IMEKO International Conference on
Metrology for Archaeology and Cultural Heritage
Lecce, Italy, October 23-25, 2017

Degradation diagnosis on Gravina Calcarenite: classification and damage indexes on the Sassi di Matera site (Southern Italy)

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Abstract
In Matera, the 2019 Culture Capital and UNESCO site, the Pleistocene Gravina Calcarenite is the main natural stone used to build. This gives a unique aspect to the ancient part of the town called Sassi. It's an awesome example of a rock-cut settlement where architecture is fit to the geological features. Unfortunately, constructions are currently in a deteriorated state and it is possible to see on the 'calcareous tuffs' several degradation morphologies. This work analyses the connection between geological features and alteration patterns in order to obtain useful informations to preserve historical building during the time. A detailed classification of the decay forms, based on a newly defined damage index, has been obtained after investigation of 100 façades considering different types of Calcarenites and evidences obtained on the surface. For each degradation morphology a specific decay degree is defined in relation with evidences on the surface of the façades. In addition, a detailed analysis of stones of the San Pietro Barisano church allowed obtaining information on structural, compositional and textural features of Calcarenite, and the related degradation morphologies

Key words: cultural heritage, damage indexes, degradation classification, alveolization, Gravina Calcarenite.

I. RESEARCH AIMS

The aims of this paper is to analyze the degradation morphologies on the historical centre of Matera, Sassi, UNESCO Cultural site and European Capital in 2019 and to connect them with different members of the Gravina Calcarenite Formation. Looking at previous indexes of decay defined for the Sassi [1] and at objective and reproducible methods for evaluating the damage on stone heritage [2] [3] [4], we propose to introduce some modifications in the existing damage indexes, considering the different members of the "Calcareous tuff" and its intrinsic properties, in order to improve the utility of this method in the decay diagnosis. In addition, our work aims at analysing with some qualitative observations, and statistical evaluations how the environmental and geomorphological conditions influenced the weathering processes, considering also that stones in natural outcrops are damaged more than those used for masonry in historical buildings. One first example of this approach has been performed on rock outcrops of the bioclastic member of the Gravina Calcarenite and on the same calcarenite used for constructing the San Pietro Barisano rupestrian church.
Analysis of porosity of the stone have been performed on samples from the facade and the bell tower in order to start to evaluate the connection with degradation patterns and intrinsic properties of the materials.

II. INTRODUCTION

Stone monuments in the cultural heritage represent an impressive and diversified artistic, scientific and historical archive. The awareness that stone damages in monuments with the consequence of an irreversible loss of the cultural heritage is increasing, starting from industrial revolution, producing great efforts for monument preservation worldwide [3]. In Matera, the 2019 Culture Capital and UNESCO site, the Pleistocene Gravina Calcarenite is the main natural stone used to build. This gives a unique aspect to the ancient part of the town, called Sassi, and especially to the rupestrian churches. The Sassi are an awesome example of a rock-cut settlement where architecture is fit to the geological and geomorphological features of the area [3] [5]. Calcarenites make up the base of the lower Pleistocene series in the Murgia area. They correspond to the se-called “tufo calcareo”, well known in the Puglia region [6]. Calcarenites have a great success as building and ornamental stone [7], due to their large availability, good workability and aesthetic appeal, together with their lightness. Moreover, their low values of thermal diffusivity and conductivity, give them excellent insulation properties. This soft and porous material was widely used in the construction of modest habitations and prestigious buildings such as important churches, Romanesque cathedrals, fortified farms, imposing castles and mediaeval towers [7] [8] [9] [10] [11] [12]. However, many constructions are currently in a deteriorated state, since numerous degradation processes, producing characteristic patterns on historical buildings, affect ‘calcareous tuffs’.

According to the NORMAL 1/88 recommendation [13] and the ICOMOS-ISCS classification [14], several authors [3] [4] [15] [16], proposed a classification of degradation morphologies observed on the monuments in order to improve the stone damage diagnosis and the evaluation and certification of preservation measures for long-term survey and maintenance of stone monuments.

