COMPREHENSIVE CHARACTERIZATION AND RATING OF THE WEATHERING STATE OF ROCK CARVED MONUMENTS IN PETRA/JORDAN- WEATHERING FORMS, DAMAGE CATEGORIES AND DAMAGE INDEX

by

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Abstract

The rock - cut monuments of ancient Petra in Jordan represent an outstanding world cultural heritage. On many of the monuments, damages due to weathering are alarming. Precise diagnosis is needed for the comprehensive characterization, understanding, rating and prediction of damages, and, for remedy and sustainable prevention. Identification, registration, documentation and evaluation of weathering forms are an important contribution to damage diagnosis. Monument mapping has been internationally established as an expert method. Systematic monument mapping has been executed at numerous rock monuments in Petra. The methodological approach and results are presented.

Introduction

The Nabataean city of Petra, has numerous monuments that were carved out of sedimentary rock about 2000 years ago. Brünnow and von Domaszewski (1904) catalogued more than 800 rock monuments of different size, architecture and function. They established a numbering system for the tombs which is still in use today. Most of the monuments appear in the form of rock-cut façades with chambers. It is rare that monuments with two, three or even four façades can be found. The Petra rock monuments rank among the most important historical monuments of the world, combining natural environment and craftsmanship in a very impressive way.

Ever since their construction all monuments have been suffering from environmental impact. On many of the monuments, the weathering damages – loss of stone material, detachment of stone material, structural disorders – are alarming and preservation measures are necessary. However, the protection of rock carved monuments requires careful intervention and rash intervention works should be avoided. All experts agree, that the realization of effective and sustainable preservation measures can only be achieved by means of a reliable damage diagnosis which includes a complexity of causes, mechanisms and results of weathering. Therefore, research results must be integrated into monument preservation plans.

The research project “Systematic registration and evaluation of damages at rock monuments in Petra” (1996-1999) aims at comprehensive damage diagnosis. The project – initiated by the authors and executed in close cooperation with Jordanian authorities – is funded by DFG-Deutsche Forschungsgemeinschaft (Germany). The aims and objectives of this project have been described in Fitzner and Heinrichs (1998a). The project combines extensive in situ investigation of the Petra rock-cut monuments and detailed material studies in the laboratory. *In situ* investigation comprises:

- description and classification of lithotypes according to color, grain size, bedding structures, stratigraphy
- description of monuments considering position, orientation, dimension, architecture, use, environment
- monument mapping considering lithology, weathering forms, joints
- measurements concerning the profile of stone tooling patterns, weathering profiles, water uptake, climate/microclimate, environment
- sampling
- detailed photo documentation

Methodology, results and interpretation of monument mapping are presented in the following.

Classification and Mapping of Weathering Forms

Weathering forms on stone monuments represent visible results of weathering processes which are initiated and controlled by interacting weathering factors. By means of weathering forms, the weathering state of stone surfaces can be described according to phenomenological criteria. The scale of visible deterioration on historical stone monuments has been classified by Viles *et al.* (1997) as follows:

- microscale (cm or less)
- mesoscale (cm to m)
- macroscale (whole façades, entire monuments)

The term "weathering forms" is used for visible stone deterioration at mesoscale. The monument mapping method has been developed by the working group "Natural stones and weathering" as a non-destructive procedure for the precise registration, documentation, evaluation and rating of weathering forms (e.g. Fitzner and Heinrichs 1998b). Monument mapping can be applied to all stone types and to to all types of stone monuments. The mapping method meets international acceptance and is approved as a well-tried method contributing essentially to:

- the improvement of scientific knowledge of stone weathering of monuments
- the establishment of a well-founded damage diagnosis of stone monuments
- deciding on economic and effective monument preservation measures.

By means of monument mapping, all weathering forms of monument surfaces are registered and documented exactly according to type, intensity and distribution.

An objective description, registration and documentation of weathering forms requires a classification scheme of weathering forms. A standard classification scheme has been established, based on investigations done at numerous monuments worldwide and considering different stone types and environmental influences (Fitzner, Heinrichs and Kownatzki 1995). This classification scheme has been developed for monuments constructed with quarried stone blocks. However, it can be also used for rock carved monuments, as practical experience in Petra has shown.

In Table 1 (1.1 - 1.4) items of the classification scheme that are relevant for the Petra rock monuments are presented with definitions, symbols and intensity classification of the weathering forms. Compared to the standard classification scheme presented in Fitzner, Heinrichs and Kownatzki (1995) some of the weathering forms have been redfined to become more specific or comprehensive for the sake of characterizing the weathering state of the Petra rock monuments. Table 1 (1.1-1.4) illustrates the hierarchical structure of the classification scheme which includes four different levels. A distinction is made between three groups of weathering forms in the uppermost level (I):

- Group 1 - loss of stone material
- Group 2 - deposits
- Group 3 - detachment

In level II, each group is subdivided into *main weathering forms,* and in level III, several main weathering forms are further subdivided into *individual weathering forms.* Individual weathering forms can be further differentiated according to intensities (level IV). The intensity classification is a result of the field-survey conducted at the Petra rock monuments. Symbols are proposed for recording weathering forms in documents and for computer supported processing of information. Symbols in level IV of the classification scheme are composed of letters for weathering forms and numbers for intensities.

In mapping the monuments of Petra, the

Table 1.1. Classification of weathering forms; Group 1 of weathering forms “Loss of stone material”.

LEVEL I
GROUP 1 OF WEATHERING FORMS: „LOSS OF STONE MATERIAL“

LEVEL II		LEVEL III		LEVEL IV	
MAIN WEATHERING FORM	SYMBOL	INDIVIDUAL WEATHERING FORM	SYMBOL	CLASSIFICATION OF INTENSITIES	SYMBOLS
Back weathering Uniform loss of stone material parallel to the original stone surface (uniform recession of stone surface).	**W**	***Back weathering due to loss of scales*** Uniform loss of stone material parallel to the stone surface due to falling down of scales.	**sW**	**Criterion: depth of back weathering (cm)** **Intensity 1:** < 1 cm **Intensity 2:** 1 – 5 cm **Intensity 3:** 5 – 10 cm **Intensity 4:** 10 – 25 cm **Intensity 5:** > 25 cm	**sW1, sW2, sW3, sW4, sW5**
		Back weathering due to loss of stone elements dependent on stone structure Uniform loss of stone material parallel to the stone surface due to falling down of stone elements dependent on stone structure.	**xW**		**xW1, xW2, xW3, xW4, xW5**
		Back weathering due to loss of undefinable stone elements Uniform loss of stone material parallel to the stone surface due to falling down of stone material. Type of preceded detachment of stone material can not be characterized.	**zW**		**zW1, zW2, zW3, zW4, zW5**
Relief Morphological change of the stone surface due to partial or selective weathering (non-uniform recession of stone surface).	**R**	***Rounding / notching*** Relief by rounding of edges or notchiung/hollowing out. Concave and/or convex soft morphological forms.	**Ro**	**Criterion: depth of relief (cm)** **Intensity 1:** < 1 cm **Intensity 2:** 1 – 5 cm **Intensity 3:** 5 – 10 cm **Intensity 4:** 10 – 25 cm **Intensity 5:** > 25 cm	**Ro1, Ro2, Ro3, Ro4, Ro5**
		Alveolar weathering Relief in the form of closely-spaced alveolae. Form comparable to honeycombs („honeycomb weathering“).	**Ra**		**Ra1, Ra2, Ra3, Ra4, Ra5**
		Relief dependent on stone structure Relief dependent on structural features such as bedding, foliation, banding etc. Frequently striped patterns.	**tR**		**tR1, tR2, tR3, tR4, tR5**
		Weathering out of stone components Relief due to selective weathering of stone components being susceptible to weathering (e.g. clay lentils) or due to loss of compact stone elements (e.g. pebbles). Hole-shaped forms.	**Rk**		**Rk1, Rk2, Rk3, Rk4, Rk5**
		Clearing out of stone components Relief in the form of protruding stone elements due to weathering of stone material around being more susceptible to weathering.	**Rh**		**Rh1, Rh2, Rh3, Rh4, Rh5**
Break out Loss of compact stone elements.	**O**	***Break out due to natural cause*** Loss of compact stone elements due to natural causes like wedge-work of roots, intersection of fractures/joints etc..	**nO**	**Criterion: volume of stone elements broken out (dm^3)** **Intensity 1:** < 1 dm^3 **Intensity 2:** 1 – 5 dm^3 **Intensity 3:** 5 – 10 dm^3 **Intensity 4:** 10 – 50 dm^3 **Intensity 5:** 50 – 100 dm^3 **Intensity 6:** > 100 dm^3	**nO1, nO2, nO3, nO4, nO5, nO6**
		Break out due to non-recognizable cause Loss of compact stone elements. Cause of break out can not be characterized.	**oO**		**oO1, oO2, oO3, oO4, oO5, oO6**

Table 1.2. Classification of weathering forms; Group 2 of weathering forms "Deposits".

LEVEL I
GROUP 2 OF WEATHERING FORMS: „DEPOSITS"

LEVEL II		**LEVEL III**		**LEVEL IV**	
MAIN WEATHERING FORM	**SYMBOL**	**INDIVIDUAL WEATHERING FORM**	**SYMBOL**	**CLASSIFICATION OF INTENSITIES**	**SYMBOLS**
Soiling Poorely adhesive deposits of dust, soil or mud particles from the air or from surface or bottom water on the stone surface.			**I**	**no differentiation of intensities**	**I**
Loose salt deposits Poorely adhesive deposits of salt aggregates.	**E**	***Efflorescences*** Poorely adhesive deposits of salt aggregates on the stone surface.	**Ee**	**Criterion: mass of salt deposits** **Intensity 1:** low **Intensity 2:** high	**Ee1, Ee2**
		Subflorescences Poorely adhesive deposits of salt aggregates below the stone surface.	**Ef**		**Ef1, Ef2**
Crust Firmly adhesive deposits on the stone surface.	**C**	***Dark-colored crust tracing the surface*** Firmly adhesive, grey to black deposits tracing the morphology of the stone surface. Here: thin soot crusts (anthropogenically).	**dkC**	**Criterion: degree of blacking** **Intensity 1:** low **Intensity 2:** high	**dkC1, dkC2**
		Dark-colored crust changing the surface Firmly adhesive, grey to black deposits changing the morphology of the stone surface. Here: thicker soot crusts (anthropogenically).	**diC**	**Criterion: thickness of crust** **Intensity 1:** low **Intensity 2:** high	**diC1, diC2**
		Light-colored crust tracing the surface Firmly adhesive, light-colored deposits tracing the morphology of the stone surface. Here: thin salt crusts.	**hkC**	**Criterion: degree of surface covering** **Intensity 1:** low **Intensity 2:** high	**hkC1, hkC2**
		Light-colored crust changing the surface Firmly adhesive, light-colored deposits changing the morphology of the stone surface. Here: thicker salt crusts.	**hiC**	**Criterion: thickness of crust** **Intensity 1:** low **Intensity 2:** high	**hiC1, hiC2**
		Colored crust tracing the surface Firmly adhesive, colored deposits tracing the morphology of the stone surface. Here: thin brown crusts (clay particles, carbonate particles, ferritic particles etc.).	**fkC**	**Criterion: degree of surface covering** **Intensity 1:** low **Intensity 2:** high	**fkC1, fkC2**
		Colored crust changing the surface Firmly adhesive, colored deposits changing the morphology of the stone surface. Here: thicker brown crusts (clay particles, carbonate particles, ferritic particles etc.).	**fiC**	**Criterion: thickness of crust** **Intensity 1:** low **Intensity 2:** high	**fiC1, fiC2**
Biological colonization Colonization by microorganisms or higher plants.	**B**	***Microbiological colonization*** Colonization by microorganisms (e.g. algae, lichen).	**Bi**	**no differentiation of intensities**	**Bi**
		Colonization by higher plants	**Bh**		**Bh**
Loose salt deposits to crust Transitional form between **Loose salt deposits (E)** and **Crust (C)**.	**E-C**	***Efflorescences to light-colored crust tracing the stone surface (salt crust)*** Transitional form between ***Efflorescences (Ee)*** and ***Light-colored crust tracing the surface (hkC).***	**Ee-hkC**	**Criterion: degree of surface covering** **Intensity 1:** low **Intensity 2:** high	**Ee-hkC1, Ee-hkC2**

Table 1.3. Classification of weathering forms; Group 3 of weathering forms “Detachment”.

