Damage diagnosis on stone monuments – weathering forms, damage categories and damage indices

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Abstract

Stone monuments represent an important part of our world´s cultural heritage. The awareness of increasing stone damage on monuments coupled with the danger of irretrievable loss of cultural heritage has resulted in great efforts worldwide for monument preservation. Meaningful damage diagnosis is required for comprehensive characterization, interpretation and rating of the stone damage. In situ investigation of monuments makes an important contribution to damage diagnosis on stone monuments. The monument mapping method is presented as an established non-destructive procedure for in situ studies on stone damage. It can be applied objectively and reproducibly to all stone types and to all kinds of stone monuments. The consequent use of weathering forms, damage categories and damage indices for precise registration, documentation, quantitative evaluation and rating of stone damages is explained. It provides a modern contribution to improvement of scientific knowledge in the field of stone deterioration and it facilitates important information on the need, urgency and appropriate types of economic and sustainable monument preservation measures. Furthermore, it is very suitable for certification and control of preservation measures and for long-term survey and maintenance of stone monuments. The innovative evaluation strategy ‘weathering forms – damage categories – damage indices’ is based on a detailed classification scheme of weathering forms, that has been developed on the basis of investigation at numerous monuments worldwide considering different stone types and different environments. The methodological approach to systematic evaluation of stone damage -based on monument mapping - is described and practical applications are demonstrated by means of some case studies.

INTRODUCTION

The history of mankind has been accompanied by the use of natural stones for buildings, monuments and art objects. In the course of time, all natural stones are affected by weathering. The interaction between stone materials and natural or anthropogenic weathering factors controls the type and extent of stone damages. Utilization of the monuments, insufficient maintenance or inappropriate restoration activities may have contributed to alarming stone damage. Due to the increasing awareness and respect for our built heritage, preservation of stone monuments has become an important public and political concern. Today, all experts agree that precise damage diagnosis is the prerequisite for understanding causes, processes and characteristics of stone damage and for sustainable monument preservation. During the last few decades, interdisciplinary research and new technologies have been introduced in damage diagnosis and monument preservation activities.

Fig. 1. Great Pyramid of Cheops and Sphinx, Cairo (Egypt).

Fig. 2. Arch de la Defense, Paris (France).

Fig. 3. Tower, Perge (Turkey).

Fig. 4. Gargoyle, Naumburg Cathedral (Germany).

A large number of investigation methods have been newly developed, often adapted from other disciplines and modified for application on stone monuments. Optimization of diagnostical procedures and well-targeted evaluation of scientific findings for monument preservation purposes remains an important research task.

A comprehensive monument mapping method has been developed by the working group 'Natural stones and weathering' / Aachen University of Technology as a non-destructive procedure for in situ studies on weathering damages at natural stones. Only this procedure allows a quantitative registration, documentation and evaluation of complete monuments, individual stone structures and sculptures according to lithotypes and to type, intensity and distribution of weathering forms, which represent the phenomenological response of the natural stones to weathering processes. Damage categories and damage indices have been introduced as new tools for consequent quantification and rating of stone damage as an important scientific contribution to damage diagnosis and monument preservation. The monument mapping method has been especially developed for historical stone monuments. It can be applied on monuments constructed with dimension stones as well as on monuments carved from bedrock (Fig. 1). In the same way it can be used on modern stone buildings (Fig. 2). Monument mapping can be applied to all stone types and to all kinds of stone buildings ranging from sculptures, individual stone structures to façades or entire monuments (Fig. 1-4).

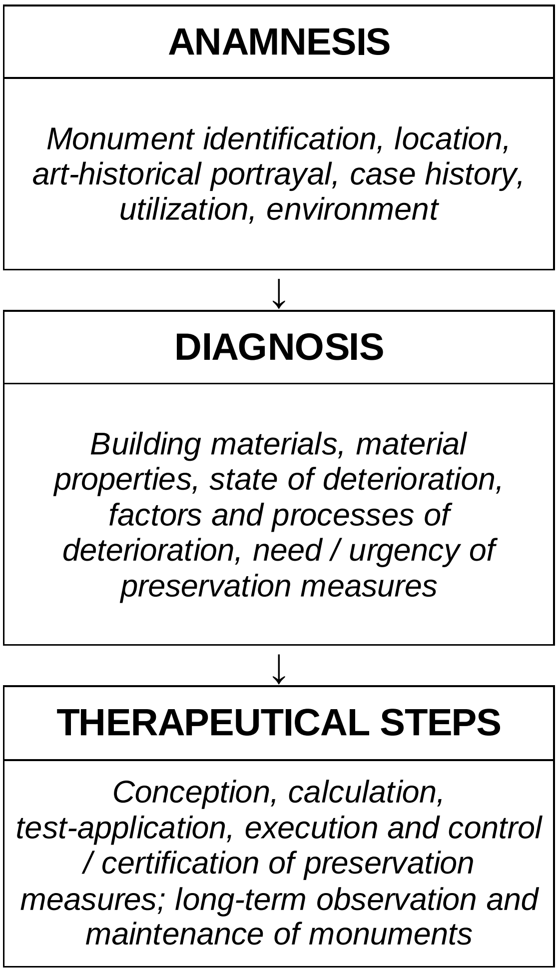

Fig. 5. Anamnesis - diagnosis - therapeutical steps.

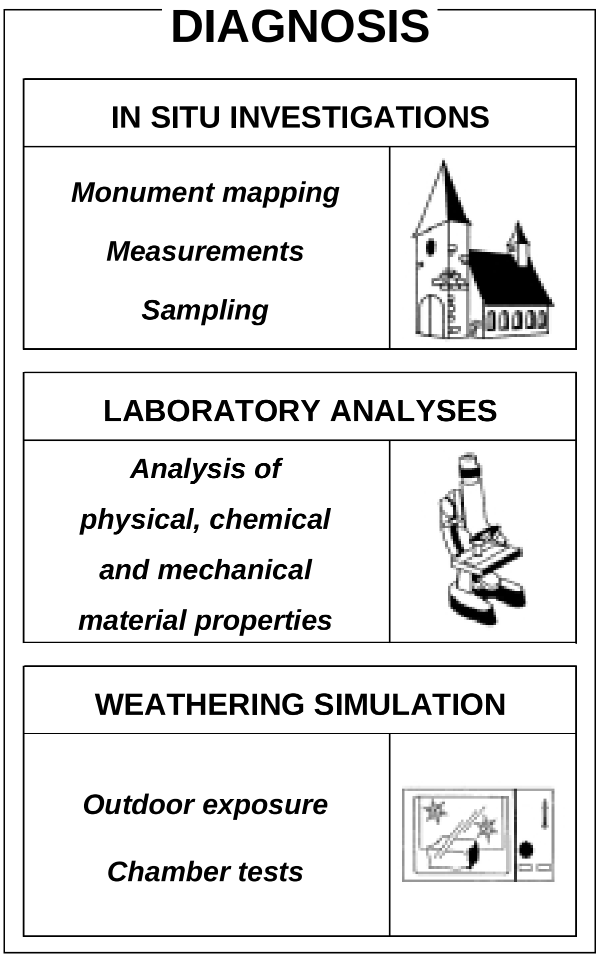

Fig. 6. Steps of diagnosis.

Diagnosis is fundamental for the improvement of scientific knowledge concerning stone deterioration. With respect to monument preservation, diagnosis is part of the well-accepted systematic approach ‘anamnesis – diagnosis – therapeutical steps’ (Fig. 5). By means of the anamnesis information, data and documents are acquired, compiled and evaluated in order to describe the monument characteristics and history. This involves

- monument identification, location – *name, type and builder of the monument; ownership / responsible authorities; dimensions; geographical position;*

exposure characteristics and surroundings over the course of time; building ground
- art-historical portrayal – *construction history; building techniques; architectonic composition; artistic elements; type and origin of building materials; historical, cultural and artistic importance*
- case history, environment – *utilization over the course of time; previous interventions / preservation activities; natural or anthropogenic impacts like earthquakes, fire, war etc; history of environmental conditions including air pollution..*

The diagnosis considers the information obtained from the anamnesis and provides the basis for appropriate therapeutical steps in order of monument preservation. Preservation strategies and preservation measures are presented e.g. in [1-4]. Only the combination of in situ investigation, laboratory analyses and weathering simulation guarantees a comprehensive scientific damage diagnosis (Fig. 6). Systematic studies of stone deterioration on monuments have to consider different scales of stone deterioration. Visible and non-visible stone deterioration can be distinguished. According to VILES et al. [5], a subdivision into nanoscale (< mm), microscale (mm to cm), mesoscale (cm to m) and macroscale (whole facades or monuments) can be made (Table 1). Nanoscale corresponds to non-visible stone deterioration, whereas microscale, mesoscale and macroscale refer to visible stone deterioration.

Table 1 Scales and parameters of stone deterioration (modified from [5]).

<table>
<tr><th colspan="2">SCALES</th><th>PARAMETERS</th><th>SCIENCES</th></tr>
<tr><td>Non-visible deterioration</td><td>Nanoscale
< mm</td><td rowspan="2">Changes of stone properties –
composition, texture, porosity, strength etc.</td><td rowspan="4">Geosciences,
material sciences,
chemistry,
physics,
microbiology</td></tr>
<tr><td rowspan="4">Visible deterioration</td><td rowspan="2">Microscale
mm to cm</td></tr>
<tr><td>Discoloration, mass loss, micromorphology</td></tr>
<tr><td>Mesoscale
cm to m</td><td>Deterioration phenomena – weathering forms</td></tr>
<tr><td>Macroscale
whole façades or monuments</td><td>Structural stability,
aesthetic appearance</td><td>Structural engineering,
architecture</td></tr>
</table>

For each scale there are a series of appropriate parameters and investigation methods for evaluation of stone deterioration. For comprehensive evaluation of stone deterioration an interdisciplinary cooperation between scientists, engineers and architects is required. The monument mapping method is part of situ investigation at monuments and is focussed on stone deterioration at the mesoscale (Fig. 6, Table 1). The method has met great international acceptance, especially in terms of applicability, information output and benefit-cost/time-ratio. The method is approved as an established procedure contributing essentially to the improvement of scientific knowledge of stone deterioration, damage diagnosis, risk prognosis, risk management and sustainable monument preservation. The method has been applied at numerous monuments worldwide.

The consequent use of weathering forms, damage categories and damage indices allows manifold scientific and practical evaluation. Weathering forms are used for detailed, objective and reproducible description of individual deterioration phenomena at mesoscale (cm to m) according to type and intensity. Based on defined schemes, all weathering forms are related to damage categories. The damage categories have been established in order to rate the different types of damage. Damage indices have been introduced for conclusive quantification and rating of damage. Damage indices are calculated based on quantitative evaluation of damage categories (Fig. 7).

WEATHERING FORMS	**Detailed description of individual weathering phenomena with quantification of intensities**

↓
Definition of damage categories,
relating of weathering forms to damage categories↓

DAMAGE CATEGORIES	**Rating of individual weathering damage**

↓
Definition of damage indices,
calculation of damage indices from proportion of damage categories↓

DAMAGE INDICES	**Conclusive quantification and rating of weathering damage**

Fig. 7. Weathering forms - damage categories - damage indices.

MONUMENT MAPPING – LITHOTYPES AND WEATHERING FORMS

The monument mapping method has been developed for the registration, documentation and evaluation of lithotypes and weathering forms at stone monuments [6-14]. Two mapping modes can be distinguished: lithological mapping and mapping of weathering forms. Prerequisites for monument mapping are plans of the areas to be investigated and classification schemes of lithotypes and weathering forms.

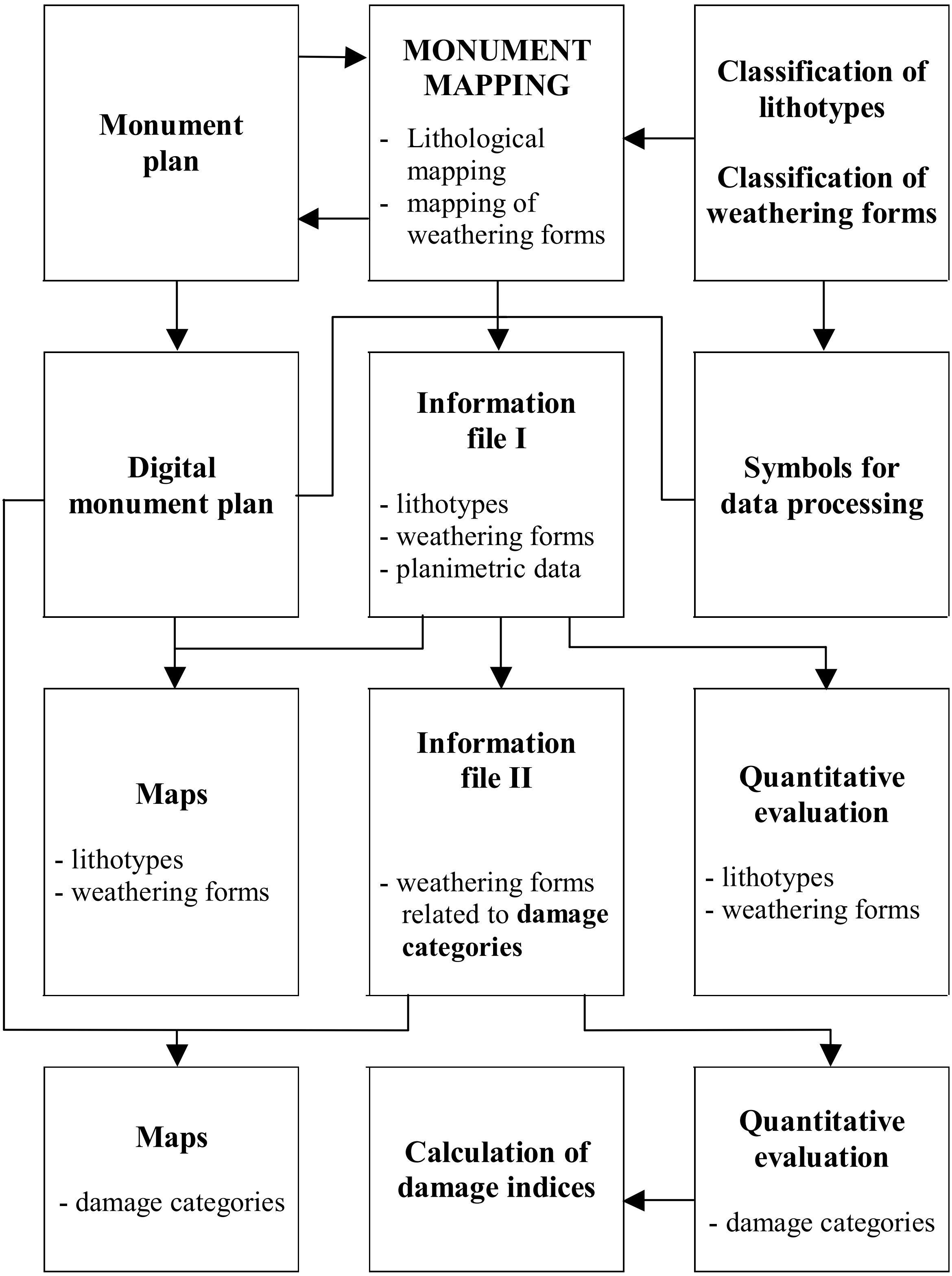

Fig. 8. Mapping procedure, data processing and evaluation.

A computer programme, VIA – Virtual Image Analyzer, has been developed for processing, illustration and systematic quantitative evaluation of mapping information.

Mapping procedure, data processing and evaluation

The mapping procedure, data processing and evaluation of mapping information are presented in Figure 8. Based on monument plans and classification schemes of lithotypes and weathering forms, lithological mapping and mapping of weathering forms are carried out. The mapping is accompanied by photodocumentation of lithotypes and weathering forms. Information on stone tooling, constructional aspects, former preservation measures or exposure characteristics should be considered additionally. Registration of lithotypes and weathering forms and computer-enhanced data processing of the information is made by means of symbols. The steps involved in data processing are:

- digital monument plans considering all delimitations of distinct areas as result of different lithotypes or different types, intensities or combinations of weathering forms,
- numbering and planimetric evaluation of all distinct areas,
- integration of mapping information on lithotypes and weathering forms by means of symbols (information file I).

The distribution of lithotypes and weathering forms is illustrated in lithological maps and maps of weathering forms. All lithotypes and weathering forms are evaluated quantitatively. Based on a correlation scheme 'weathering forms – damage categories', all weathering forms are related to damage categories (information file II). The damage categories are illustrated in maps and are evaluated quantitatively. Based on the quantitative evaluation of damage categories, damage indices are calculated. The joint evaluation of the monument mapping considering lithotypes, weathering forms, damage categories and damage indices as well as information from anamnesis and the significance of the evaluations with respect to methodology, research and monument preservation are presented in Figure 9. In situ measurements, sampling, laboratory analyses and weathering simulations can be well-directed by means of these mapping results.

Classification and mapping of lithotypes

In many monuments different stone types were used due to architectural, constructional and artistical considerations or availability and workability of stone material. Rebuilding or stone replacement in the course of restoration measures may have resulted in additional stone types. For correlation between stone types and weathering behaviour, precise knowledge of all stone types used is required. The need for exact registration and documentation of stone types increases with spatial heterogenity of distribution and diversity of stone types. The first step of lithological mapping comprises an inventory of all different stone types. Well-established petrographical classification schemes are used for the description of lithotypes. Besides petrographical classification, regional names or trade names and information on their provenance should be considered.

