still remain. These deficiencies will be corrected in the mapping data, but not in time for this work. The mapping pictures in Appendix 1 have been scanned from the original documents. The monitoring of temperature and relative humidity on the site went quite well, despite some minor problems, such as mice biting the cables etc. These fortunately had no effect on the monitoring. However during the course of this study, I realized it would have been better to set the recording interval to 1 hour instead of two hours. It is the more common procedure and the results would have been more accurate.

The most difficulties were encountered when analyzing the salt samples. The samples should have been mixed with less water; the ration should have been 1:5, now it was ca. 1:28. This was due to the fact that it was the first time I did such a test and I misinterpreted the notes I took the proportion from. However it turned out for the better, as this urged me to send the samples to professional laboratories with the result of much more detailed and accurate information. In addition, I learned a whole lot more than I would have, had the analysis with strips gone smoothly. Hopefully the results of this work will be found interesting and useful for future research.
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Published References


Glossary

**Alveolar weathering**
“Formation, on the stone surface, of cavities (alveoles) which may be interconnected and may have variable shapes and sizes (generally centimetric). *Honeycomb* is a term commonly used to describe alveolization” (ICOMOS 2008)

**Biological colonization**
“Colonization of the stone by plants and micro-organisms as bacteria, cyanobacteria, algae, fungi and lichen (symbioses of the latter three). Biological colonization also includes influences by other organisms such as animals nesting on and in stone. Equivalent term: biological growth” (ICOMOS 2008)

**Cracks**
“Individual fissure, clearly visible by the naked eye, resulting from separation of one part from another” (ICOMOS 2008) See also *fracture, star crack, haircrack, splitting.*

**Cryptoflorescence**
see *subflorescence.*

**Damage**
“Human perception of the loss of value due to decay.” (ICOMOS 2008)

**Deflation**
“Process where wind erosion creates blowout depressions or deflation hollows by removing and transporting sediment and soil.” (Pidwirny 2006)
Delamination

“Detachment process affecting laminated stones (most of sedimentary rocks, some metamorphic rocks...). It corresponds to a physical separation into one or several layers following the stone laminas. The thickness and the shape of the layers are variable. The layers may be oriented in any direction with regards to the stone surface.” (ICOMOS 2008) See also exfoliation.

Deterioration

“Process of making or becoming worse or lower in quality, value, character, etc...; depreciation.” (ICOMOS 2008)

Dew

“Condensation of water on the Earth's surface because of atmospheric cooling.” (Pidwirny 2006)

Dew point

“Dew point is the temperature at which water vapor saturates from an air mass into liquid or solid usually forming rain, snow, frost or dew. Dew point normally occurs when a mass of air has a relative humidity of 100%. If the dew point is below freezing, it is referred to as the frost point.” (Pidwirny 2006)

Differential erosion

“occurs when erosion does not proceed at the same rate from one area of the stone to the other. As a result, the stone deteriorates irregularly. This feature is found on heterogeneous stones containing harder and/or less porous zones. Differential erosion is generally found on sedimentary and volcanic stones. Differential erosion is synonymous with "relief formation", i.e. to the formation of irregularities on
the stone surface. Differential erosion may result in loss of components or loss of matrix of the stone” (ICOMOS 2008)

**Efflorescence**
The crystallization of salts on the surface of masonry. (Honeyborne 1990:154)
“Generally whitish, powdery or whisker-like crystals on the surface. Efflorescences are generally poorly cohesive and commonly made of soluble salts crystals.” (ICOMOS 2008)

**Erosion**
“Loss of original surface, leading to smoothed shapes.” (ICOMOS 2008)

**Exfoliation**
Subtype of delamination. "Consists in the detachment of multiple thin stone layers (cm scale) that are sub-parallel to the stone surface. The layers may bend, twist in a similar way as book pages.” (ICOMOS 2008)

**Flaking**
“Scaling in thin flat or curved scales of submillimetric to millimetric thickness, organized as fish scales.” (ICOMOS 2008)

**Fracture**
“Crack that crosses completely the stone piece.” (ICOMOS 2008)

**Granular disintegration**
“Occurs in granular sedimentary (e.g. sandstone) and granular crystalline (e.g. granite) stones. Granular disintegration produces debris referred to as a "rock meal’ and can often be seen accumulating at the foot of wall
actively deteriorating. If the stone surface forms a cavity (coving), the detached material may accumulate through gravity on the lower part of the cavity. The grain size of the stone determines the size of the resulting detached material.” (ICOMOS 2008)
See also powdering, sanding