LEVEL I
GROUP 3 OF WEATHERING FORMS: „DETACHMENT“

LEVEL II		**LEVEL III**		**LEVEL IV**	
MAIN WEATHERING FORM	**SYMBOL**	**INDIVIDUAL WEATHERING FORM**	**SYMBOL**	**CLASSIFICATION OF INTENSITIES**	**SYMBOLS**
Granular disintegration Detachment of grainy stone particles, individual grains or grain aggregates.			**G**	**Criteria: mass of detaching stone material or depth of disintegration** **Intensity 1:** low **Intensity 2:** medium **Intensity 3:** high	**G1, G2, G3**
Crumbling Detachment of larger compact stone elements (crumbs).			**P**	**Criterion: mass/volume of detaching stone material** **Intensity 1:** low **Intensity 2:** medium **Intensity 3:** high	**P1, P2, P3**
Flaking Detachment of small, thin stone elements (flakes) parallel to the stone surface. Either detachment of only one layer of flakes or detachment of stacks of flakes.			**F**	**Criteria: mass of detaching stone material or depth of disintegration** **Intensity 1:** low **Intensity 2:** medium **Intensity 3:** high	**F1, F2, F3**
Contour scaling Detachment of larger, platy stone elements (scales) parallel to the stone surface, not following any stone structure.	**S**	***Scales due to tooling of the stone surface*** Detachment of mainly thin scales due to tooling of the stone surface by stonemason.	**qS**	**no differentiation of intensities**	**qS**
		Single scale Detachment of an individual scale.	**eS**	**Criterion: thickness (cm)** **Intensity 1:** < 0.5m **Intensity 2:** 0.5 – 1 cm **Intensity 3:** 1 – 2 cm **Intensity 4:** 2 – 5 cm **Intensity 5:** > 5 cm	**eS1, eS2, eS3, eS4, eS5**
		Multiple scales Detachment of a stack of scales.	**mS**		**mS1, mS2, mS3, mS4, mS5**
Detachment of stone elements dependent on stone structure Detachment of mainly larger stone elements following any stone structure (esp. bedding).	**X**	***Exfoliation*** Detachment of mainly larger stone elements following any stone structure. Stone elements detach parallel to stone surface.	**Xl**	**Criterion: thickness/mass of detaching stone elements** **Intensity 1:** low **Intensity 2:** high	**Xl1, Xl2**
		Splitting up Detachment of mainly larger stone elements following any stone structure. Stone elements detach not parallel to stone surface.	**Xv**	**Criteria: thickness/mass of detaching stone elements or closeness of splitting planes** **Intensity 1:** low **Intensity 2:** high	**Xv1, Xv2**
Detachment of crusts with stone material Detachment of crusts with stone material sticking to the crust.			**K**	**Criterion: mass of detaching material** **Intensity 1:** low **Intensity 2:** high	**K1, K2**

Table 1.4. Classification of weathering forms; Group 3 of weathering forms "Detachment" (continuation).

LEVEL I
GROUP 3 OF WEATHERING FORMS: „DETACHMENT" – (continuation)

LEVEL II		LEVEL III		LEVEL IV	
MAIN WEATHERING FORM	SYMBOL	INDIVIDUAL WEATHERING FORM	SYMBOL	CLASSIFICATION OF INTENSITIES	SYMBOLS
Granular disintegration to flaking Transitional form between **Granular disintegration (G)** and **Flaking (F)**..			**G-F**	**Criteria: mass of detaching stone material or depth of disintegration** **Intensity 1:** low **Intensity 2:** medium **Intensity 3:** high	**G-F1,** **G-F2,** **G-F3**
Flaking to contour scaling Transitional form between **Flaking (F)** and **Contour scaling (S).**			**F-S**	**Criterion: mass of detaching stone material** **Intensity 1:** low **Intensity 2:** medium **Intensity 3:** high	**F-S1,** **F-S2,** **F-S3**
Flaking to crumbling Transitional form between **Flaking (F)** and **Crumbling (P).**			**F-P**	**Criterion: mass of detaching stone material** **Intensity 1:** low **Intensity 2:** medium **Intensity 3:** high	**F-P1,** **F-P2,** **F-P3**
Granular disintegration to crumbling Transitional form between **Granular disintegration (G)** and **Crumbling (P).**			**G-P**	**Criterion: mass of detaching stone material** **Intensity 1:** low **Intensity 2:** medium **Intensity 3:** high	**G-P1,** **G-P2,** **G-P3**
Crumbling to contour scaling Transitional form between **Crumbling (P)** and **Contour scaling (S).**			**P-S**	**Criterion: mass/volume of detaching stone material** **Intensity 1:** low **Intensity 2:** medium **Intensity 3:** high	**P-S1,** **P-S2,** **P-S3**

level IV classification was applied. Plans of the monuments were prepared considering the original architecture. All occuring weathering forms and their intensities were mapped, and areas of different weathering forms or different intensities of weathering forms were delimitated on the plans. Lithological mapping and mapping of joints were made contemporaneously with mapping of the weathering forms. The classification of lithotypes and results of lithological mapping will be presented in a next publication.

Evaluation of Weathering Forms

A computer programme was tailored for optimal processing, illustration and evaluation of mapping information. The basic steps of processing are:

- digitizing monument plans with delimitations of distinct areas (*basic plan*)
- numbering and planimetric evaluation of all areas (*basic list*)
- integration of mapping information by means of symbols (*information list*)

Table 2 shows a section of an information list. The basic plan and information list represent the basis for mapping and for quantitative evaluations. Maps based on groups of weathering forms have turned out to be very suitable for the Petra monuments. Examples are presented for Tomb No. 70 located in the Outer as-Sīq (Fig. 1). Figures 2-4

Table 2. Information list; example (section).

Number of area	Size (pixel)*	Lithotype	Weathering forms and its intensities
.	.	.	.
.	.	.	.
200	5932	mIN-m-fSd	sW2 F-S2 G1 fkC1 I Ee-hkC1
201	12700	mIN-m-fSd	Ro2 F-S2 fkC1 I
202	21288	mIN-m-fSd	zW2 G1 fkC1 I Ee-hkC1
203	700	mIN-m-fSd	Ro1 eS4 G2 I
204	7160	mIN-m-fSd	Ro3 F-S2 fkC1 I Ee-hkC1
205	5693	mIN-m-fSd	Ro2 F-S2 fkC1 I Ee-hkC1
206	362	mIN-m-fSd	Ro2 G2 I
207	3228	mIN-m-fSd	Ro2 F-S2 fkC1 I
208	5408	mIN-m-fSd	Ro2 F-S3 fkC1 I
209	26821	mIN-m/r-fSd	Ro3 G1 fkC1 I Ee1
210	9987	mIN-m/r-fSd	Ro3 G2 I Ee1
211	20027	mIN-m/r-fSd	Ro3 fkC1 I G1 Ee1
212	33139	mIN-m/r-fSd	Ro2 fkC1 I G-F1 Ee-hkC1
213	2378	mIN-m/y-fSd	Ro3 G2 I Ee1
214	465	mIN-m/y-fSd	Ro2 G1 fkC1 I Ee1
215	653	mIN-m/y-fSd	Ro2 G1 fkC1 I Ee1
.	.	.	.
.	.	.	.

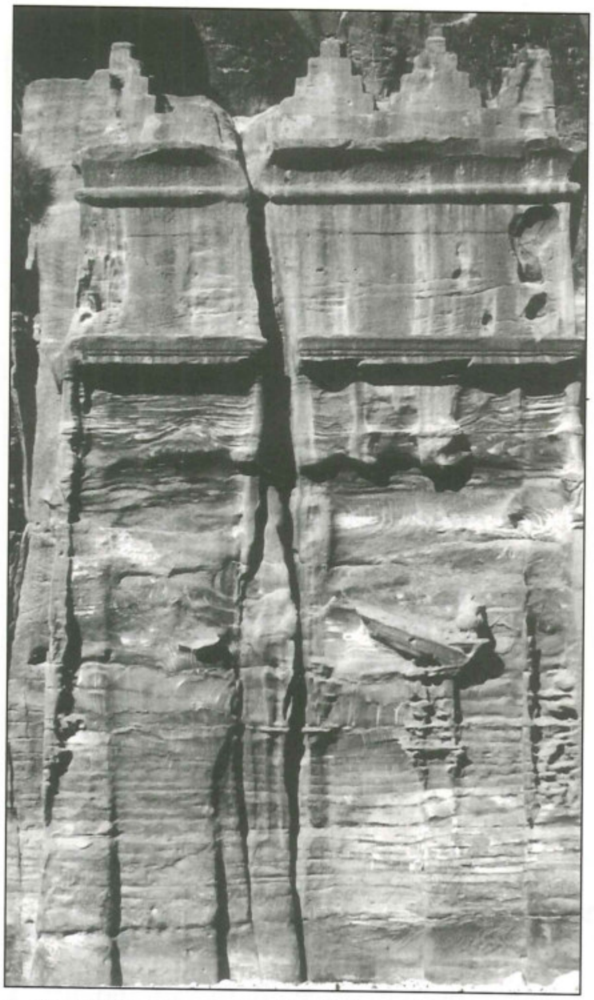
* Area in m^2 can be calculated considering scale of monument plan.

show maps down for the east façade of Tomb No. 70 which consider weathering forms of the three groups: "loss of stone material" (Fig. 2), "deposits" (Fig. 3) and "detachment" (Fig. 4). Maps like these were prepared for more than twenty monuments. The maps can be considered as "layers", which together provide information on all existing weathering forms. By means of such maps, all weathering forms can be exactly located. Furthermore, they reveal zones of weathering forms, which can be indicators for the type or intensity of weathering processes and environmental impacts.

Computer supported processing of mapping information facilitates quick and reliable quantitative evaluation of weathering forms (Fig. 5). The comparison of mapping results enhances the information about the influence of lithotypes and monument characteristics like location, orientation and geometry, on the susceptibility of monument surfaces to weathering.

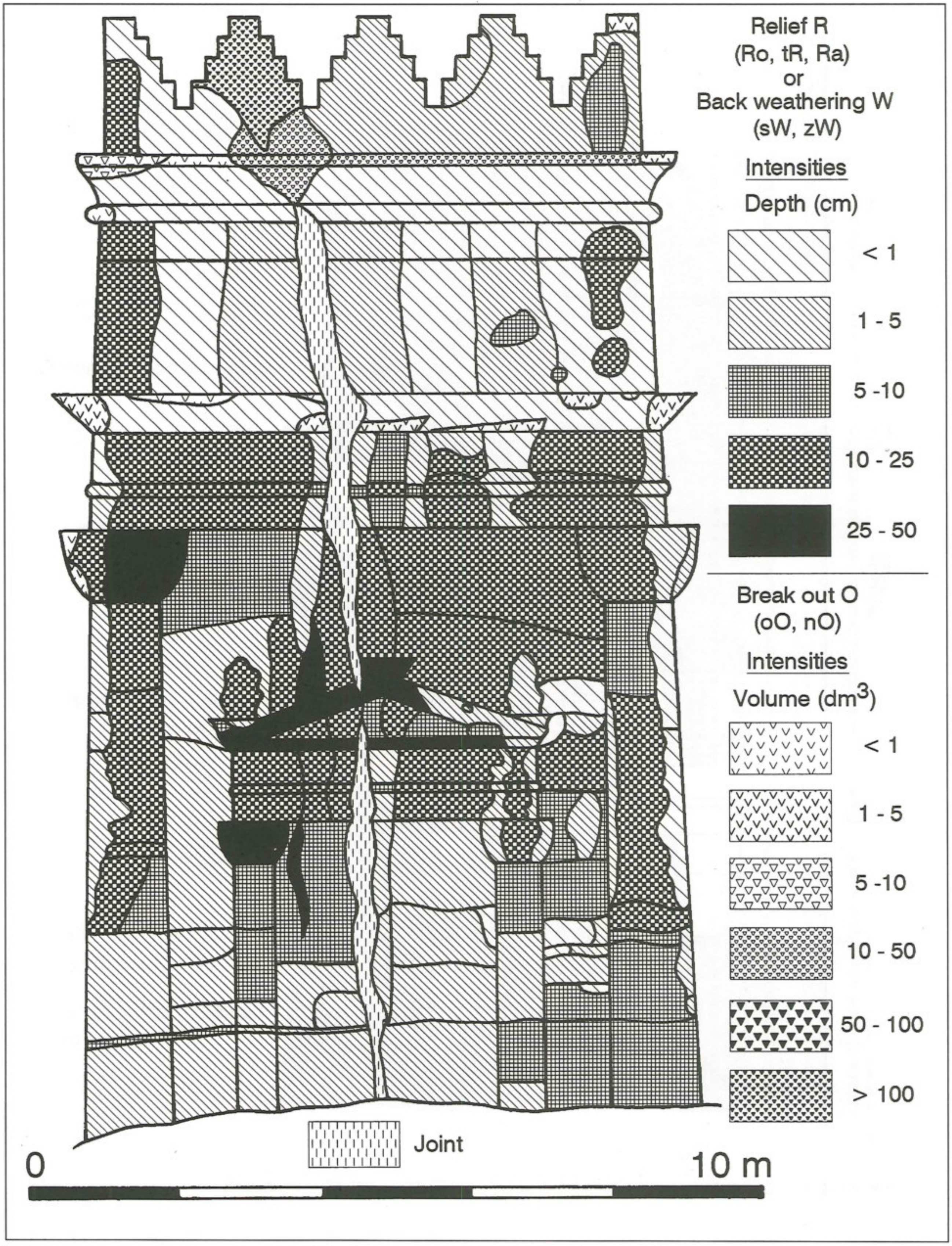
Assessment of Weathering Progression

Mapping and quantification of weathering forms characterized by the "loss of stone material" allow the calculation of average weathering rates (Fig. 6). Average weathering rates contribute to reliable weathering prognoses only in a limited way, because they assume linear weathering progression. Supplementary information is needed. Interrelations and successions of weathering forms have been evaluated additionally for the assessment of weathering progression. Statistical evaluation has been made referring to the interrelation between "loss of stone material", "detachment" and "deposits". In Figure 7 (a and b) the relation between loss of stone material and detachment of stone material is shown for the fine-

