EVALUATION OF WEATHERING DAMAGES ON MONUMENTS CARVED FROM ROCKS IN PETRA/JORDAN - RESEARCH PROJECT 1996-1999

by

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Abstract

Severe weathering damage can be noted on monuments carved from bedrock in ancient Petra/Jordan. Interventions for preservation of this important cultural heritage are necessary. Precise damage diagnosis is required for effective and economic monument preservation. Within the framework of a research project (1996-1999) systematic studies are executed in Petra for better understanding of stone weathering and damages of the monuments. Aims of the project and preliminary results are described.

Introduction

The ancient Nabataean city of Petra is situated in the mountainous region of southwestern Jordan. The monuments of Petra rank among the most important cultural monuments of the world. In 1985 UNESCO inscribed Petra on the list of World Cultural Heritage. The complex of historical monuments at Petra is very significant for the cultural identity of Jordan. Today Petra is an important region with ever increasing tourism in Jordan.

The monuments in Petra can be subdivided into three groups:

Group I - The central part of Petra was covered by residential and public buildings, markets and sanctuaries like temples constructed with cut stone. Most of the buildings are severely damaged or partially destroyed and covered by debris. During the last years several archaeological sites have been excavated.

Group II - At the sides of the mountain ridges many hundred monuments - tombs, sanctuaries, places of worship - were carved from sedimentary bedrock. The rock-cut monuments represent today the most conspicuous evidence of Nabataean culture and are the main attraction for tourism. At many rock monuments severe weathering damage can be noted.

Group III - Numerous technical structures like water channels, cisterns, dams or stairways were either built with cut stones or carved from bedrock. Many of these technical structures are partly destroyed and can no longer be utilized.

In 1998 the World Monument Fund (WMF) has inscribed Petra on the list of the one hundred most endangered monument assemblies of the world. Remedial and preventive preservation measures are required. Experts agree, that a reliable damage analysis is the fundamental prerequisite for characterization, interpretation and valuation of damages and for planning and execution of effective and economic preservation measures. Strategy for monument preservation should follow three main lines:

1) Monument characterization
   - object identification
   - escription of location
   - environment
   - art-historical assessment
   - case history
2) Diagnosis
   - stone inventory
   - stone properties
   - damages
   - causes and processes of deterioration
   - prognoses of damages
3) Preservation measures
   - conception, management
   - test application
   - cost calculation
   - execution

certification
monitoring, long-term control
maintenance.

Research Project

The research group "Natural stones and weathering" at the Geological Institute of the Aachen University of Technology / Aachen-Germany started first investigations in Petra more than ten years ago. These studies - concentrated on monuments carved from bedrock - were executed in cooperation with the late Prof. K. Khdeir (Yarmouk University/Irbid), Prof. T. Akasheh (Yarmouk University/Irbid; Higher Council for Science and Technology/Amman), the Department of Antiquities, Amman/Petra (S. Tell, Dr G. Bisheh, Dr F. Zayadine, Dr S. Farajat) and the Petra National Trust. The research activities were supported with funds from the German Foreign Ministry and from Deutscher Akademischer Austauschdienst (DAAD). Results of these first stu-dies are published in Fitzner and Heinrichs (1994). Furthermore, scientific reports were distributed to the participating institutions. In 1995 the authors submitted a project proposal to Deutsche Forschungsgemeinschaft / Bonn-Germany (DFG) entitled "Systematic registration and evaluation of damages at monuments in Petra". The project planned for three years started in 1996 with funds from DFG. Main items of the project are:

- I - documentation of the actual state of monuments carved from bedrock
- II- evaluation and correlation of information on the state of monuments
- III - approach to a weathering model
- IV - evaluation of results for monument preservation

These four items are further differenciated in Table 1. The research shall contribute to:

- improvement of scientific knowledge of stone weathering at Petra monuments carved from bedrock
- detection of urgency and appropriate types of preservation measures

Based on a survey of monuments, considering variety of stone types and monument characteristics, and interdisciplinary discussions with Jordanian scientists, 22 monuments were selected for detailed investigation. These monuments are listed in Table 2. According to the project programme four field campaigns were carried out in 1996/1997.

Investigations - Methodology and Results

The investigation programme combines *in situ* investigation and laboratory tests. The *in situ* activities comprise description of stone types, description of monuments, monument mapping, measurements sampling and photographic documentation (Table 3).

The Petra area is predominantly composed of Cambrian and Lower Ordovician sedimentary rocks. In Figure 1 different lithostratigraphical classifications of this Lower Palaeozoic clastic series in Jordan and Petra are compared. Comparing the lithostratigraphical classifications by Pflüger (1990, 1995) and Jaser and Barjous (1992), "Nabataeica Sandstone" and "Siyagh Sandstone" (Pflüger) and "Umm Ishrin Sandstone - lower part" (Jaser and Barjous) are probably equivalent, although they were attributed by these authors to different stratigraphical units.

For detailed investigation on weathering damages as regards stone types, a more differenciated lithological classification is necessary. Based on a detailed survey of lithotypes in Petra - as far as they concern the rock-hewn monuments – a subdivision of twenty-five lithotypes was made considering stratigraphic age, stone colour, grain size and bedding structure. The lithological classification will be presented as soon as supplementary petrographical studies are completed.

Table 1. Project activities.

I	**Registration and documentation of the actual state of the monuments carved from bedrocks**	■ *Identification, characterization and classification of stone types occuring at Petra monuments* ■ *Registration and documentation of stone types at monuments according to type and distribution* ■ *Registration and documentation of weathering forms at monuments according to type, intensity and distribution* ■ *Registration of monument characteristics such as position, geometry, tooling of stone surface, remains of stucco, fissures/joints, microclimatic conditions, exposition characteristics regarding rain and water run-off etc.* ■ *Determination of stone properties*
II	**Evaluation and correlation of information on the actual state of the monuments**	■ *Evaluation of interelations between the groups of weathering forms „loss of stone material", „detachment of stone material" and „deposits"* ■ *Evaluation of chronological sequences of weathering forms* ■ *Correlation of weathering forms and stone properties* ■ *Evaluation of weathering bahaviour of the different stone types* ■ *Characterization of weathering profiles* ■ *Evaluation of weathering factors and processes*
III	**Approach to a weathering model**	■ *Compilation of results on weathering factors, weathering processes and weathering characteristics (forms, products, profiles)* ■ *Consideration of latest scientific findings regarding stone weathering* ■ *Deduction of a weathering model which describes the development of weathering damages, considering causes, processes, phenomena and rates of weathering*
IV	**Evaluation of results for monument preservation**	■ *Valuation of damages* ■ *Valuation of stone types regarding susceptibility to weathering* ■ *Damage prognosis* ■ *Estimation of urgency of preservation measures* ■ *Definition of requirements for remedial and preventive preservation measures* ■ *Proposals of effective types of preservation measures*

Table 2. Monuments under investigation.

Tomb-No.*	Name	Position	Altitude (m above sea level)	Orientation in * (360°-division)	Investigation area	Dimension of investigation area (m²)**
9	Sahrij Tomb	Southern flank of Ar Ramla	975	A: 330 (NNW) B: 60 (ENE) C: 150 (SSE) D: 240 (WSW)	4 facades (A-D)	A: 7,3 B: 9,2 C: 10,5 D: 9,2
12	-	Southern part of Ar Ramla	980	240 (WSW)	Entire facade	127,2
70	-	Outer Siq	890	A: 354 (N) B: 84 (E)	2 facades (A,B)	A. 107,7 B: 117,8
90	Obelisk	Near to the High Place	1070	A: 340 (NNW) B: 60 (ENE) C: 170 (S) D: 260 (W)	4 sides (A-D)	A: 7,3 B: 9,2 C: 10,5 D: 9,2
137	-	Near to the Main Theater	900	155 (SSE)	Entire facade	19,8
229	Renaissance Tomb	Wadi al Farasa	900	244 (WSW)	Entire facade	101,2
239	Soldier's Tomb	Wadi al Farasa	920	60 (ENE)	Entire facade	132,3
450	-	End of M'arras Hamdan / way up to Ad Dayr	910	80 (E)	Entire facade	5,5
452	Lion Triclinium Lion Tomb	End of M'arras Hamdan / way up to Ad Dayr	910	130 (SE)	Entire facade	54,9
455	-	Wadi Kharrouba	950	242 (WSW)	Entire facade	69,0
462	Ad Dayr Monastery	Western flank of al Qattar	1050	230 (SW)	Lower left part	498,3
634	-	Wadi Turkmaniya	900	90 (E)	Entire facade	225,6
649	Tomb with the Armour	Mughur an Nasara	950	252 (WSW)	Entire facade	235,7
675	-	Mughur al Mataha	950	96 (E)	Entire facade	75,2
676	-	Mughur al Mataha	950	74 (ENE)	Entire facade	122,5
731	Carmine Tomb	Northwest flank of al Khubtha	925	298 (WNW)	Entire facade	239,8
763	Tomb of Sextius Florentinus	Northwestern flank of al Khubtha	915	344 (NNW)	Entire facade	149,9
765	Palace Tomb	Western flank of al Khubtha	920	290 (WNW)	Lower left part (A), lower right part (B)	A: 236,1 B: 233,3
770	Silk Tomb	Western flank of al Khubtha	910	280 (W)	Entire facade	200,2
771	-	Western flank of al Khubtha	905	280 (W)	Entire facade	240,3
778	-	Western flank of al Khubtha	940	270 (W)	Entire facade	215,3
813	Unaishu Tomb	Southwest flank of al Khubtha	920	260 (W)	Entire facade	234,9

* according to BRÜNNOW & VON DOMASZEWSKI (1904)

** considering two-dimensional projection of the surface

Table 3. Field work.