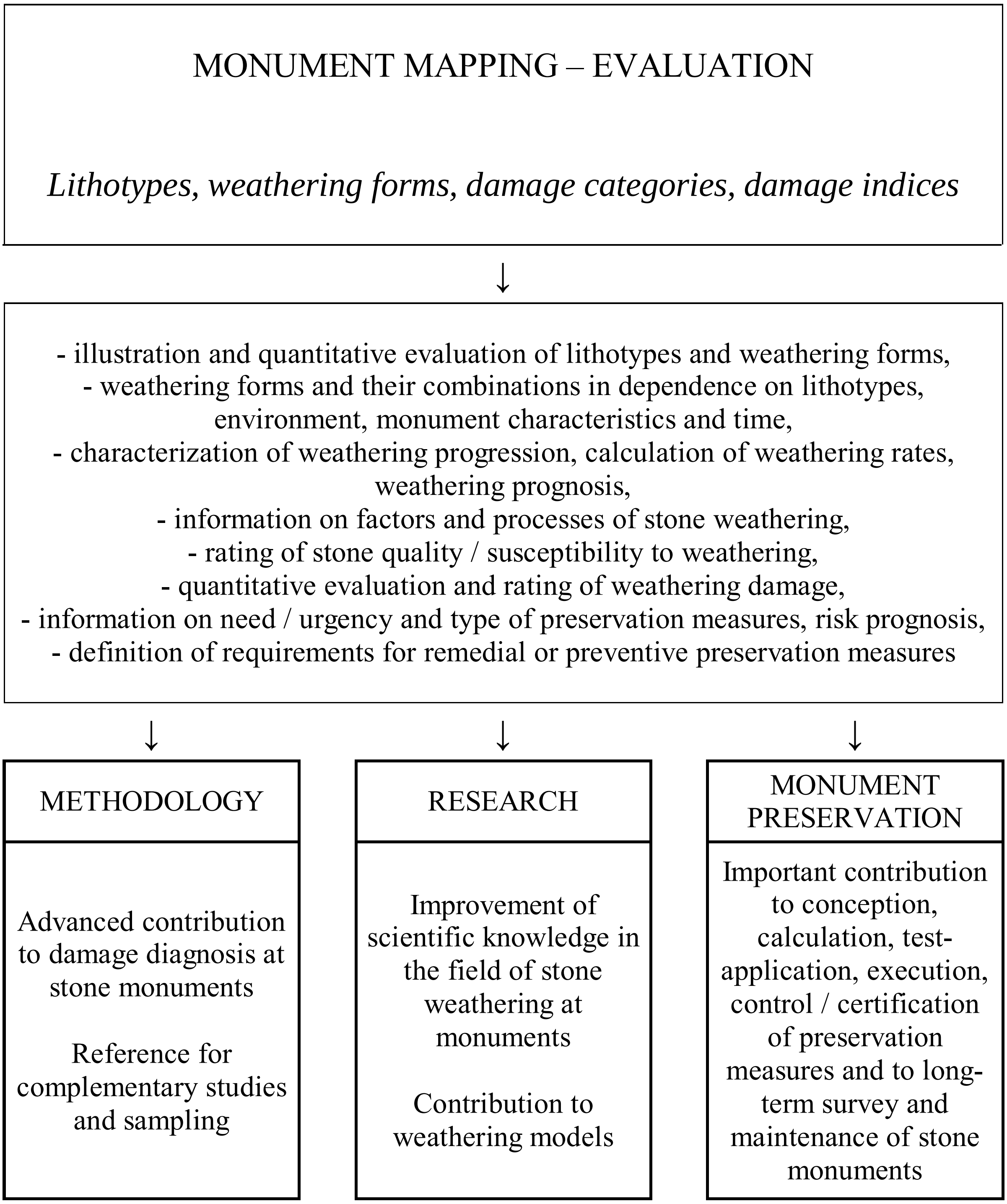

Fig. 9. Evaluation of monument mapping.

In the course of lithological mapping, the investigation area is mapped systematically referring to type and distribution of natural stones. The information is illustrated in lithological maps and the lithotypes are evaluated quantitatively. Quantitative evaluation of lithotypes can be made according to number or area of dimension stones.

An example of lithological mapping with quantitative evaluation of lithotypes is shown in Figure 10. Seven lithotypes were used at this part of the Minster St. Quirin in Neuss (Germany). Mainly large-sized dimension stones from trachytes, trachy-andsite, basalt and slate were used predominantely for mouldings, columns, capitals, lisenes and main arches, whereas very small-sized dimension stones from tuffs were used for the central ashlar parts. The two modes of the quantitative evaluation show very different results.

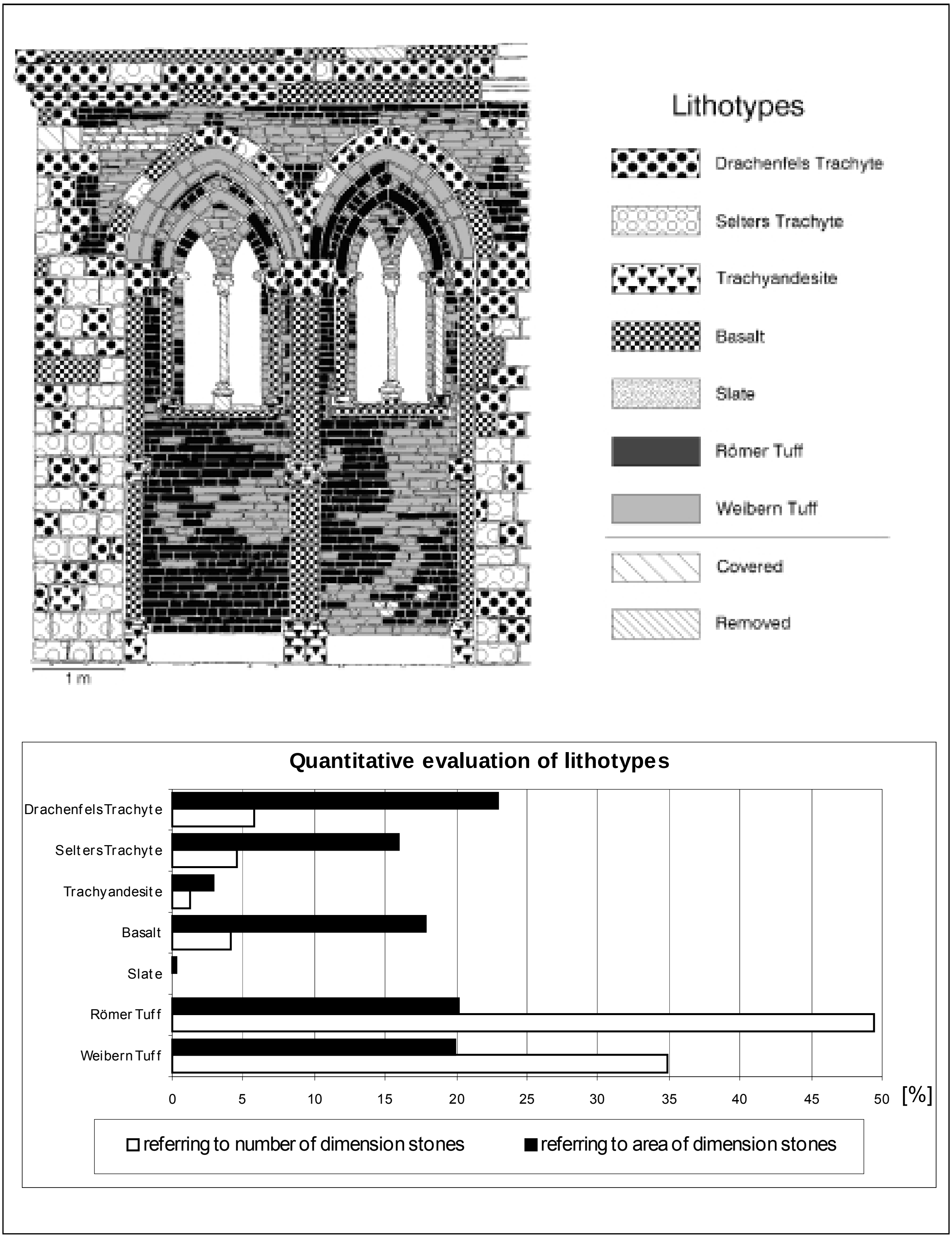

Fig. 10. Lithological map and quantitative evaluation of lithotypes. Minster St. Quirin, part of the tower, Neuss (Germany).

Classification and mapping of weathering forms

Weathering forms are used for precise description of deterioration phenomena at the mesoscale (cm to m). They represent the visible results of weathering processes which are initiated and controlled by weathering factors. Unlike petrographical classification schemes, a detailed classification scheme of weathering forms did not previously exist. The working group ‘Natural stones and weathering’ has developed such a detailed classification of weathering forms as the basis for precise, objective and reproducible registration and documentation [6]. Components of the classification scheme are four levels of differentiation, definitions of weathering forms, symbols for registration and data processing, parameters for intensity classification of the weathering forms and a photoatlas. Recently, the classification scheme has been updated. Figure 11 shows the hierarchical structure of the classification scheme. Four *groups of weathering forms* are distinguished in the uppermost level I: group 1 – loss of stone material, group 2 – discoloration / deposits, group 3 – detachment, group 4 – fissures / deformation.

LEVEL I	4 GROUPS OF WEATHERING FORMS
↓	
LEVEL II	25 MAIN WEATHERING FORMS
↓	
LEVEL III	75 INDIVIDUAL WEATHERING FORMS
↓	
LEVEL IV	DIFFERENTIATION OF INDIVIDUAL WEATHERING FORMS ACCORDING TO INTENSITIES

Fig. 11. Structure of the classification scheme of weathering forms.

In level II, each group of weathering forms is subdivided into *main weathering forms*. These are further differentiated into *individual weathering forms* in level III of the classification scheme. In level IV, each individual weathering form is additionally differentiated according to its intensity. The complete classification scheme of weathering forms is presented in Table 2 (2.1 – 2.8). A standard intensity classification of weathering forms is not suitable. It should be adjusted to range of intensities surveyed at a monument or an assembly of monuments. The necessity of individual, well-directed intensity classification is demonstrated in Table 3. The intensity classifications for the weathering form ‘back weathering’ presented for two monuments in Egypt consider the very different intensity range of ‘back weathering’ at these monuments. The very different size of dimension stones used at the two monuments controls the intensity classification. Unlike relative intensity classification, the precise quantitative definition of the intensity classes –- allows the comparison between the surveys of different monuments even in such cases of different intensity classifications for different monuments.

Table 2.1 Classification scheme of weathering forms.

LEVEL I – GROUP OF WEATHERING FORMS
Group 1 - Loss of stone material

LEVEL II		LEVEL III		LEVEL IV	
MAIN WEATHERING FORMS		INDIVIDUAL WEATHERING FORMS		CLASSIFICATION OF INTENSITIES (PARAMETERS)	
Back Weathering Uniform loss of stone material parallel to the original stone surface.	**W**	***Back weathering due to loss of scales*** Uniform loss of stone material parallel to the stone surface due to contour scaling.	sW	Depth of back weathering (mm, cm)	sW_1 ↓ sW_n
		Back weathering due to loss of crumbs / splinters Uniform loss of stone material parallel to the stone surface due to crumbly disintegration.	uW		uW_1 ↓ uW_n
		Back weathering due to loss of stone layers dependent on stone structure Uniform loss of stone material parallel to the stone surface due to exfoliation.	xW		xW_1 ↓ xW_n
		Back weathering due to loss of crusts Uniform loss of stone material parallel to the original stone surface due to detachment of crusts with adherent stone material.	cW		cW_1 ↓ cW_n
		Back weathering due to loss of undefinable stone aggregates / pieces Uniform loss of stone material parallel to the original stone surface. The type of the preceding detachment of stone material can not be characterized.	zW		zW_1 ↓ zW_n
Relief Morphological change of the stone surface due to partial or selective weathering.	**R**	***Rounding / notching*** Relief by rounding of edges or notching / hollowing out. Concave or convex soft forms.	Ro	Depth of relief (mm, cm)	Ro_1 ↓ Ro_n
		Alveolar weathering Relief in the form of alveolae. Form comparable to honeycombs.	Ra		Ra_1 ↓ Ra_n
		Weathering out dependent on stone structure Relief dependent on structural features such as bedding, foliation, banding etc. Frequently striped pattern.	tR		tR_1 ↓ tR_n
		Weathering out of stone components Relief due to selective weathering of sensitive stone components (clay lenticles, nodes of limonite etc.) or due to break out of compact stone components (pebbles, fossil fragments etc.). Hole-shaped forms.	Rk		Rk_1 ↓ Rk_n
		Clearing out of stone components Relief in the form of protruding compact stone components (pebbles, fossil fragments, concretions) due to selective weathering.	Rh		Rh_1 ↓ Rh_n
		Roughening Finest relief / alteration of gloss due to corrosion or loss of smallest stone particles on smoothed stone surfaces.	Rr		Rr_1 ↓ Rr_n
		Microkarst Relief due to corrosion, especially on carbonate rocks.	Rm		Rm_1 ↓ Rm_n
		Pitting Relief in the form of small pits due to biogenically induced corrosion, esp. on carbonate rocks.	Rt		Rt_1 ↓ Rt_n
		Relief due to anthropogenic impact Relief in the form of scratches etc.	aR		aR_1 ↓ aR_n

Table 2.2 Classification scheme of weathering forms.

LEVEL I – GROUP OF WEATHERING FORMS Group 1 – Loss of stone material					
LEVEL II		**LEVEL III**		**LEVEL IV**	
MAIN WEATHERING FORMS		INDIVIDUAL WEATHERING FORMS		CLASSIFICATION OF INTENSITIES (PARAMETERS)	
Break out Loss of compact stone fragments.	**O**	***Break out due to anthropogenic impact*** Break out due to war, vandalism etc.	aO	Volume of break out (cm^3, dm^3) or depth of break out (cm)	aO_1 ↓ aO_n
		Break out due to constructional cause Break out due to statics, wedge effect of rusting iron etc.	bO		bO_1 ↓ bO_n
		Break out due to natural cause Break out due to wedgework of roots, earthquakes, intersection of fractures etc.	nO		nO_1 ↓ nO_n
		Break out due to non-recognizable cause	oO		oO_1 ↓ oO_n

LEVEL I – GROUP OF WEATHERING FORMS Group 2 – Discoloration / Deposits					
LEVEL II		**LEVEL III**		**LEVEL IV**	
MAIN WEATHERING FORMS		INDIVIDUAL WEATHERING FORMS		CLASSIFICATION OF INTENSITIES (PARAMETERS)	
Discoloration Alteration of the original stone color.	**D**	***Coloration*** Chromatic alteration / coloring due to chemical weathering of minerals (e.g. oxidation of iron and manganese compounds), due to intrusion / accumulation of coloring matter or due to staining by biogenic pigments.	Dc	Degree – change of color	Dc_1 ↓ Dc_n
		Bleaching Chromatic alteration / decolorization due to chemical weathering of minerals (e.g. reduction of iron and manganese compounds) or extraction of coloring matter (leaching, washing out)..	Db		Db_1 ↓ Db_n
Soiling Dirt deposits on the stone surface.	**I**	***Soiling by particles from the atmosphere*** Poorly adhesive, mainly grey to black deposits of dust, soot, fly ash etc.	pI	Mass of deposits or degree – covering of the surface	pI_1 ↓ pI_n
		Soiling by particles from water Poorly adhesive, mainly grey to brown deposits of dust, soil or mud particles.	wI		wI_1 ↓ wI_n
		Soiling by droppings Deposits of droppings from birds, e.g. from pigeons.	gI		gI_1 ↓ gI_n
		Soiling due to anthropogenic impact Paint, graffities, posters etc.	aI		aI_1 ↓ aI_n

Table 2.3 Classification scheme of weathering forms.