Fitzner and Heinrichs [4] [3] introduced objective and reproducible methods to evaluate the damage on stone monuments in order to obtain thematic maps of the decay applicable to all stone types. They present a monument mapping method that establishes a non-destructive procedure for in situ studies of stone damage. The authors carried out the assessment of the weathering typologies and their intensities based on a classification scheme which takes into considerations the main levels of decay, each of them subdivided into sub-levels. Following this classification scheme they inventoried and mapped all the observed degradation typologies. De Gennaro et al. [15] and Carta et al. [16], proposed a semi-quantitative assessment of the decay, while Gizzi et al. [1] propose, on the Sassi, a linear damage index and a progressive damage index based on the intensity and the spatial distribution of weathering forms on the basis of insolation and wind exposure. Furthermore, Pellizzer & Sabatini, 1976 [18] demonstrated that building stone has a less degradation than a stone in its natural formation environments, but only in absence of environmental pollution [19].

III GEOLOGICAL SETTING

Calcarenite di Gravina Formation is a lower Pleistocene stratigraphic unit onlapping the Cretaceous Altamura limestone successions of the Apulia Foreland. It makes up continuous exposures of intrabasinal biocalcarenites and biocalcirudites and/or terrigenous calcarenites [20]. The Subappenine clay formation and terraced regressive deposits occur on top of the calcarenites (Fig.1). Calcarenite di Gravina can be subdivided in two informal members [21]. The lower member is mainly lithoclastic, having clasts derived from erosion of Cretaceous limestone, and is composed of accretional units bounded by erosion surfaces. These units are stacked in a backstepping configuration, onlapping onto the underlying Cretaceous rocks and are interpreted to record a punctuated transgression onto the Matera paleo-island as result of the regional subsidence of the Apulian foreland. The upper member is predominantly bioclastic and represents the downslope accumulation of skeletal debris produced within a platform environment, resulting from the partial submersion of the Matera paleo-island. This carbonate-dominated system was subsequently drowned by Pleistocene siliciclastics derived from the erosion of the Apennines thrust belt [17]. In the calcarenites it is possible to recognize sediments of marine environment (littoral and deeper sea, as far as the shelf transition) and of continental environments (eolic and lagoonal). The areal facies distribution was controlled by the paleomorphology of the Cretaceous substratum [6] [22].

Ancient parts of the Matera town, and especially the Sassi, are dug and built in the left flank of the Gravina valley. Here, both members of the Gravina Calcarenites, with predominance of the bioclastic member, crop out. Sassi are subdivided in three main districts: Sasso Barisano, Civita and Sasso Caveoso. The first two are built and dug inside to the bioclastic member of calcarenites while the Sasso Caveoso is mainly inside to the litoclastic member, characterized by a typical microconglomeratic interval.

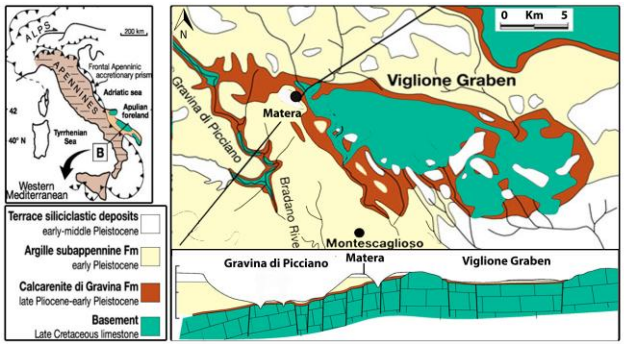

Fig. 1 - Litological maps of Matera and Murgia Materana by Mateau-Vincens 2008, modified.

IV METHODS

Degradation diagnosis is made with in situ investigation on 100 façades in the Matera Sassi (Fig.2). Here grottoes, churches, crypts and houses, show different construction typologies: in particular, these can be built, dug, partially dug and partially built. A detailed classification of the principal degradation patterns has been defined on the basis of the main effects and on the UNI11182 [23] standard and the International Council On Monument and Site –International Scientific Committee for Stone (ICOMOS-ISCS). The method used for mapping facade consists in a non-destructive procedure for in situ studies of stone damage. According to the NORMAL 1/88 recommendation [13] and the ICOMOS-ISCS classification [14], it is defined a classification with 5 categories of decay and 40 subcategories introduced specifically for the Gravina Calcarenite. The five main effects of degradation processes are: *Loss of materials* consisting in the subtraction of the stone materials due both to the weathering agents and human and animal activities.