Description of lithotypes color, grain size, bedding structure, stratigraphy
Description of monuments position, orientation, dimension, architecture, use, environment
Monument mapping lithology, weathering forms, joints
Measurements profile of stone tooling patterns, drilling resistance, water uptake, climate/microclimate
Sampling
Photodocumentation

Position, orientation and environment of the monuments were described. Furthermore, it was recorded, whether the monuments were cut into existing near-vertical rock sections - *little removal of outcropping rock, stone material already affected by weathering* - or into gentle slopes - *considerable removal of outcropping rock, "fresh" stone material* (Pflüger 1995). For example, according to our calculations about 7,500 cubic metres of stone material were removed for carving the two obelisks near to the High Place.

Information on surface tooling, stucco/plaster, channels for water run-off and use of monuments was registered additionally. Remains of stucco/plaster can be found at many monuments in Petra. Frequently, finer low-relief tooling patterns of stone surface correspond to thin layers of stucco, whereas

	JORDAN					PETRA	
	POWELL (1989)	BENDER (1968, 1974)	LLOYD (1969)	WETZEL & MORTON (1959)	QUENNEL (1951) BURDON (1959)	PFLÜGER (1990, 1995)	JASER & BARJOUS (1992)
ORDOVICIAN (ARENIG)	[Ram-Group] Umm Sahm Sandstone Formation	Bedded, brownish weathered sandstone	Um Sahm Formation	[Petra-Series] Grès d'Um Sahm	Umm Sahm Sandstone	(shaded)	(shaded)
?	[Ram-Group] Disi Sandstone Formation	Massive whitish weathered sandstone	[Disi Group] Disi Formation	[Petra-Series] Grès de Ram	Ram Sandstone	Disi Sandstone	[Ram-Sandstone Group] Disi Sandstone Formation
CAMBRIAN	[Ram-Group] Umm Ishrin Sandstone Formation	Massive brownish weathered sandstone	[Disi Group] Ishrin Formation	[Petra-Series] Grès de Quanaya	[Quweira-Series] Upper Quweira Sandstone	Ed-Deir Sandstone Habis Sandstone Temple Sandstone	[Ram-Sandstone Group] Umm Ishrin Sandstone Formation: Upper part Middle part Lower part
CAMBRIAN	[Ram-Group] Burj Dolomite Shale Formation / Abu Kusheiba Sandstone Formation	Dolomite-limestone-shale formation / White fine-sandstone	[Disi Group] —	[Petra-Series] Calcaire et marne gréseuse de Burj	[Quweira-Series] Burj Series	Siyagh Sandstone Nabataeica Sandstone	(shaded)
CAMBRIAN	[Ram-Group] Salib Arkosic Sandstone Formation	Bedded arkose sandstone, Basal conglomerate	Saleb Arkose	[Petra-Series] Grès et Conglomérats de Quweira	[Quweira-Series] Lower Quweira Sandstone	Saleb Arkose	[Ram-Sandstone Group] Salib Arkosic Sandstone Formation

1. Lithostratigraphy of Cambrian and Ordivician sedimentary rocks in central and south Jordan. Nomenclature and correlation.

coarser high-relief tooling patterns correspond to thicker layers of stucco coating. Today, most of the stucco/plaster coating is lost.

Dimension of chambers in monuments and the thickness of the front chamber wall were registered with respect to the static situation in the lower parts of the monuments.

Detailed information on weathering *factors* like climate, biosphere, pollutants or technical influences, on weathering *processes* and on weathering *characteristics* like weathering forms, weathering profiles and weathering products would be an optimal basis for understanding stone weathering.

As experience has shown, investigation on weathering factors and weathering processes is very difficult and results obtained are unsatisfactory. Therefore, it appears more suitable to approach characterization and interpretation of stone weathering by evaluating weathering characteristics. 'Phenomenological' methods and measuring procedures can be applied for *in situ* investigation of weathering characteristics at stone monuments. Based on investigation in Petra and at numerous stone monuments worldwide, the working group "Natural stones and weathering" at the Geological Institute of the Aachen University of Technology has developed the monument mapping method as a reliable phenomenological procedure for investigation on weathering forms (Fitzner, Heinrichs and Kownatzki 1995 and 1997; Fitzner, Heinrichs and Volker 1997, Kownatzki 1997). This method provides precise information on the weathering state of stone monuments. At present, monument mapping represents the only method, which allows to describe, document and evaluate entire stone surfaces according to type, intensity and distribution of visible weathering damages. Monument mapping can be applied to all stone types and stone objects. The mapping method is based on a detailed classification of weathering forms according to phenomenologic-geometric criteria. The complete classification scheme with definitions and photo-catalogue of weathering forms is presented in Fitzner, Heinrichs and Kownatzki (1995). The classification scheme has a hierarchical structure. It comprises four "*groups of weathering forms*" in the uppermost level: "loss of stone material", "discolouration/deposits", "detachment of stone material" and "fissures/deformation". In the second level a subdivision into 29 "*main weathering forms*" is made. In the third level of the classification scheme several main weathering forms are further differentiated into "*individual weathering forms*", 60 in total. In the case of main weathering forms without further differentiation into individual weathering forms, the main weathering form serves at the same time as individual weathering form In the fourth level all individual weathering forms can be further differentiated according to intensities. A standardized intensity classification is not feasible. It has to be adjusted to monuments under investigation. Intensity parameters are discussed in Fitzner, Heinrichs and Kownatzki (1995) and Kownatzki (1997). In Tables 4a and 4b all weathering forms are listed with number codes. The first number refers to the group of weathering forms, the second number to the main weathering form, the third number to individual weathering forms. Additionally, symbols are proposed for recording the weathering forms in mapping documents and for computer-supported processing of mapping information (Kownatzki 1997).

Plans of the monuments under investigation were prepared as documents for monument mapping in Petra. The elevations - drawn to scale - show the original geometry of the monuments. Available photo-

Table 4a. Classification of weathering forms.

No.	Weathering form	Symbol
1	LOSS OF STONE MATERIAL	
1.1	Back weathering	W
1.1.1	Back weathering due to loss of scales	sW
1.1.2	Back weathering due to loss of stone elements dependent on stone structure	xW
1.1.3	Back weathering due to loss of crusts	cW
1.1.4	Back weathering due to loss of undefinable stone elements	zW
1.2	Relief	R
1.2.1	Rounding / notching	Ro
1.2.2	Alveolar weathering	Ra
1.2.3	Weathering out dependent on stone structure	tR
1.2.4	Weathering out of stone components	Rk
1.2.5	Clearing out of stone components	Rh
1.2.6	Roughening	Rr
1.2.7	Microkarst	Rm
1.2.8	Pitting	Rt
1.3	Break out	O
1.3.1	Break out due to direct anthropogenic influence	aO
1.3.2	Break out due to constructional cause	bO
1.3.3	Break out due to natural cause	nO
1.3.4	Break out due to non-recognizable cause	oO
2	DISCOLORATION / DEPOSIT	
2.1	Discoloration	D
2.1.1	Coloration	Dc
2.1.2	Bleaching	Db
2.2	Soiling	I
2.2.1	Soiling by pollutants from the atmosphere	pI
2.2.2	Soiling by particles from surface water or bottom water	wI
2.2.3	Soiling by droppings	gI
2.2.4	Soiling due to direct anthropogenic influence	aI
2.3	Loose salt deposits	E
2.3.1	Efflorescences	Ee
2.3.2	Subflorescences	Ef
2.4	Crust	C
2.4.1	Dark-colored crust tracing the stone surface	dkC
2.4.2	Dark-colored crust changing the surface	diC
2.4.3	Light-colored crust tracing the stone surface	hkC
2.4.4	Light-colored crust changing the surface	hiC
2.4.5	Colored crust tracing the stone surface	fkC
2.4.6	Colored crust changing the surface	fiC
2.5	Biological colonization	B
2.5.1	Microbiological colonization	Bi
2.5.2	Colonization by higher plants	Bq
2.6	Discoloration to crust	D-C
2.7	Soiling to crust	I-C
2.8	Loose salt deposits to crust	E-C
2.9	Biological colonization to crust	B-C

grammetric plans (e.g. in McKenzie 1990) and larger-sized photos, supplemented by measuring at the monuments, served for plan preparation. Consideration of original monument architecture was necessary as reference for quantification of weathering damages and weathering rates and for evaluation of damage chronology.

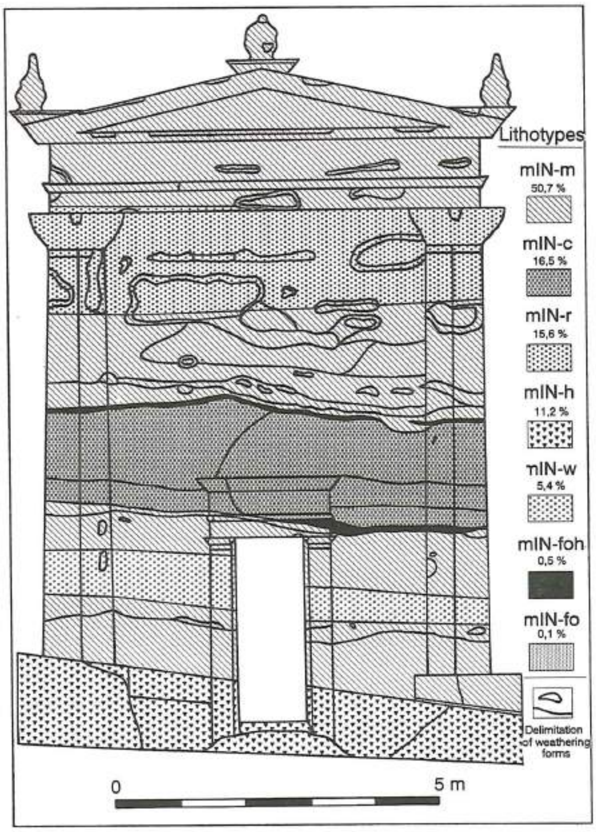
Based on stone inventory and classification of weathering forms, *lithological mapping* and *mapping of weathering forms* were executed at 22 monuments. Areas of different lithotypes and weathering forms were delimited in monument plans. At large monuments, up to 1000 areas were distinguished.