LEVEL I – GROUP OF WEATHERING FORMS Group 2 – Discoloration / Deposits					
LEVEL II		**LEVEL III**		**LEVEL IV**	
MAIN WEATHERING FORMS		INDIVIDUAL WEATHERING FORMS		CLASSIFICATION OF INTENSITIES (PARAMETERS)	
Loose salt deposits Poorly adhesive deposits of salt aggregates.	**E**	***Efflorescences*** Poorly adhesive deposits of salt aggregates on the stone surface.	Ee	Mass of deposits or degree – covering of the surface	Ee_1 ↓ Ee_n
		Subflorescences Poorly adhesive deposits of salt aggregates below the stone surface, e.g. in the zone of detachment of scales.	Ef	Mass of deposits	Ef_1 ↓ Ef_n
Crust Strongly adhesive deposits on the stone surface.	**C**	***Dark-colored crust tracing the surface*** Compact deposit, grey- to black-colored, tracing the morphology of the stone surface. Mainly due to deposition of pollutants from the atmosphere.	dkC	For dkC, hkC and fkC: degree – covering of the surface for diC, hiC and fiC: thickness of the crust (mm)	dkC_1 ↓ dkC_n
		Dark-colored crust changing the surface Compact deposit, grey- to black-colored, changing the morphology of the stone surface. Mainly due to deposition of pollutants from the atmosphere. E.g. gypsum crust with impurities.	diC		diC_1 ↓ diC_n
		Light-colored crust tracing the surface Compact deposit, light-colored, tracing the morphology of the stone surface. Mainly due to precipitation processes. Light-colored crusts of salt minerals, calc-sinter or silica.	hkC		hkC_1 ↓ hkC_n
		Light-colored crust changing the surface Compact deposit, light-colored, changing the morphology of the stone surface. Mainly due to precipitation processes. Light-colored crusts of salt, calc-sinter or silica.	hiC		hiC_1 ↓ hiC_n
		Colored crust tracing the surface Compact deposit, colored, tracing the morphology of the stone surface. Mainly due to precipitation processes. E.g. colored crusts of salt minerals or iron/manganese crusts.	fkC		fkC_1 ↓ fkC_n
		Colored crust changing the surface Compact deposit, colored, changing the morphology of the stone surface. Mainly due to precipitation processes. Eg. colored crusts of salt minerals or iron/manganese crusts.	fiC		fiC_1 ↓ fiC_n
Biological colonization Colonization by microorganisms or higher plants.	**B**	***Microbiological colonization*** Colonization by microflora (fungi, algae, lichen) and bacteria. Biofilms.	Bi	Degree – covering of the surface	Bi_1 ↓ Bi_n
		Colonization by higher plants	Bh		Bh_1 ↓ Bh_n

Table 2.4 Classification scheme of weathering forms.					
LEVEL I – GROUP OF WEATHERING FORMS **Group 2 – Discoloration / Deposits**					
LEVEL II		**LEVEL III**		**LEVEL IV**	
MAIN WEATHERING FORMS		INDIVIDUAL WEATHERING FORMS		CLASSIFICATION OF INTENSITIES (PARAMETERS)	
Discoloration to crust Transitional form between discoloration (D) and crust (C).	**D-C**	***Coloration to dark-colored crust tracing the surface*** Transitional form between coloration (Dc) and dark-colored crust tracing the surface (dkC).	Dc-dkC	Degree – covering of the surface	Dc-dkC_1 ↓ Dc-dkC_n
		Coloration to colored crust tracing the surface Transitional form between coloration (Dc) and colored crust tracing the surface (fkC).	Dc-fkC		Dc-fkC_1 ↓ Dc-fkC_n
Soiling to crust Transitional form between soiling (I) and crust (C).	**I–C**	***Soiling by particles from the atmosphere to dark-colored crust tracing the surface*** Transitional form between soiling by particles from the atmosphere (pI) and dark-colored crust tracing the surface (dkC).	pI-dkC	Degree – covering of the surface	pI-dkC_1 ↓ pI-dkC_n
		Soiling by particles from the atmosphere to dark-colored crust changing the surface Transitional form between soiling by particles from the atmosphere (pI) and dark-colored crust changing the surface (diC).	pI-diC	Thickness of the deposit (mm)	pI-diC_1 ↓ pI-diC_n
Loose salt deposits to crust Transitional form between loose salt deposits (E) and crust (C).	**E–C**	***Efflorescences to light-colored crust tracing the surface*** Transitional form between efflorescences (Ee) and light-colored crust tracing the surface (hkC).	Ee-hkC	Degree – covering of the surface	Ee-hkC_1 ↓ Ee-hkC_n
		Efflorescences to light-colored crust changing the surface Transitional form between efflorescences (Ee) and light-colored crust changing the surface (hiC).	Ee-hiC	Thickness of the deposit (mm)	Ee-hiC_1 ↓ Ee-hiC_n
Biological colonization to crust Transitional form between biological colonization (B) and crust (C).	**B-C**	***Microbiological colonization to dark-colored crust tracing the surface*** Transitional form between microbiological colonization (Bi) and dark-colored crust tracing the surface (dkC).	Bi-dkC	Degree – covering of the surface	Bi-dkC_1 ↓ Bi-dkC_n
		Microbiological colonization to dark-colored crust changing the surface Transitional form between microbiological colonization (Bi) and dark-colored crust changing the surface (diC).	Bi-diC	Thickness of the deposit (mm)	Bi-diC_1 ↓ Bi-diC_n

Table 2.5 Classification scheme of weathering forms.

LEVEL I – GROUP OF WEATHERING FORMS
Group 3 – Detachment

LEVEL II		LEVEL III		LEVEL IV	
MAIN WEATHERING FORMS		INDIVIDUAL WEATHERING FORMS		CLASSIFICATION OF INTENSITIES (PARAMETERS)	
Granular disintegration Detachment of individual grains or small grain aggregates.	**G**	***Granular disintegration into powder*** Detachment of smallest stone particles (stone powder).	Gp	Mass of detaching stone material	Gp_1 ↓ Gp_n
		Granular disintegration into sand Detachment of small grains as individual grains or small grain aggregates (stone sand).	Gs		Gs_1 ↓ Gs_n
		Granular disintegration into grus Detachment of larger grains as individual grains or small grain aggregates (stone grus). Especially on granites.	Gg		Gg_1 ↓ Gg_n
Crumbly disintegration Detachment of larger compact stone pieces of irregular shape.	**P**	***Crumbling*** Detachment of larger compact stone pieces in the form of crumbs.	Pu	Volume of detaching stone pieces (cm^3, dm^3) or mass of detaching stone material	Pu_1 ↓ Pu_n
		Splintering Detachment of larger compact stone pieces in the form of splinters. E.g. on compact carbonate rocks and quartzites.	Pn		Pn_1 ↓ Pn_n
		Crumbling to splintering Transitional form between crumbling (Pu) and splintering (Pn).	Pu-Pn		Pu-Pn_1 ↓ Pu-Pn_n
Flaking Detachment of small, thin stone pieces (flakes) parallel to the stone surface.	**F**	***Single flakes*** Detachment of one layer of flakes parallel to the stone surface.	eF	Mass of detaching stone material	eF_1 ↓ eF_n
		Multiple flakes Detachment of a stack of flakes parallel to the stone surface.	mF		mF_1 ↓ mF_n
Contour scaling Detachment of larger, platy stone pieces parallel to the stone surface, but not following any stone structure.	**S**	***Scale due to tooling of the stone surface*** Detachment of mainly thin scales due to tooling of the stone surface.	qS	Thickness of the scales resp. stack of scales (mm, cm) or mass of detaching stone material	qS_1 ↓ qS_n
		Single scale Detachment of one layer of scales.	eS		eS_1 ↓ eS_n
		Multiple scales Detachment of a stack of scales.	mS		mS_1 ↓ mS_n

Table 2.6 Classification scheme of weathering forms.

LEVEL I – GROUP OF WEATHERING FORMS Group 3 – Detachment					
LEVEL II		**LEVEL III**		**LEVEL IV**	
MAIN WEATHERING FORMS		INDIVIDUAL WEATHERING FORMS		CLASSIFICATION OF INTENSITIES (PARAMETERS)	
Detachment of stone layers dependent on stone structure Detachment of larger stone sheets or plates following the stone structure.	**X**	***Exfoliation*** Detachment of larger stone layers (sheets, plates) following any stone structure (bedding, banding etc.) and the stone surface. Structural feature is oriented parallel to the stone surface.	XI	Thickness of detaching stone layers resp. stack of layers (mm, cm)	XI_1 ↓ XI_n
		Splitting up Detachment of larger stone layers (sheets, plates) following any stone structure (bedding, banding etc.), but not the stone surface. Structural feature is not oriented parallel to the stone surface.	Xv	Number of detaching stone layers resp. splits	Xv_1 ↓ Xv_n
Detachment of crusts with stone material Detachment of crusts with stone material sticking to the crust.	**K**	***Detachment of a dark-colored crust tracing the stone surface***	dkK	Mass of detaching material or thickness of detaching layers (mm)	dkK_1 ↓ dkK_n
		Detachment of a dark-colored crust changing the stone surface	diK		diK_1 ↓ diK_n
		Detachment of a light-colored crust tracing the stone surface	hkK		hkK_1 ↓ hkK_n
		Detachment of a light-colored crust changing the stone surface	hiK		hiK_1 ↓ hiK_n
		Detachment of a colored crust tracing the stone surface	fkK		fkK_1 ↓ fkK_n
		Detachment of a colored crust changing the stone surface	fiK		fiK_1 ↓ fiK_n
Granular disintegration to flaking Transitional form between granular disintegration (G) and flaking (F).	**G-F**	***Granular disintegration into sand to single flakes*** Transitional form between granular disintegration into sand (Gs) and single flakes (eF).	Gs-eF	Mass of detaching stone material	$Gs\text{-}eF_1$ ↓ $Gs\text{-}eF_n$
		Granular disintegration into grus to single flakes Transitional form between granular disintegration into grus (Gg) and single flakes (eF).	Gg-eF		$Gg\text{-}eF_1$ ↓ $Gg\text{-}eF_n$

Table 2.7 Classification scheme of weathering forms.

LEVEL I – GROUP OF WEATHERING FORMS Group 3 – Detachment					
LEVEL II		**LEVEL III**		**LEVEL IV**	
MAIN WEATHERING FORMS		INDIVIDUAL WEATHERING FORMS		CLASSIFICATION OF INTENSITIES (PARAMETERS)	
Granular disintegration to crumbly disintegration Transitional form between granular	**G-P**	***Granular disintegration into sand to single flakes*** Transitional form between granular disintegration into sand (Gs) and crumbling (Pu).	Gs-Pu	Mass of detaching stone material	Gs-Pu$_1$ ↓ Gs-Pu$_n$
		Granular disintegration into grus to crumbling Transitional form between granular disintegration into grus (Gg) and crumbling (Pu).	Gg-Pu		Gg-Pu$_1$ ↓ Gg-Pu$_n$
Flaking to crumbly disintegration Transitional form between flaking (F) and crumbly disintegration (P).	**F-P**	***Single flakes to crumbling*** Transitional form between single flakes (eF) and crumbling (Pu).	eF-Pu	Mass of detaching stone material	eF-Pu$_1$ ↓ eF-Pu$_n$
		Single flakes to splintering Transitional form between single flakes (eF) and splintering (Pn).	eF-Pn		eF-Pn$_1$ ↓ eF-Pn$_n$
Crumbly disintegration to contour scaling Transitional form between crumbly disintegration (P) and contour scaling (S).	**P-S**	***Crumbling to single scale*** Transitional form between crumbling (Pu) and single scale (eS).	Pu-eS	Mass of detaching stone material or volume of detaching stone pieces (cm^3, dm^3)	Pu-eS$_1$ ↓ Pu-eS$_n$
		Splintering to single scale Transitional form between splintering (Pn) and single scale (eS).	Pn-eS		Pn-eS$_1$ ↓ Pn-eS$_n$
Flaking to contour scaling Transitional form between flaking (F) and contour scaling (S).	**F-S**	***Single flakes to single scale*** Transitional form between single flakes (eF) and single scale (eS).	eF-eS	Mass of detaching stone material	eF-eS$_1$ ↓ eF-eS$_n$
		Multiple flakes to multiple scales Transitional form between multiple flakes (mF) and multiple scales (mS).	mF-mS		mF-mS$_1$ ↓ mF-mS$_n$

Table 2.8 Classification scheme of weathering forms.					
LEVEL I – GROUP OF WEATHERING FORMS **Group 4 – Fissures / deformation**					
LEVEL II		**LEVEL III**		**LEVEL IV**	
MAIN WEATHERING FORMS		INDIVIDUAL WEATHERING FORMS		CLASSIFICATION OF INTENSITIES (PARAMETERS)	
Fissures Individual fissures or systems of fissures due to natural or constructional causes.	**L**	***Fissures independent of stone structure*** Individual fissures or systems of fissures independent of structural features such as bedding, foliation, banding etc..	vL	Number of fissures and dimension of fissures – length, width (mm, cm)	vL_1 ↓ vL_n
		Fissures dependent on stone structure Individual fissures or systems of fissures dependent on structural features such as bedding, foliation, banding etc.	tL		tL_1 ↓ tL_n
Deformation Bending / buckling of mainly thin stone slabs due to plastic deformation. Especially on marble slabs.	**V**	***Deformation, convex***	lV	Amplitude of bending / buckling	lV_1 ↓ lV_n
		Deformation, concave	rV		rV_1 ↓ rV_n

Table 3 Intensity classification of the weathering form 'back weathering' for two monuments in Cairo (Egypt).							
Weathering form 'back weathering (W)' Intensity classification (W_1 - W_7) according to ***depth of back weathering in cm***							
Monuments	**Intensity classes**						
	W_1	W_2	W_3	W_4	W_5	W_6	W_7
El-Merdani Mosque composed of **small** dimension stones	*< 0.2*	*0.2 – 0.5*	*0.5 – 1.0*	*1.0 – 3.0*	*3.0 – 5.0*	*5.0 – 10*	*> 10*
Great Pyramid of Cheops composed of **huge** dimension stones	*< 5.0*	*5.0 – 15*	*15 – 25*	*25 – 50*	*50 – 75*	*75 – 100*	*> 100*

By means of monument mapping, all weathering forms are registered systematically according to type, intensity, combinations and distribution. The information is illustrated on maps of weathering forms. Examples are shown for a part of the northern wall of Karnak Temple in Luxor (Egypt) (Fig. 12 - 15). Illustration of weathering forms according to groups of weathering forms has turned out to be effective here. Figures 14 and 15 show all weathering forms of group 1 - ‘loss of stone material’ and group 3 - ‘detachment’. In the same way, weathering forms of group 2 – ‘discoloration / deposits’ and group 4 – ‘fissures / deformation’ are illustrated in other maps not reproduced here. The maps represent layers, which – when superimposed - provide complete information on weathering forms, their combinations and intensities.

Fig. 12. Karnak Temple, Luxor (Egypt).

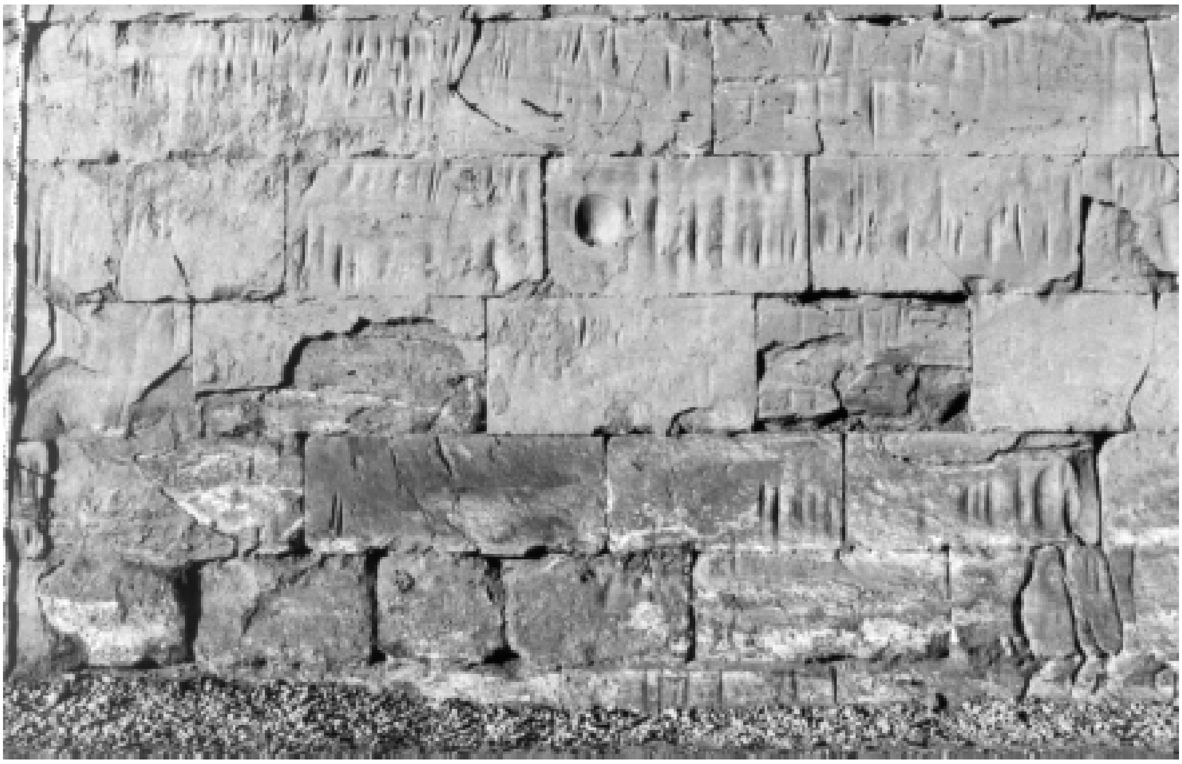

Fig. 13. Karnak Temple, northern wall, Luxor (Egypt).