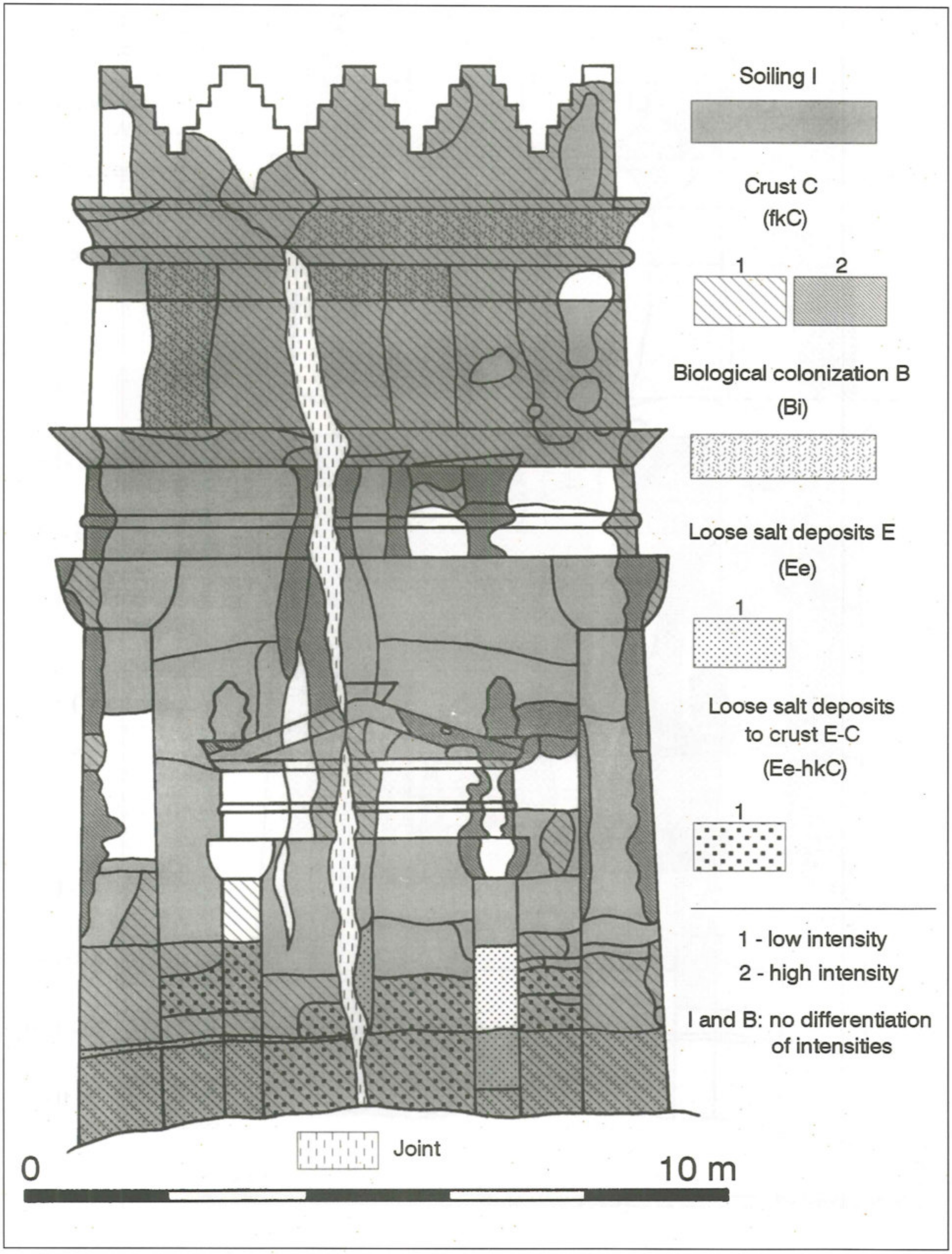


1. Tomb No. 70-east façade; Outer as-Sīq.

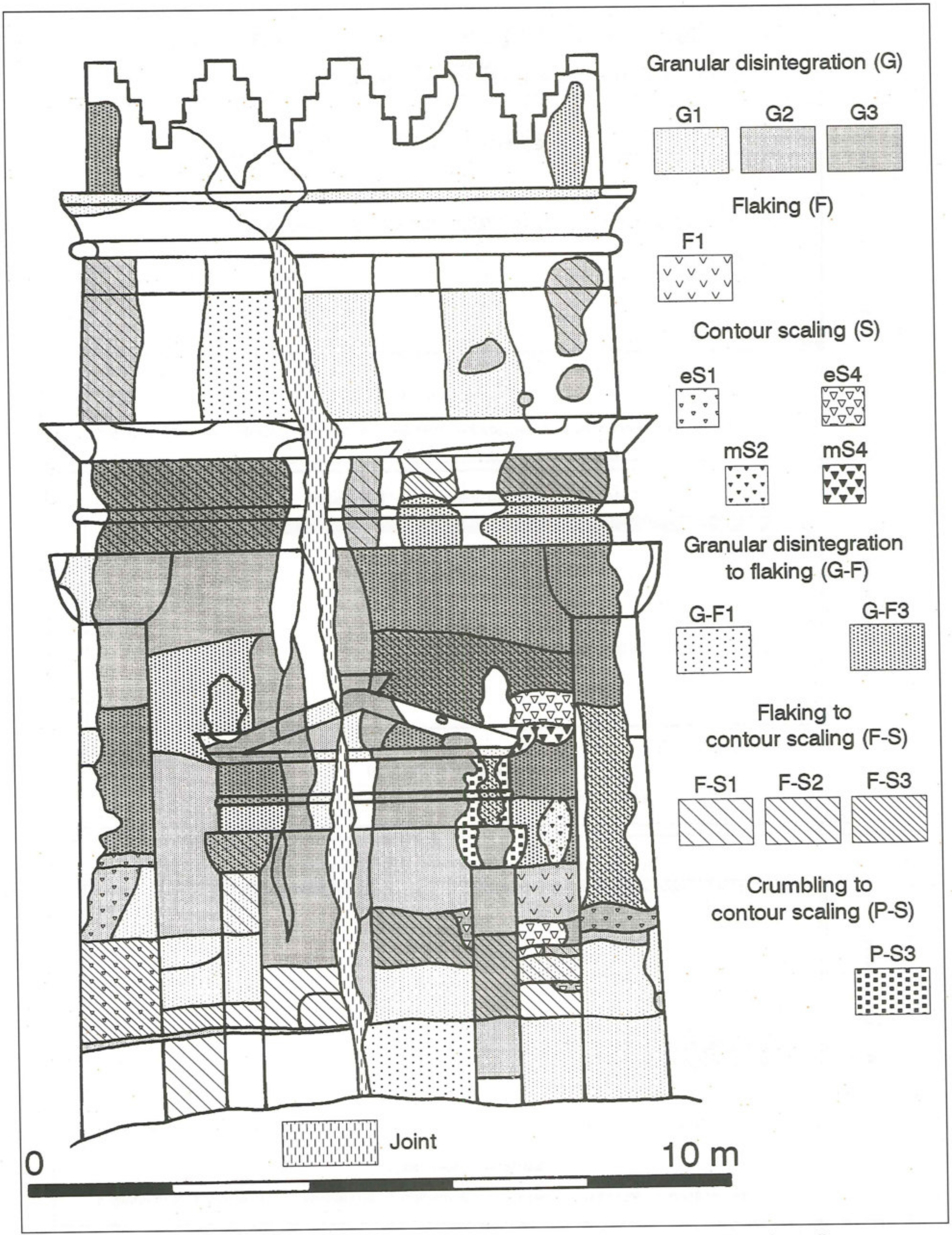
grained lithotypes of the Umm Ishrin Sandstone Formation and the coarser ad-Dīsī Sandstone Formation. The four very frequent weathering forms characterizing present detachment are: contour scaling, flaking to contour scaling, granular disintegration to flaking, and granular disintegration. The order of listing of these weathering forms corresponds to the decreasing size of detaching stone elements. The increasing loss of stone material corresponds to the decreasing size of detaching stone elements from larger sized elements (contour scaling) via medium-sized and small-sized stone elements (flaking to contour scaling, granular disintegration to flaking) to smallest-sized elements (granular disintegration). Comparison of the two lithological units reflects the influence of stone type on the succession of weathering forms. In case of the ad-Dīsī sandstone transitions from larger sized detaching stone elements to smaller sized detaching stone elements occur earlier. A less compact fabric of this lithotype can be inferred. The intensity of stone detachment has been additionally considered as a key parameter for characterizing interrelations between loss of stone material and detachment of stone material. Here, a correlation between frequency and intensity of stone detachment was found. An increasing loss of stone material corresponds to a decreasing frequency of contour scaling and decreasing thickness of scales. Frequency and intensity of granular disintegration increase at the same time (Fig. 8). Interrelations between the loss of stone material and deposits enhances information for assessing the weathering progression. An increasing loss of stone material corresponds to a decreasing frequency of soiling and biological colonization and to a decreasing frequency and intensity of crust formation, in particular, the formation of a colored crust tracing the stone surface (Fig. 9 a and b). Observations indicate that the formation of this type of crust mainly results from the deposition and consolidation of carbonatic and clayish particles from the environment due to wind and rain water. The weathering forms "soiling" and "colored crust tracing the surface" differ only in the consolidation of particles and in the degree of adhesion to the stone surface. The formation of colored crust tracing the stone surface is preceded by soiling. This finding is of vital importance for characterizing weathering progression. Soiling and crust formation need a stable stone surface for a certain period. The period increases from soiling to crust formation. The following interrelations between detachment of stone material and deposits can be derived. The succession of the weathering forms: contour scaling, flaking to contour scaling, granular disintegration to flaking and final granular disinte-



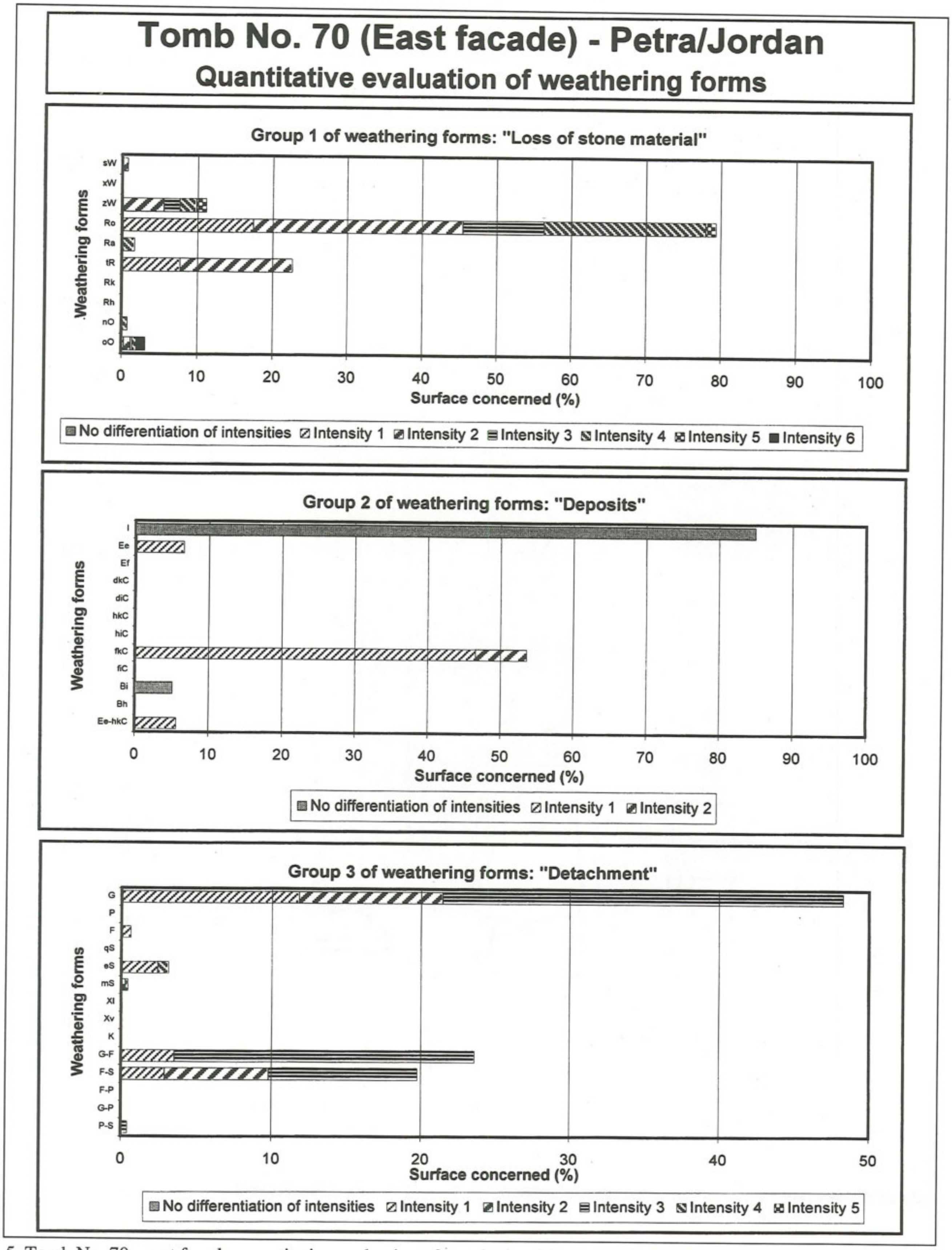
2. Tomb No. 70 - east façade; mapping of weathering forms; group of weathering forms: "Loss of stone material".