Table 4b. Classification of weathering forms.

No.	Weathering form	Symbol
3	**DETACHMENT**	
3.1	**Granular disintegration**	G
3.1.1	Granular disintegration into powder	Gp
3.1.2	Granular disintegration into sand	Gs
3.1.3	Granular disintegration into grus	Gg
3.2	**Crumbling**	P
3.3	**Splintering**	Q
3.4	**Flaking**	F
3.4.1	Single flakes	eF
3.4.2	Multiple flakes	mF
3.5	**Contour scaling**	S
3.5.1	Scale due to tooling of the stone surface	qS
3.5.2	Single scale	eS
3.5.3	Multiple scales	mS
3.6	**Detachment of stone elements dependent on stone structure**	X
3.6.1	Exfoliation	XI
3.6.2	Splitting up	Xv
3.7	**Detachment of crusts with stone material**	K
3.8	**Granular disintegration to flaking**	G-F
3.9	**Flaking to contour scaling**	F-S
3.10	**Flaking to crumbling**	F-P
3.11	**Granular disintegration to crumbling**	G-P
3.12	**Crumbling to splintering**	P-Q
3.13	**Crumbling to contour scaling**	P-S
3.14	**Splintering to contour scaling**	Q-S
4	**FISSURES / DEFORMATION**	
4.1	**Fissures**	L
4.1.1	Fissures independent of stone structure	vL
4.1.2	Fissures dependent on stone structure	tL
4.2	**Fissures dependent on stone structure to splitting up**	tL-Xv
4.3	Deformation	V

A computer software - VIA - has been developed for processing, illustration and evaluation of mapping information. The monument plans with delimitations of stone surface units are digitalized. The computer programme numbers all stone surface units and calculates their surface area. A data file with number, coordinates and surface area of all stone surface units has been created and all mapping information is integrated. The information can be organized systematically, can be illustrated in plans with colours and symbols and can be evaluated quantitatively for scientific aims and monument preservation purposes. Figure 2 shows the lithological mapping of Tomb 455 (Wādī Kharrūba) with quantitative evaluation. Seven different lithotypes - slightly inclined to ENE - occur at this monument. Documentation of lithotypes is necessary for evaluation of weathering characteristics as regards lithotypes.

For Tomb 778, a monument located at the western slope of al Khubtha, illustration and evaluation of mapping information are presented (Fig. 3). Figure 4 shows the original architecture of the monument façade and the projection of the front chamber wall. In Figure 5 the monument plan with all delimited and numbered areas is presented.

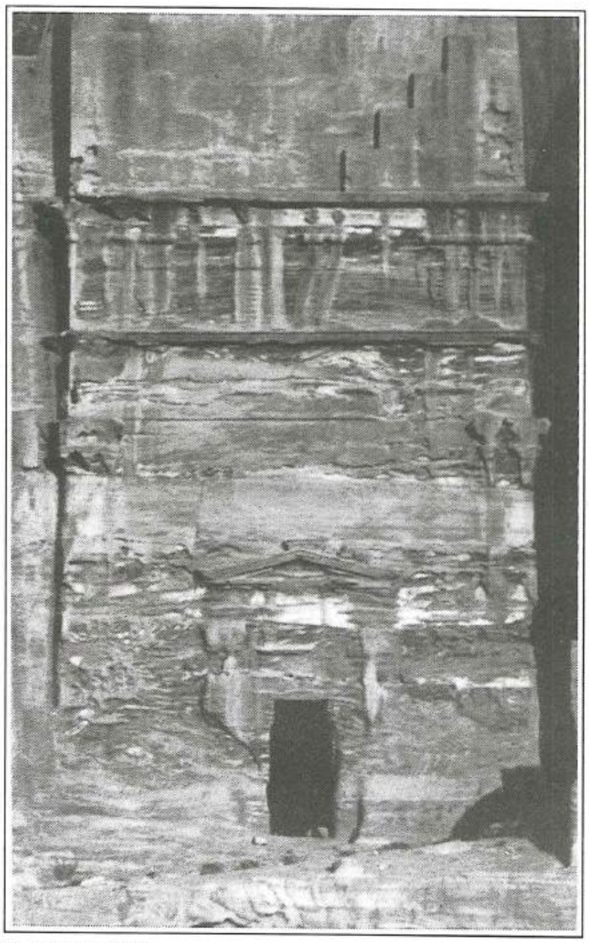


2. Tomb 455. Lithological mapping with quantitative evaluation of lithotypes.

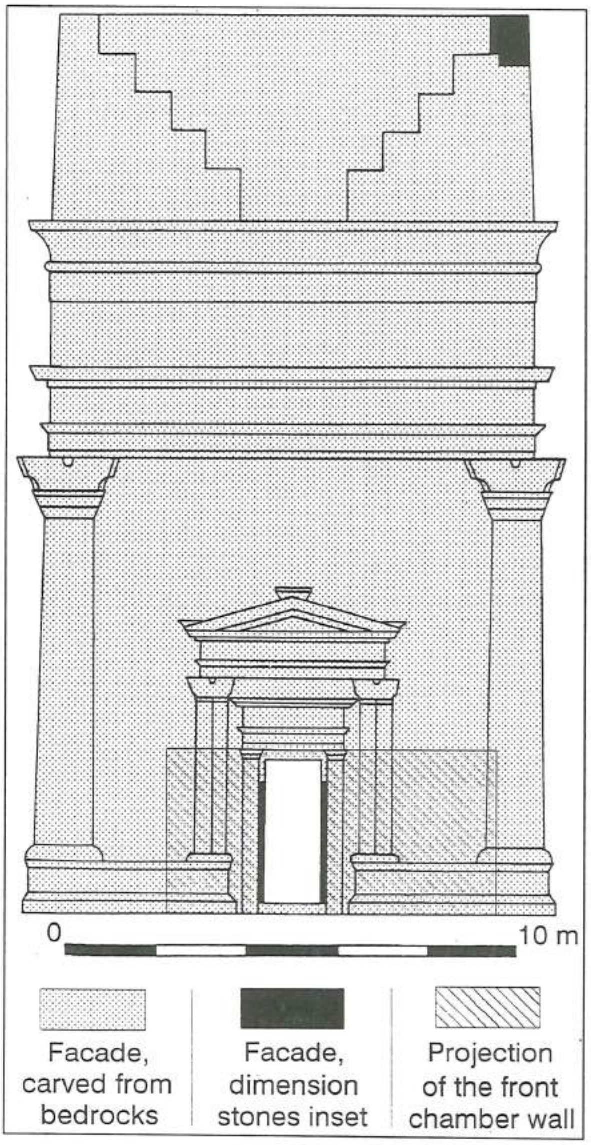
Weathering forms can be illustrated in plan according to different modes. Three main modes can be distinguished:

1) All weathering forms are illustrated in the same plan
2) Weathering forms are illustrated according to "groups of weathering forms"
3) Single weathering forms or combinations of weathering forms are illustrated.

Figures 6 and 7 present illustrations of weathering forms according to groups of weathering forms. In Figure 6 all weathering forms attributed to "loss of stone material" are shown. The weathering forms are marked with symbols. Intensities are marked by different grey tones. The plan