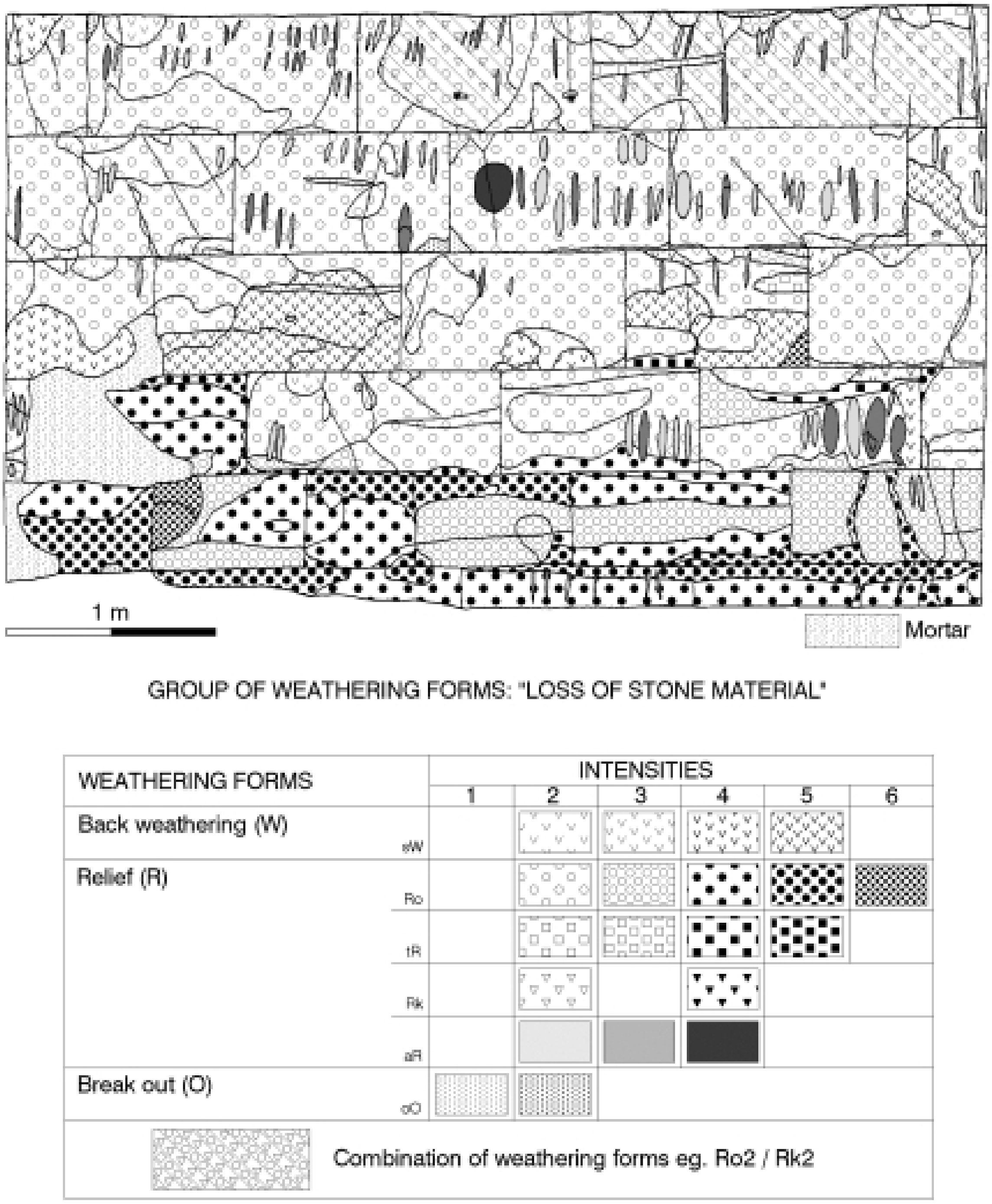

Fig. 14. Map of group 1 of weathering forms: 'Loss of stone material'. Karnak Temple, northern wall, Luxor (Egypt).

All weathering forms are evaluated quantitatively. The quantitative evaluation of weathering forms for part of the northern wall of Karnak Temple is presented in Table 4.

The mapping results of weathering forms in group 1 - ‘loss of stone material’ allow the calculation of average weathering rates. Figure 16 shows a map of average weathering rates for the Silk Tomb, a monument carved from bedrock about 2000 years ago in Petra (Jordan).

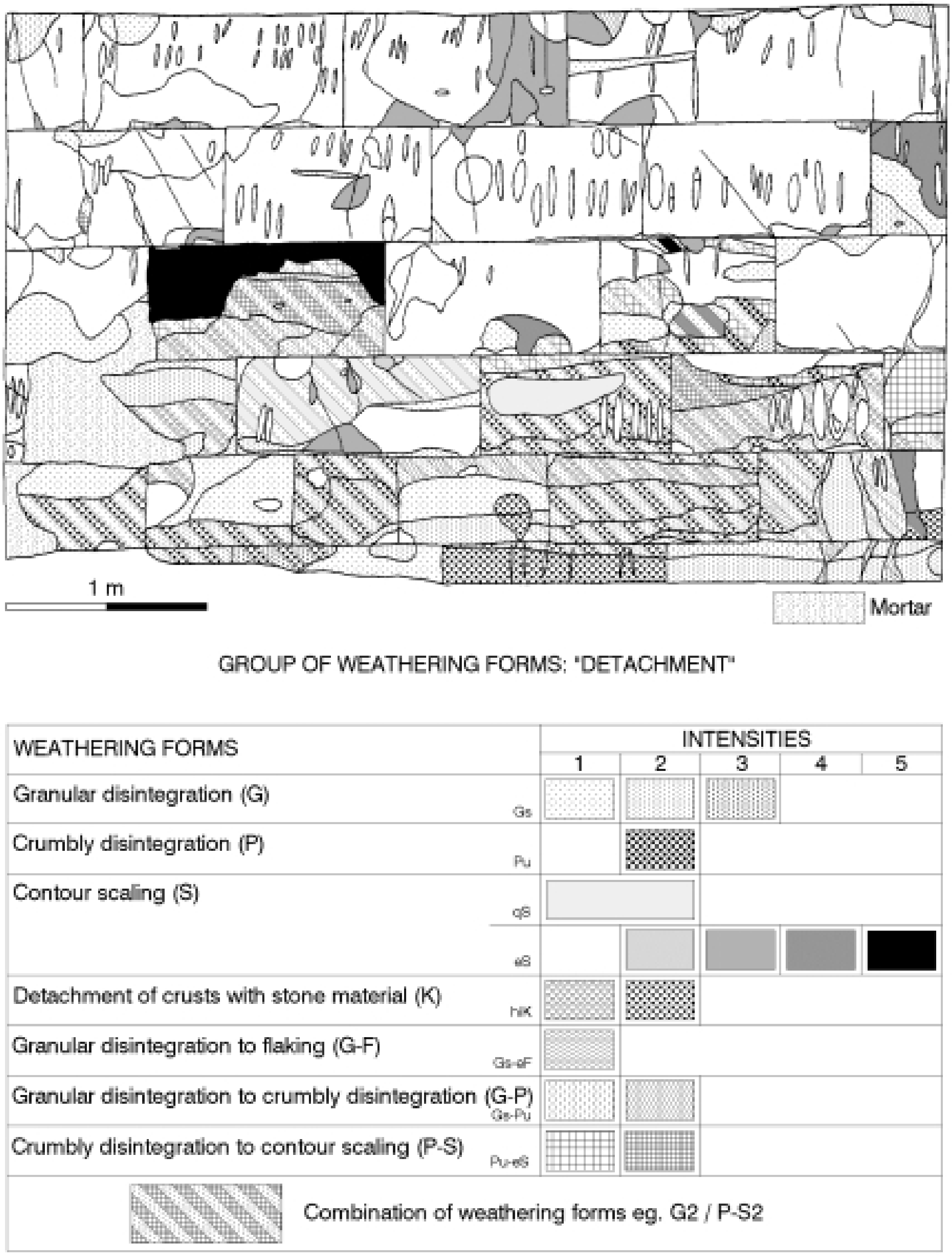

Fig. 15. Map of group 3 of weathering forms: 'Detachment'. Karnak Temple, northern wall, Luxor (Egypt).

Additionally, the average weathering rate for the entire monument has been determined. Evaluation of weathering rates contributes to assessment of weathering progression and to weathering prognosis and rating of stone durability. In Table 5 two monuments in Petra (Jordan) are compared with respect to lithotypes and average weathering rates.

Table 4 Quantitative evaluation of weathering forms. Karnak Temple, northern wall, Luxor (Egypt).

Intensities of weathering forms (shaded) | Area-% (unshaded)

BACK WEATHERING (W)	depth of back weathering (cm) < 0.5	0.5-1	1–3	3-5	5-10	10-25	> 25
Back weathering due to loss of scales (sW)	-	0.1	1.5	2.7	5.1	-	-

RELIEF (R)	depth of relief (cm) < 0.5	0.5-1	1-3	3-5	5-10	10-25	> 25
Rounding / notching (Ro)	-	60.9	8.9	10.5	5.5	0.6	-
Weathering out dependent on stone structure (tR)	-	0.1	0.4	0.3	0.2	-	-
Weathering out of stone components (Rk)	-	8.9	-	< 0.1	-	-	-
Relief due to anthropogenic impact (aR)	-	1.6	0.9	0.3	-	-	-

BREAK OUT (O)	volume of break out (cm^3) < 10	10-125	125-500	500-1000	1000-2500	> 2500
Break out due to non-recognizable cause (oO)	0.2	0.2	-	-	-	-

SOILING (I)	mass of deposits low	high
Soiling by particles from water (wI)	86.4	13.6

LOOSE SALT DEPOSITS (E)	mass of salt deposits low	high
Efflorescences (Ee)	1.8	0.9
Subflorescences (Ef)	< 0.1	-

CRUST (C)	mass of deposits, thickness of the crust low	high
Dark-colored crust tracing the surface (dkC)	0.3	-
Light-colored crust changing the surface (hiC)	6.9	24.5

GRANULAR DISINTEGRATION (G)	mass of detaching stone material low	medium	high
Granular disintegration into sand (Gs)	16.4	16.9	0.7

CRUMBLY DISINTEGRATION (P)	mass of detaching stone material low	medium	high
Crumbling (Pu)	-	1.1	-

CONTOUR SCALING (S)	thickness of the scales (cm) < 0.5	0.5-1	1-3	3-5	> 5
Scale due to tooling of the stone surface (qS)	3.5				
Single scale (eS)	-	0.1	3.0	1.7	2.1

DETACHMENT OF CRUSTS WITH STONE MATERIAL (K)	mass of detaching stone material low	medium	high
Detachment of a light-colored crust changing the surface (hiK)	8.1	11.0	-

GRANULAR DISINTEGRATION TO FLAKING (G-F)	mass of detaching stone material low	medium	high
Granular disintegration into sand to single flakes (Gs-eF)	0.2	-	-

GRANULAR DISINTEGRATION TO CRUMBLY DISINTEGRATION (G-P)	mass of detaching stone material low	medium	high
Granular disintegration into sand to crumbling (Gs-Pu)	5.0	1.2	-

CRUMBLY DISINTEGRATION TO CONTOUR SCALING (P-S)	mass of detaching stone material low	medium	high
Crumbling to single scale (Pu-eS)	4.3	2.7	-

FISSURES (L)	number and dimension (length, width) of fissures low / small	high / large
Fissures independent of stone structure (vL)	35.5	26.1
Fissures dependent on stone structure (tL)	-	5.2

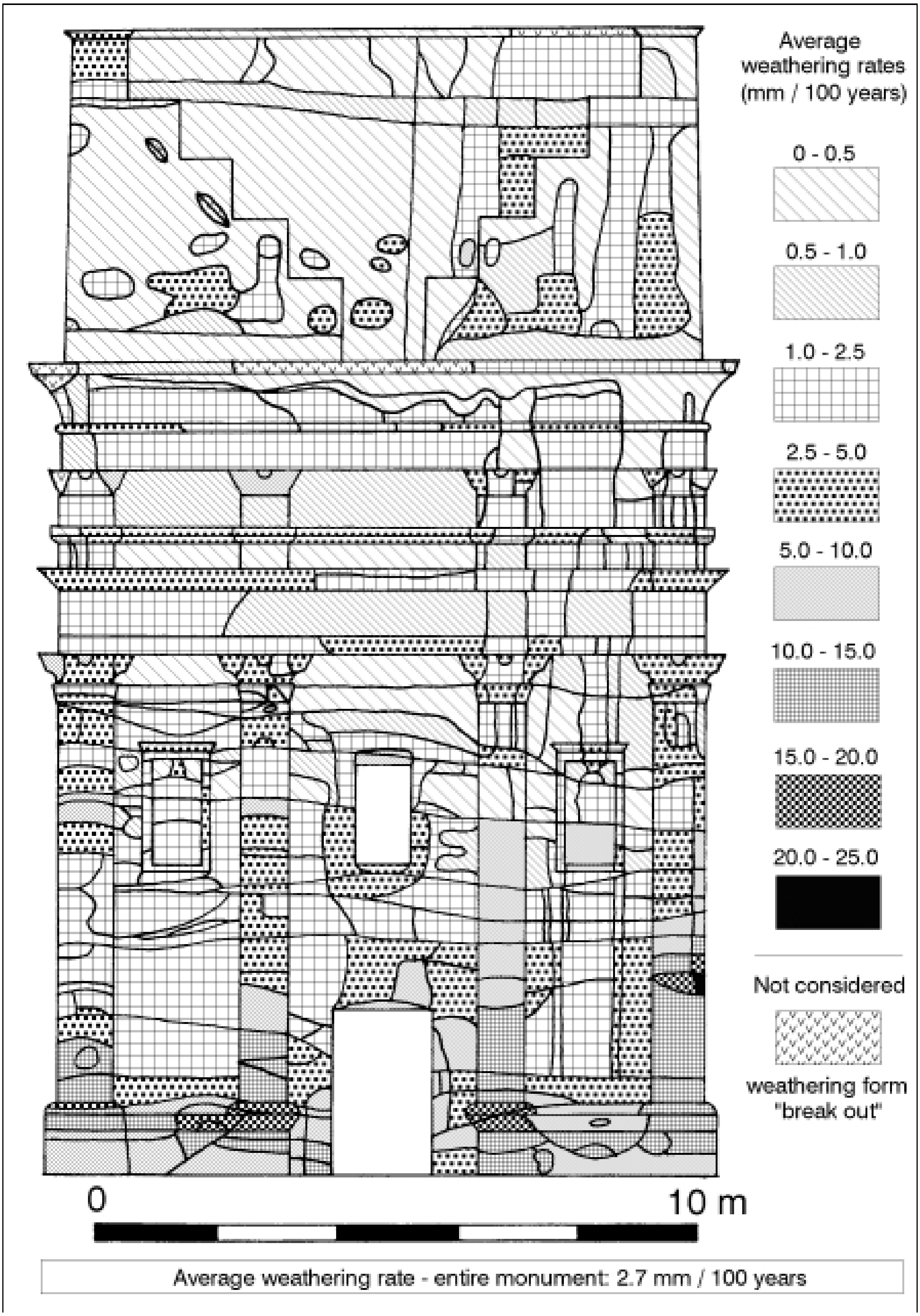

Fig. 16 Weathering rates. Silk Tomb (No. 770), Petra (Jordan).

Table 5. Lithotypes, petrographical properties and average weathering rates. Tombs No. 770 and No. 9, Petra (Jordan).		
	Tomb No. 770	**Tomb No. 9**
Lithotype	multicolored, massive sandstone	white, massive sandstone
Stratigraphy	Umm Ishrin Sandstone Formation (Cambrian)	Disi Sandstone Formation (Ordovician)
Petrographic classification	matrix-rich sandstone	quartz sandstone
Matrix-grain ratio	0.23	0.09
Mean grain size (mm)	0.17 fine-grained	0.31 medium-grained
Grain contacts (number per cm^2 –thin section analysis)	~ 4.500	~ 1.400
Type of grain contacts	mainly long or concavo-convex contacts	mainly point contacts
Total porosity (Vol.-%)	17.4	21.3
Median pore radius (µm)	13.0	115.0
Drilling resistance (-)	~ 4.5	~ 2.0
AVERAGE WEATHERING RATE (mm / 100 years)	2.7	4.7

The results reveal significantly lower stone durability of the Ordovician sandstone in Tomb No. 9 compared to the Cambrian sandstone in Tomb No. 770. Higher susceptibility of the Ordovician sandstone to weathering is caused by weaker grain bonds, unfavourable porosity characteristics and lower strength / hardness.

Deduction of chronological sequences of weathering forms creates an important additional approach to providing realistic information on the progress of weathering. Statistical evaluation of recent weathering forms referring to the interrelation between ‘loss of stone material’, ‘detachment’ and ‘deposits’ has been made, jointly considering different monuments carved from the same sandstone type in Petra (Jordan) (Fig. 17 and 18). In Figure 17 interrelations between ‘loss of stone material’ and type of ‘detachment of stone material’ are presented. In Figure 18 interrelations between ‘loss of stone material’ and type / intensity of ‘deposits’ are shown. In the Petra area crust formation is preceded by soiling. From ‘soiling’ to ‘crust’ consolidation of particles and adhesion to the stone surface increases. The Figures 17 and 18 show, that increasing loss of stone material corresponds to decreasing size of detaching stone elements from larger-sized elements (contour scaling) via medium-sized elements (flaking to contour scaling) to small-sized and smallest-sized elements (granular disintegration to flaking, granular disintegration) and at the same time to decreasing frequency and intensity of deposits. The decreasing frequency and intensity of deposits on the detaching stone elements reveals increasing velocity of stone detachment in the course of weathering progression.

From the co-existence of weathering forms presented, a chronological succession of these combinations of weathering forms can be assumed as very probable.

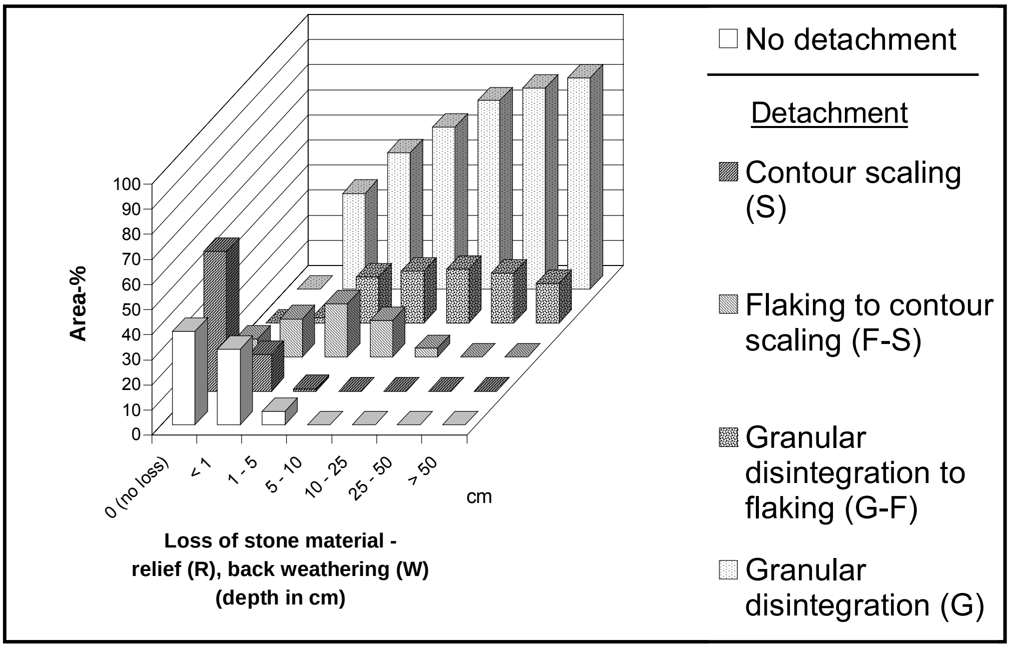

Fig. 17 Interrelations between recent weathering forms referring to 'loss of stone material' and 'detachment of stone material'. Tombs carved from Ordovician sandstone, Petra (Jordan).

