Summary

The monuments of the ancient Nabataean city of Petra in Southwest Jordan represent prominent masterpieces of the world´s cultural heritage. Petra is of great importance for the cultural identity and the socio-economic development of Jordan. In Petra many hundred monuments were carved by the Nabataeans from sedimentary bedrocks about 2000 years ago. These rock-cut monuments witness in a most impressive way the unique architectural art and craftsmanship of the Nabataeans. In 1985 Petra was inscribed on the UNESCO list of outstanding World Cultural Heritage.

All monuments have suffered damage from weathering. On many monuments the weathering damage is alarming. In 1998, 2000 and 2002 the World Monuments Fund (WMF) inscribed Petra on the list of the one hundred most endangered monument assemblies of the world. Due to the increase of damage and the danger of further irretrievable loss of cultural heritage, the preservation of the monuments has become an ever-increasing international concern.

Sustainable monument preservation requires a scientific material and damage diagnosis. Due to the lack of detailed and reliable diagnostical information for the Petra monuments, conception and implementation of effective and economic, remedial and preventive preservation measures were impossible so far.

It was the scientific aim of the studies to provide a comprehensive damage diagnosis as basis for the decision of well-directed monument preservation measures.
This damage diagnosis considers causes, processes, charakteristics, state and progression of stone weathering and includes the rating of weathering damage on the rock-cut monuments. The studies combined in-situ investigation and laboratory analysis. They were funded by the Deutsche Forschungsgemeinschaft (DFG) and were supported by Jordanian organizations / institutions such as the Department of Antiquities of Jordan, the Petra Regional Council, the Higher Council of Science and Technology, the Petra National Trust and the Queen Rania´s Institute of Tourism and Heritage / Hashemite University.

The first step of the diagnostical studies was focused on the inventory, petrographical characterization and classification of the lithotypes occurring at the rock-cut monuments. A detailed lithostratigraphical classification and sufficient representative information on stone properties did not exist. A survey of lithotypes was made with their detailed differentiation according to macroscopical characteristics (stone colour, grain size, stone structure). This was the basis for the elaboration of a new lithostratigraphical classification of the clastical sedimentary rocks (differ-

ent siltstones and sandstones). Established stratigraphical terms for the principle units of the Cambro-Ordivician rock series in Petra were considered (Umm Ishrin Sandstone Formation / Cambrian, Disi Sandstone Formation / Ordovician). This new lithostratigraphical classification comprises sixteen main lithotypes and nine sublithotypes.

All lithotypes were studied with respect to mineral composition (spectrum of minerals, modal composition), textural and structural characteristics (mean grain size, grain size distribution, sorting, grain-matrix-relation, type and number grain contacts, bedding characteristics), porosity properties (densities, total porosity, pore sizes, pore size distribution, pore surface), hygric properties (water adsorption at atmospheric pressure, water adsorption at pressure, saturation coefficient, capillary water uptake, water uptake coefficient, water penetration coefficient, water capacity, water vapour permeability, hygric dilatation, water desorption) and petrophysical properties (ultrasonic velocity, drilling resistance).
Many procedures were applied for the petrographical investigation of the twenty-five lithotypes such as X-ray diffraction, transmitted light microscopy with image analysis, scanning electron microscopy, mercury porosimetry, nitrogen adsorption (BET-method), various standardized water adsorption, permeability and desorption tests, dilatometry, ultrasonic measurements and drilling resistance measurements.

The results have ensured the precise petrographical description of all lithotypes. They have revealed considerable differences of the lithotypes in their petrographical properties.
As a trend, the grain-matrix-ratio, the total porosity, the mean pore size, the mean size of the pore entries, the water uptake and water penetration potential increase from the siltstones to the coarser-grained sandstones, whereas the number of grain contacts, the anisotropy of the fabric, the pore surface, the water vapour diffusion resistance, the hygric dilatation and the strength / hardness decrease.

A classification scheme of the stone parameters – specially adjusted to the petrographical range of the lithotypes - was developed as the basis for a conclusive petrographical characterization and comparison of the lithotypes. Accordingly, the twenty-five lithotypes could be ranged in nine main petrographical classes with eight subclasses.

The monument mapping method and supplementary in-situ measurements were applied for the assessment of the weathering damage on the rock-cut monuments. Twenty-two representative monuments were selected for investigation considering the range of lithotypes and differences in location, dimension, architectural composition and exposure characteristics of the monuments (total investigation area ~ 4.000 m^2). The monument mapping method – developed by the working group „Natural stones and weathering“ / Geological Institute of the RWTH Aachen University, Germany – was used as an internationally well-accepted non-destructive procedure that allows to register and evaluate information on lithology and state of weathering in a precise and reproducible way. It can be applied to all stone types. Originally, this method was developed for monuments built of dimension stones. In Petra it has proved to be applicable successfully to monuments carved from bedrocks. Plans of the monuments selected for mapping were prepared reconstructing their original architecture.