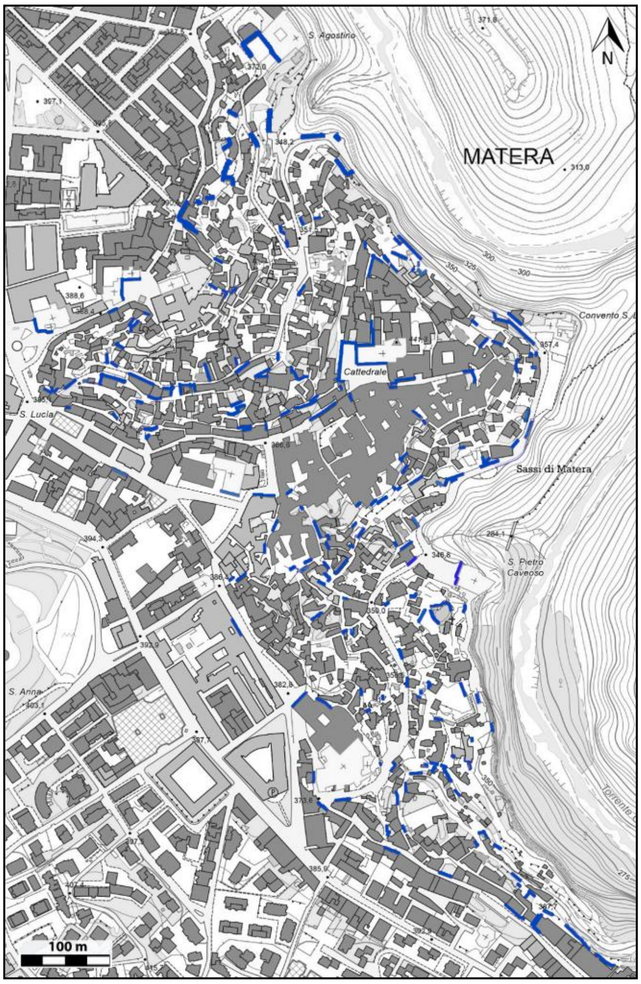

Fig. 2 – Sassi map with the façades analyzed for mapping the degradation patterns in blue.

It is possible to recognize roughening, erosion, coving, rounding, missing parts and holes, alveolization, microcarst, pitting, perforation and mechanical damage as abrasion, impact damage, cut, incision, scratch, keying and rubbings. *Detachment* consists in the alteration of the stone due to processes that cause the total or partial removal of material, due mainly to chemical-induced phenomena produced by the weathering agents and the salts contained inside the rock. It results in sanding, powdering, bursting, blistering, fragmentation, delamination as exfoliation and scaling, peeling and coating detachment. *Crack and Deformation* that are the results of separation of the one part from another and the change in the shape due to the formation of a single or multiple fractures. *Discoloration and Deposits* are change in the stone colour in hue, value and chrome, due to visual occlusions produced by overlying materials: these can be represented by stains, staining, rising, graffiti, soiling and patina, crust and encrustation, efflorescence and subflorescence and superficial deposits. Visual occlusions are due also to the *Biological colonization* of plants, algae, mold, moss and lichen. Following the aforementioned classification scheme it is possible to inventor and map all the observed degradation typologies and to obtain qualitative and quantitative statistical data on the area undergoing decay. For each degradation morphology is defined a specific degree of decay in relation with objective evidence on the surfaces of the facades. These data are organized in a form, where both in situ observation and identification of degradation morphologies are reported. In order to carry out the analysis, we first selected an example of prestigious monument both dug and built: the San Pietro Barisano rupestrian church, which is located in the Sasso Barisano District, within the bioclastic member of the Gravina Calcarenite. A map of the different decay forms was compiled on the main facades facing East and South East, and on the bell tower facing North and East, in relation with the identified degradation patterns. The areal importance of the decay is expressed with 4 different percentages, normalized at 1 and reported in the deterioration patterns table (0,25 - weakly present, 0,50 present, 0,75 very present, 1 present on the total facade area).

