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Stone properties and weathering phenomena of the Miocene Cusano Limestones (a.k.a. Perlato Royal Coreno): the case of the basement of the Santa Chiara Monastery bell tower (Naples - Italy)

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Abstract - Cusano limestone is an ornamental stone cropping out in the central-southern Italy and extensively used for the historical buildings construction with structural and architectonic purposes.

Artificial weathering experiments were conducted on Cusano limestones coming from La Valle and Canale quarries, located in the Benevento and Frosinone provinces (Italy) respectively. Rock specimens were subjected to standardized freeze-thaw cycles and salt crystallization tests; to this aim non-destructive and destructive tests were carried out including open porosity and p-wave velocity measurements and mechanical testing.

Finally the main deterioration morphologies affecting the Cusano limestone were identified through a detailed study on the façades of the bell tower of the Santa Chiara monastery in Naples.

Riassunto - La Pietra di Cusano è un materiale di gran pregio affiorante diffusamente nell'Italia centro-meridionale e ampiamente usato per la costruzione di edifici e monumenti a scopi architettonici e strutturali. In questo lavoro sono riportati i risultati dei test di invecchiamento artificiale condotti su provini prelevati presso le cave La Valle e Canale, rispettivamente ricadenti nelle province di Frosinone e Benevento (Italia). Sui campioni di roccia è stata testata la resistenza al gelo ed alla cristallizzazione dei Sali; a tal fine, sono state eseguite prove distruttive e non (porosità aperta, velocità di propagazione del suono, prove di resistenza a rottura).

In questo lavoro sono inoltre riportati i risultati di uno studio di dettaglio effettuato sul degrado delle pietre del basamento della Torre Campanaria del Monastero di Santa Chiara a Napoli, interamente realizzato in Pietra di Cusano.

Key words: *Limestone; lithological features; freeze-thaw; salt crystallization; Cusano Limestone; weathering.*

General setting

The Cusano limestones or Bryozoan and Lithothamnion limestones (BLL), commercially known as *Perlato Royal Coreno*, are widespread in the central and southern Apennines of Italy (Fig. 1), including Matese Mts., Mt. Camposauro, Trebulani Mts., Mt. Massico, Aurunci Mts. and the hills south of Cassino, such as Mt. Trocchio and Mt. Porchio (Accordi *et al.*, 1988; Bonardi *et al.*, 1988).

Several findings prove that the stone has been

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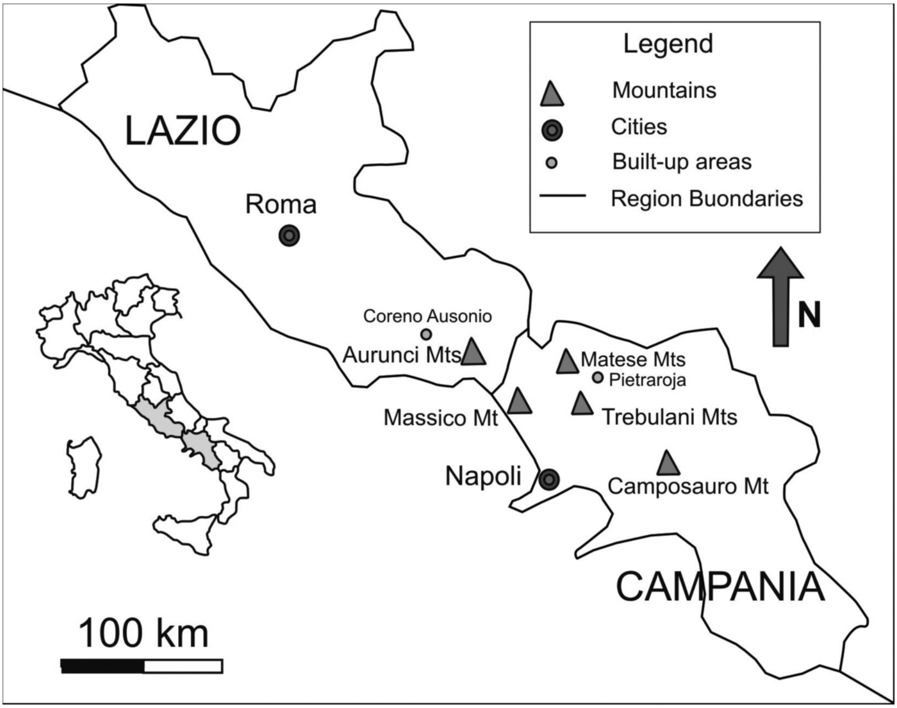