In the course of monument mapping, all lithotypes and their distribution as well as types, intensities, combinations and distributions of weathering forms were registered. The weathering forms represent the phenomenological responses of stone to weathering processes, which are initiated and controlled by the interaction between stone and weathering factors. A computer programme - developed by the Aachen working group „Natural stones and weathering“ - was used for the processing, illustration and quantitative evaluation of the information registered.
Lithological maps were prepared illustrating the distribution of the lithotypes. These maps and their quantitative evaluation represented the basis for the characterization and rating of damage in dependence upon lithotypes. A great diversity and heterogeneous distribution of lithotypes was found to be very characteristical for most of the rock monuments in Petra.
The Aachen working group „Natural stones and weathering“ has developed a standard classification scheme of weathering forms as prerequisite for the objective and reproducible registration and documentation of weathering forms.
This standard classification scheme is a result of the investigation of numerous stone monuments worldwide, considering different stone types and environments. Based on a systematic survey of weathering forms in Petra it was modified in order to ensure optimal applicability to the rock-cut monuments there. The classification scheme comprises four levels of differentiation: level I – groups of weathering forms, level II – main weathering forms, level III – individual weathering forms, level IV – individual weathering forms with additional differentiation according to intensity.

That level of highest precision (level IV) was applied for monument mapping in Petra. So, the weathering forms were precisely registered jointly considering type and extent, the latter being assessed by means of measurable or estimable intensity parameters.

Maps of weathering forms were prepared distinctly illustrating the distribution of the weathering forms. Separate maps according to the four groups of weathering forms – 1 / loss of stone material, 2 / deposits, 3 / detachment of stone material, 4 / fissures (here including joints) – have turned out meaningful. All weathering forms and their intensities were evaluated quantitatively.

Maps and quantitative evaluation of the weathering forms guaranteed the precise description of all investigation areas with respect to their state of weathering. Coloured maps and quantitative evaluation of weathering forms were presented by means of examples. Their explanation has considered the diversity of lithotypes and exposure characteristics.

More than fourty different weathering forms with a considerable range of their intensities and many hundred different combinations of weathering forms with either very heterogeneous or striking zonal distribution were stated. These findings in all evidence an extreme diversity of weathering damage on the rock-cut monuments.

The combined evaluation of information gathered from lithological mapping and mapping of weathering forms allowed to line out characteristical associations of weathering forms in dependence on lithotypes and phases of weathering. Here, clear correlations were found between associations of weathering forms and petrographical classes of the lithotypes.

Weathering forms allowed the precise description of weathering phenomena. Damage categories and damage indices were used for the rating of damage evoked by the weathering forms of the groups „loss of stone material", „deposits" and „detachment of stone material". Six damage categories were defined - 0 / no damage, 1 / very slight damage, 2 / slight damage, 3 / moderate damage, 4 / severe damage and 5 / very severe damage. Their order of listing corresponds to increasing necessity and urgency of preservation measures.
A correlation scheme „weathering forms – damage categories" was developed specially for the Petra monuments, in which all weathering forms – considering type and intensity – were related to damage categories. The high historical and artistical importance of the monuments was taken into account. Based on this correlation scheme, damage categories first were determined seperately for the three groups of weathering forms „loss of stone material", „deposits" and „detachment of stone material". In the next step of evaluation, a scheme was elaborated for the derivation of damage categories jointly considering all weathering forms of these three groups. The damage categories were illustrated in maps and were evaluated quantitatively. Damage indices were used for the overall quantification and rating of weathering damage. Their calculation was based on the quantitative evaluation of the damage categories.

By means of damage categories and damage indices all monuments under investigation were precisely described and judged according to extent of weathering damage. Heterogeneous distribution or zoning of damage as a consequence of different lithotypes or exposure characteristics were lined out. The maps of damage categories locate those parts of the monuments which interventions should focus on. The damage categories and damage indices enhance risk prognosis for the rock-cut monuments.

Damage indices also were determined for the individual lithotypes. This made an important contribution to the rating of their susceptibility to weathering. Finally, rankings of the investigation areas according to damage indices were made. The rankings quantify different extents of damage ranging from rather well-preserved to seriously damaged monuments. In these rankings increasing damage index corresponds to increasing need and urgency of monument preservation measures.