Three samples of calcarenite, taken at different heights, have been analyzed: the first it is representative of the crypt, the second of the lower part of the bell tower and the main facade and the third of the middle part of the bell tower (Fig. 3). These samples have been investigated by mesoscopic and microscopic observations. Modal analysis at the Optical Microscope and image analysis with ImageJ software have been used to determine the relative abundance of voids and clasts. With image analysis it has been possible to determine also the percentage of lithoclasts, bioclasts and cement.

Fig. 3 – San Pietro Barisano rupestrian church panoramic view and prospect of theme with the localization of the three samples analyzed.

V. RESULTS and DISCUSSION

A. Degradation analysis and classification

The analysis of 100 façades in the Sassi of Matera, located for the 51% in the Sasso Barisano, 23% in the Sasso Caveoso and 25% in the Civita districts shows that the 77% of them are totally built and the 17% are totally dug. The 44 % of the observed buildings shows decay patterns on all surface area, the 36% only in the lower part, the 15% in the upper part and the 13% only on the edge of the buildings. Very likely, this distribution is strongly influenced by the action of the weathering.

The most present decay patterns are originated by the Loss of material as it is shown in Fig.4. In particular alveolization, known by many authors also as honeycomb, tafoni, cavernous weathering, and sometimes fretting, box work and fluting [24] [25], is the most common degradation morphology. It is the result of erosion by wind and waves and it is commonly found only on porous and relatively coarse-grained rocks like sandstone or calcarenite that can absorb a huge amount of water. Other frequently observed degradation forms are Soiling and Patina with the 63%, Moss and Lichen with the 60%, Fracture with the 49% and Peeling and Coating Detachment with the 46% and the 34%.

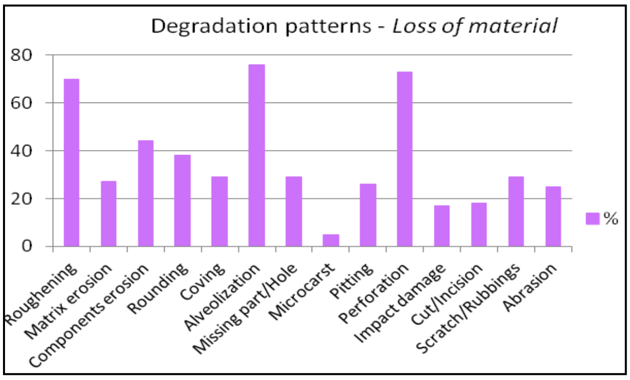

Fig. 4 – Histograms of the decay patterns percentage for the Loss of Materials category.

Among the processes that may trigger alveolization, sun exposure is an important condition in the development of honeycomb because any saline water within the pores of the rock is drawn to the surface where salt crystallizes as the water evaporates [24]. Alveolization is very often associated with other surface evidences connected to loss of materials (roughness, hole, differential erosion, coving, rounding). In relation with these morphologies and the degree of depth of alveolar forms is possible to recognize five degree of alveolization intensity, as depicted in Fig. 5.

Alveolization weathering is present everywhere in the Sassi area and particularly on calcarenites of the bioclastic member. It is more widespread on the façades facing SE (i 2,9) and less present on those facing N (i 1), while is intermediate on facades facing NW, NE and SE (i 2,5), E and W (i 2,0) (Fig.6). In calcarenites of the lithoclastic member, erosion by loss of component appears generally more frequent.