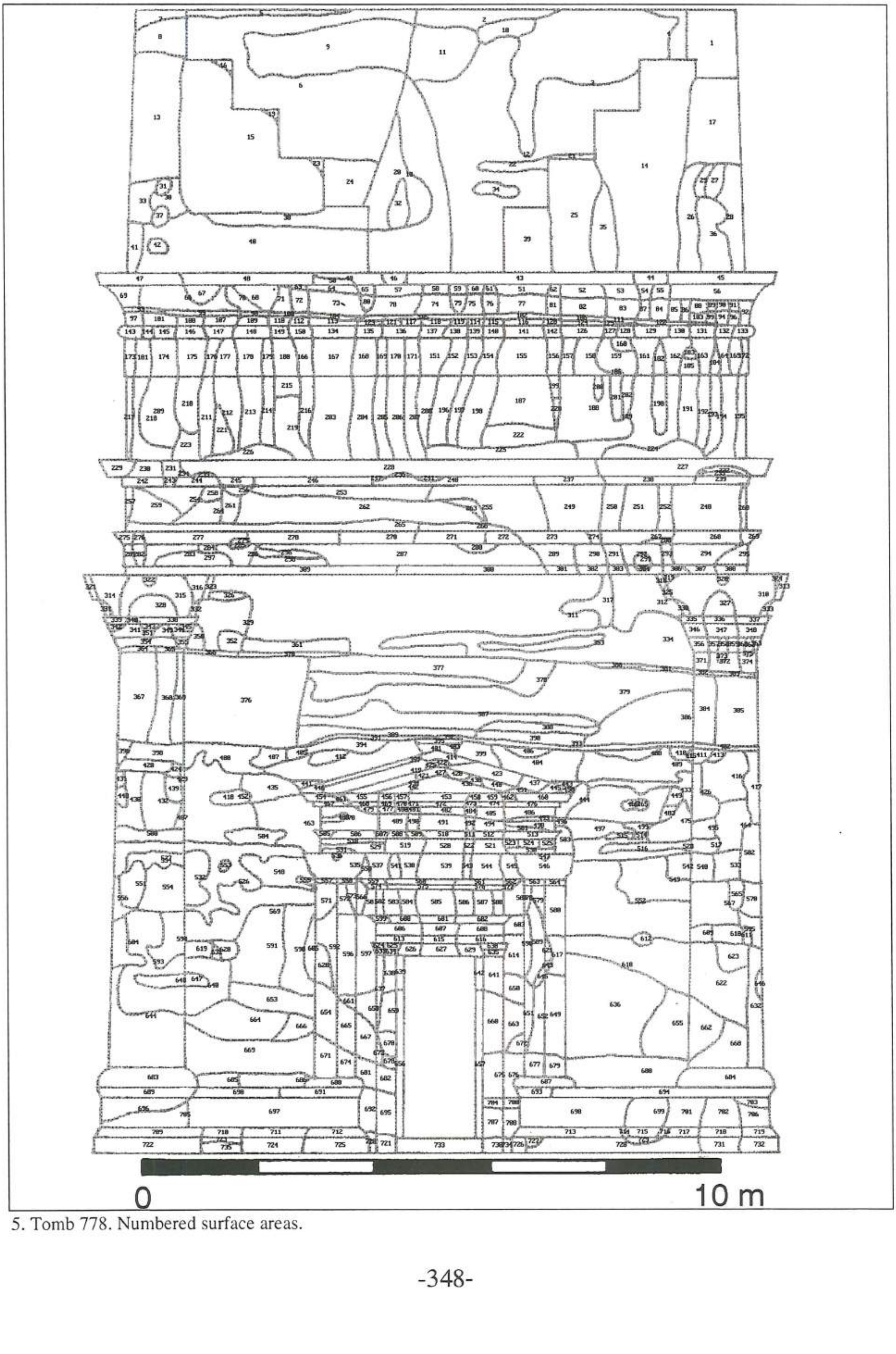
3. Tomb 778.



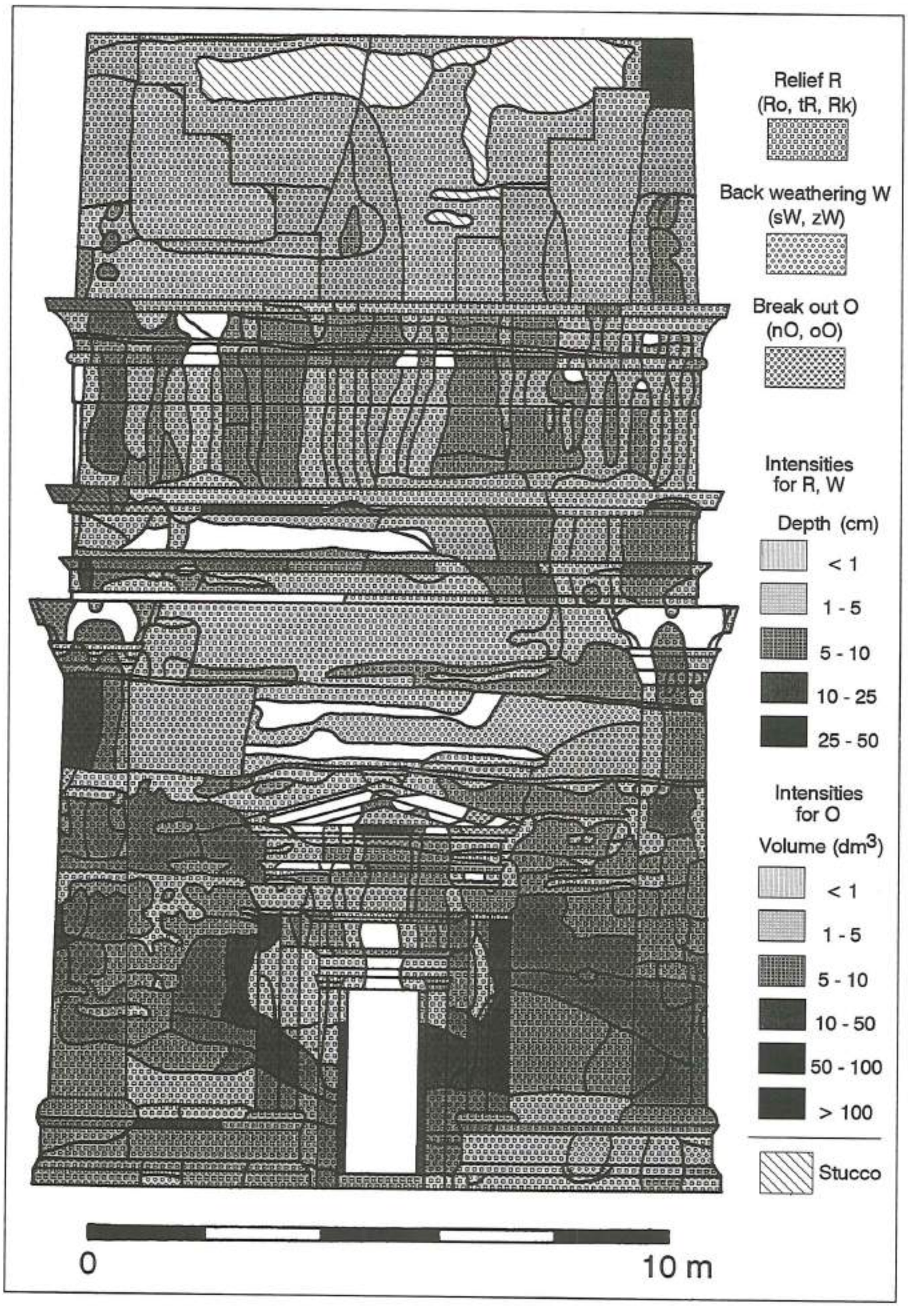
4. Elevation of Tomb 778 with original architecture.

"loss of stone material" can be used for calculation of weathering rates. Necessity of interventions such as stone repair or structural interventions can be evaluated. In Figure 7 all weathering forms attributed to "deposits" are marked. In the same way, a plan with all weathering forms describing "detachment of stone material" can be made, which would characterize stone surface areas in danger of losing stone material and which would indicate future progress of weathering. Additionally, this plan would allow first information on weathering profiles and mechanical behaviour of stone. Urgency and suitability of interventions such as fixation of loose stone elements, stone treatment or surface coating could be evaluated. All plans illustrate type, intensity and distribution of weathering forms as function of lithotypes and exposition. Zones of weathering forms are delineated, which indicate weathering factors like humidity, salt load or mechanical stress. Calculation of average weathering rates - based on evaluation of weathering forms attributed to "loss of stone material" - is shown for the façade of Tomb 778 in Figure 8. Abu Safat (1988) determined maximum weathering rates of 11 mm / 100 years for carved stone surfaces in Petra. Our results show, that the average rate can be significantly higher.

All weathering forms can be evaluated quantitatively. In Table 5 and Figure 9 quantitative evaluation of weathering forms refers to the entire façade of Tomb 778. This type of evaluation allows to compare