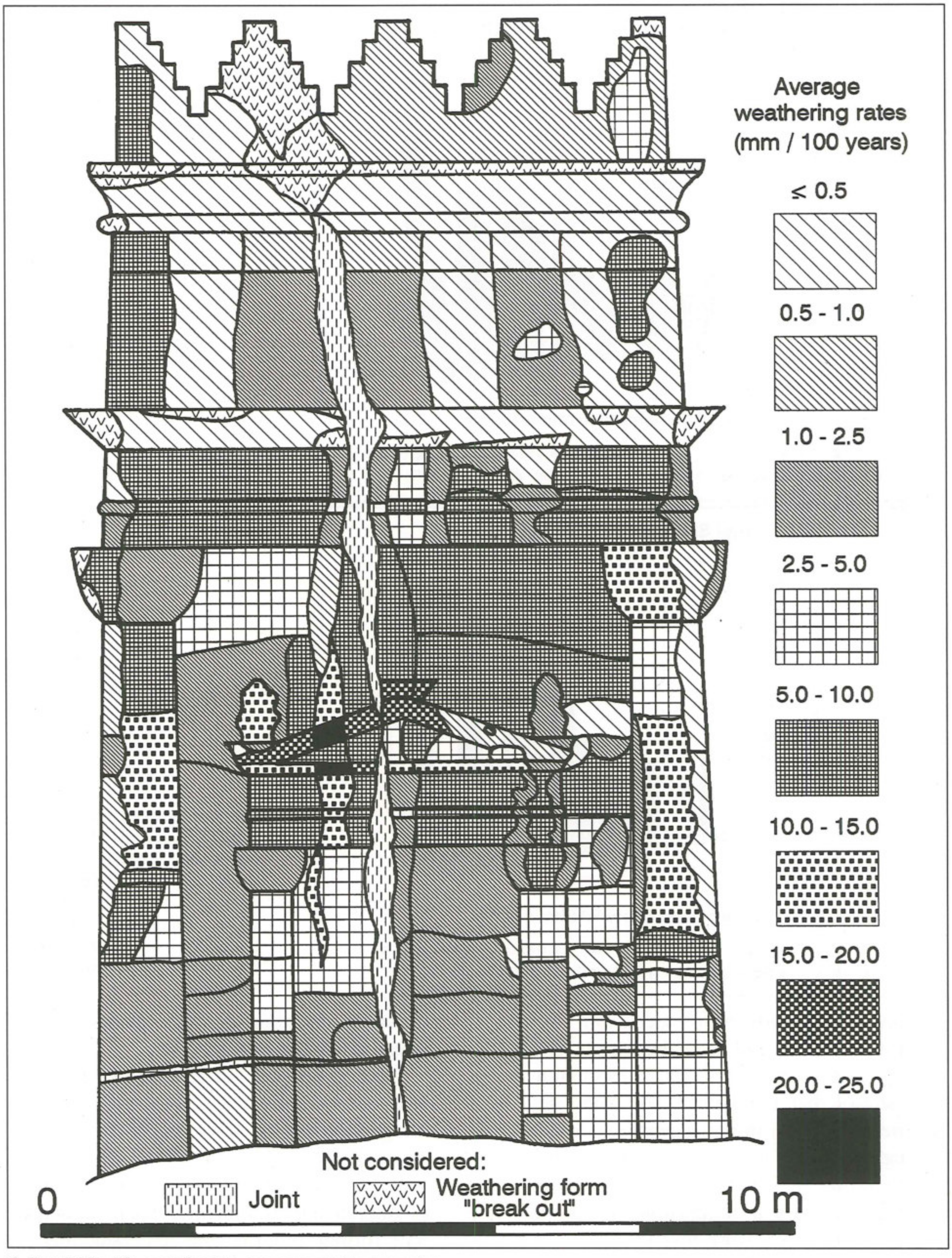
3. Tomb No. 70 - east façade; mapping of weathering forms; group of weathering forms: "Deposits".



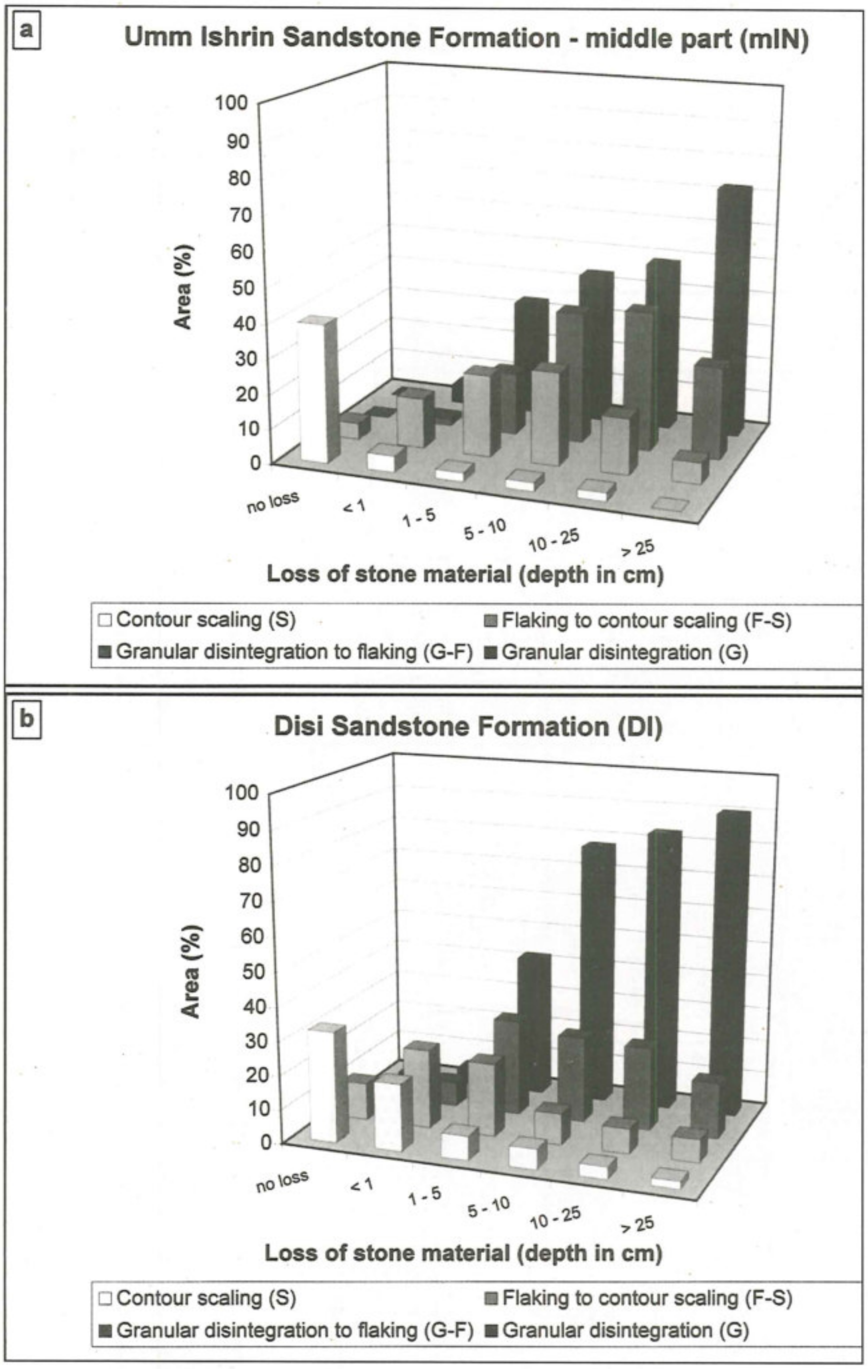
4. Tomb No. 70 - east façade; mapping of weathering forms; group of weathering forms: "Detachment".



5. Tomb No. 70 - east façade; quantitative evaluation of weathering forms.



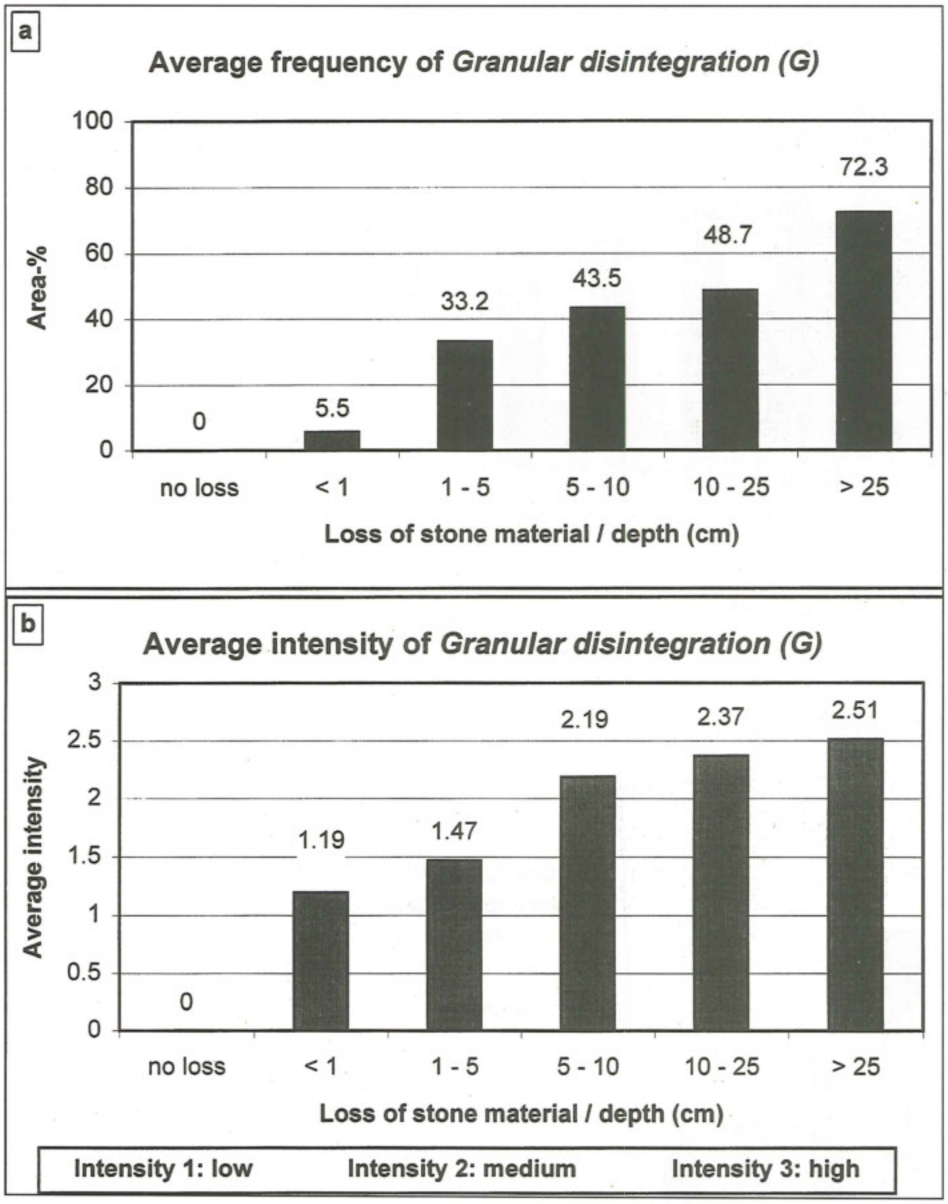
6. Tomb No. 70 - east façade; average weathering rates.



7:a,b. Relation between loss of stone material (considered weathering forms: relief/R and back weathering/W) and detachment of stone material (S, F-S, G-F, G); a - Umm Ishrin Sandstone Formation / middle part (mIN); b - ad-Dīsī Sandstone Formation (DI).

gration, corresponds to a decreasing frequency in soiling and to a decreasing frequency and intensity of crust formation. This shows that the velocity of stone detachment increases in the sequence: contour scaling, flaking to contour scaling, granular disintegration to flaking and final granular disintegration. As a conclusion, it can be stated that the increasing loss of stone material correlates with an increasing velocity of stone detachment. This shows a non-linear weathering progression.

The discussed interrelations between weathering forms and assessment of weathering progression have considered entire monuments and main litho-stratigraphic units. Consideration of characteristic parts of monuments and all individual lithotypes will further promote the understanding of weathering progression. Weathering prog-



8: a,b. Relation between loss of stone material (considered weathering forms: relief / R and back weathering/W) and granular disintegration (G). Umm Ishrin Sandstone Formation/middle part (mIN); a-Average frequency; b-Average intensity.