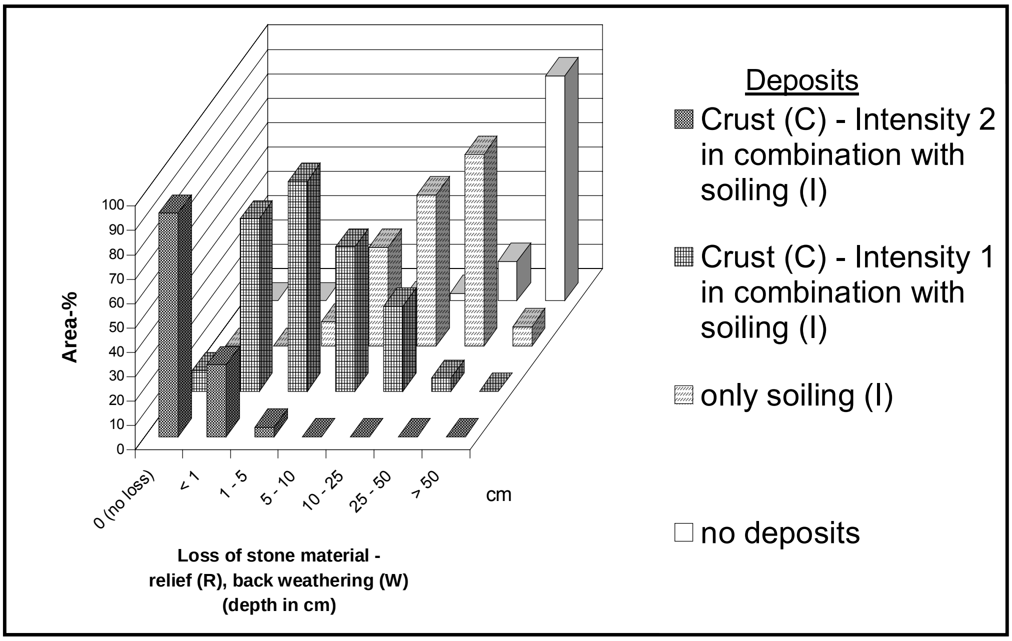

Fig. 18 Interrelations between recent weathering forms referring to 'loss of stone material' and 'deposits'. Tombs carved from Ordovician sandstone, Petra (Jordan).

Quantification of weathering progression remains an important aim of such systematic evaluation of weathering forms and their interrelations.

EVALUATION OF DAMAGE - DAMAGE CATEGORIES AND DAMAGE INDICES

While weathering forms allow precise description of deterioration phenomena, damage categories have been established for subsequent rating of individual damage. Damage indices have been introduced as a further tool for conclusive quantification and rating of stone damage. They complete the consistent approach to characterization, evaluation, quantification and rating of visible stone damages and to risk prognosis and risk management [14].

Damage categories

For rating of individual damage, six damage categories have been defined: 0 – no visible damage, 1 – very slight damage, 2 – slight damage, 3 – moderate damage, 4 – severe damage, 5 – very severe damage. Based on correlation schemes, all weathering forms are related to damage categories. The development of suitable correlation schemes 'weathering forms – damage categories' must consider the intensities of weathering forms, the proportion of degradated stone parts to total structural element (e.g. dimension stone), the function of the structural elements as well as the historical and artistical value of the structural elements (Fig. 19). The development of correlation schemes of weathering forms and damage categories should be made in cooperation with all experts involved in the monument preservation activities. Examples of correlation schemes of weathering forms and damage categories are presented in [6, 12, 13]. The section of a correlation scheme of weathering forms and damage categories presented in Table 6 refers to studies at El-Merdani Mosque in Cairo (Egypt) (see also section 'Case studies').

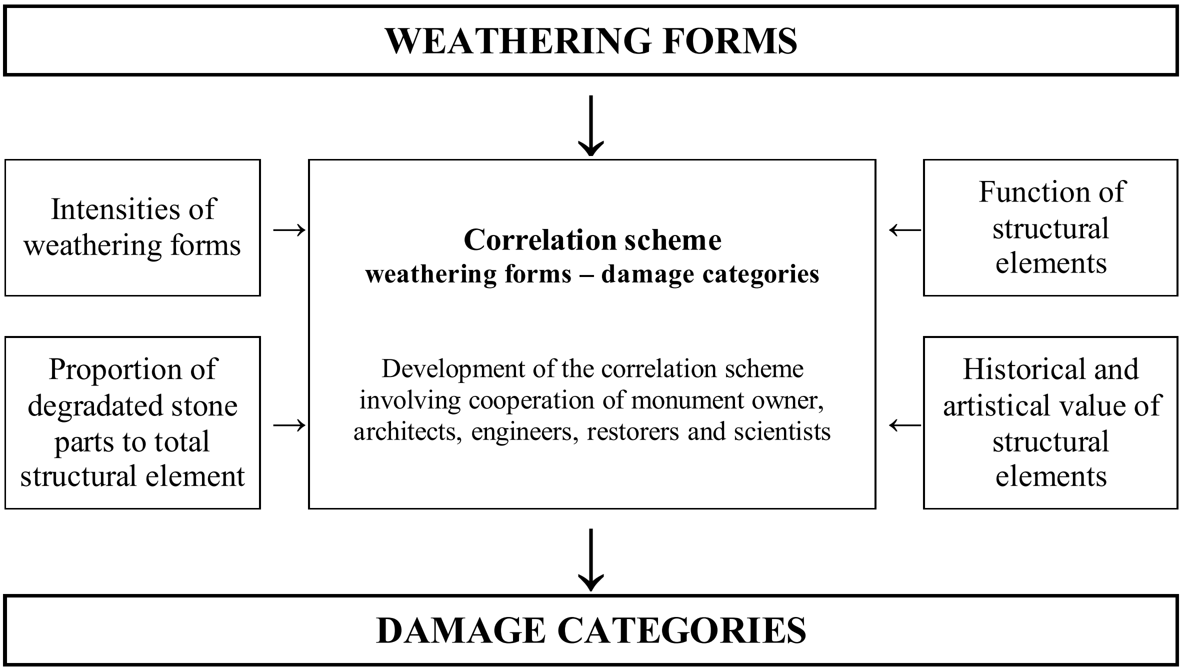

Fig. 19 Relating of weathering forms to damage categories.

Table 6 Correlation scheme of weathering forms and damage categories - section. El-Merdani Mosque, Cairo (Egypt).

Weathering form		Depth (mm)						
Weathering form: BACK WEATHERING (W)	Intensity	< 2	2-5	5-10	10-30	30-50	50-100	> 100
	Damage category	1	2	3	4	4	5	5

Weathering form		Volume (cm^3)				
Weathering form: BREAK OUT (O)	Intensity	< 10	10-125	125-500	500-1000	> 1000
	Damage category	2	3	4	5	5

Weathering form		Thickness (mm)				
Weathering form: CONTOUR SCALING (S)	Intensity	< 2	2-5	5-10	10-20	> 20
	Damage category	1	2	3	4	4

DAMAGE CATEGORIES		
0 – no visible damage	1 – very slight damage	2 – slight damage
3 – moderate damage	4 – severe damage	5 – very severe damage

The high historical importance of the mosque as one of the finest examples of Islamic architecture in the historical center of Cairo has been taken into account. Damage categories are proposed for the weathering forms in dependence upon their intensities. Thus, higher damage categories correspond to higher intensities of the weathering forms. Table 7 shows the damage categories for the weathering form „relief" for the Minster St. Quirin in Neuss (Germany) and the Great Pyramid of Cheops in Cairo (Egypt). The different intensity range of the weathering form „relief" at the two monuments is controlled by the size of the dimension stones. For relating the weathering form to damage categories, the proportion of degradated stone parts to total dimension stone has been considered.

As a first step, damage categories are determined for each group of weathering forms. In the next step, schemes are developed for derivation of final damage categories considering all groups of weathering forms.

Table 7 Relating of the weathering form 'relief' to damage categories for two monuments with different range of intensity of the weathering form.

Monument	Weathering form: Relief (R)					
Minster St. Quirin – Neuss (Germany), composed mainly of very small dimension stones	Intensities - depth of relief in cm	< 0.5	0.5 - 1	1 - 2	2 - 3	> 3
Great Pyramid of Cheops – Cairo (Egypt), composed of huge dimension stones		< 5	5 - 15	15 - 25	25 - 50	> 50
DAMAGE CATEGORIES		1	2	3	4	5

The damage categories are illustrated in maps and are evaluated quantitatively. Examples of determination, illustration and quantitative evaluation of damage categories are presented in section 4. With respect to monument preservation, damage categories are very suitable indicators for need and urgency of interventions. Maps of damage categories locate those parts of monuments which interventions have to focus on.

Damage indices

Damage indices have been introduced for conclusive quantification and rating of weathering damage at stone monuments [13, 14]. Calculation of damage indices is based on the quantitative evaluation of damage categories (Table 8). A linear damage index and a progressive damage index have been defined. According to the calculation modes, both damage indices range between 0 and 5.0. The linear damage index corresponds to the average damage category, whereas the progressive damage index emphasizes the proportion of higher damage categories.

Table 8 Linear and progressive damage index.

LINEAR DAMAGE INDEX DI_{lin} =	PROGRESSIVE DAMAGE INDEX DI_{prog} =
$\frac{(A\cdot 0)+(B\cdot 1)+(C\cdot 2)+(D\cdot 3)+(E\cdot 4)+(F\cdot 5)}{100}$ ↓ $\frac{B+(C\cdot 2)+(D\cdot 3)+(E\cdot 4)+(F\cdot 5)}{100}$	$\sqrt{\frac{(A\cdot 0^2)+(B\cdot 1^2)+(C\cdot 2^2)+(D\cdot 3^2)+(E\cdot 4^2)+(F\cdot 5^2)}{100}}$ ↓ $\sqrt{\frac{B+(C\cdot 4)+(D\cdot 9)+(E\cdot 16)+(F\cdot 25)}{100}}$
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
$\sum_{A}^{F} = 100$	
$0 \leq DI_{lin} \leq 5$	$0 \leq DI_{prog} \leq 5$

The following relation arises: progressive damage index ≥ linear damage index. Figure 20 shows the possible range of the relation between the linear and the progressive damage index. Figure 21 shows for each linear damage index the corresponding maximum difference between progressive damage and linear damage index. The deviation of the progressive damage index from the linear damage index increases as the proportion of higher damage categories increases (Table 9).

The application of damage indices ensures reliable and reproducible quantification and rating of weathering damage and provides important information on need and urgency of preservation measures Table 10). Increasing damage indices correspond to increasing need and urgency of intervention. Linear and progressive damage index have to be jointly considered for rating need and urgency of intervention. Even in the case of a low linear damage index, a considerable proportion of high damage categories may be found (Table 9).

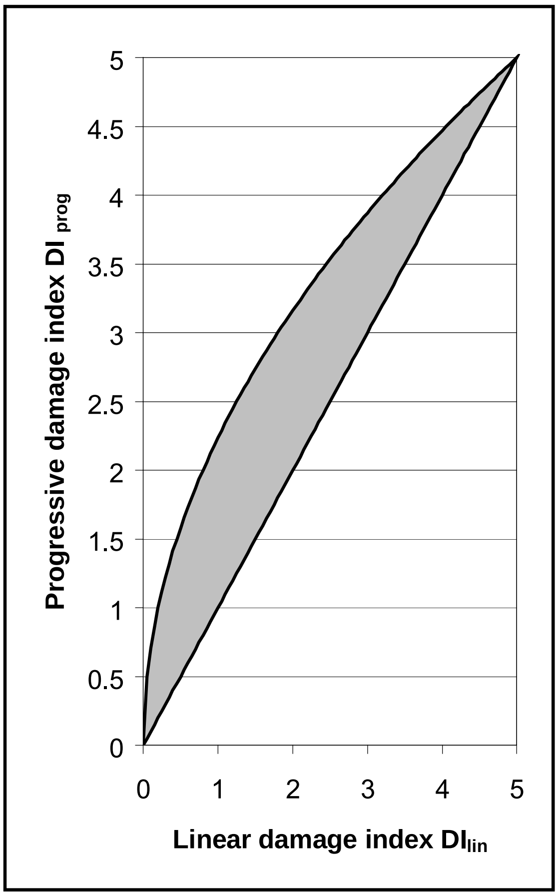

Fig. 20. Range of the relation between the linear damage index and the progressive damage index.

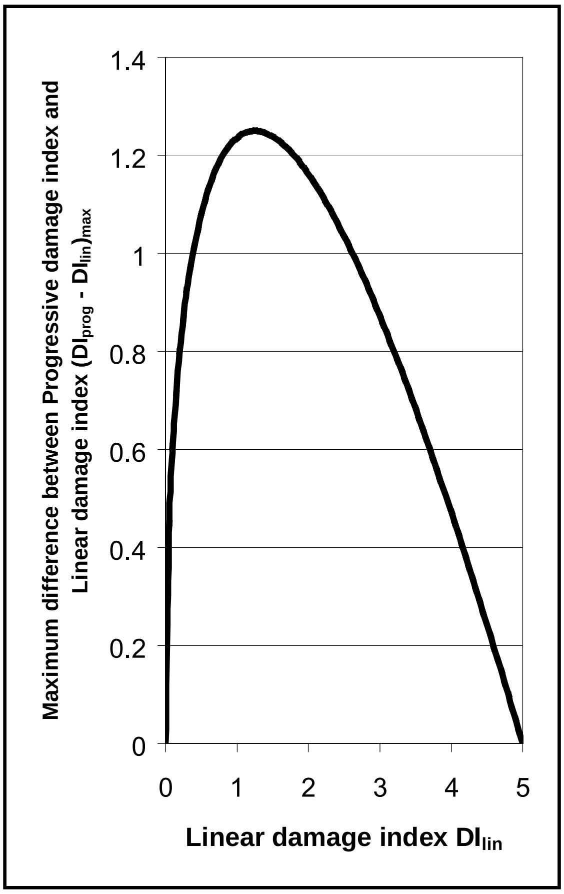

Fig. 21. Maximum difference between progressive damage index and linear damage index.

In this case, the high deviation of the progressive damage index from the linear damage index also indicates a need for preservation measures.

Table 9. Linear damage index and range of progressive damage index for different proportions of damage categories.

<table>
<tr><th colspan="6">Proportion of damage categories – area-%</th><th rowspan="2">Linear damage index DI_{lin}</th><th rowspan="2">Progressive damage index DI_{prog}</th><th rowspan="2">Need / urgency of intervention</th></tr>
<tr><th>Damage category 0</th><th>Damage category 1</th><th>Damage category 2</th><th>Damage category 3</th><th>Damage category 4</th><th>Damage category 5</th></tr>
<tr><td>-</td><td>100</td><td>-</td><td>-</td><td>-</td><td>-</td><td rowspan="4">1.0</td><td>1.0</td><td rowspan="4">↓ increasing ↓</td></tr>
<tr><td>40</td><td>30</td><td>20</td><td>10</td><td>-</td><td>-</td><td>1.4</td></tr>
<tr><td>60</td><td>10</td><td>10</td><td>10</td><td>10</td><td>-</td><td>1.7</td></tr>
<tr><td>80</td><td>-</td><td>-</td><td>-</td><td>-</td><td>20</td><td>2.2</td></tr>
</table>

CASE STUDIES

The consequent use of weathering forms, damage categories and damage indices obtained from monument mapping is demonstrated for five case studies. Emphasize is given to the application and significance of damage categories and damage indices.

Table 10. Objectives of damage indices.
OBJECTIVES OF DAMAGE INDICES
GENERAL OBJECTIVE Conclusive quantification and rating of stone damage for entire stone monuments or single stone structures
Comparison and ranking of different stone monuments regarding their state of damage
Comparison and ranking of different structures of a monument regarding state of damage, considering e.g. different age, orientation or other exposure characteristics, zonation of damages etc.
Comparison and rating of stone materials regarding their susceptibility to deterioration
Risk estimation, risk prognosis
Contribution to risk management, judgement of need and urgency of intervention
Judgement / certification and long-term control of monument preservation measures
Contribution to long-term survey and maintenance of monuments

In all five cases, mapping of weathering forms was made according to the most differentiated level IV of the classification scheme of weathering forms (individual weathering forms with differentiation of intensities). The following case studies are presented:

1) Karnak Temple in Luxor (Egypt)
   - correlation scheme of weathering forms and damage categories;
   - scheme for determination of final damage categories by joint consideration of damage categories referring to the individual groups of weathering forms;
   - damage categories referring to groups of weathering forms and damage categories jointly considering all weathering forms, quantitative evaluation of damage categories;
   - damage indices for rating of damages according to groups of weathering forms and damage indices jointly considering all weathering forms;
2) Monuments carved from bedrocks in Petra (Jordan)
   - damage indices for characterization of damage zonation (vertical profile);
   - damage indices for ranking of different structures of a monument considering different orientation;
   - damage indices for ranking of many monuments regarding state of damage and need / urgency of intervention;
3) El-Merdani Mosque in Cairo (Egypt)
   - damage categories and damage indices for characterization of damage zonation (vertical profile);

4) Church of Sao Francisco de Assis in Ouro Preto (Brazil)
   - damage categories and damage indices for rating of stone durability,
5) Minster St. Quirin in Neuss (Germany)
   - damage categories and damage indices for judgement / certification of restoration measures and for long-term survey of the monument.