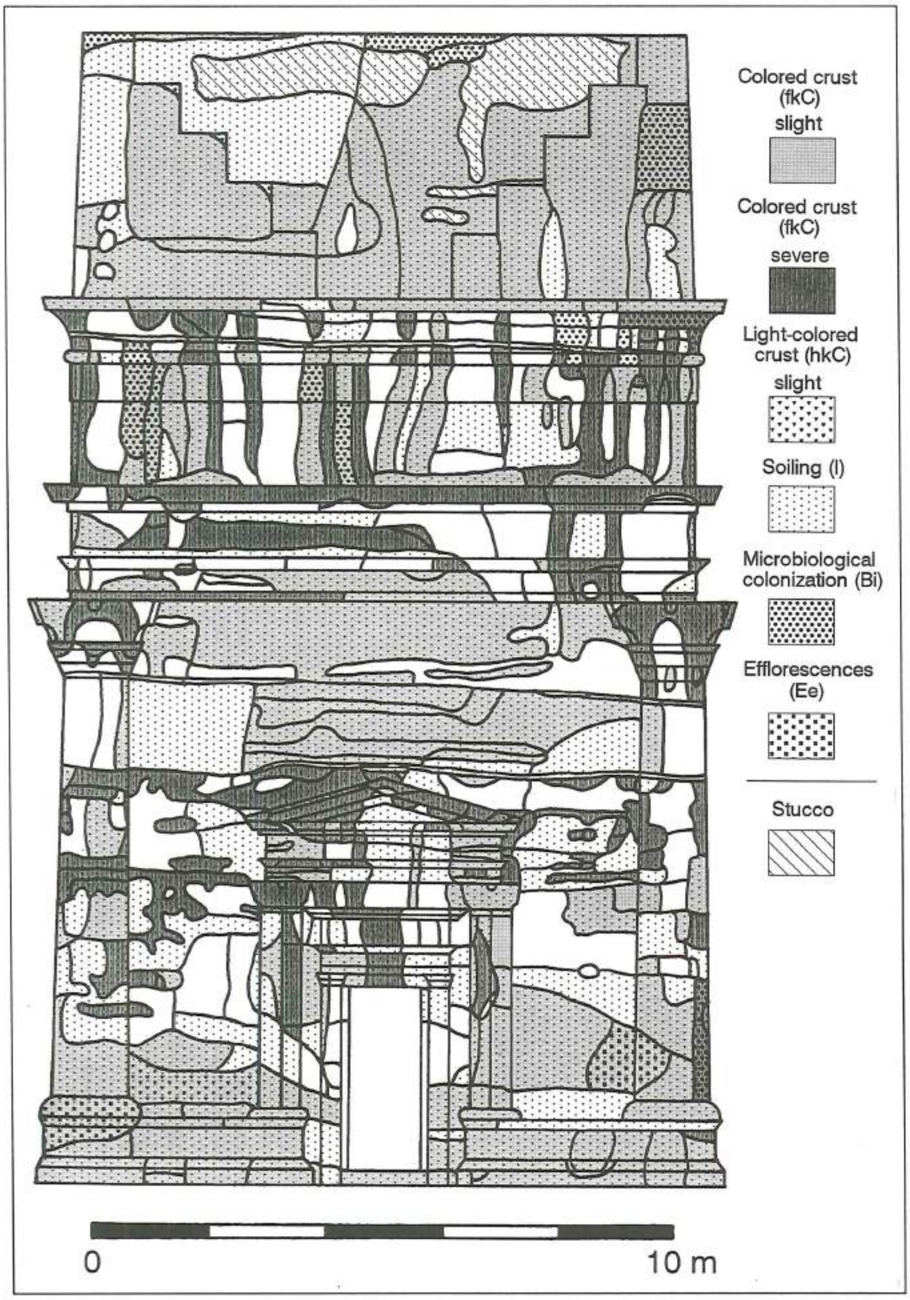


5. Tomb 778. Numbered surface areas.



6. Tomb 778. Mapping of weathering forms. Group of weathering forms: "Loss of stone material".

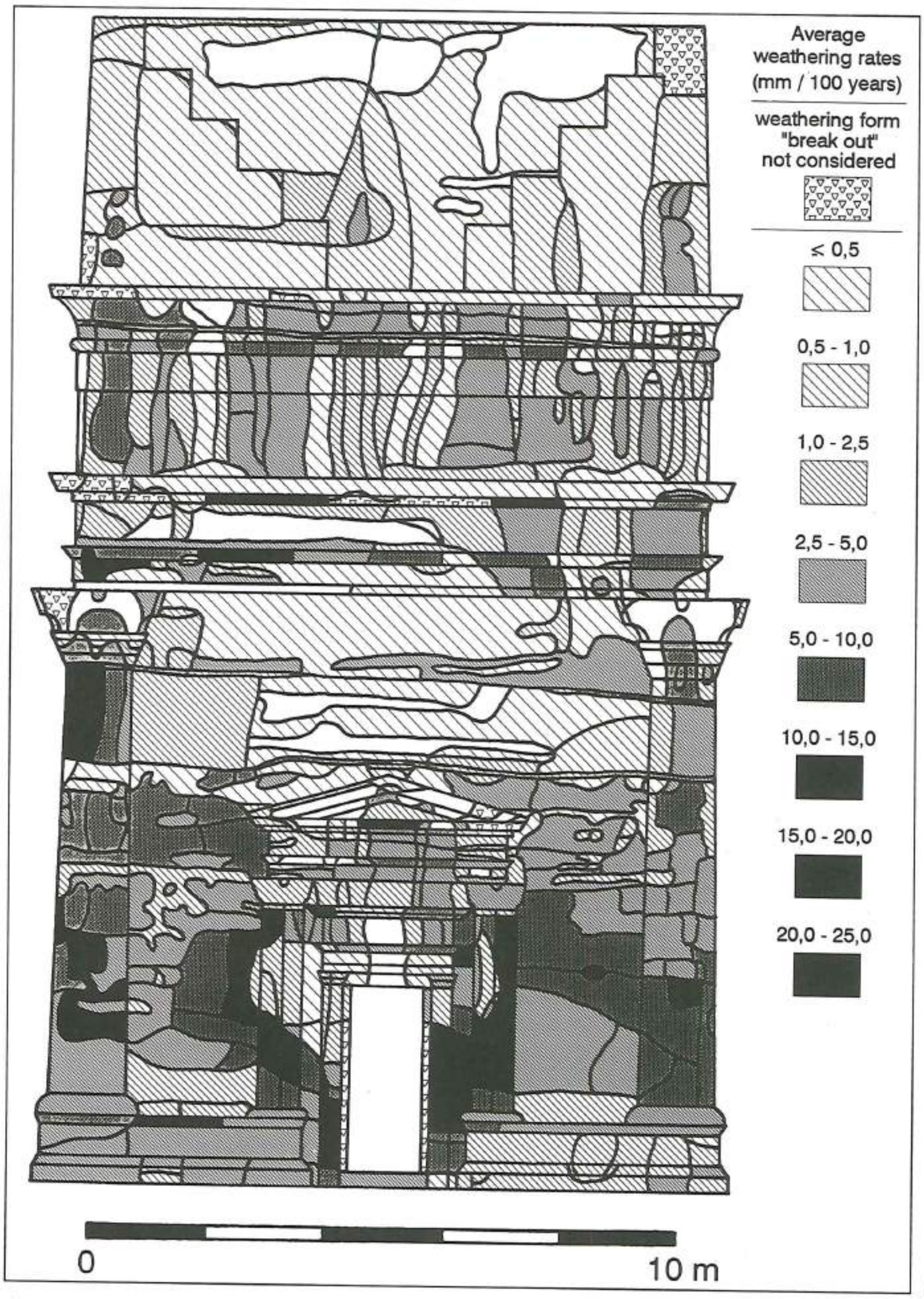
weathering forms at different monuments as function of monument characteristics and environment. For each monument quantitative evaluation of weathering forms has been made as function of lithotypes. Weathering behaviour of different lithotypes can be compared. The computer programme allows quantification of single weathering forms and combinations of weathering forms. Precise information on interrelations between weathering forms is guaranteed, especially on interrelations between "loss of stone material", "deposits" and "detachment of stone material". This type of evaluation allows the identification of chronological sequences of weathering forms. A chronolgical sequence is shown in Figure 10 for the multicoloured, fine- to medium-grained sandstone (middle part of the Cambrian Umm Ishrin Sandstone Formation) - the predominant lithotype at Tomb 778 covering 90 % of the façade. Four weathering forms describing recent "detachment of stone material" can be stated: "*contour scal-*



7. Tomb 778. Mapping of weathering forms. Group of weathering forms "discolouration/ deposit".

ing", "*flaking to contour scaling*", "*granular disintegration to flaking*" and "*granular disintegration*". Figure 10 shows the sequence of these weathering forms as function of weathering progression. The progression of weathering intensity is characterized by increase of loss of stone material, decrease of deposits and decreasing size of detaching stone elements. Velocity of detachment and loss of stone material increase in this chronological sequence. This chronological sequence can be further specified considering intensities of the weathering forms attributed to "detachment of stone material". In Figure 11 the intensities of these weathering forms again are presented as function of increasing loss of stone material and decrease of deposits. "*Contour scaling*", "*flaking to contour scaling*", "*granular disintegration to flaking*" and "*granular disintegration*" reach their highest intensity during the stage of predominance.

Chronological sequences of weathering



8. Tomb 778. Weathering rates.

forms are important for understanding the development of weathering damages. Considering exposition characteristics, this evaluation can be made even more detailed. During the field campaign in winter, surface areas exposed to rain and surface areas sheltered from rain by mouldings or protruding architectural elements were documented (Fig. 12). Zones affected by intense rainwater run-off and weathered surface areas nearby or between such water run-off zones are marked additionally. In Figure 13 a quantitative evaluation of weathering forms as function of exposition characteristics is presented. The weathering forms "granular disintegration" (G), "granular disintegration to flaking" (G-F), "flaking to contour scaling" (F-S) and "contour scaling/single scale" (eS) are evaluated quantitatively referring to surface areas next to water run-off zones (see A) and to the total façade of Tomb 778 (see B). Area (A) is characterized by above-average susceptibility to stone detachment. Based on such evaluations, ex-

Table 5. Tomb 778. Quantitative evaluation of weathering forms.

1, 2, 3... **Intensity degrees**

LOSS OF STONE MATERIAL

Relief (R)	1	2	3	4	5
Rounding/notching (Ro)	26.35 %	23.78 %	22.30 %	12.10 %	2.56 %
Weathering out dependent on stone structure (tR)	1.26 %	0.41 %			
Weathering of stone components (Rk)			0.03 %	0.02 %	

Back weathering (W)	1	2	3	4	5
Back weathering due to loss of scales (sW)	1.91 %	0.37 %			
Back weathering due to loss of undefinable stone elements (zW)		0.35 %	0.30 %		

Break out (O)	1	2	3	4	5	6
Break out due to non-recognizable cause (oO)	0.01 %	0.20 %	0.23 %	0.50 %	0.26 %	0.50 %

DISCOLORATION / DEPOSITS

	no differentiation of intensities
Soiling (I)	80.23 %

Crust (C)	1	2
Colored crust tracing the surface (fkC)	49.40 %	13.92 %
Dark-colored crust tracing the surface (dkC)	0.15 %	
Light-colored crust tracing the surface (hkC)	0.70 %	

Loose salt deposits (E)	1	2
Efflorescences (Ee)	1.17 %	

Biological colonization (B)	no differentiation of intensities
Microbiological colonization (Bi)	2.92 %

DETACHMENT

Granular disintegration (G)	1	2	3
Granular disintegration into sand (Gs)	4.45 %	4.78 %	1.60 %