Fissures and joints were rated seperately with respect to damage they evoke on the monuments. The number of fissures and joints and their dimension (length, width) at the surface of the monuments were considered in combination as parameters for the calculation of a damage index specially introduced for the judgement of the fissures and joints. This damage index is a suitable indicator of need and urgency of preservation measures such as structural stabilization or reinforcement, filling / sealing or prevention from breaking out of stone blocks.

The overall rating of damage on the Petra monuments and the discussion of preservation measures must consider the damage indices relating to the weathering forms of the groups „loss of stone material“, „deposits“ and „detachment of stone material“ in combination with the damage index relating to fissures / joints.
In-situ drilling resistance measurements have provided supplementary information on the state of weathering. The drilling resistance - a parameter of stone hardness – was calculated as a function of depth. This allows the quantitative characterization of weathering profiles.
The measurements considered different lithotypes and weathering forms. Drilling resistances obtained from measurements on unweathered stone samples in the laboratory served as referential data.

The results of the in-situ measurements have allowed to characterize different forms of stone detachment by means of weathering profiles and, thus, have improved the understanding of stone detachment as process preceding loss of stone material. Differences in dependence on lithotypes were lined out. Furthermore, the results have provided information on the depth effect of weathering. The trend was found – considering comparable exposure conditions of the lithotypes - that the depth effect of weathering increases from the compact, finer-grained to the friable, coarser-grained lithotypes. The results were considered as additional indicators of susceptibility to weathering.

The characterization, quantification and prognosis of weathering progression is an important concern of scientific damage diagnosis. Reliable information on weathering progression did not exist for the rock-cut monuments in Petra. Due to the lack of referential archive documents and information on the state of weathering damage in the past, alternative steps of evaluation were introduced for the assessment of weathering progression exclusively from information on the recent state of weathering. They were based on the results obtained from mapping and quantitative evaluation of lithotypes and weathering forms.

The determination of weathering rates has turned out to be suitable for an estimation of weathering progression. Their calculation is based on the evaluation of the weathering forms characterizing loss of stone material. The weathering rates quantify the average recession of the stone surface over the time. They are calculated from the hitherto total extent of stone surface recession and the age of the monument. Weathering rates were determined for all particular areas of the monuments under investigation and then were illustrated in maps. These maps document in all a considerable range and a heterogeneous distribution of weathering rates due to different lithotypes and exposure characteristics. The weathering rates range between less than 0.5 up to a maximum of 35 mm / 100 years. In a next step, average weathering rates were determined for entire monuments or their parts under investigation. Additionally, weathering rates were determined for individual lithotypes considering comparable exposure conditions. This allowed the comparison of their susceptibility to weathering.

Comparing the three most important lithotypes, it was found that the average weathering rates and, thus, the susceptibility to weathering increase from the oldest to the more friable youngest lithotype.

Weathering rates allow weathering prognosis, taking into account that they describe a continuously linear weathering progression as per calculation mode. Since linearity of weathering progression is not realistic, further steps of evaluation were necessary in order to achieve information on real weathering progression.

The approach based on the principle finding that the occurrence of different weathering forms next to each other on the monuments also reflects their chronological sequence. The systematic evaluation of all weathering forms characterizing loss of stone material, deposits on the stone surface and current detachment of stone material has allowed to deduce statistical successions of weathering forms for the most important lithotypes. They describe weathering progression according to types, combinations and intensities of weathering forms. Different chronological sequences of weathering forms were found for the lithotypes as the consequence of differences in their petrographical properties.

The successions of weathering forms were used for the calculation of weathering progression factors. Their determination considered the intensities of stone detachment and allochthonous deposits on the detaching stone elements in relation to loss of stone material. The intensity of allochthonous deposits on detaching stone elements was considered as relative time indicator. It reflects the durability of the stone surface and is inversely proportional to the velocity of stone detachment. The weathering progression factors were used for the calculation of weathering progression curves which quantify realistically the recession of stone surfaces over time. The weathering progression curves obtained for the most important lithotypes have shown slow weathering progression in the early phases of weathering, followed by a continuous acceleration of weathering progression approximating linearity only in very advanced phases of weathering.

The extrapolation of the weathering progression curves allows reliable quantitative weathering prognosis. Future loss of stone material can be predicted either relating to depth, volume or weight of stone material. Weathering prognoses were made for two monuments as examples. According to the prognoses, the stone surface of these monuments will receed within the next hundred years for 2 – 3 cm on average. The stone surface of individual parts of the monuments will receed in worst case for 8 cm. For that monument composed of Cambrian sandstones this means, that more than four cubic metres or more than nine tons of stone material will be lost in the next hundred years. These prognoses are quite alarming and they indicate the need and urgency of preservation measures for many monuments in Petra.