**Haircrack**
“Minor crack with width dimension < 0.1 mm.” (ICOMOS 2008)

**Lichen**
“Vegetal organism forming rounded millimetric to centimetric crusty or bushy patches, often having a leathery appearance, growing generally on outside parts of a building. Lichen are most commonly grey, yellow, orange, green or black and show no differentiation into stem, root and leaf.” (ICOMOS 2008)

**Pitting**
“Pitting consists in point-like millimetric or submillimetric shallow cavities. The pits generally have a cylindrical or conical shape and are not interconnected, although transitions patterns to interconnected pits can also be observed.” (ICOMOS 2008)

**Powdering**
sometimes employed for describing granular disintegration of finely grained stones. (ICOMOS 2008)

**Pulverization**
see sanding.
Relative humidity  
“The ratio between the actual amount of water vapor held in the atmosphere compared to the amount required for saturation. Relative humidity is influenced by temperature and atmospheric pressure.” (Pidwirny 2006)

Rounding  
Preferential erosion of originally angular stone edges leading to a distinctly rounded profile. Rounding can especially be observed on stones which preferably deteriorate through granular disintegration, or when environmental conditions favor granular disintegration. (ICOMOS 2008)

Sanding  
“Granular disintegration of sandstones Damage generally starts from the surface of the material. On crystalline marble, granular disintegration may reach several centimeters, sometimes more.” (ICOMOS 2008)

Scaling  
“Detachment of stone as a scale or a stack of scales, not following any stone structure and detaching like fish scales or parallel to the stone surface. The thickness of a scale is generally of millimetric to centimetric scale, and is negligible compared to its surface dimension. The plane of detachment of the scales is located near the stone surface (a fraction of millimeters to several centimeters).” (ICOMOS 2008)

Splitting  
“Fracturation of a stone along planes of weakness such as microcracks or clay/silt layers, in case those structural elements are orientated vertically. For instance, a column
may split into several parts along bedding planes if the load above it is too high.” (ICOMOS 2008)

**Star crack**

“Crack having the form of a star. Rusting iron or mechanical impact are possible causes of this type of damage.” (ICOMOS 2008)

**Subflorescence**

Crystallization of salts within the pores of the building material (Honeyborne 1990:154).

“Poorly adhesive soluble salts, commonly white, located under the stone surface. Subflorescences are hidden, unless the stone layer over them detaches. In that case, salt crystals become visible on the newly exposed surface.” (ICOMOS 2008)

**Temperature**

“Temperature is defined as the measure of the average speed of atoms and molecules. The higher the temperature the faster they move.” (Pidwirny 2006)

**Weathering**

” Any chemical or mechanical process by which stones exposed to the weather undergo changes in character and deteriorate.” (ICOMOS 2008)
Appendices

Appendix 1  Damage Mapping 2005

Appendix 2  Temperature and Relative Humidity on Jabal Haroun

Appendix 3  Salt Analysis by Novalab Oy - Research report
Pictures CH06, 07 and 14 have been taken in 2003, while the rest have been taken in 2005. Below are the explanations for symbols used in the damage mapping.
Damage mapping 2005
Damage mapping 2005

(CH07)

(CH08)
Damage mapping 2005
Damage Mapping in 2005

Damage mapping 2005

CH13

CH14
Comparison of temperature and relative humidity values on Jabal Harun and in Wadi Musa in 2005.

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TUTKIMUSRAPORTTI N:o K 135/08/1-5

Tilaaja Susanna Eklund

Tulopäivä 7.2.2008  Analysoinnin aloituspäivä 20.2.2008

Tehtävä Näytteen Cl-, NO$_3$- sekä Al-, B-, Ca-, Cu-, Fe-, K-, Mg-, Mn-, Na-, P-, S- ja Zn- pitoisuuden analysointi.

Näyte Yksi raaputettu suolanäyte hiekkakivirakenteiden pinnoilta sekä neljä selluloosanäytettä, joihin suola on imeytetty

Analyysimenetelmät

Tulokset

Tulokset on ilmoitettu pitoisuuksina tulokosteassa näytteessä.

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<th>Ca (mg/kg)</th>
<th>Cu (mg/kg)</th>
<th>Fe (mg/kg)</th>
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<th>Mg (mg/kg)</th>
<th>Mn (mg/kg)</th>
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<th>CO$_3$ (mg/kg)</th>
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</table>

Karkkila 12.4.2008
Novalab Oy

Matti Mäkelä
laboratorionjohtaja

Tulokset pätevät vain testatuille näytteille. Raportin saa kopioida vain kokonaan ilman testauslaboratorion lupaa.