Crumbling (P)	1	2	3
	0.22 %	0.01 %	0.43 %

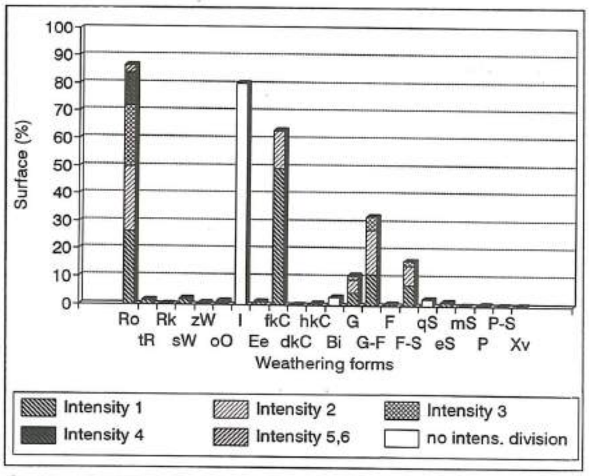
Flaking (F)	1	2	3
Single flakes (eF), multiple flakes (mF)	0.72 %	0.06 %	

Contour scaling (S)	no differentiation of intensities
Scale due to tooling of the stone surface (qS)	2.26 %

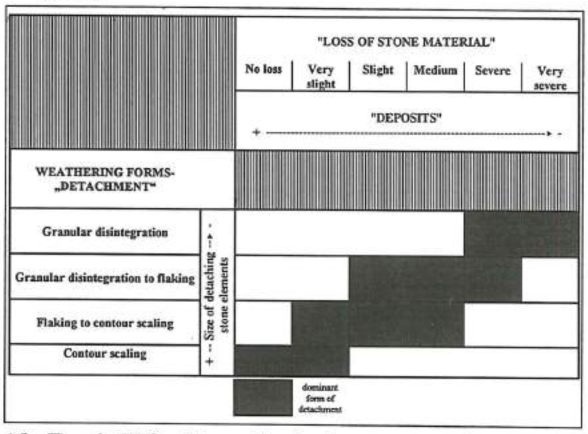
	1	2	3	4	5
Single scale (eS)	1.00 %	0.26 %	0.01 %	0.18 %	
Multiple scales (mS)			0.13 %		

Detachment of stone elements dependent on stone structure (X)	1	2
Splitting up (Xv)		0.16 %

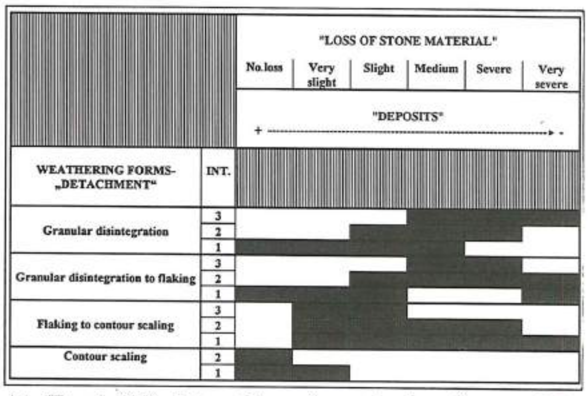
	1	2	3
Granular disintegration to flaking (G-F)	11,29 %	16,16 %	4,94 %
Flaking to contour scaling (F-S)	7,58 %	6.82 %	1.74 %
Crumbling to contour scaling (P-S)	0.14 %	0.05 %	0.03 %



9. Tomb 778. Quantitative evaluation of weathering forms.



10. Tomb 778. Chronological sequence of stone detachment.



11. Tomb 778. Intensities of weathering forms of the group "detachment".

position characteristics can be judged. Weathering factors and weathering processes can be evaluated and intervention such as control of water run-off can be planned.

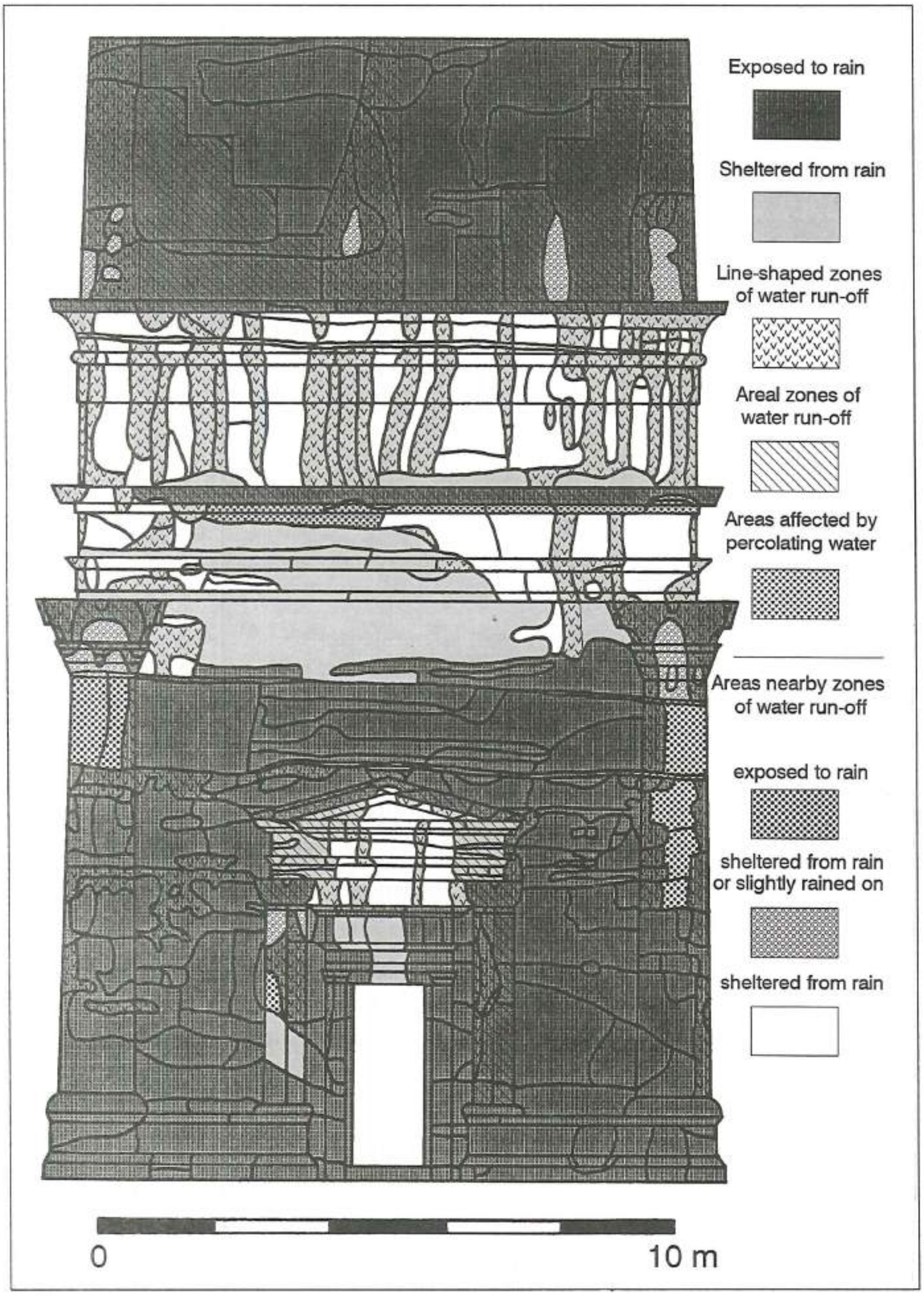
Evaluation of mapping information provides precise information on the development of weathering forms as function of lithotypes, exposition, monument characteristics and time. Judgement of damages is a further practical research aim. For this purpose damage categories have been established. Contrary to measurable weathering forms, damage categories do not provide information on type or intensity of individual weathering phenomena. Damage categories consider and summarize all registered weathering forms and their intensities in form of a conclusive rating. Six damage categories have been established: 0 = no visible damage, I = very slight damage, II = slight damage, III = moderate damage, IV = severe damage, V = very severe damage. A correlation scheme has been developed for weathering forms and damage categories. The transformation of weathering forms into damage categories can be done by means of computer programme VIA considering defined correlation. The damage categories can be illustrated graphically and can be evaluated quantitatively (Fig. 14). Based on quantitative evaluation of damage categories, the linear damage index and progressive damage index can be calculated, both ranging from 0 to 5 (Fig. 15). Linear damage index corresponds to average damage category, whereas the progressive index emphasizes proportion of higher damage categories. Considering damage indices, monuments can be compared with respect to urgency of monument preservation measures (Fig. 16).

In addition to mapping procedure, measurements were executed at carved stone surfaces in Petra:

- profile measurements
- drilling resistance measurements
- capillary water uptake measurements
- microclimatic measurements.

Based on mapping results, measurements could be well-directed and executed at representative monument areas.

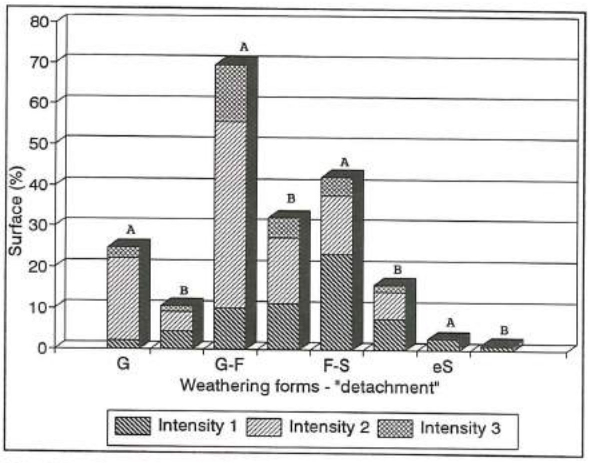
Profile measurements were made at monuments with remains of original stone-tooling patterns. Surface morphology was



12. Tomb 778. Exposure characteristics.

measured. Original morphology of stone surface and geometry of detaching stone elements were evaluated. Fine, low-relief surface tooling frequently was followed by detachment of thin scales. Coarse, high-relief surface-tooling was often followed by detachment of thicker scales.