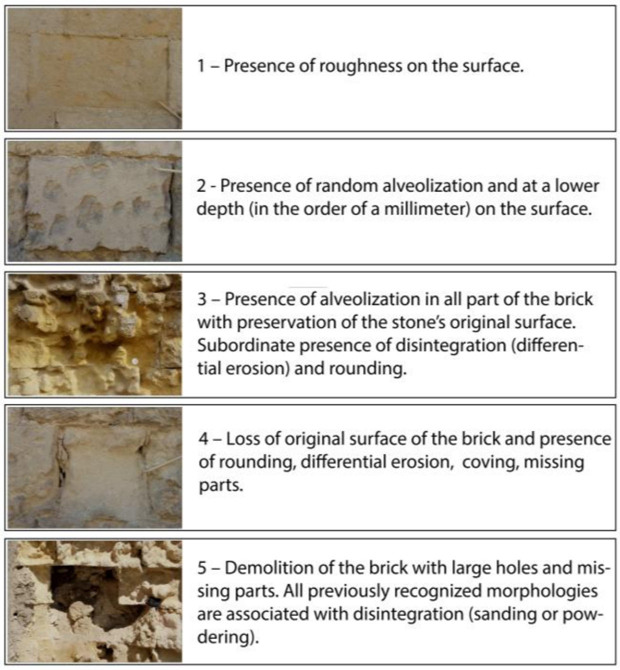

Fig. 5 –Classification of alveolization intensity

The San Pietro Barisano church shows, on the principal façade facing East, a predominance of intensity 2; the right principal façade, facing SE, shows the 3, 4 and 5 degree of intensity with predominance of intensity 4, while the bell tower shows the predominance of intensity 1 in the built area and intensity 3 in the dug area (Tab.1).

Table 1 – Intensity of alveolization respect the exposition to the sun irradiation.

Alveolization intensity (*i*)	Façade E (%)	Façade SE (%)	Bell tower (%)
1° degree	8,9	3,4	11,6
2° degree	23,3	8,2	4,7
3° degree	3,6	9,2	7,4
4° degree	1,4	16,4	1,7
5° degree	0,0	1,8	0,0
Tot area	37,3	39	25,5

B. Mesoscopic observation and optical microscope characterization

At the mesoscopic scale rocks of the San Pietro Barisano Church display a whitish color and a moderate degree of homogeneity. This appearance depends on the presence of organogenous and sedimentary structures such as levels of calcareous grains, fossils and bioturbations. The observed honeycomb geometry, which dominates the degradation morphologies, is not only a function of the surface patterns, but it depends also on movement of water from the rock interior to the surface. For this reason, a textural characterization of the Gravina Calcarenite by optical microscopy, modal and image analysis (ImageJ software) was made in order to observe the mutual disposition of grains and voids that may influence the weathering and dissolution processes.

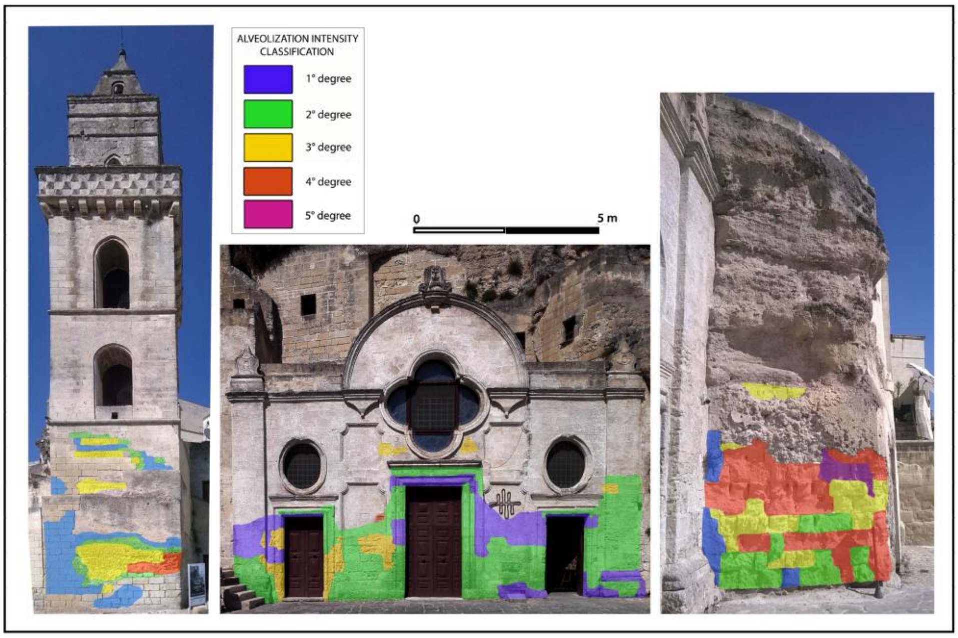

Fig. 6 - Alveolization intensity on the surface of the San Pietro Barisano façades

Samples are poorly to moderately sorted, cement supported grainstone [26], with circumgranular and needlelike micritic microcristalline cement. The matrix is absent.