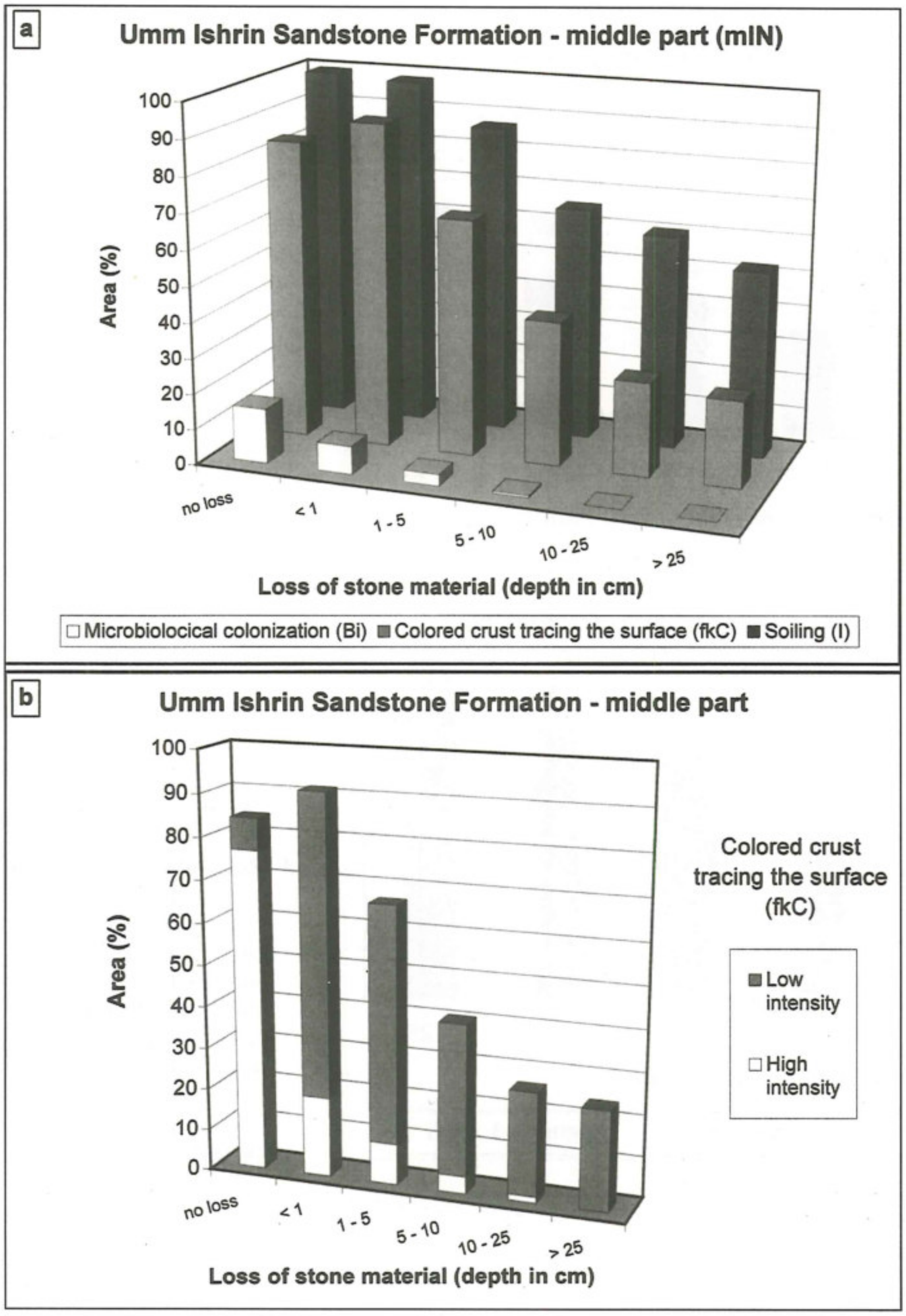
nosis will become an important part of the "life cycle" analysis of monuments.

Rating of Weathering - Damage Categories; Damage index

Weathering forms allow precise description and mapping of the state of weathering. The rating of damages is necessary for all kinds of preservation measures and interventions. For this issue, damage categories and damage indices have been established (Fig. 10). Six damage categories have been defined:

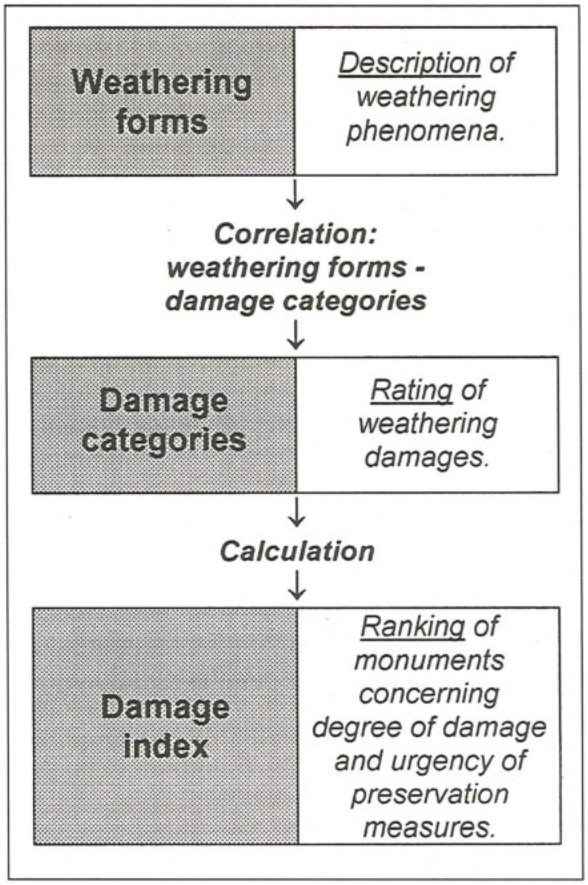
0- no visible damages
1- very slight damages
2- slight damages
3- moderate damages
4- severe damages
5- very severe damages

A scheme, which relates weathering forms to damage categories has been defined for the Petra rock monuments considering all intensities of the weathering forms (Table 3). All weathering forms included within the groups, "loss of stone material" and "detachment", have been taken into account. All weathering forms are transformed into damage categories. Dam-



9:a,b. Relation between loss of stone material (considered weathering forms: relief/R and back weathering/W) and deposits. Umm Ishrin Sandstone Formation / middle part (mIN); a - Deposits: Bi, fkC, I; b - Deposit: fkC.

age categories are derived seperately for "loss of stone material" and "detachment". The highest damage categories for "loss of stone material" and "detachment" are jointly considered for determining the final damage category (Fig. 11). Table 4 shows an information list with the number of areas delimitated at a monument surface, weathering forms describing "loss of stone material" and "detachment", damage categories for "loss of stone material" and "detachment" and determination of the final damage categories. Damage categories can be illustrated in maps and can be evaluated quantitatively. In Figures 12-17, examples are presented for Tombs No. 70, No. 239 (Roman Soldier Tomb), No. 649 (Tomb with the Armour), No. 770 (Silk Tomb), No. 765 (Palace Tomb) and No. 462 (Monastery). The same evaluations are available



10. Weathering forms, damage categories and damage index.

for other monuments. Damage categories do not only serve as a comparative rating of damages. Locations of susceptible parts of monument surfaces are lined out, and the influence of monument characteristics like orientation and geometry can be quantified. Other influences may be inferred such as uncontrolled water run-off , rising humidity in combination with salt load or mechanical stress as a consequence of monument statics. This means that damage categories provide categories an important contribution for risk estimation and for well-targeted risk management. Thus, the urgency of intervention for monument preservation is indicated by damage categories.

Based on the quantitative evaluation of damage categories, linear damage index and progressive damage index can be calculated (Table 5). The linear damage index corresponds to the average damage category, whereas the progressive index emphasizes the proportion of higher damage categories (Table 6). Linear and progressive damage indices should always be considered in combination. Both damage indices range from 0 to 5.0. The following relation is deduced: progressive damage index ⩾ linear damage index.

Damage indices have been calculated for the conclusive rating of the damage state considering each monument as a whole. The comparison of monuments by means of damage indices allows ranking of monuments according to:

- state of damage
- susceptibility to deterioration
- urgency of intervention

For monuments with more than one facade, damage indices have been calculated individually for each façade. This facilitates the rating of a monument's exposure and rating the environmental impacts on façade orientation like insolation, wind, wetting/ drying and salt crystallization.

Figure 18 (a-d) shows a quantitative evaluation of damage categories for the four façades of Tomb No. 9. Significant differences can be recognized in the distribution of damage categories. Linear and progressive damage indices have been calculated for the different façades (Fig. 19 a). The damage indices reveal a significant influence of façade orientation on the susceptibility to deterioration. Comparable results have been derived for the two façades of Tomb No. 70 located in the Outer as-Sīq (Fig. 19 b). In Table 7, a quantitative evaluation of damage categories as well as linear and progressive damage indices are presented for the Petra rock monuments. A ranking of the monuments is presented based on linear damage index (Fig. 20 a) and progressive damage index (Fig. 20 b). A significant range of damage indices can be recognized. An increase of damage indices corresponds to an increasing urgency for intervention.

Table 3. Weathering forms related to damage categories.

▨ *Intensities of weathering forms* ☐ **Damage categories**

GROUP OF WEATHERING FORMS: LOSS OF STONE MATERIAL

Back weathering (W)	depth (cm)				
	< 1	1 – 5	5 - 10	10 – 25	> 25
Back weathering due to loss of scales (sW)	1	2	3	4	5
Back weathering due to loss of stone elements dependent on stone structure (xW)	1	2	3	4	5
Back weathering due to loss of undefinable stone elements (zW)	1	2	3	4	5

Relief (R)	depth (cm)				
	< 1	1 – 5	5 - 10	10 – 25	> 25
Rounding / notching (Ro)	1	2	3	4	5
Alveolar weathering (Ra)	1	2	3	4	5
Relief dependent on stone structure (tR)	1	2	3	4	5
Weathering out of stone components (Rk)	1	2	3	4	5
Clearing out of stone components (Rh)	1	2	3	4	5

Break out (O)	volume (dm^3)					
	< 1	1 – 5	5 – 10	10 - 50	50 - 100	> 100
Break out due to natural cause (nO)	2	3	4	5	5	5
Break out due to non-recognizable cause (oO)	2	3	4	5	5	5

GROUP OF WEATHERING FORMS: DETACHMENT

Granular disintegration (G)	low	medium	high
	1	2	3

Crumbling (P)	low	medium	high
	1	2	3

Flaking (F)	low	medium	high
	1	2	3

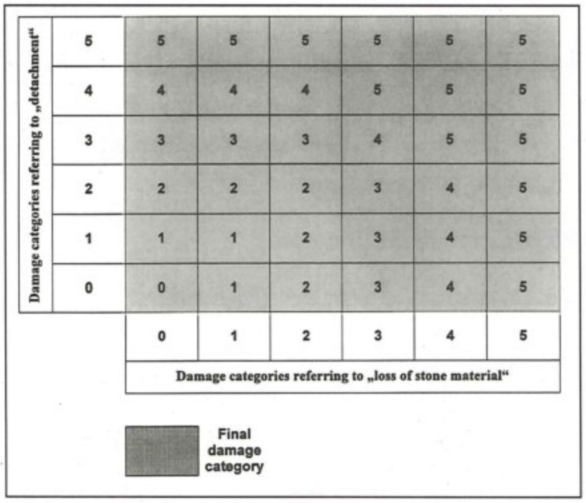
Contour scaling (S)	no differentiation
Scale due to tooling of stone surface (qS)	1

	thickness (cm)				
	< 0.5	0.5 - 1	1 - 2	2 – 5	> 5
Single scale (eS)	1	1	2	2	3
Multiple scales (mS)	1	1	2	2	3

Detachment of stone lelements dependent on stone structure (X)	low	high
Exfoliation (Xl)	2	3
Splitting up (Xv)	2	3

Detachment of crusts with stone material (K)	low	high
	1	2

	low	medium	high
Granular disintegration to flaking (G-F)	1	2	3
Flaking to contour scaling (F-S)	1	2	3
Flaking to crumbling (F-P)	1	2	3
Granular disintegr. to crumbling (G-P)	1	2	3
Crumbling to contour scaling (P-S)	2	3	4



Damage categories referring to „detachment“	5	5	5	5	5	5	5
	4	4	4	4	5	5	5
	3	3	3	3	4	5	5
	2	2	2	2	3	4	5
	1	1	1	2	3	4	5
	0	0	1	2	3	4	5
		0	1	2	3	4	5
		Damage categories referring to „loss of stone material“					

▨ **Final damage category**

11. Determination of final damage categories.

Conclusions

A comprehensive damage diagnosis is required as a basis for effective and economic monument preservation. Monument mapping has been established internationally as a scientific method contributing essentially to reliable damage diagnosis of stone monuments. The method has been applied successfully on numerous monuments worldwide. Within the framework of a research project 1996-1999, monument mapping has been executed at many rock monuments in Petra/Jordan. For the mapping of weathering forms, a detailed classification scheme has been developed with definitions of the weathering forms and intensity classification that essentially serves for the Petra rock monuments. Weathering forms serve for an objective and reproducible registration of weathering phenomena at monument surfaces. The evaluation of weathering forms improves scientific knowledge in stone weathering, contributing to an assessment of weathering progression as well as to deriving key factors of weathering. While weathering forms are of a descriptive character, damage categories have been established for the subsequent rating of damages. Damage categories facilitate risk estimation and risk management. Furthermore, they can reveal the intensity of environmental impacts on monument characteristics such as location, geometry or orientation. The damage index can be calculated from the proportion of damage categories for a conclusive rating of the state of damage, taking into consideration the entire monument. Comparing damage indices for different monuments, provides the possibility of ranking these monuments.