Drilling resistance measurements were carried out with a drilling equipment developed in Germany. The procedure is almost non-destructive. Drilling resistance profiles are calculated from drilling time and drilling depth. Drilling resistance profiles provide information on material strength and can be used for characterization of damage development. In Petra many macroscopically sound rocks are characterized by rather low drilling resistance. This result confirms the weak grain bond of most lithotypes, described in literature as "friable stones". Drilling resistance profiles as function of weathering forms are shown in Figure 17. "Granular disintegration" shows continuous increase of drilling resistance from stone



13. Tomb 778. Quantitative evaluation of stone detachment. A: surface areas next to zones of water run-off, B: entire façade. Weathering forms: G = granular disintegration, G-F = granular disintegration to flaking, F-S = flaking to contour scaling, eS = contour scaling/single scale.

surface to stone interior. For "contour scaling - single scale" the profile quantifies thickness of scale and width of the zone of detachment.

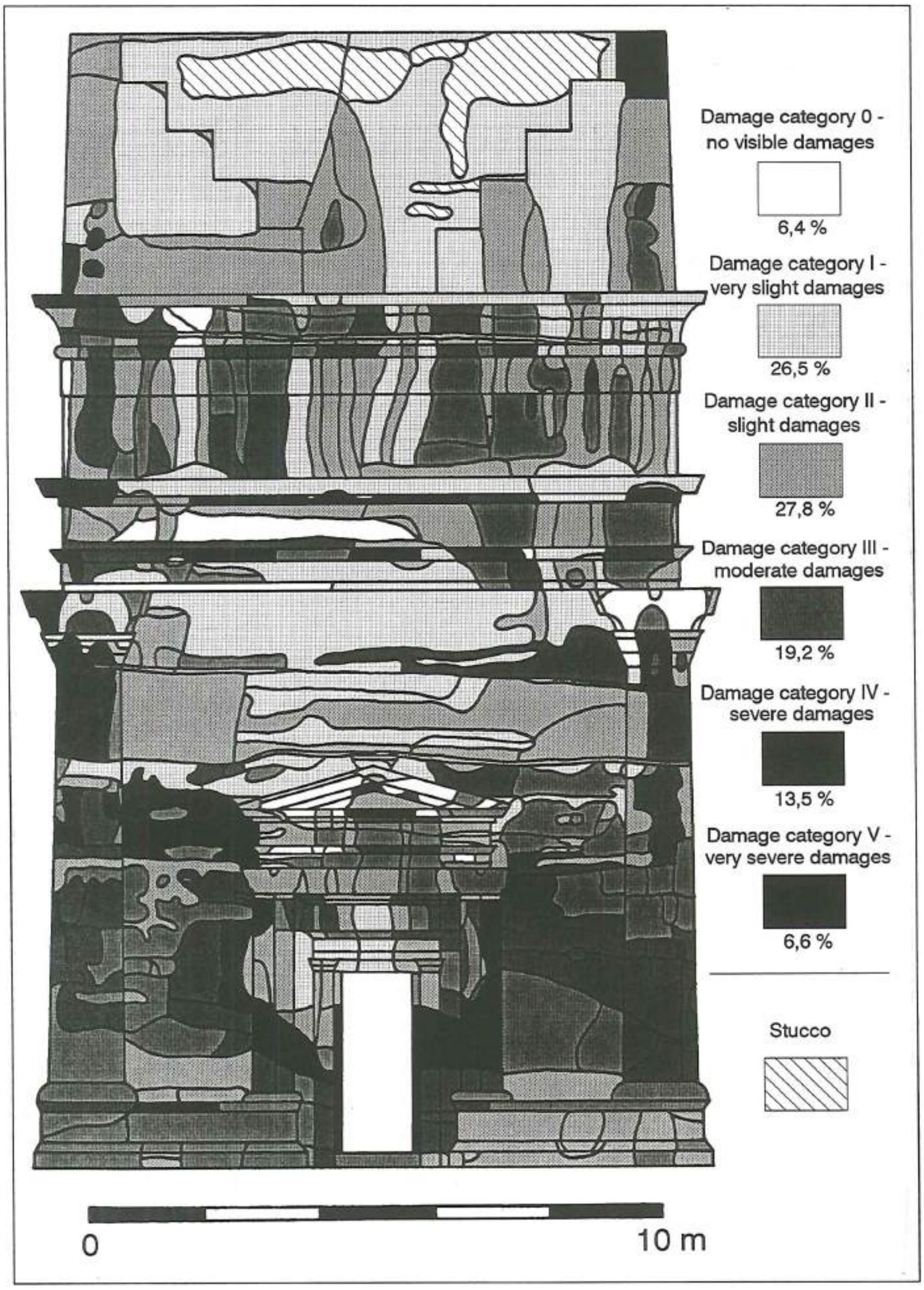
Water intake measurements were made for quantification of water uptake and water penetration depth as function of time and used for characterization of water migration. Lithotypes in different states of weathering were considered. The non-destructive Karsten tube method was applied. Water intake measurements are presented in Figure 18. Water intake rates corresponding to three different weathering states of a whitish, medium- to coarse grained sandstone (upper part of Umm Ishrin Sandstone Formation) are presented. By means of a computer programme, time of water intake and penetration depth can be calculated. An improved version of the computer programme has been recently developed by Rapp, Wendler and Snethlage (1997).

During the four field campaigns in Petra climatic and microclimatic measurements were taken. Air temperature, air humidity (Petra region, monuments) and stone surface temperatures (monuments) were measured. Stone surface measurements were made at the monuments in a period of 24 hours. For each monument a measuring grid was recorded an a monument plan. Stone surface temperatures were measured with an infrared thermometer. Corresponding air temperature and air humidity were also registered. Stone surface temperatures can be illustrated as temperature curves (course of temperature) or by means of isotherm plans (distribution of temperature). Temperature curves of minimum, maximum and average stone surface temperatures are shown in Figures 19 and 20 for the Silk Tomb (exposed W) and the Sextius Florentinus Tomb (exposed N). The higher variation of stone surface temperature at the Silk Tomb is a consequence of direct sun radiation. The average difference between maximum and minimum stone surface temperature at the Sextius Florentinus Tomb was 8°C, at the Silk Tomb 20°C. Heating and cooling rates can be calculated.

The climate measurements allow characterization of seasonal and daily variation of climatic conditions in Petra. They provide detailed information on microclimatic conditions at the monuments. The results can be evaluated as regards seasons, lithotypes, weathering state, and exposure characteristics. The climatic data are very important for nature-adapted weathering simulation tests. However, for judgement of climatic weathering factors not only recent climatic conditions should be considered. Climate variations during the last 2000 years should also be taken into account. Variations in the past have been described by Shehadeh (1985).

At the moment petrographical studies and weathering simulation tests are carried out on stone samples from Petra. Table 6 shows stone properties being analysed. Main aims of these laboratory analyses are:

- petrographical classification of all lithotypes,
- characterization and comparison of stone properties as regards lithotype and state of weathering,



14. Tomb 778. Damage categories with quantitative evaluation.

- identification of weathering products,
- characterization of weathering profiles,
- chronology of stone alteration,
- characterization of weathering behaviour of stone properties,
- rating of lithotypes regarding susceptibility to weathering,
- information on weathering factors and weathering processes.

Final Aims

The project has a scientific and a practical aim. Based on compilation of all results obtained from *in situ* investigation and laboratory studies and considering latest scientific findings, a weathering model for the Petra monuments carved from bedrock shall be developed. This model shall describe and explain the development of weathering damages at the monuments considering weathering factors, processes and characteristics as well as stone types and monument characteristics.

The second aim of the project is an ef-

Determination of **Linear damage index** DI_{lin}:

$$DI_{lin} = \frac{(A \cdot 0) + (B \cdot 1) + (C \cdot 2) + (D \cdot 3) + (E \cdot 4) + (F \cdot 5)}{100}$$

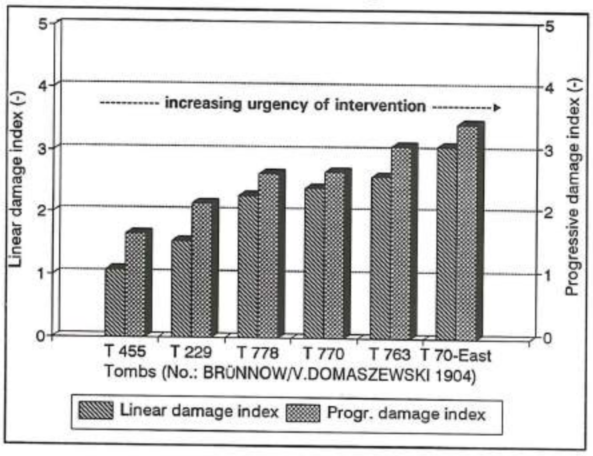
Determination of **Progressive damage index** DI_{prog}:

$$DI_{prog} = \sqrt{\frac{(A \cdot 0^2) + (B \cdot 1^2) + (C \cdot 2^2) + (D \cdot 3^2) + (E \cdot 4^2) + (F \cdot 5^2)}{100}}$$