Samples from the base of the façade and bell tower (sample 2) shows also some red and brownish oxides patinas on the calcitic grains. In each sample, analyzed bioclasts are typical of shallow marine environments.

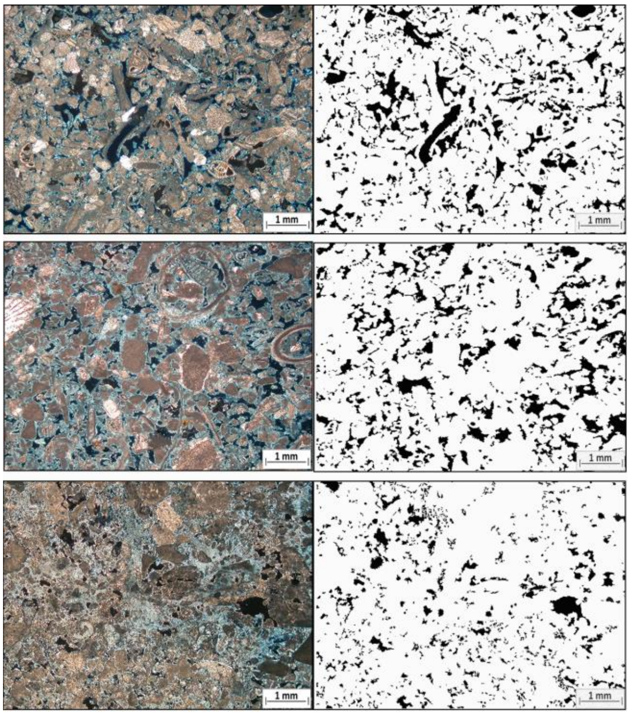

Fig. 7 - Sample1,2,3: image at Nx, 2X magnification. ImageJ processing with porosity in black

The fossil content consists of sponges, corals, echinoids, foraminifera, red algae, serpulids, bivalves, lamellibrancs and gastropods. Lithoclastic grains derive from the Cretaceous Altamura limestone (Fig. 7).

Porosity analysis

Porosity has been determined with modal and Image analysis methods. The results are shown in table 2. The recognized porosity types are interparticle, intraparticle, moldic and vuggy in every sample.

Table 2 – Porosity analysis on three samples from St. Pietro Barisano Church

Sample1	modal analysis (%)	immage analysis (%)
Voids	18,9	17,0
Cement	11,2	
Bioclast	48,0	83,0
Litoclast	21,9	
Sample2	**modal analysis (%)**	**immage analysis (%)**
Voids	17,5	16,9
Cement	13,3	
Bioclast	41,1	82,1
Litoclast	28,1	
Sample3	**modal analysis (%)**	**immage analysis (%)**
Voids	9,7	9,6
Cement	18,7	
Bioclast	38,4	90,4
Litoclast	33,2	

VI. CONCLUSIONS

Prevailing degradation morphologies of the Bioclastic Gravina Calcarenite making up the St. Pietro Barisano Church are mainly represented by loss of material, specifically alveolization. Five classes of intensity degree of alveolization have been recognized and this parameter may be added to the existing decay indexes, in order to provide a more detailed description of the degradation processes. In the same Church, textural characterization of Calcarenite shows a bioclastic content in the range between 48% and 38,4% and a lithoclastic content in the range between 21,9% and 33,2% Modal and Image analysis show a porosity range between 9,6% and 18,9% and content of cement between 11,2% and 18,7%.

Our preliminary analyses on 100 facades distributed in the whole Sassi of Matera area allows the characterization of the main degradation morphologies. In addition, we may indicate that alveolization is more frequent in the bioclastic member, whereas erosion by loss of component is widespread in the lithoclastic member. Further analyses will be carried out to outline the relationships of porosity and cementation with degradation morphologies and processes.

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