Fig. 1 - Location of the main outcrop areas of the BLL in the Lazio and Campania regions.

extensively used since Roman times in the archaeological sites of Minturno, Cassino and Pompei (Consorzio per la valorizzazione del Perlato Royal Coreno, 2002). The same stone has been used in the Medieval period for the construction of the bell tower of the Santa Chiara monastery in Naples and in modern times too (e.g., the Bourbon Bridge on the Garigliano river in Minturno, built in the 19th century under the Bourbon reign, and the Montecassino Abbey, rebuilt in the 1950s after being destroyed during World War II).

MATERIALS AND METHODS

The investigated samples were collected both in the active La Valle quarry, situated at Coreno Ausonio (province of Frosinone) and in the abandoned Canale quarry at Pietraroja (province of Benevento). Unaltered blocks (approximate size 100x50x50 cm) were sampled taking into consideration the original orientation of bedding. The sedimentological analysis was carried out on 37 polished rock slabs, with a low magnification hand lens, and on 40 thin sections with an optical microscope. The petrographical and petrophysical characterization were carried out according to the European-suggested standards (UNI EN, Normal) and ISRM norms and to the experimental procedure described in previous works (Angrisani, 2010; Angrisani *et al.*, in press).

Ageing tests such as salt crystallization tests and freeze-thaw cycling were also conduced.

During salt crystallization tests (UNI EN 12370) dried samples were immersed in a 14% solution of $Na_2SO_4 \cdot 10H_2O$, dried and allowed to cool to room temperature. Such cycles were carried out 15 times. Because of the low porosity of the rock, after the tests the samples presented no fractures, only a slight loss in weight and a moderate efflorescence on their surface.

According to the UNI EN 12371, frost resistance simulation consists of a 6-h freezing period in a climatic chamber followed by 6-h thawing period, during which the specimens are totally immersed in water. The samples were subjected to 20 freeze-thaw cycles. After completion of the established runs the samples were removed from the weathering cycling and subjected to non-destructive (open porosity and P-wave velocity measurements) and destructive testing (uniaxial compressive strength tests), aimed at verifying the possible variations of physical and mechanical properties.

Results

Lithological features

As observed on polished rock slabs and in thin sections, the main biogenic components are bryozoans, corallinacean algae, mollusk shells, with minor contribution of serpulids and balanids. Larger benthic phoraminiphera (*i.e.*, *Amphistegina* sp., *Gypsina* sp., *Elphidium* sp., *Heterostegina* sp.), along with planctonic phoraminiphera and echinoid remains are abundant in the matrix.

Eight lithofacies were identified in the BLL of the Coreno Ausonio district (La Valle quarry) on the basis of the textural characters, the relative abundance of the main biogenic components and the rhodolith dimension and shape as observed on polished rock slabs and in thin sections (Angrisani, 2010).

By integrating the sedimentological description with the commercial classification used in the Coreno Ausonio district, it was possible to correlate each lithofacies to a specific commercial rock type as defined in the Perlato Royal Coreno handbook (Consorzio per la Valorizzazione del Perlato Coreno, 2002).

The identified lithotypes are given in Table 1.

Table 1
Sedimentological characterization of the BBL from La Valle querries (Angrisani et al.*, in press).*

Rock type (Consorzio per la valorizzazione del Perlato Coreno, 2002)	**Lithofacies (Embry and Klovan, 1971)**	**Main macroscopic characteristics**
Perlato	Rhodolith rudstone	Large Rhodoliths (at least 10 cm in diameter).
Mezza Perla	Rhodolith floatstone	Smaller often distinctly elongated Rhodoliths than in Perlato.
Perlatino	Rhodolith and Oyster rudstone - floatstone	Small Rhodoliths and abundant Mollusks shells.
Risatino	Red Algae and Bryozoan grainstone - packstone	Absence of large Rhodoliths.
Botticino	Red Algae and Bryozoan rudstone	Absence of Rhodoliths
Conchigliato	Bryozoan, Coralline Algae and Mollusk shells rudstone	Rare and small Rhodoliths and abundant Mollusk shells.
Svirgolato	Bryozoan, Oyster and Red Algae rudstone	Abundant Mollusk shells.
Nocciolato	Bryozoan, Coralline Algae and Mollusk shells rudstone	Abundant Bryozoans.