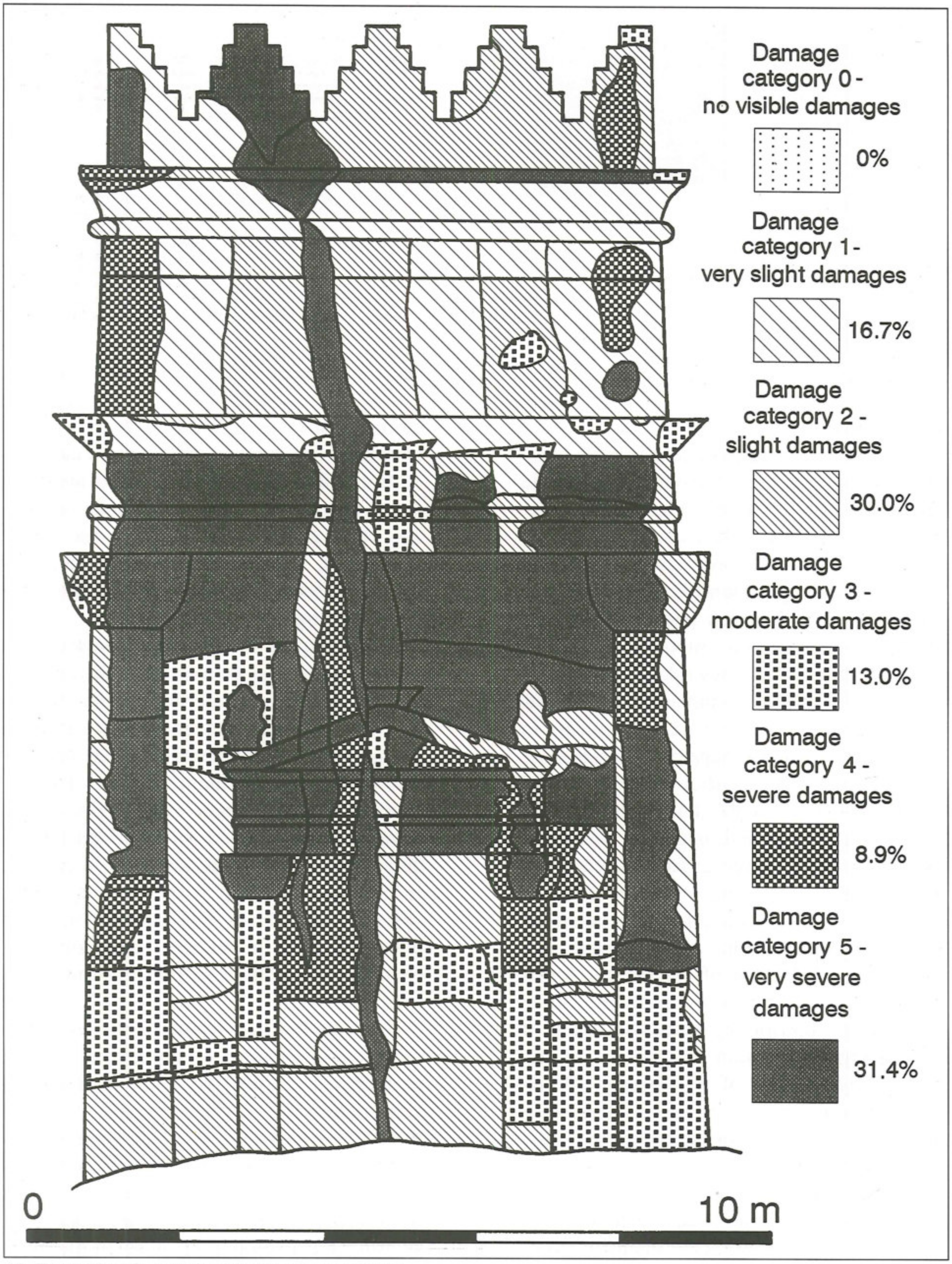
Table 4. Derivation of final damage categories - examples.

Monument surface - numbers of partial areas	Weathering forms – „*loss of stone material*“	Weathering forms – „*detachment of stone material*“	Damage categories – „*loss of stone material*“ *(DCL)*	Damage categories – „*detachment of stone material*„ *(DCD)*	Final damage category
.		.	.	.	.
.		.	.	.	.
200	sW2	F-S2	**DCL2***	**DCD2***	2
201	Ro2	F-S2	**DCL2**	**DCD2**	2
202	zW2 tR1	G1 eS3	**DCL2** *DCL1*	*DCD1* **DCD2**	2
203	Ro1	eS4 G1	**DCL1**	**DCD2** *DCD1*	2
204	Ro3	G-F2	**DCL3**	**DCD2**	3
205	Ro2	F-S2	**DCL2**	**DCD2**	2
206	Ro2 tR1	G1 F-S2	**DCL2** *DCL1*	*DCD1* **DCD2**	2
207	Ro5	G3 G-F1	**DCL5**	**DCD3** *DCD1*	5
208	Ra4	G3 G-F2	**DCL4**	**DCD3** *DCD2*	5
209	Ro3 tR2	G2 F-S1	**DCL3** *DCL2*	**DCD2** *DCD1*	3
210	Ro3	G1 G-F3	**DCL3**	*DCD1* **DCD3**	4
.	.	.	.	.	.
.	.	.	.	.	.

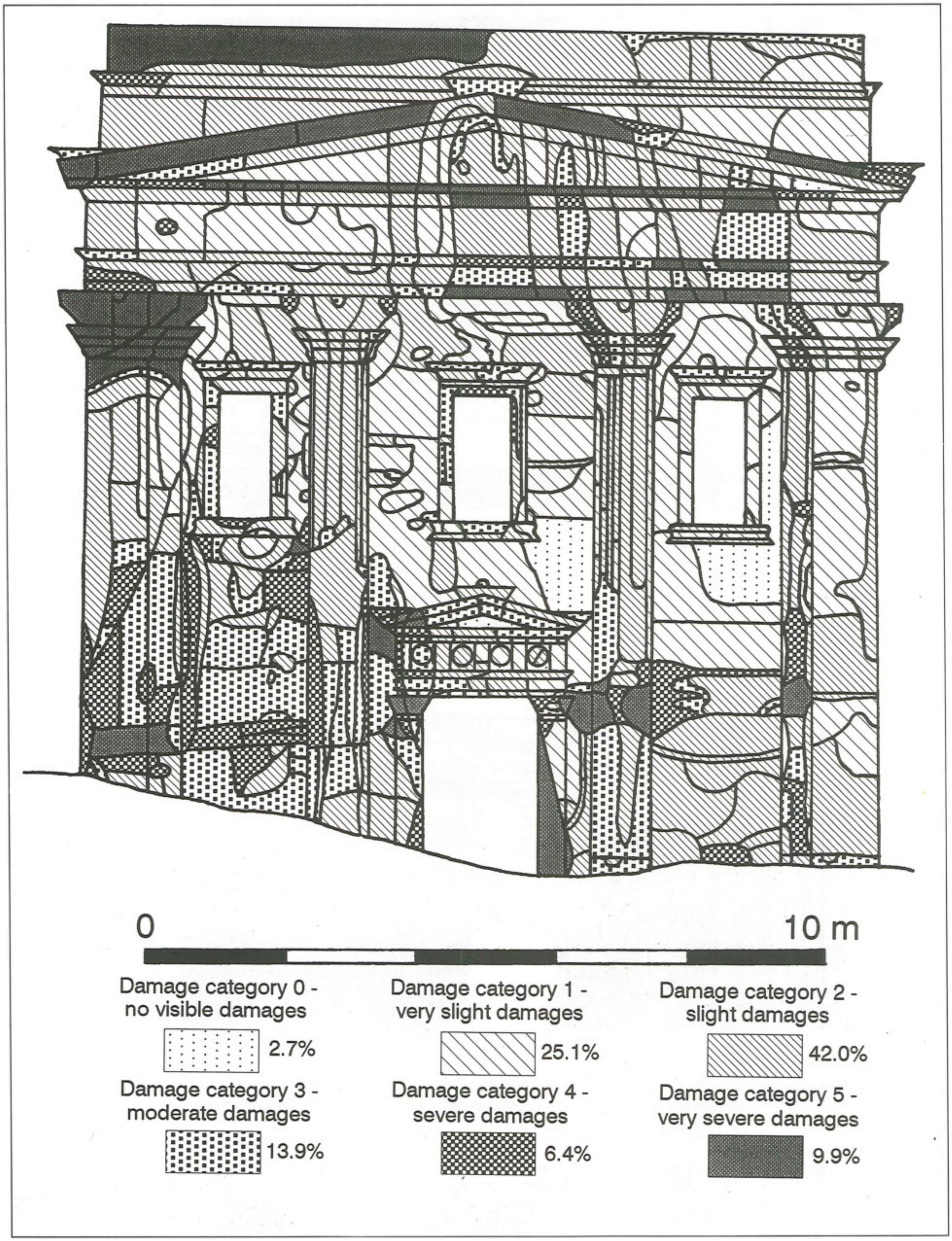
*** (damage categories marked with bold letters/numbers) – relevant for derivation of final damage categories.**

With respect to monument preservation activities, damage indices show the urgency of intervention, considering a monument as a whole. Damage categories also indicate the urgency of intervention, since they locate those parts of a monument on which intervention has to focus. Weathering forms have to be considered for the deduction of appropriate types of preservation measures. Information obtained from mapping represents an ideal basis for optimal long-term observation of monuments and for well-founded certification of preservation measures.

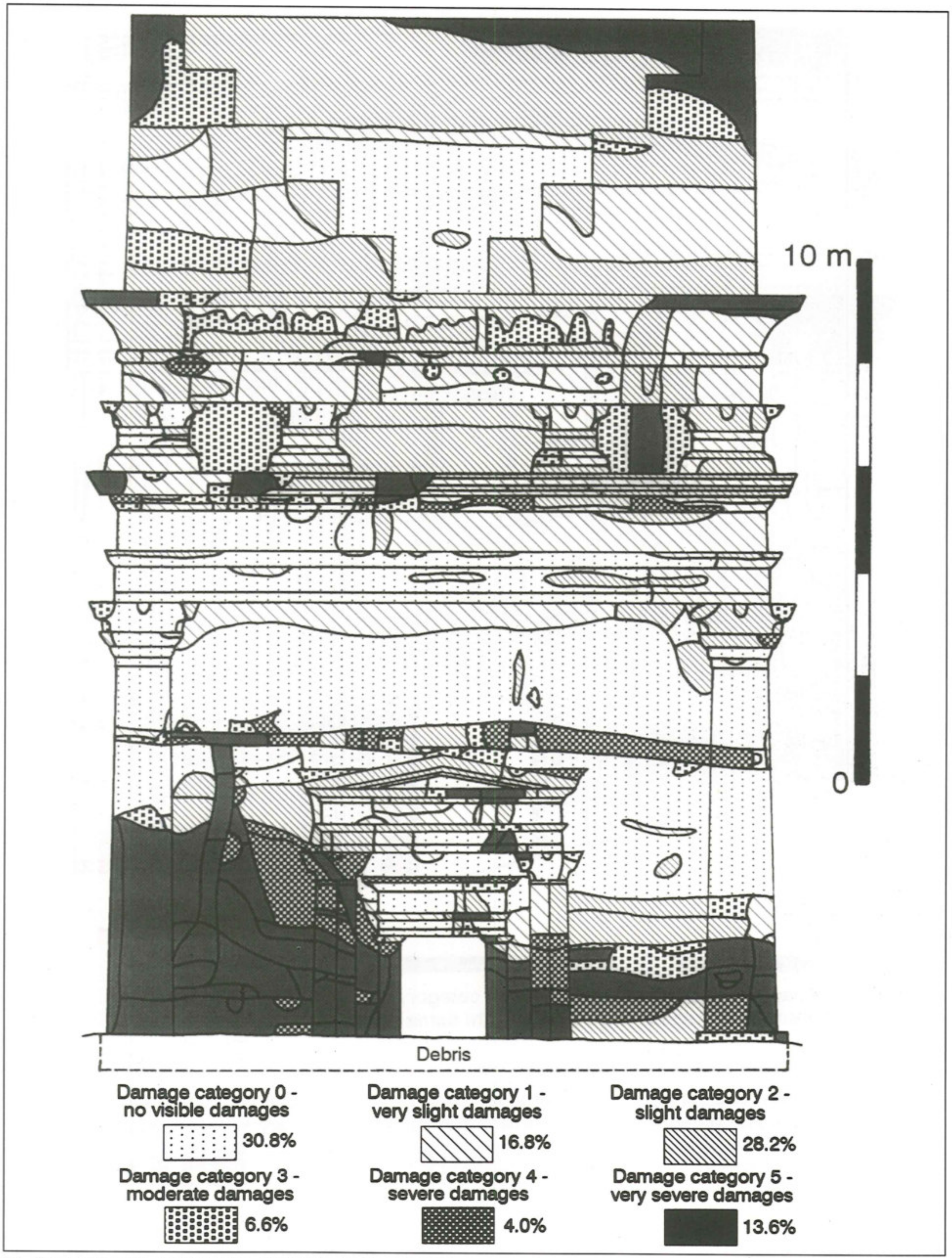
Presentation of results obtained from monument mapping of the Petra rock-cut monuments, as well as from additional in situ studies and laboratory analyses within the framework of the research project "Systematic registration and evaluation of weathering damages at monuments in Petra" will be continued in upcoming publications, considering the exploitation of scientific findings for practical monument preservation.