Table 11 Relating of weathering forms to damage categories. Karnak Temple, northern wall, Luxor (Egypt).

Intensities of weathering forms (grey cells) — Damage categories (white cells)

BACK WEATHERING (W)	depth of back weathering (cm)						
	< 0.5	0.5-1	1–3	3-5	5-10	10-25	> 25
Back weathering due to loss of scales (sW)	1	1	2	3	4	5	5
RELIEF (R)	depth of relief (cm)						
	< 0.5	0.5-1	1-3	3-5	5-10	10-25	> 25
Rounding / notching (Ro) Weathering out dependent on stone structure (tR) Weathering out of stone components (Rk) Relief due to anthropogenic impact (aR)	1	1	2	3	4	5	5
BREAK OUT (O)	volume of break out (cm^3)						
	< 10	10-125	125-500	500-1000	1000-2500	> 2500	
Break out due to non-recognizable cause (oO)	1	2	3	3	4	5	
SOILING (I)	mass of deposits						
	low	high					
Soiling by particles from water (wI)	1	1					
LOOSE SALT DEPOSITS (E)	mass of salt deposits						
	low	high					
Efflorescences (Ee) Subflorescences (Ef)	1	2					
CRUST (C)	mass of deposits, thickness of the crust						
	low	high					
Dark-colored crust tracing the surface (dkC)	1	2					
Light-colored crust changing the surface (hiC)	2	3					
GRANULAR DISINTEGRATION (G)	mass of detaching stone material						
	low	medium	high				
Granular disintegration into sand (Gs)	1	2	3				
CRUMBLY DISINTEGRATION (P)	mass of detaching stone material						
	low	medium	high				
Crumbling (Pu)	1	2	3				
CONTOUR SCALING (S)	thickness of the scales (cm)						
	< 0.5	0.5-1	1-3	3-5	> 5		
Scale due to tooling of the stone surface (qS)	1	1					
Single scale (eS)	1	1	2	3	4		
DETACHMENT OF CRUSTS WITH STONE MATERIAL (K)	mass of detaching stone material						
	low	medium	high				
Detachment of a light-colored crust changing the surface (hiK)	1	2	3				
GRANULAR DISINTEGRATION TO FLAKING (G-F)	mass of detaching stone material						
	low	medium	high				
Granular disintegration into sand to single flakes (Gs-eF)	1	2	3				
GRANULAR DISINTEGRATION TO CRUMBLY DISINTEGRATION (G-P)	mass of detaching stone material						
	low	medium	high				
Granular disintegration into sand to crumbling (Gs-Pu)	1	2	3				
CRUMBLY DISINTEGRATION TO CONTOUR SCALING (P-S)	mass of detaching stone material						
	low	medium	high				
Crumbling to single scale (Pu-eS)	1	2	3				
FISSURES (L)	number and dimension (length, width) of fissures						
	low / small	high / large					
Fissures independent of stone structure (vL) Fissures dependent on stone structure (tL)	2	3					

Karnak Temple in Luxor (Egypt)

The historical monuments in Upper Egypt represent a cultural heritage of outstanding value. Ancient Thebes with its Necropolis, Luxor Temple, Karnak Temple, Medinet Habu and Ramesseum has been inscribed into the UNESCO-list of world cultural heritage as a ‘striking testimony to Egyptian civilisation at its height’.

DCLS – Damage categories for 'loss of stone material'	DCDT - Damage categories for 'detachment'	DCDD - Damage categories for 'discoloration / deposits': 0			1			2			3		
0	0	0	2	3	1	2	3	2	2	3	3	3	3
	1	1	2	3	1	2	3	2	2	3	3	3	3
	2	2	2	3	2	2	3	2	2	3	3	3	3
	3	3	3	4	3	3	4	3	3	4	3	3	4
	4	4	4	5	4	4	5	4	4	5	4	4	5
1	0	1	2	3	1	2	3	2	2	3	3	3	3
	1	1	2	3	1	2	3	2	2	3	3	3	3
	2	2	2	3	2	2	3	2	2	3	3	3	3
	3	3	3	4	3	3	4	3	3	4	3	3	4
	4	4	4	5	4	4	5	4	4	5	4	4	5
2	0	2	2	3	2	2	3	2	2	3	3	3	3
	1	2	2	3	2	2	3	2	2	3	3	3	3
	2	2	3	3	2	3	3	2	3	3	3	3	3
	3	3	3	4	3	3	4	3	3	4	3	3	4
	4	4	4	5	4	4	5	4	4	5	4	4	5
3	0	3	3	4	3	3	4	3	3	4	3	3	4
	1	3	3	4	3	3	4	3	3	4	3	3	4
	2	3	3	4	3	3	4	3	3	4	3	3	4
	3	4	4	5	4	4	5	4	4	5	4	4	5
	4	5	5	5	5	5	5	5	5	5	5	5	5
4	0	4	4	5	4	4	5	4	4	5	4	4	5
	1	4	4	5	4	4	5	4	4	5	4	4	5
	2	4	4	5	4	4	5	4	4	5	4	4	5
	3	5	5	5	5	5	5	5	5	5	5	5	5
	4	5	5	5	5	5	5	5	5	5	5	5	5
5	0	5	5	5	5	5	5	5	5	5	5	5	5
	1	5	5	5	5	5	5	5	5	5	5	5	5
	2	5	5	5	5	5	5	5	5	5	5	5	5
	3	5	5	5	5	5	5	5	5	5	5	5	5
	4	5	5	5	5	5	5	5	5	5	5	5	5
DCFD - Damage categories for 'fissures / deformation'		0	2	3	0	2	3	0	2	3	0	2	3

Fig. 22. Scheme for determination of final damage categories (bold, italic numbers) by joint consideration of damage categories referring to the four groups of weathering forms. Karnak Temple, northern wall, Luxor (Egypt).

Studies on stone deterioration at Karnak Temple have been executed in the framework of a German-Egyptian research cooperation. The investigated stone structures at Karnak Temple were constructed with Silsila sandstone.

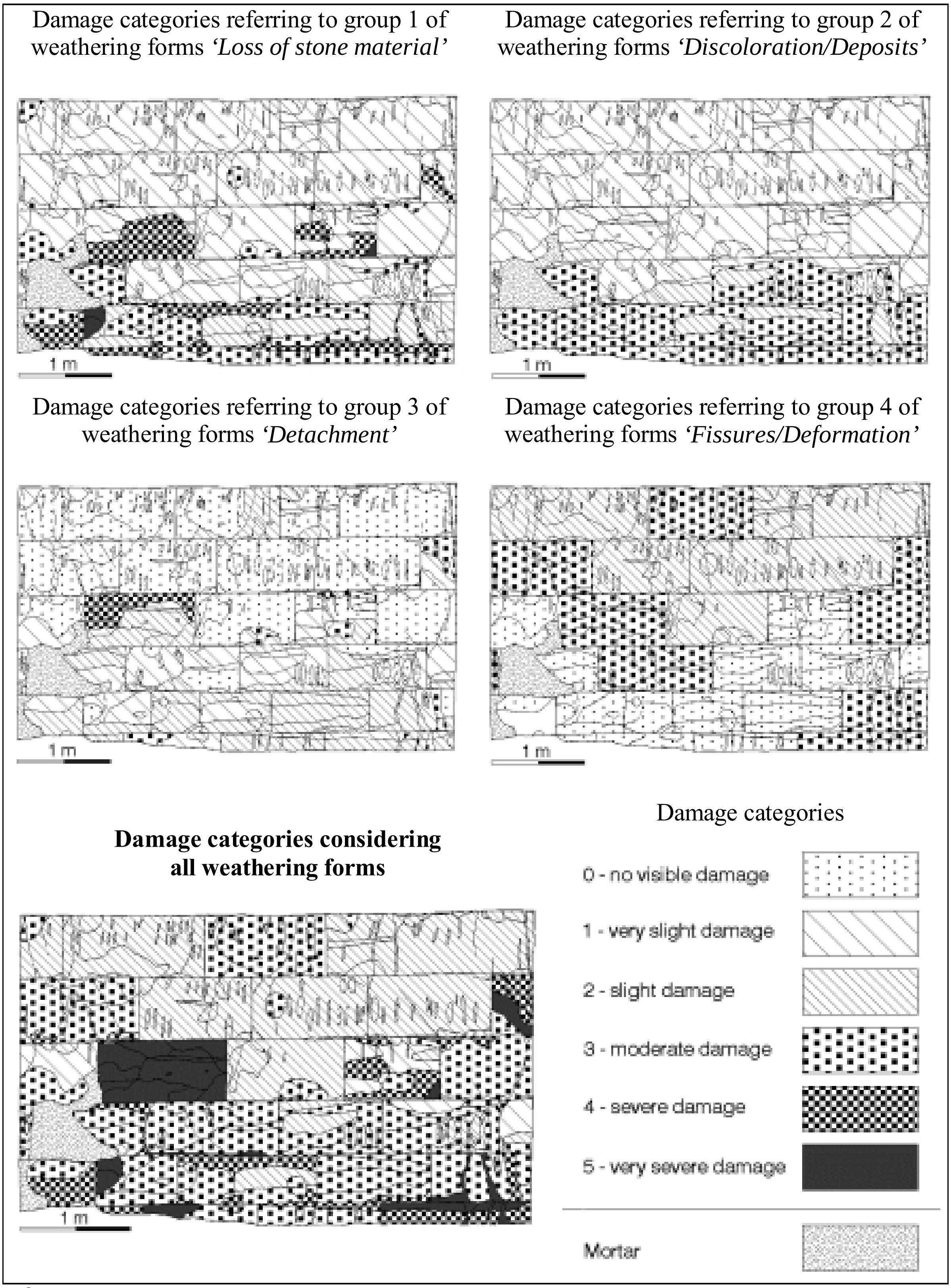

Fig. 23. Maps of damage categories. Karnak Temple, northern wall, Luxor (Egypt).

The evaluation of stone damages by means of weathering forms, damage categories and damage indices is demonstrated for a part of the northern wall of Karnak Temple (Fig. 13).

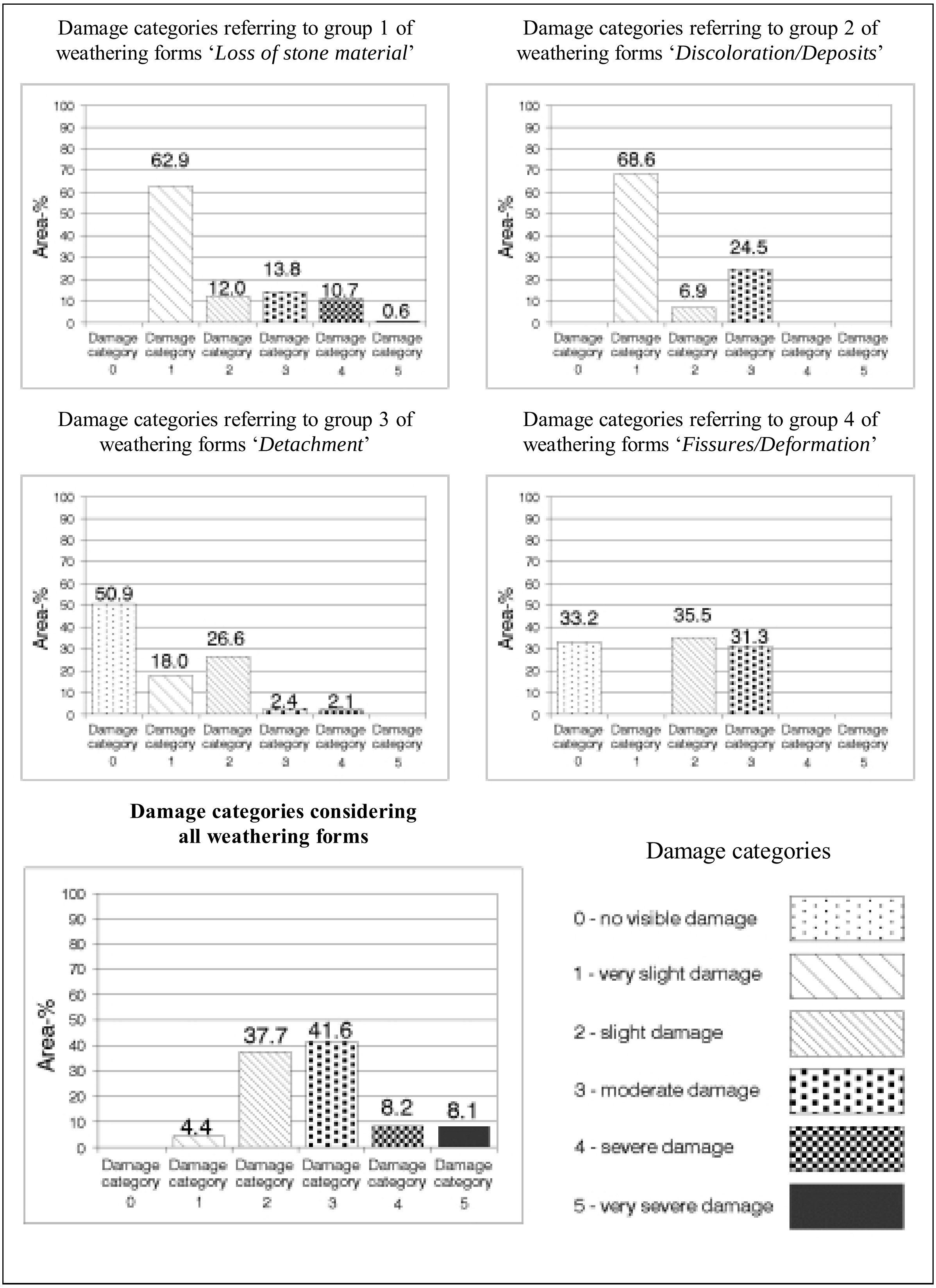

Fig. 24. Quantitative evaluation of damage categories. Karnak Temple, northern wall, Luxor (Egypt).

Weathering forms were mapped in detail. Examples for illustration of the weathering forms registered at this investigation area and quantitative evaluation of all weathering forms are presented in Figures 14 and 15 and in Table 4. Table 11 shows the correlation scheme of weathering forms and damage categories. As a first step, damage categories have been determined according to groups of weathering forms. As the second step, a scheme has been developed for the derivation of final damage categories jointly considering all groups of weathering forms (Fig. 22). The damage categories are illustrated in maps (Fig. 23) and are evaluated quantitatively (Fig. 24). Damage indices have been calculated referring to groups of weathering forms and considering all weathering forms (Fig. 25). Maps and quantitative evaluation of the damage categories and the damage indices exhibit considerable need and urgency of intervention. Interventions especially have to solve the loss of stone material, deposits and fissures. For remedy of these damages, interventions like stone repair, cleaning, desalination and structural reinforcement are under consideration.

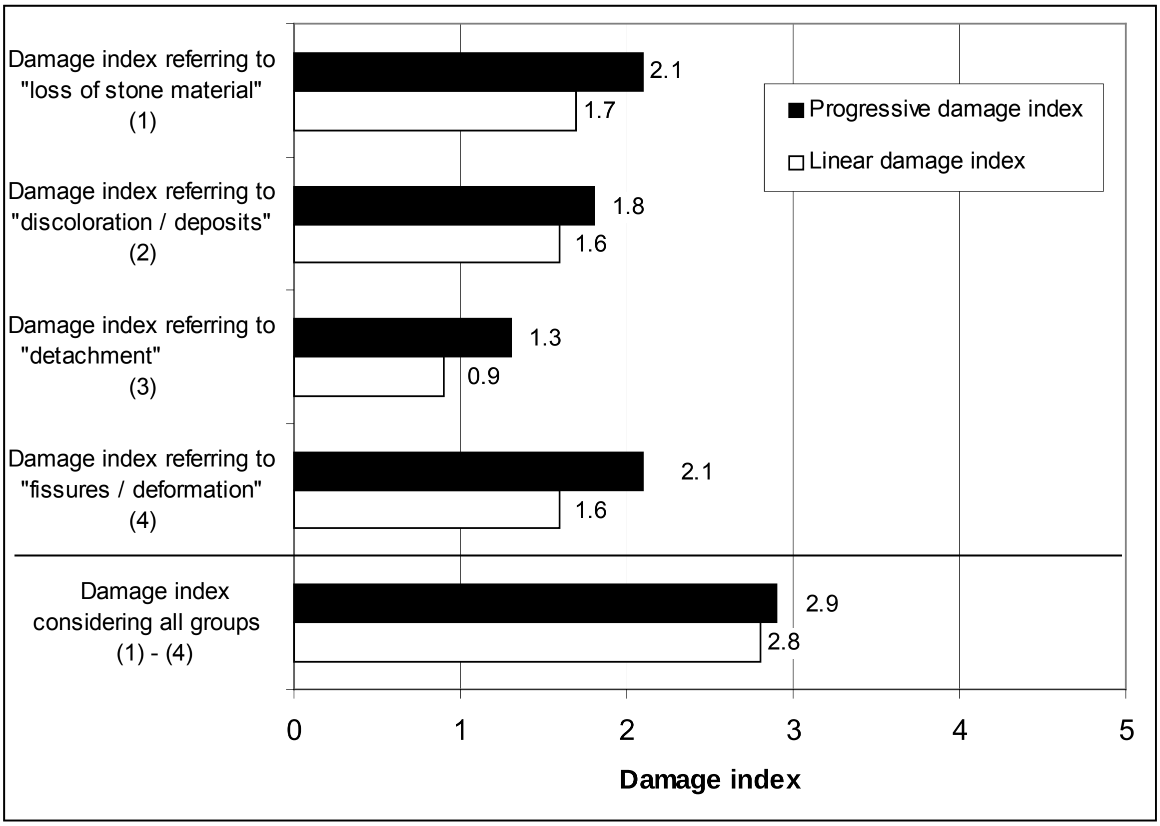

Fig. 25. Damage indices. Karnak Temple, northern wall, Luxor (Egypt).