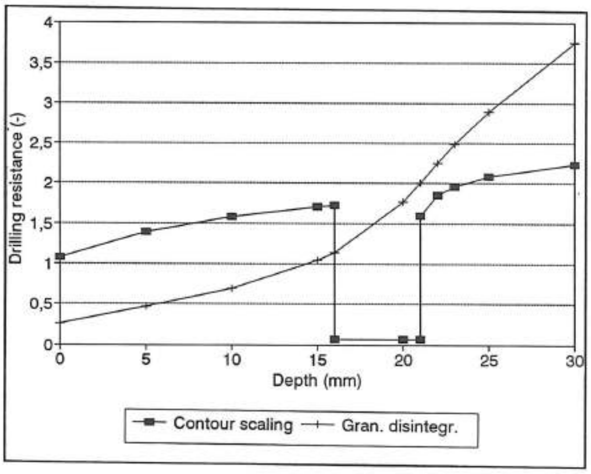
A = Area - damage category 0 (%)
B = Area - damage category 1 (%)
C = Area - damage category 2 (%)
D = Area - damage category 3 (%)
E = Area - damage category 4 (%)
F = Area - damage category 5 (%)

$\Sigma A\text{-}F = 100$

15. Linear and progressive damage index.

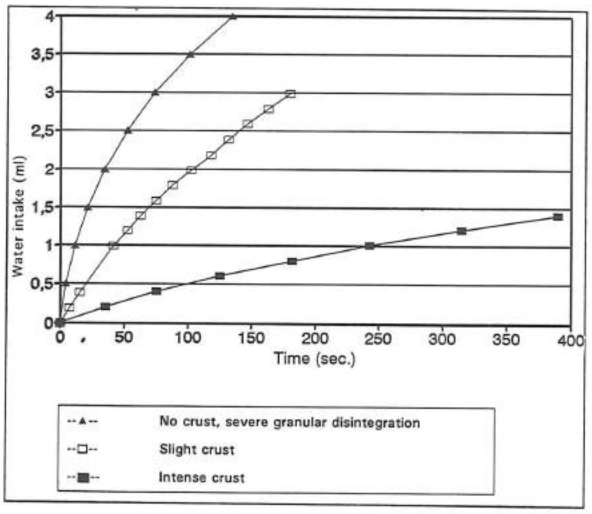


16. Damage indices for Petra monuments.

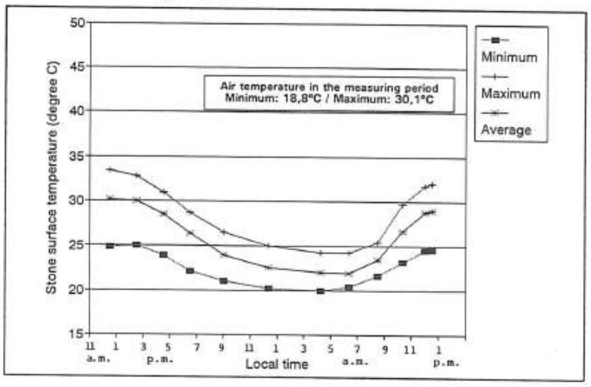


17. Drilling resistance profiles. Weathering forms: "granular disintegration" and "contour scaling".

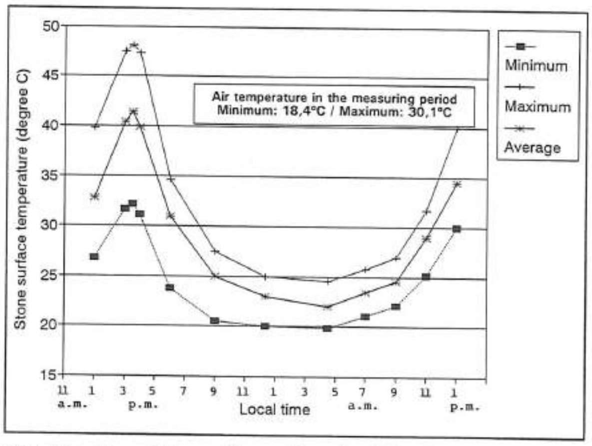
fective contribution to the monument preservation. Reliable characterization, interpretation and evaluation of damages will allow to calculate the urgency of interventions, to define requirements for re-



18. Soldier's Tomb. White medium- to coarse-grained sandstone. Water intake as regards weathering forms.



19. Silk Tomb. West-exposed façade. Stone surface temperatures in a period of 24 hours. Measurement in October 1996.



20. Sextius Florentinus Tomb. North-exposed façade. Stone surface temperatures in a period of 24 hours. Measurement in October 1996.

medial and preventive preservation measures and to propose effective types of preservation measures.

Table 6. Laboratory tests.

COMPOSITION		- Mineral composition - Chemical composition
TEXTURE	GRAIN CHARACTERISTICS	- Grain size - Shape, roundness
TEXTURE	FABRIC	- Grain contacts - Grain orientation
TEXTURE	POROSITY PROPERTIES	- Density - Total porosity - Pore size distribution - Specific surface area
HYGRIC PROPERTIES		- Water adsorption - Water desorption - Water vapour permeability - Hygric dilatation
THERMAL PROPERTIES		- Thermal conductivity - Thermal dilatation
MECHANICAL PROPERTIES		- Strength - Hardness
WEATHERING BEHAVIOUR		- Change of stone properties as function of weathering processes *weathering simulation*

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Bibliography

Abu Safat, M.
1988 Verwitterung und Hangabtragung im "Nubischen Sandstein" Südjordaniens. *Erlanger Geographische Arbeiten*, H. 49, Erlangen: Palm & Enke Verlag.

Bender, F.
1968 *Geologie von Jordanien.* Beiträge zur regionalen Geologie der Erde, Bd. 7. Berlin-Stuttgart: Borntraeger.

Bender, F.
1974 *Geology of Jordan.* Contributions to the Regional Geology of the Earth, Supplementary Edition of Vol. 7, Berlin-Stuttgart: Borntraeger.

Burdon, D.J.
1959 *Handbook of the Geology of Jordan.* Colchester-Great Britain: Benham and Company Limited/ Government of the Hashemite Kingdom of Jordan.

Brünnow, R. and von Domaszewski, A.
1904 *Die Provincia Arabia.* Vol. 1. Strassburg.

Fitzner, B. and Heinrichs, K.
1994 Damage diagnosis at monuments carved from bedrocks in Petra/Jordan. Pp. 663-672 in *Soprintendenza ai Beni Artistici e Storici di Venezia.* Proceedings of the IIIrd International Symposium on the Conservation of Monuments in the Mediterranean Basin, *Stone and Monuments: Methodologies for the Analyses of Weathering and Conservation*, Venice, 22-25 June 1994.

Fitzner, B., Heinrichs, K.and Kownatzki, R.
1995 Weathering forms - classification and mapping. Pp. 41-88 in Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, *Denkmalpflege und Naturwissenschaft, Natursteinkonservierung* I. Berlin: Ernst and Sohn.
1997 Weathering forms at natural stone monuments - classification, mapping and evaluation. Pp. 105-127 in *International Journal for Restoration of Buildings and Monuments,* Vol. 3, Stuttgart: Aedificatio Verlag/Fraunhofer IRB Verlag.

Fitzner, B., Heinrichs, K. and Volker, M.
1997 Monument mapping - a contribution to monument preservation. Pp. 347-355 in F. Zezza (ed.), *Proceedings of the E.C. Research Workshop : Origin, mechanisms and effects of salts on degradation of monuments in marine and continental environment,* Bari, 25-27 March: C.U.M. / University School of Monument Conservation. Bari.

Jaser, D. and Barjous, M.O.
1992 *Geotechnical studies and geological mapping of ancient Petra city.* Town Mapping Project, Bulletin 1, Amman: Hashemite Kingdom of Jordan / Ministry of Energy and Mineral Resources / Natural Resources Authority / Geological Directorate / Geological mapping division.

Kownatzki, R.
1997 *Verwitterungszustandserfassung von Natursteinbauwerken unter besonderer Berücksichtigung phänomenologischer Verfahren.* Dissertation, RWTH Aachen, Aachener Geowissenschaftliche Beiträge, Band 22. Aachen: Verlag der Augustinus Buchhandlung.

Lloyd, J.W.
1969 *The hydrogeology of the southern desert of Jordan.* UNDP/FAO 212, Technical Report No. 1. Rome.

McKenzie, J.
1990 *The Architecture of Petra.* British Academy Monographs in Archaeology, No. 1. New York: Oxford University Press.

Pflüger, F.
1990 *Flash flood conglomerates and Cambrian transgression in Petra/Jordan.* Unveröffentlichte Diplomarbeit, Universität Tübingen.
1995 Archaeo-geology in Petra, Jordan. *ADAJ* 29: 281-295.

Powell, J.H.
1989 *Stratigraphy and sedimentation of the phanerozoic rocks in central and south Jordan - Part A: Ram and Khreim Groups.* 1:50.000 Geological mapping series, Geo. Bulletin No. 11, Amman: Hashemite Kingdom of Jordan / Ministry of Energy and Mineral Resources / Natural Resources Authority / Geological Directorate.

Quennel, A.M.
1951 The geology and mineral resources of (former) Trans-Jordan. Pp. 85-115 in *Colonial Geology and Mineral Resources,* Vol. 2, No. 2. London.

Rapp, K., Wendler, E. and Snethlage, R.
1997 Zerstörungsfreie Messung der Wasseraufnahme - Verbessertes Auswerteverfahren für die Messmethode nach Karsten. P. 288 in *Berichte der Deutschen Mineralogischen Gesellschaft.* Beihefte zum *European Journal of Mineralogy* Vol. 9, No. 1. Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung.

Shehadeh, N.
1985 The climate of Jordan in the Past and Present. Pp. 25-37 in *SHAJ* II. London: Rout-

lege and Kegan Paul Ltd/Amman: Department of Antiquities.
Wetzel, R. and Morton, D.M.
1959 Contribution à la géologie de la Transjordanie. Pp. 95-191 in *Notes et Mémoires sur le Moyen-Orient,* Tome VII. Paris: Musée National d'Histoire Naturelle.