The information achieved on weathering forms, weathering profiles, extent of damage and weathering progression has allowed the comparative rating of the lithotypes regarding their susceptibility to weathering. The compact and homogeneous, very fine-grained to fine-grained sandstones have turned out to be least susceptible to weathering. The susceptibility increases in direction of the coarser-grained sandstones with increasing porosity, water uptake and water penetration potential and decreasing content of matrix and decreasing strength / hardness. This sandstone are prone to contour scaling, flaking or granular disintegration. The susceptibility to weathering also increases from the comparably weathering resistant sandstones in direction of the siltstones. Their susceptibility to weathering finds its expression in their proneness to splitting – as a consequence of their very anisotropic fabric – and to crumbly disintegration resulting from the intersection of splits and narrow-spaced joints characteristically affecting these lithotypes.

Reliable information on weathering factors and weathering processes causing the weathering damage on the rock-cut monuments in Petra did not exist until now. While there is agreement that physical weathering decisively controls stone weathering in Petra, the main factors and processes are under very controversial discussion. The own observations, the results of microclimatic measurements and mineralogical-geochemical laboratory analyses of stone samples (surface samples, drill cores) in combination with the results obtained from characterization, documentation, quantitative evaluation and rating of weathering damage have allowed a reliable valuation of weathering factors and processes.

Microclimatic measurements were carried out at the monuments (air temperatures, stone surface temperatures, in all approx. 100.000 data) considering seasonal and diurnal variations. Intense temperature loading could be stated for many rock-cut monuments, especially for the south- to west-exposed monuments due to insolation. High stone surface temperatures – up to 55 °C at maximum - occur at these monuments, high heating and cooling rates are characteristical. The comparison of temperature load and weathering damage has not shown any clear interdependencies. Very slight up to very severe weathering damage occurs as well on highly temperature-loaded monuments as on those monuments insignificantly affected by temperature loading. Temperature weathering has turned out not to primarily cause the weathering damage on the monuments.

Clear correlations could be stated between humidity impact and weathering damage. In winter periods waterfall-like water run-off at the rock-monuments and floods were observed indicating the water impact potential.
The observations in that periods of rainfall have allowed to map exposure characteristics regarding humidity influences (areas exposed to rain, areas sheltered from rain, areas affected by water run-off). It was found that the south- to west-exposed monuments are most effected by precipitation, whereas north- to east-exposed monuments are rather sheltered from rain. Water run-off affects monuments especially in those cases where channels above the monuments – built by the Nabateaens for the control of water run-off – are eroded or filled with debris. The lower parts of many monuments are additionally affected by rising humidity. Different types and extents of humidity impact correlate with patterns of weathering forms and degree of damage. This proofs water / humidity to be the weathering factor decisively causing and controlling stone weathering on the rock-cut monuments. Salt weathering was found to be the main and most harmful humidity-induced weathering process. The results of mineralogical-geochemical studies have shown that most types of stone detachment are linked to the presence of salts. Halite represents the prevailing salt mineral. Gypsum, niter and sylvite occur as further salt minerals. Type, quantity, spatial distribution and crystallization cycles control typ and intensity of stone detachment. Geochemical analyses of rain water have shown that a considerable proportion of the salt components in the stone derives from rain, especially in the case of halite.
Wind can be considered as another weathering factor affecting the Petra monuments. Although it does not cause stone disintegration, it contributes significantly to the erosion of loose stone

material.

The results presented in all have provided statistically reliable information on the characteristics of stone weathering at the rock-cut monuments in Petra, considering the mutual relationships between lithotypes / stone properties, exposure characteristics, weathering factors, weathering processes, weathering phenomena, state of weathering damage and weathering progression.
The results facilitate the planning and implementation of appropriate monument preservation measures. This concerns immediate safeguarding measures, measures for remedy of damage and preventive measures in the same way. The results indicate need and urgency of preservation measures. Prevention of stone blocks from breaking out, fixation of loose stone material, structural stabilization / reinforcement, stone repair, filling / sealing of fissures and joints, repair / reactivation of channels for the control of water run-off, control of rising humidity, desalination, cleaning and surface protection represent preservation measures under consideration. Careful test applications are recommended in order to check applicability and success of the preservation measures.
A consistent concept of damage diagnosis including many new meaningful steps of evaluation has been presented. This diagnosis concept can be applied in research and monument preservation practice. It can be recommended for long-term monitoring of stone monuments and for the control / certification of preservation measures.