Monuments carved from bedrocks in Petra (Jordan)

In the ancient Nabataean city of Petra in Jordan almost one thousand monuments such as tombs, sanctuaries or places of worship were carved from Cambro-ordovician sedimentary bedrocks about 2000 years ago. In 1985 Petra was inscribed into the UNESCO-list of world cultural heritage. At many monuments weathering damage is alarming. In 1998 the World Monument Fund inscribed Petra into the list of the one hundred most endangered monument assemblies of the world.

Fig. 26. Monastery (No. 462), Petra (Jordan).

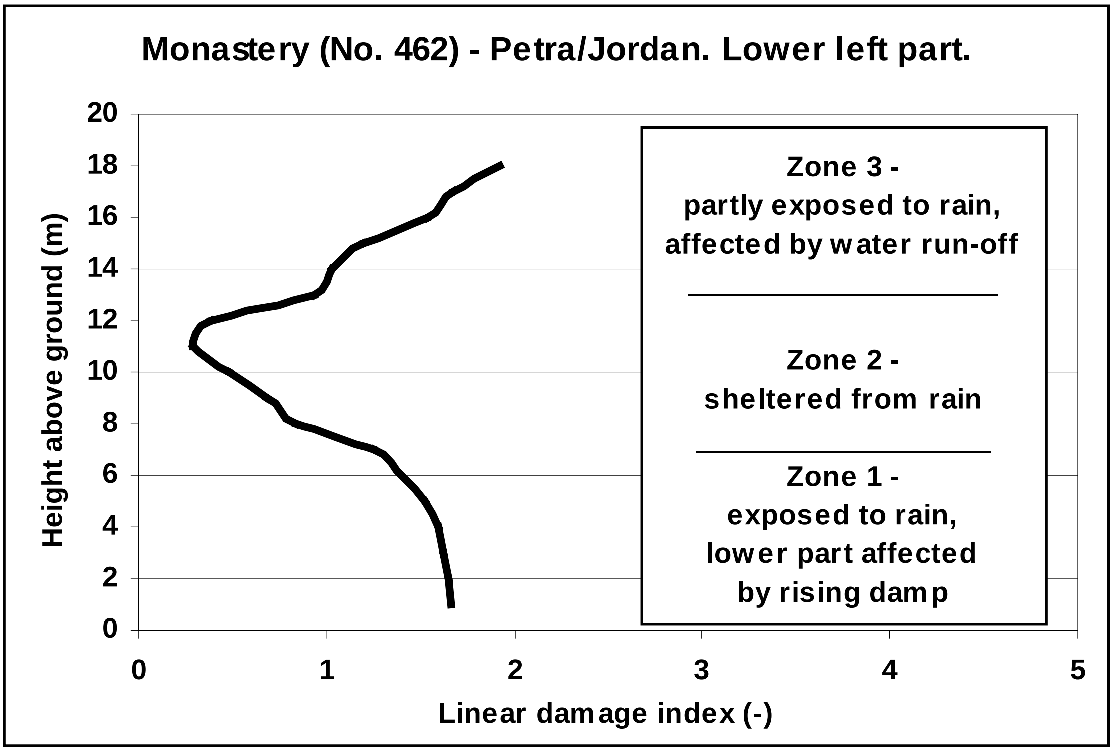

Fig. 27 Linear damage index across a vertical in relation to exposure characteristics. Monastery (No. 462), Petra (Jordan). Lower left part of the monument.

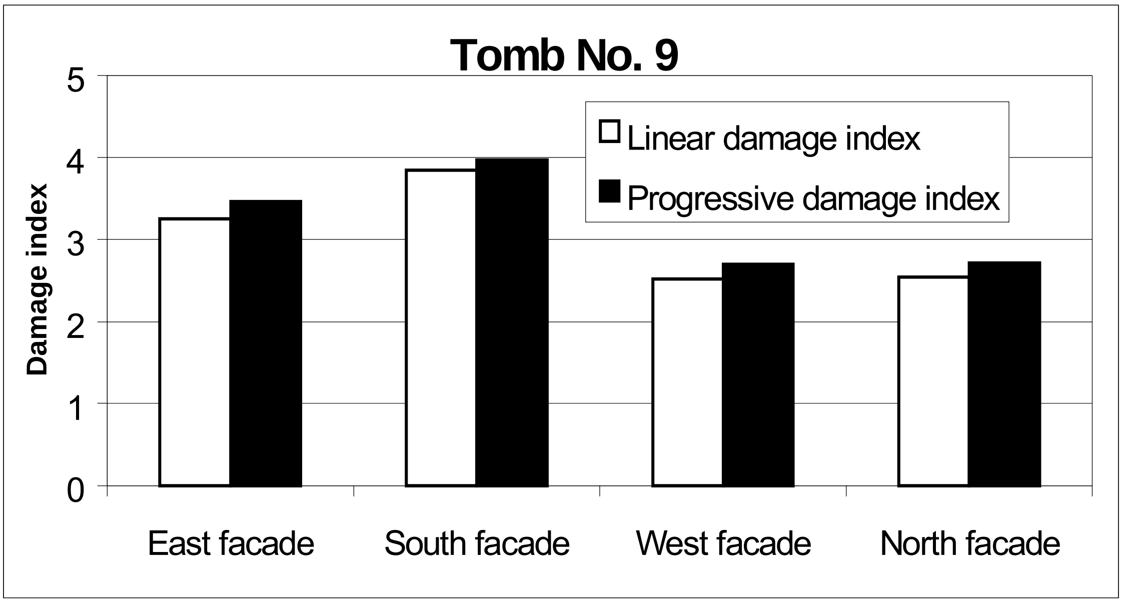

Fig. 28. Damage indices for the different façades of a monument. Tomb No. 9, Petra (Jordan).

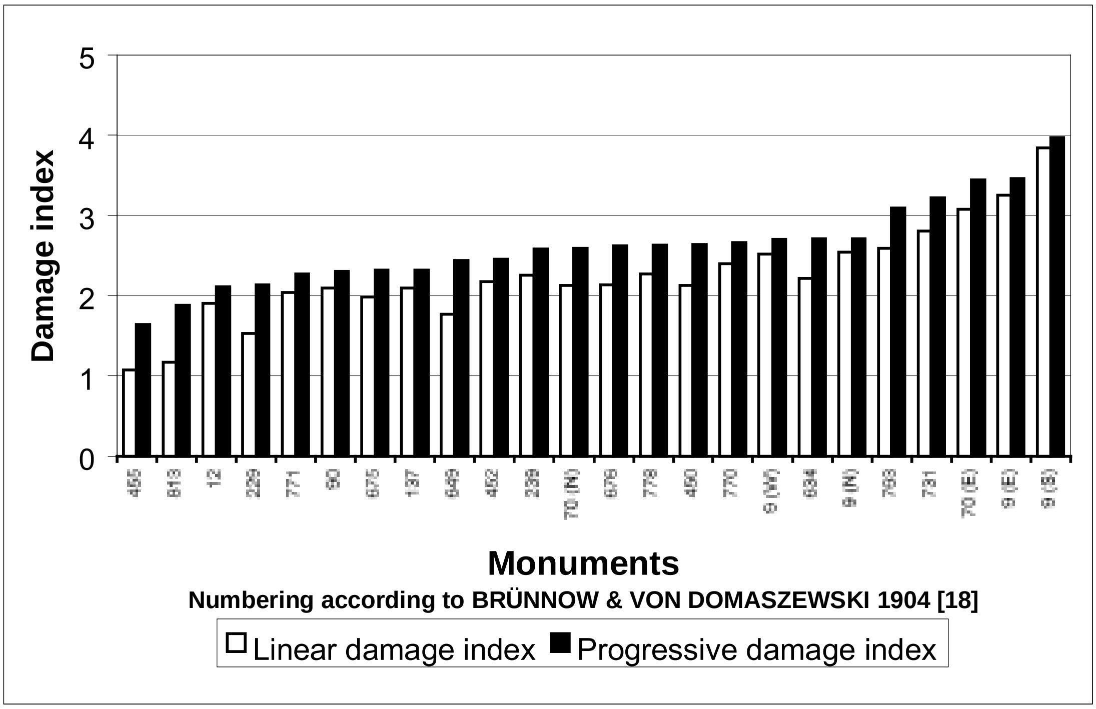

Fig. 29. Ranking of different monuments by means of damage indices. Monuments carved from bedrock, Petra (Jordan).

Research works have been carried out within the framework of the research project 'Systematic registration and evaluation of damages at monuments carved from bedrocks in Petra', funded by Deutsche Forschungsgemeinschaft (DFG) [13, 15-17]. The application of damage indices for scientific and practical purposes is presented by three examples.

The first example refers to the lower left part of the so-called Monastery (Ed-Der, Tomb No. 462), one of the most famous monuments in Petra (Fig. 26). Damage indices have been determined via weathering forms and damage categories in order to characterize damage zonation across a vertical profile in correlation with exposure characteristics. Damage indices have been calculated individually for sections of 1 m height (Fig. 27). Systematic evaluation of damage zonations allows statistical information on weathering damage in relation to monument exposure characteristics and environmental influences.

The second example refers to Tomb No. 9. Damage indices have been determined for quantification of damage on the monument in relation to the orientation of the façades. The four façades of the tomb show significantly different damage indices (Fig. 28). The highest damage indices, which correspond to the most severe state of damage, are stated for the south façade of the monument. This type of evaluation contributes to the assessment and rating of interrelations between stone material, microclimatic influences and stone deterioration. The damage indices in combination show a high susceptibility of the sandstone to weathering and they indicate the urgency of preservation measures.

The third example refers to all monuments studied in Petra. One aim of the studies was comparison of monuments regarding their state of damage and ranking of the monuments with respect to need and urgency of preservation measures. Based on mapping of weathering forms and evaluation by means of damage categories, damage indices have been determined for all monuments. The results in Figure 29 outline the wide range of damage to the monuments. The ranking of the monuments corresponds to increasing need and urgency of preservation measures. Priorities of interventions can be defined.

El-Merdani Mosque in Cairo (Egypt)

The El-Merdani Mosque is located in the Islamic center of Cairo in Egypt, declared by UNESCO as a world cultural heritage site. The mosque was built in the 14th century. It was restored a century ago, but is again in need of intervention. Different varieties of porous limestones from the Mokattam mountains near Cairo were used for construction. Studies at El-Merdani Mosque have been carried out within the framework of the E.C. Concerted Action ‘Study, characteruzation and analysis of degradation phenomena of ancient, traditional and improved building materials of geologic origin used in construction of historical monuments in the Mediterranean area’. Weathering damage, especially at the lower parts of the mosque, is striking. Results have revealed extreme examples of salt weathering damage, mainly due to salt-loaded rising damp. This situation can be observed on many monuments in historical Cairo.

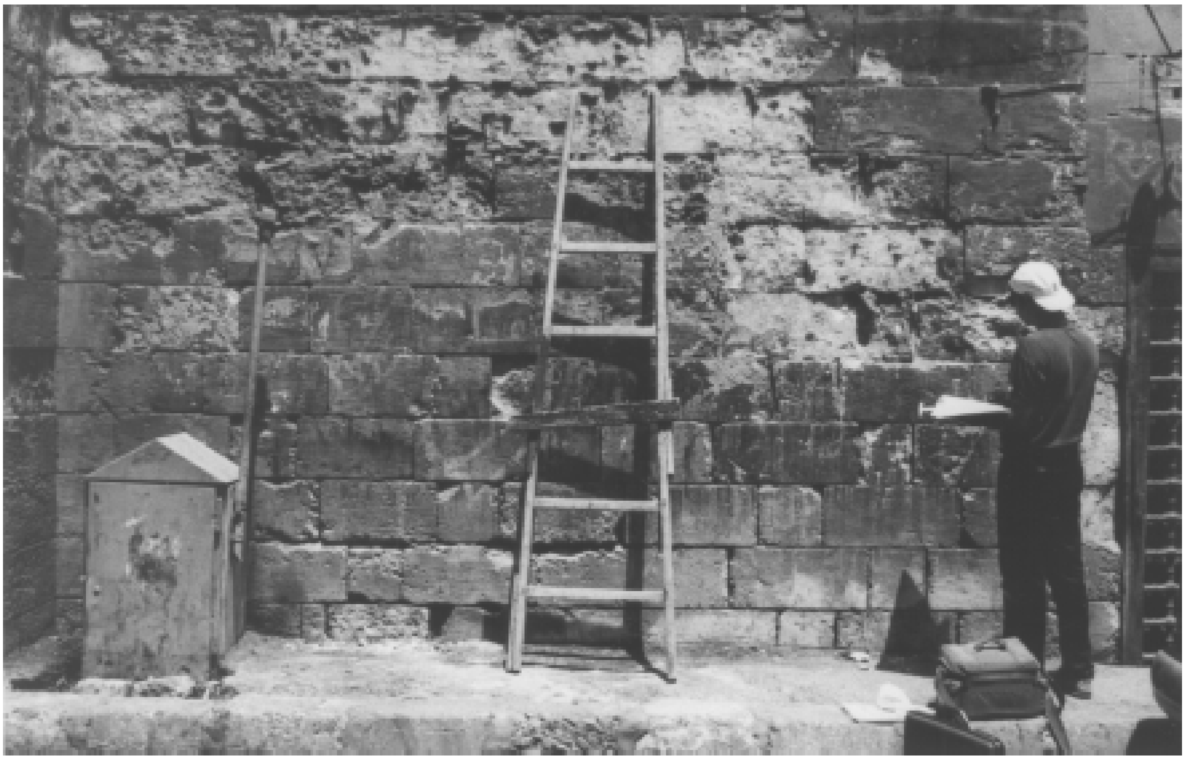

Fig. 30. El-Merdani Mosque, southern wall, Cairo (Egypt).

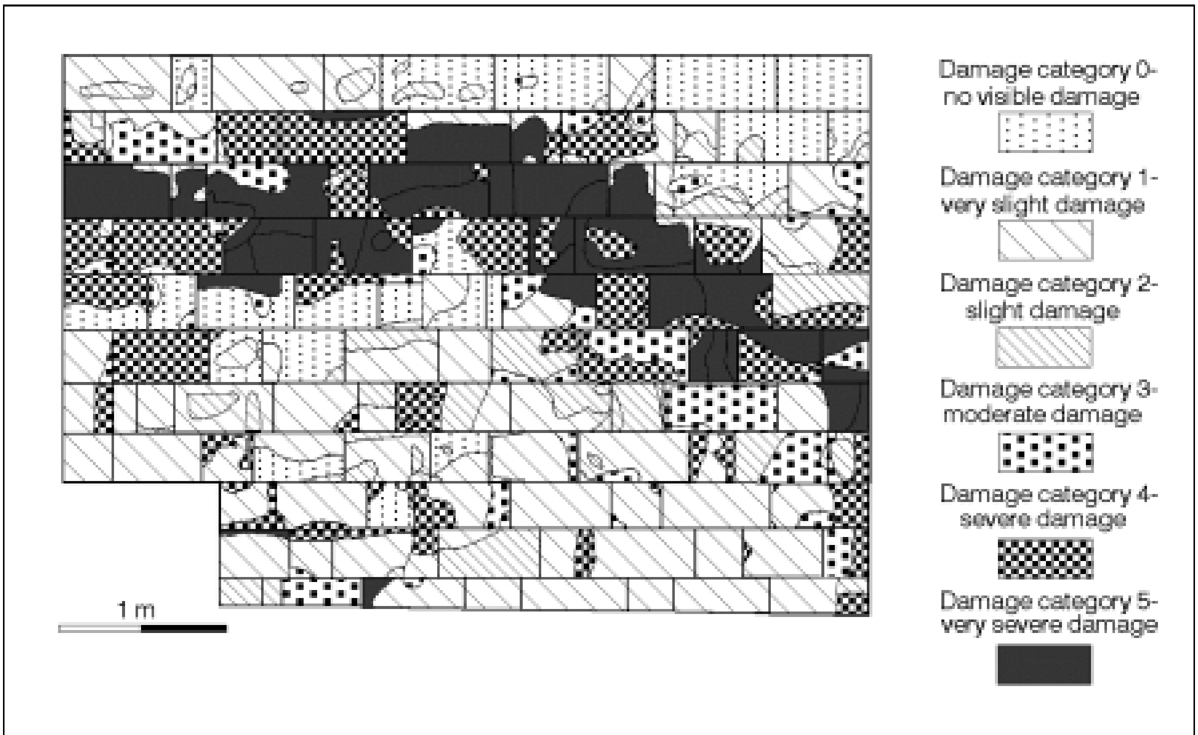

Fig. 31. Map of damage categories. El-Merdani Mosque, southern wall, Cairo (Egypt).