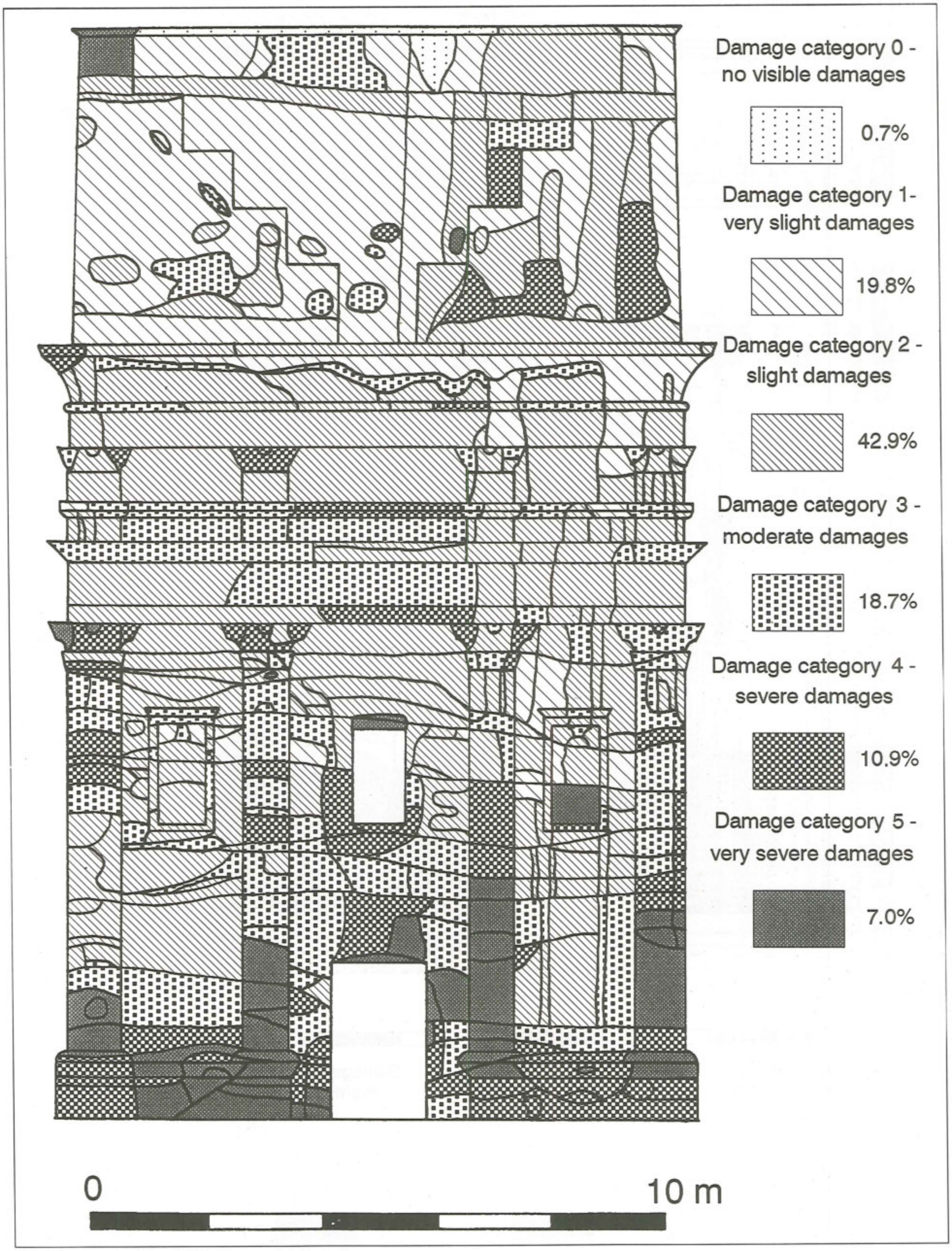
12. Tomb No. 70 - east façade; damage categories.



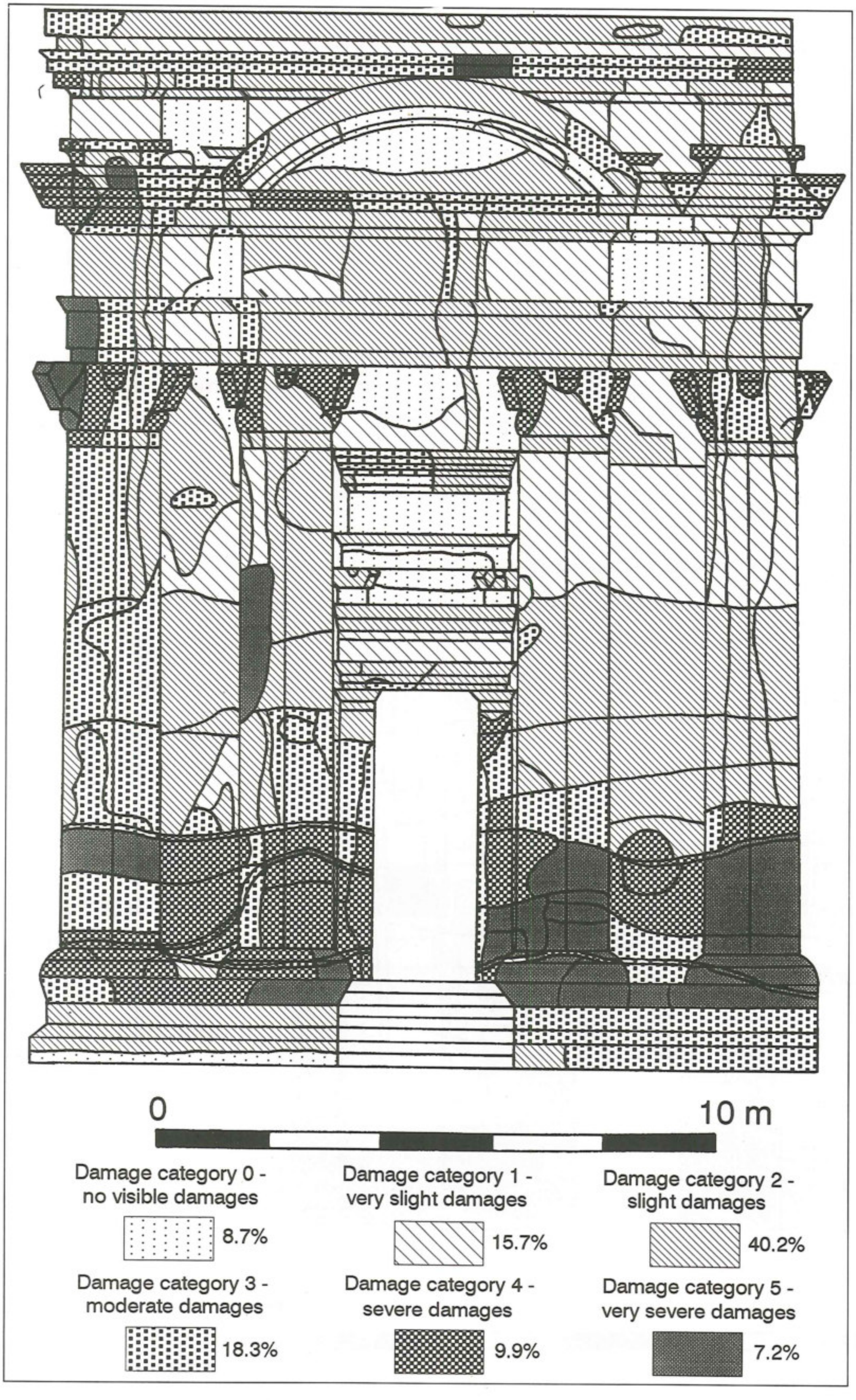
13. Tomb of the Roman Soldier (No. 239); damage categories.



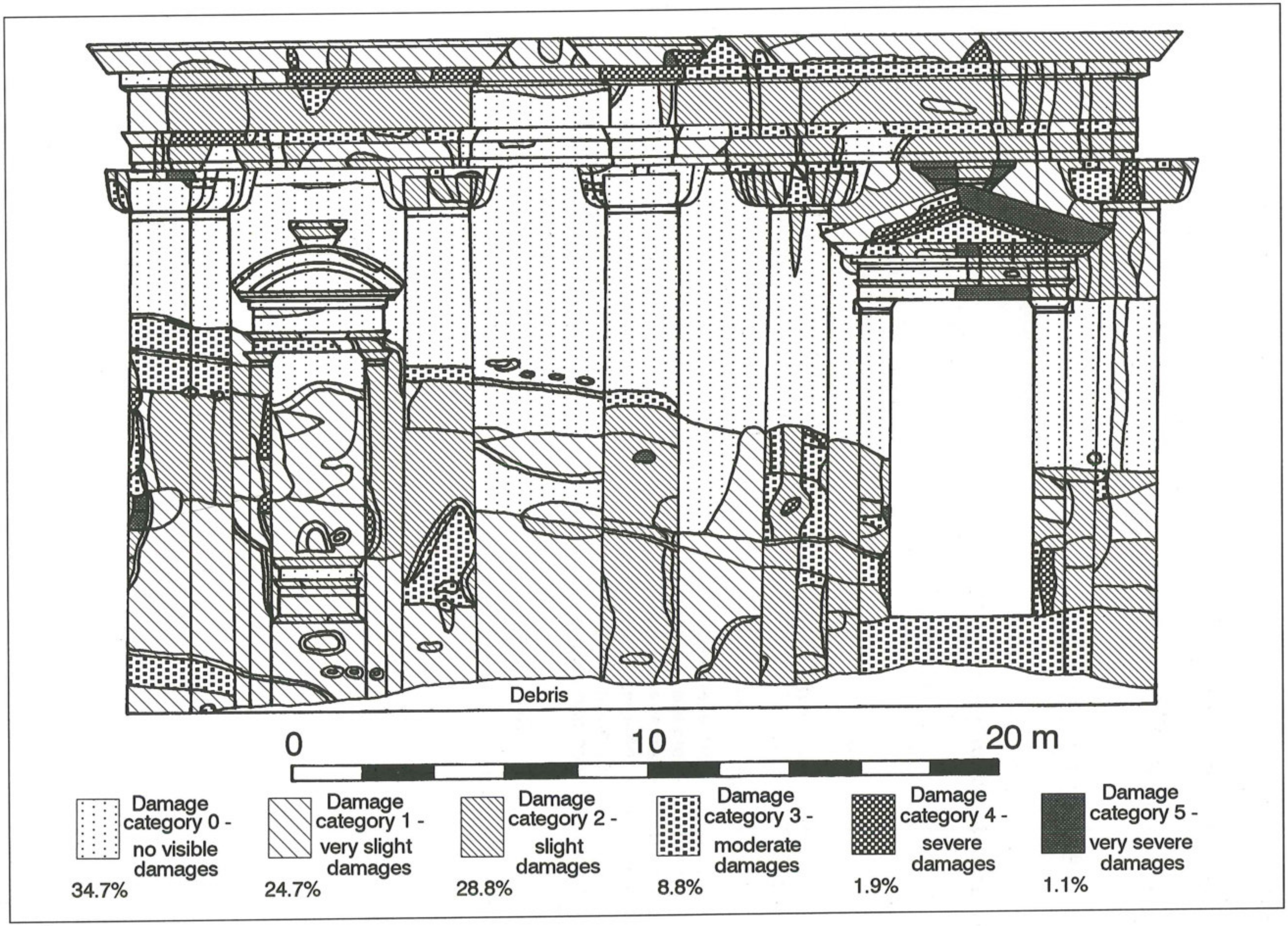
14. Tomb with the Armour (No. 649); damage categories.



15. Silk Tomb (No. 770); damage categories.



16. Palace Tomb (No. 765) - lower left part (A); damage categories.



17. Monastery (No. 462) - lower left part (A); damage categories.

Table 5. Linear and progressive damage index.

Linear damage index DI_{lin}:

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

$$\downarrow$$

$$\frac{B+(C\cdot 2)+(D\cdot 3)+(E\cdot 4)+(F\cdot 5)}{100}$$

Progressive damage index DI_{prog}:

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

$$\downarrow$$

$$\sqrt{\frac{B+(C\cdot 4)+(D\cdot 9)+(E\cdot 16)+(F\cdot 25)}{100}}$$

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

$$\sum_{A}^{F} = 100$$

Table 6. Linear and progressive damage index for different cases of damage category distribution.

Case	Damage categories (% of monument surface)						DI_{lin}	DI_{prog}
	0	1	2	3	4	5		
I	-	-	-	*100 %*	-	-	3.00	3.00
II	-	-	*50 %*	-	*50 %*	-	3.00	3.16
III	-	*50 %*	-	-	-	*50 %*	3.00	3.61
IV	*40 %*	-	-	-	-	*60 %*	3.00	3.87