Characterization of damage zonation by means of damage categories and damage indices is presented. Results are shown for an investigation area on the southern façade of the mosque (Fig. 30). Figure 31 shows the map of damage categories. A clear zonation of damage can be seen: mainly slight damage in the lower part, mainly severe or even very severe damage in the middle to upper part, and very slight damage in the uppermost part. Salt load can be recognized as a very important weathering factor affecting the monument. Efflorescences, subflorescences and salt crusts are characteristic depositional weathering forms. Surface samples from different damage zones acoross a vertical profile have been analyzed geochemically with respect to salt contents (Fig. 32). In order to compare vertical profiles of salt load and damage, damage indices have been determined for each row of dimension stones (Fig. 33). Comparing Figures 32 and 33, a clear correlation between salt load and the extent of damage can be seen. The zone of highest damage indices corresponds to the main zone of salt precipitation resulting in the most intense salt weathering processes and stone deterioration. The presented mode of damage evaluation contributes to the assessment of weathering factors and weathering processes as well as to risk estimation and to identification of risk areas on a monument.

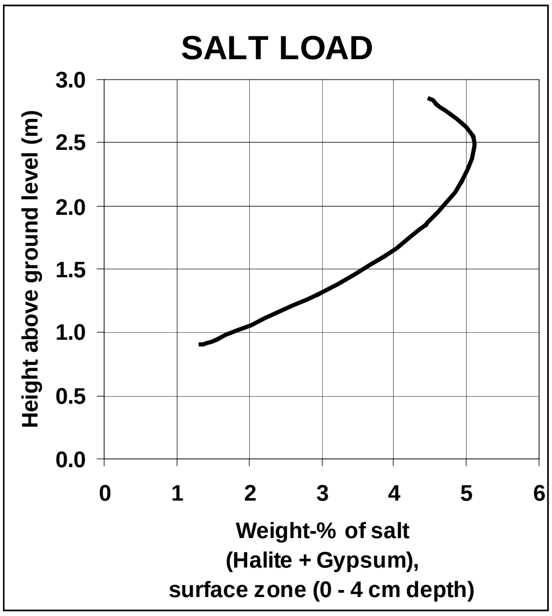

Fig. 32. Salt load across a vertical profile. El-Merdani Mosque, southern wall, Cairo (Egypt).

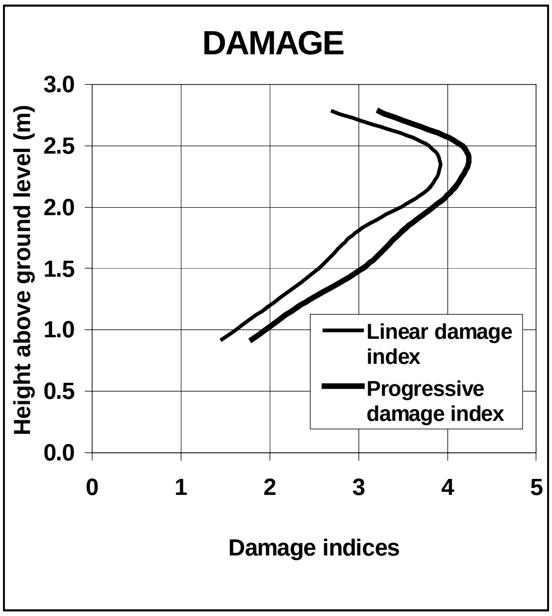

Fig. 33. Damage indices across a vertical profile. El-Merdani Mosque, southern wall, Cairo (Egypt).

Church of São Francisco de Assis in Ouro Preto (Brazil)

The town of Ouro Preto in the state of Minas Gerais can be considered as a masterpiece of colonial architecture in Brazil. It was declared by UNESCO as a world cultural heritage site in 1980. The Church of São Francisco de Assis was built in the 18^{th} century. Local quartzites were used for the ashlar parts of the church, soapstones – soft stone material that can be worked easily – for decoration parts of the monument.

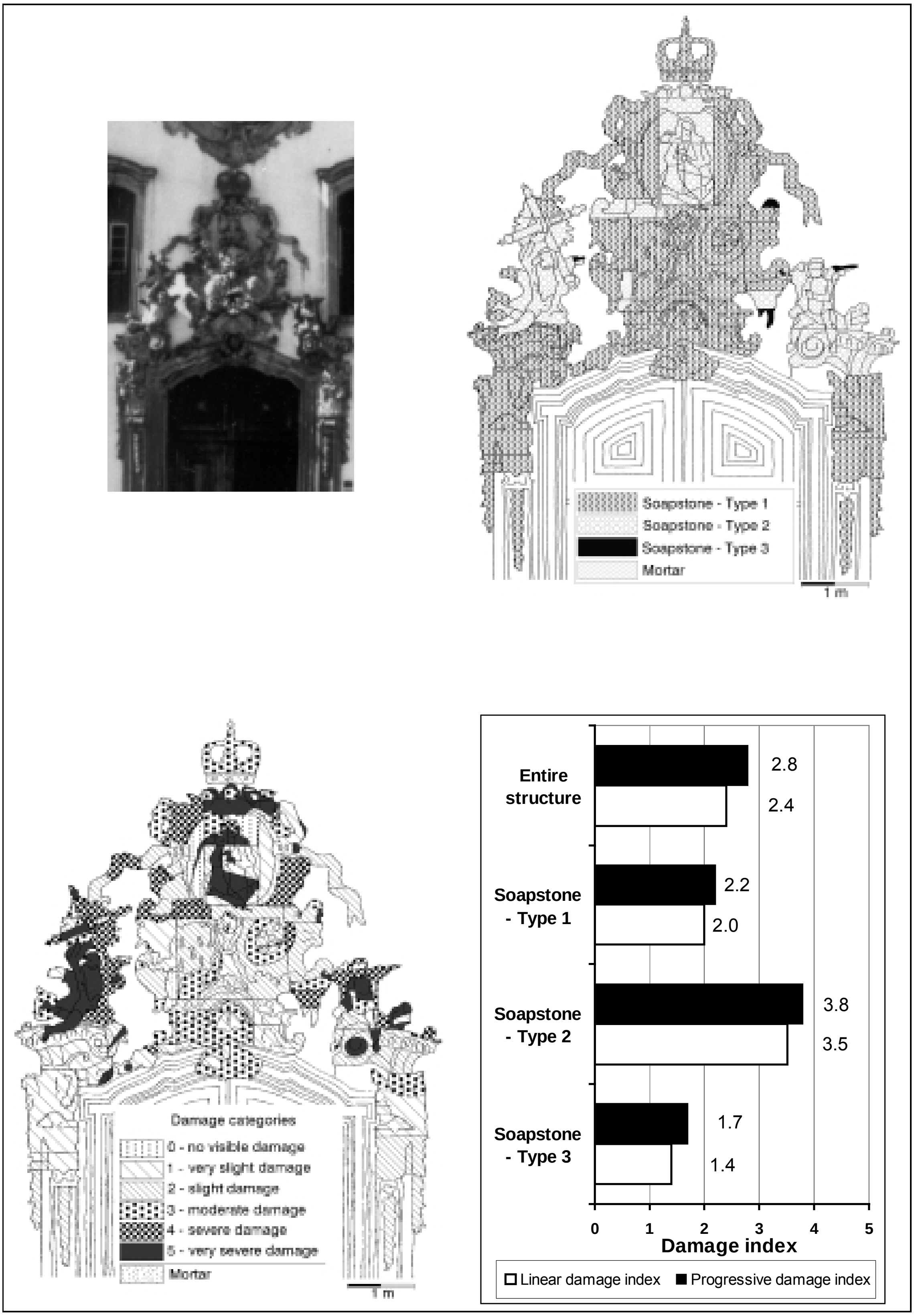

Fig. 34. Church of São Francisco de Assis, soapstone decoration of the main portal, Ouro Preto (Brazil). Lithological map, map of damage categories, damage indices.

Studies at this monument were carried out in the framework of the German-Brazilian project 'IDEAS – Investigation into devices against environmental attack on stones'. The case study demonstrates the evaluation of mapping information for rating of stone durability. The investigation area, the lithological map, the map of damage categories and damage indices for the entire structure and for the individual lithotypes are presented in Figure 34. Three different soapstone types were used at this structure. Soapstone - type 1 and soapstone – type 2 represent original stone material, small pieces of soapstone – type 3 were used for replacement in the frame of former restoration works. The map of damage categories shows that very slight and slight damage mainly affect soapstone – type 1, severe and very severe damages mainly soapstone – type 2. The damage indices for the entire soapstone decoration indicate considerable need for urgent preservation measures. Comparing the damage indices for the two original stone materials, the higher susceptibility of soapstone – type 2 to deterioration becomes obvious. Especially on those parts made from this soapstone type interventions are very urgent. Soapstone – type 3 used for stone replacement in an earlier restoration phase also has suffered damages. However, the low number and small size of the soapstone pieces does not allow a reliable rating of durability. The presented mode of evaluation contributes to selection of appropriate and durable stone material in case of stone replacement.

Minster St. Quirin in Neuss (Germany)

The Minster St. Quirin in Neuss in Germany (Fig. 35) dates back to the 13th century. Several times parts of the monument were destroyed by war or fire. Rebuilding and restoration works have resulted in various changes of architectural structure and stone materials. Today, more than ten stone types can be found on the façades, mainly different trachytes, volcanic tuffs and basalt, subordinately limestones, sandstones and slates (see Fig. 10). Sytematic studies have been carried out at the monument in order to produce precise damage diagnosis and appropriate restoration measures. The suitability of damage diagnosis by means of monument mapping for the judgement and certification of restoration measures is demonstrated. The methodological approach involving cooperation of scientists, curators, representatives of monument authorities, architects, engineers and restorers has comprised precise damage diagnosis, development of a restoration concept based on the results of damage diagnosis, execution and documentation of the restoration measures, reevaluation after restoration and judgement of the restoration measures (Fig. 36). For judgement of the restoration measures, the state of damage before and after restoration has been compared by means of damage categories and damage indices. The quantitative evaluation of damage categories before and after restoration is shown for a part of the monument in Figure 37. The very severe and severe damage and most of the moderate damage have been remedied or reduced in the course of restoration. Damage indices have been calculated from the proportion of damage categories before and after restoration. In Figure 38 damage indices before and after restoration are compared for different parts of the monument. The linear damage index is presented as an example. A significant reduction of damage indices after restoration can be seen in all cases, certifying a good success of the restoration measures carried out.

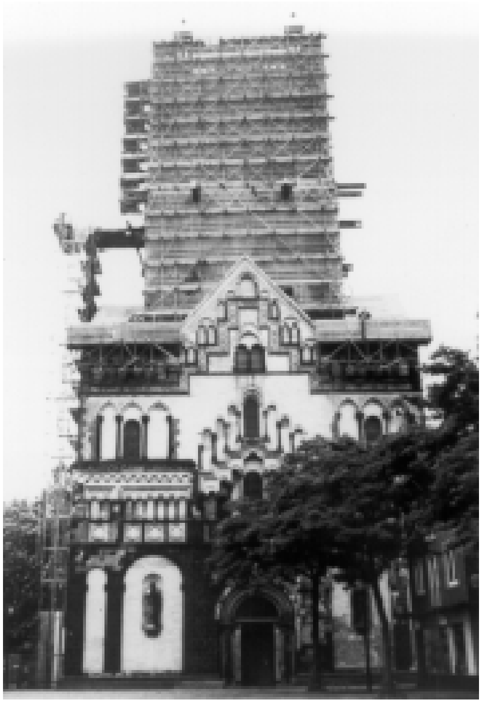

Fig. 35. Minster St. Quirin, Neuss (Germany).

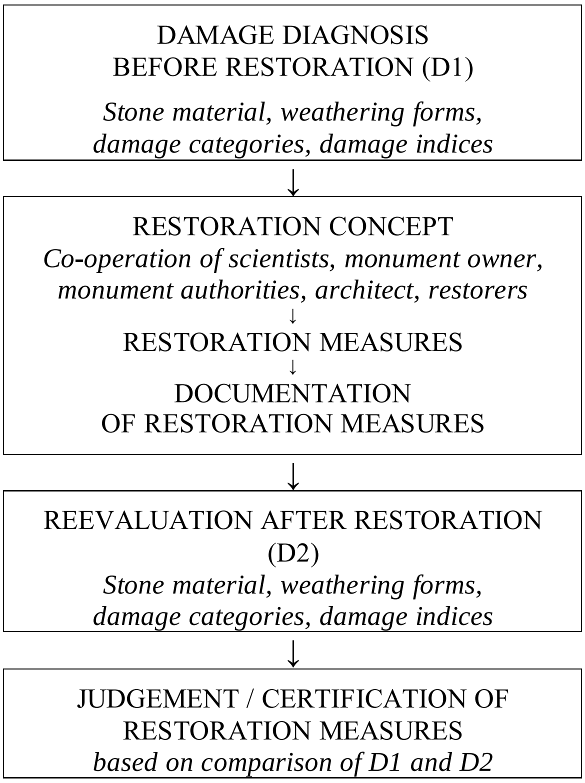

Fig. 36. Damage diagnosis for monument restoration.

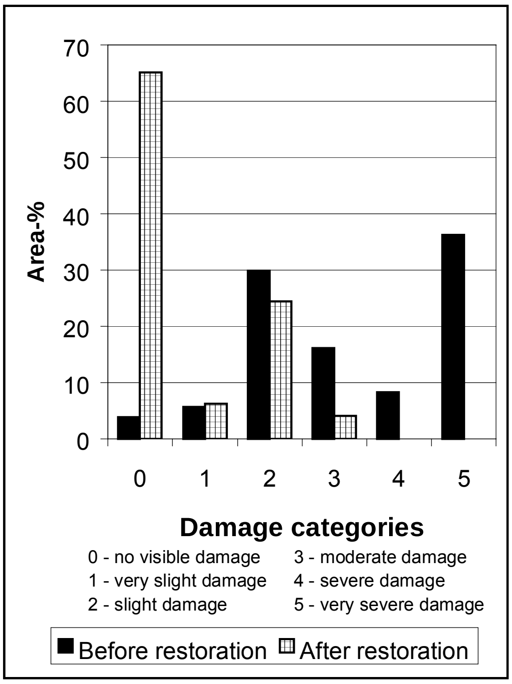

Fig. 37. Damage categories before and after restoration. Minster St. Quirin, part of the tower, Neuss (Germany).

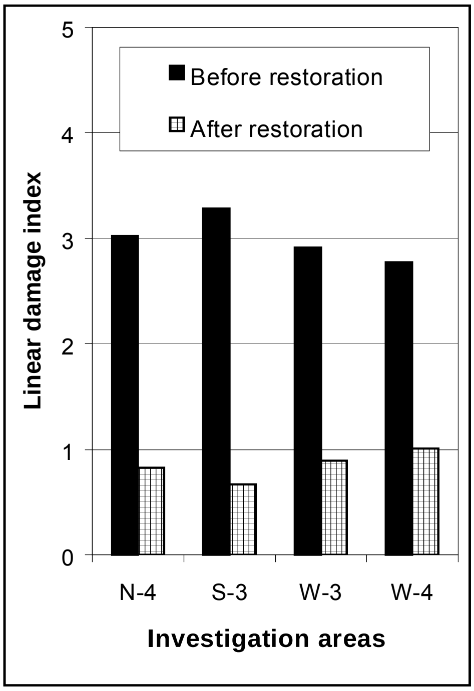

Fig. 38. Linear damage index before and after restoration. Minster St. Quirin, parts of the tower, Neuss (Germany).

The diagnostic results obtained from reevaluation after restoration (lithotypes, weathering forms, damage categories and damage indices) represent the reference for future reevaluation and restoration activities and for maintenance of the monument.

CONCLUSIONS

Precise damage diagnosis is required for characterization, interpretation, rating and prediction of weathering damage on stone monuments and is vital for sustainable monument preservation. The monument mapping method has been developed as a modern scientific procedure for in situ studies and evaluation of weathering damage. The mapping method ensures an important contribution to comprehensive and reliable damage diagnosis. It has met great international acceptance and has been applied successfully at numerous monuments worldwide. The consequent use of weathering forms, damage categories and damage indices means a consistent strategy for characterization, quantitative evaluation and rating of weathering damages at stone monuments as well as an important basis for deduction of appropriate and economic monument preservation measures. Evaluation of damages is based on lithological mapping and mapping of weathering forms. A detailed classification scheme of weathering forms has been developed as prerequisite for objective and reproducible description and registration of deterioration phenomena. Damage categories have been established for rating of individual damages. Damage indices have been introduced as very practical tool for conclusive quantification and rating of weathering damage on stone monuments. From scientific point of view evaluation by means of weathering forms, damage categories and damage indices provides important information on:

- weathering damage in dependence on lithotypes, environmental influences and monument exposure characteristics,
- development of weathering damage, weathering rates / weathering progression,
- factors and processes of stone weathering,
- stone durability.

It contributes essentially to the improvement of scientific knowledge in the field of stone weathering at monuments and to the development of weathering models.

With respect to monument preservation practice, the results obtained from monument mapping represent an important contribution to deduction, test-application and execution of efficient and economic monument preservation measures. The mapping method ensures a high benefit-cost-ratio. Costs for the in situ studies and evaluation of results amorthize from effective and economic preservation measures. Damage indices and damage categories indicate the need and urgency of preservation measures. Maps of damage categories locate those parts of a monument which interventions have to focus on. Type, intensity and spatial distribution of weathering forms have to be considered for derivation of appropriate types of preservation measures. The consequent use of weathering forms, damage categories and damage indices means a very suitable strategy for control / certification of preservation measures and for regular reevaluation of monuments in the framework of long-term survey and maintenance of monuments. The consistent evaluation strategy based on monument mapping can be recommended to organisations, monument authorities and monument owners involved in planning and decision making of monument preservation policies and strategies as well as to architects, engineers, restorers, conservators, consultants, project managers or construction companies involved in damage diagnosis and monument preservation activities.

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