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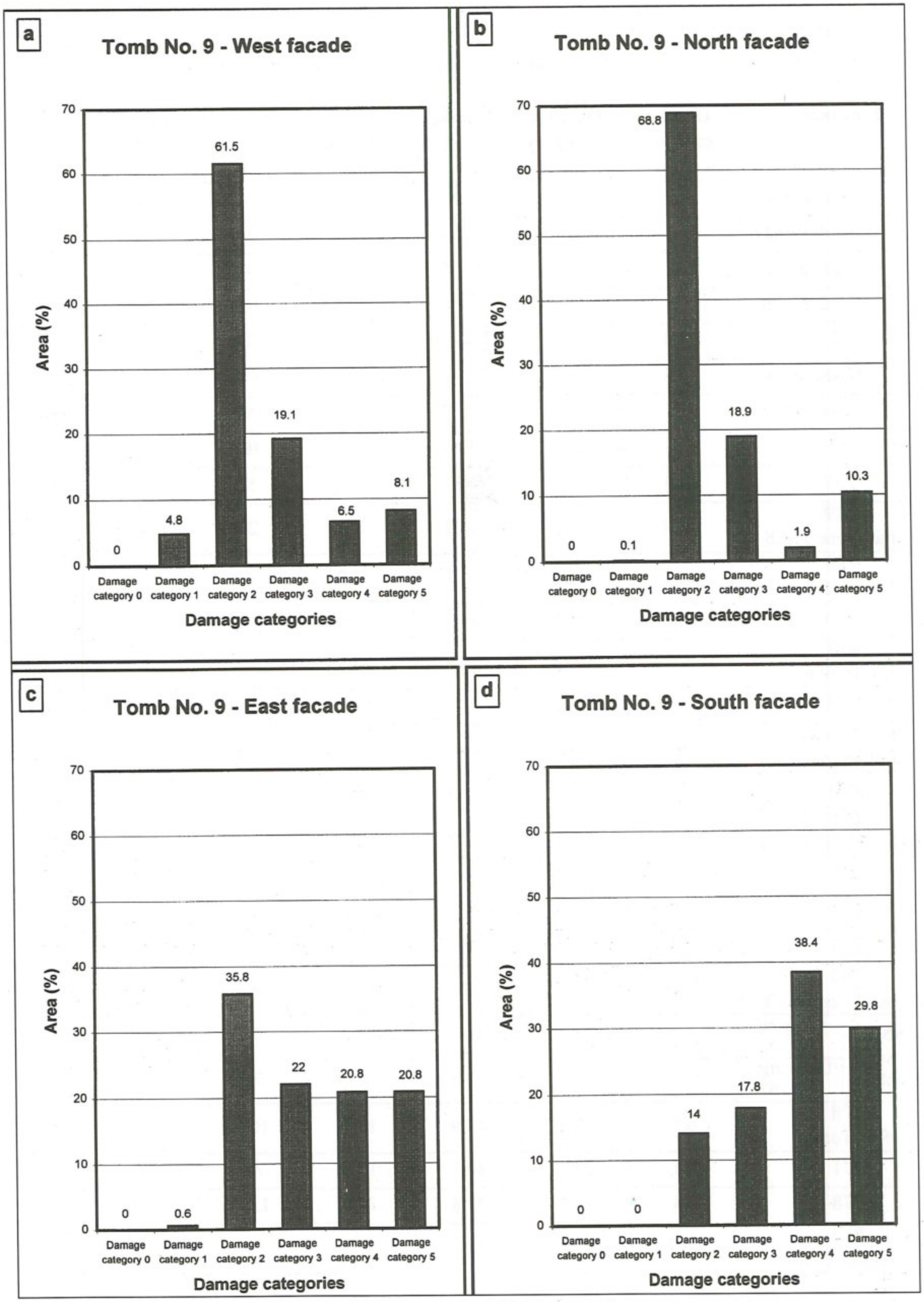
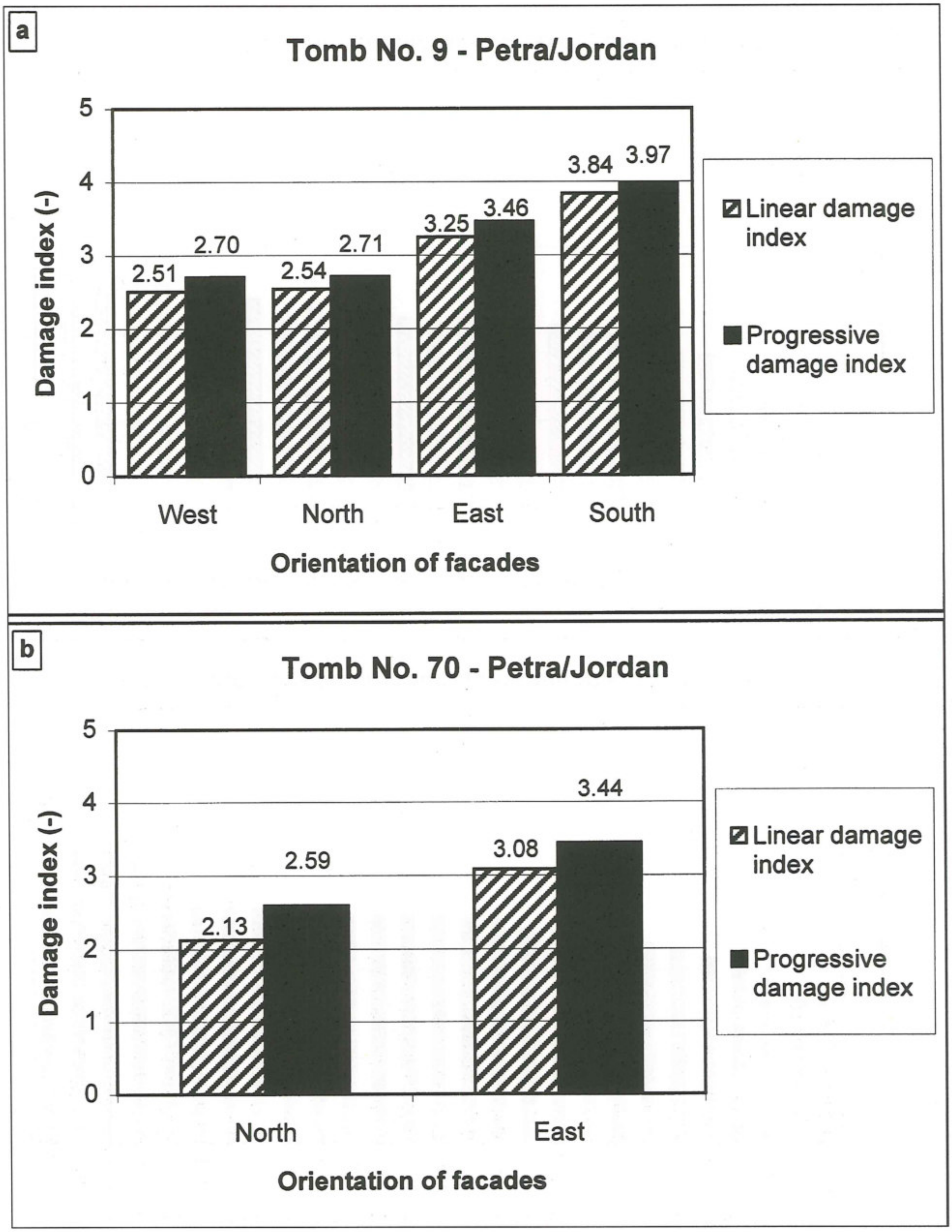


18 a-d. Tomb No. 9. Quantitative evaluation of damage categories for the four façades.

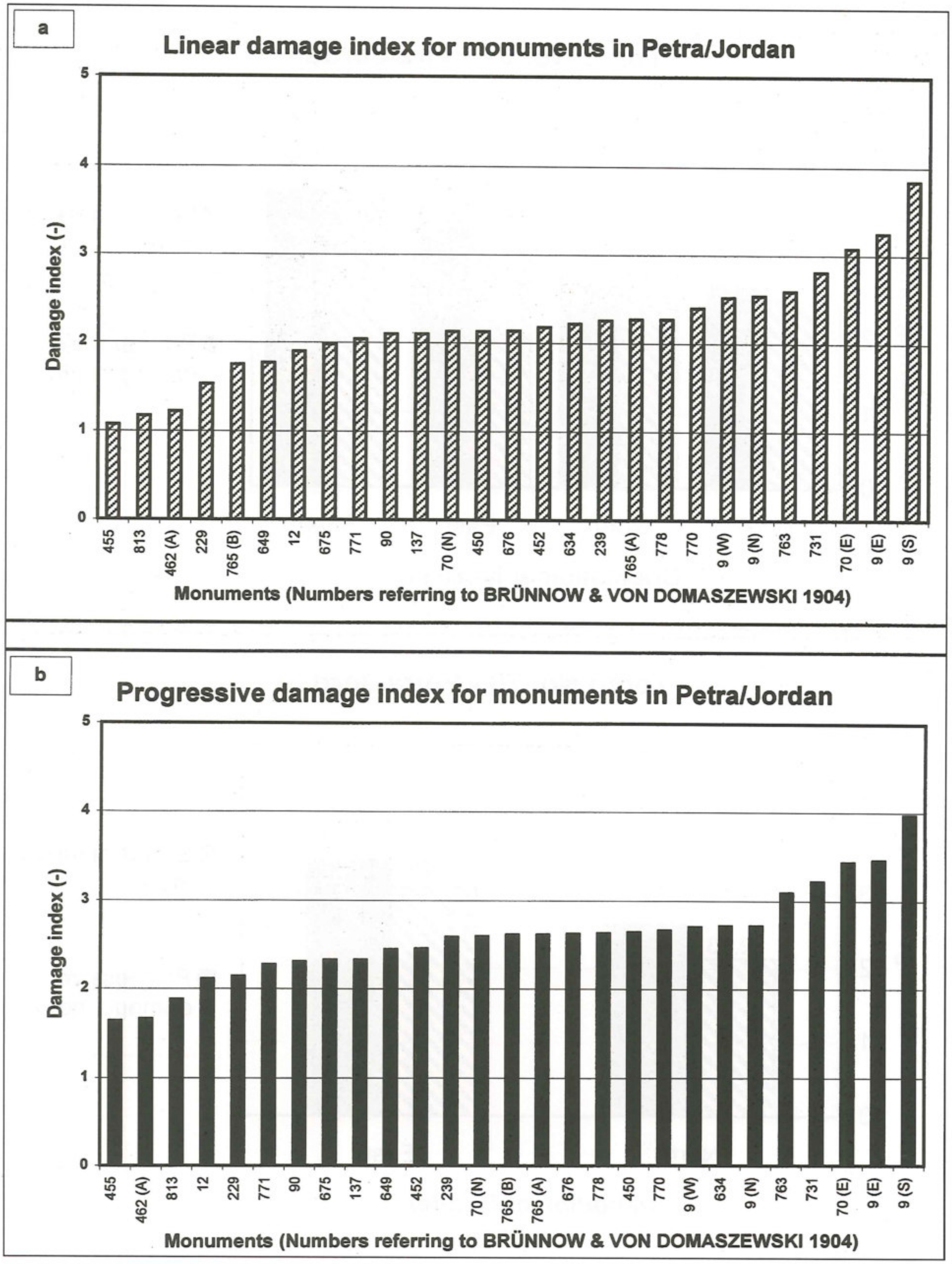
Table 7. Quantitative evaluation of damage categories, linear damage index (DI_{lin}) and progressive damage index (DI_{prog}) for rock monuments in Petra.

Monument*		**Quantitative eavaluation of damage categories (%)**						**Damage index (-)**	
		Damage category 0	**Damage category 1**	**Damage category 2**	**Damage category 3**	**Damage category 4**	**Damage category 5**	**DI** ***lin***	**DI** ***prog***
9	West facade	0	4.8	61.5	19.1	6.5	8.1	2.52	2.70
	North facade	0	0.1	68.8	18.9	1.9	10.3	2.54	2.71
	East facade	0	0.6	35.8	22.0	20.8	20.8	3.25	3.46
	South facade	0	0	14.0	17.8	38.4	29.8	3.84	3.97
12		3.4	29.9	46.2	15.3	4.3	0.9	1.90	2.11
70	North facade	9.3	32.7	25.6	10.1	12.3	10.0	2.13	2.59
	East facade	0	16.7	30.0	13.0	8.9	31.4	3.08	3.44
90		0	22.6	59.6	5.1	10.4	2.3	2.10	2.30
137		0.9	26.8	46.3	17.3	5.0	3.7	2.10	2.32
229 Renaissance Tomb		27.4	33.3	19.8	7.4	2.4	9.7	1.53	2.14
239 Soldier Tomb		2.7	25.1	42.0	13.9	6.4	9.9	2.26	2.58
450		18.4	16.9	31.9	6.3	18.8	7.7	2.13	2.64
452 Lion Triclinium		5.9	20.6	36.6	27.5	5.2	4.2	2.18	2.45
455		49.3	14.1	21.3	11.0	4.0	0.3	1.07	1.64
462 – Monastery Lower left part (A)		34.7	24.7	28.8	8.8	1.9	1.1	1.22	1.66
634		13.6	19.7	34.9	9.7	7.1	15.0	2.22	2.71
649 Tomb with the armour		30.8	16.8	28.2	6.6	4.0	13.6	1.77	2.44
675		0.5	42.4	36.7	6.4	6.7	7.3	1.98	2.32
676		5.8	40.9	22.5	9.9	6.5	14.4	2.14	2.62
731		6.1	17.2	29.1	5.2	22.4	20.0	2.81	3.22
763 Sextius Florentinus T.		11.6	15.6	30.3	10.0	9.7	22.8	2.59	3.09
765 Palace Tomb	Lower left part (A)	8.7	15.7	40.2	18.3	9.9	7.2	2.27	2.61
	Lower right part (B)	42.7	13.6	12.7	4.7	9.2	17.1	1.75	2.61
770 Silk Tomb		0.7	19.8	42.9	18.7	10.9	7.0	2.40	2.66
771		0.1	33.3	40.1	17.2	7.5	1.8	2.04	2.27
778		6.4	26.5	27.8	19.2	13.5	6.6	2.27	2.63
813 Unaishu Tomb		46.7	19.8	19.5	4.3	3.0	6.7	1.17	1.88

* Numbers referring to BRÜNNOW & VON DOMASZEWSKI (1904).



19:a,b. Linear and progressive damage index of façades with different orientation; a - Tomb No. 9; b - Tomb No. 70.



20: a,b. Damage index for rock monuments in Petra; a -linear damage index; b- progressive damage index.

Bibliography

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

Fitzner, B. and Heinrichs, K.
1998a Evaluation of weathering damages at monuments carved from bedrocks in Petra/Jordan-A research project 1996-1999. *ADAJ* 42: 341-360.
1998b Damage diagnosis at natural stone monuments-mapping and measurements. Pp. 170-172 in CICOP/Spain - Centro Internacional para la Conservacion del Patrimonio, *Proceedings of the 4th International Congress on Restoration of Buildings and Architectural Heritage,* La Habana-Cuba, 13.-17.07.1998.

Fitzner, B., Heinrichs, K. and Kownatzki, R.
1995 Weathering forms-classification and mapping. Pp. 41-88 in *Denkmalpflege und Naturwissenschaft, Natursteinkonservierung* I, Berlin: Ernst and Sohn.

Viles, H. A. , *et al.*
1997 Group Report: What is the state of our knowledge of the mechanisms of deterioration and how good are estimates of rates of deterioration. Pp. 95-112 in N.S Baer and R. Snethlage (eds.), *Saving our architectural heritage-The conservation of historic stone structures,* Report of the Dahlem Workshop, Berlin, 3-8 March 1996, John Wiley & Sons Ltd.