Mineralogical and chemical properties

Quantitative mineralogical composition was determined from X-ray diffraction measurements and chemical analyses. The X-ray powder diffraction pointed out the presence of calcite and, in minor amount, quartz in all the lithofacies. The insoluble residue is essentially made of quartz and smectite, kaolinite, illite and rarely titanium oxide and feldspar.

X-ray spectrometric analysis confirmed the homogeneous composition of the material, essentially made of CaO, and highlights the presence of a minor amount of MgO in the Canale quarry samples than in the La Valle ones (Table 2).

Petrophysical analysis

The main average physical-mechanical parameters on fresh unweathered material are given in Table 3.

Table 2
XRF chemical analysis - mean values and standard deviations of La Valle specimens. ND means that the oxide is undetectable through the used analysis method (Angrisani et al.*, in press).*

Major elements (%)													
Quarry		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	TOT
Canale	Mean values	0.48	0.02	ND	0.07	0.01	0.61	54.70	0.05	0.04	0.33	43.70	100
	St. Dev.	0.179	0.005	-	0.035	0.001	0.130	0.621	0.016	0.016	0.279	2.279	-
La Valle	Mean values	0.47	0.01	ND	0.04	0.01	0.94	54.84	0.04	0.03	0.12	43.50	100
	St. Dev.	0.060	0.004	-	0.019	0.004	0.258	0.640	0.016	0.013	0.020	2.020	-

Table 3
Petrophysical characterization - mean values and standard daviations of Canale and La Valle specimens (Angrisani et al.*, in press).*

Quarry	Apparent density (kN/m³)	Bulk density (kN/m³)	Open porosity (%)	Compactness	Imbibition capacity (%)	Capillarity coeffi.(g/cm²*s$^{0.5}$)	P-wave dry velocity (m/s)	P-wave wet velocity (m/s)	UCS (MPa)	Brazilian strength (Mpa)	Rupture energy (J)	Abrasion resistance (mm)	Hardness Rockwell (HR30T)	Flextural strength (MPa)
Canale	25.90	26.32	1.43	0.99	0.51	7.61E-05	5976	6167	170	8.82	3.24	17.56	72.26	11.0
St.dev.	0.286	0.099	0.006	0.009	0.336	6.782E-05	270.28	252.76	12.54	1.095	0.660	1.032	1.756	1.311
La Valle	25.92	26.33	1.55	0.99	0.57	7.24E-05	6103	6283	199	-	-	-	-	-
St.dev.	0.036	0.089	0.003	0.005	0.067	5.20E-06	62.12	51.61	8.31	-	-	-	-	-

BLL from both the sites showed good performance in terms of mechanical strength, abrasion resistance and rupture energy. It evidently implies that the rock could be successfully used as a dimension stone.

Ageing tests

Freeze-thaw cycling and salt crystallization tests and were conduced to investigate the BLL durability.

It was observed that open porosity exhibits only very moderate increase after freeze-thaw experiments while the decrease of P-wave velocity and of UCS was of 5% and 8% respectively (Angrisani et al, in press). After the test the specimens rarely presented fractures or loss of material.

Salt crystallization tests showed that the samples exhibit only moderate or slight efflorescence generally localized at the edges of the cubic specimens.

Although the rock must be classified as frost-resistant, the results of the experimental weathering of BLL carried out in this study proved the higher sensitivity to freeze-thaw action then to crystallizing salt.

Weathering forms on the basement of the Santa Chiara Monastery bell tower

The Santa Chiara Monastery is a religious complex located in the ancient centre of Naples. The bell tower, separated from the main building, began in 1328 and was completed in Renaissance times. The most frequent decay morphologies affecting the BLL used for the construction of its basement are black crusts (due to the deposition of atmospheric dust), efflorescence (provoked and intensified by marine aerosol), detachment (probably because of the dissolution and the breaking along the calcite-filled fractures), scaling, stains (due to chemical attack by water and air pollutants, but also to encrusted dust and sometimes even vandalism) and rarely exfoliation, pitting and vegetation (Normal 1/88). Integration (i.e. lacks filled up with different materials) and joints are often observed on all the façades of the bell tower basement.

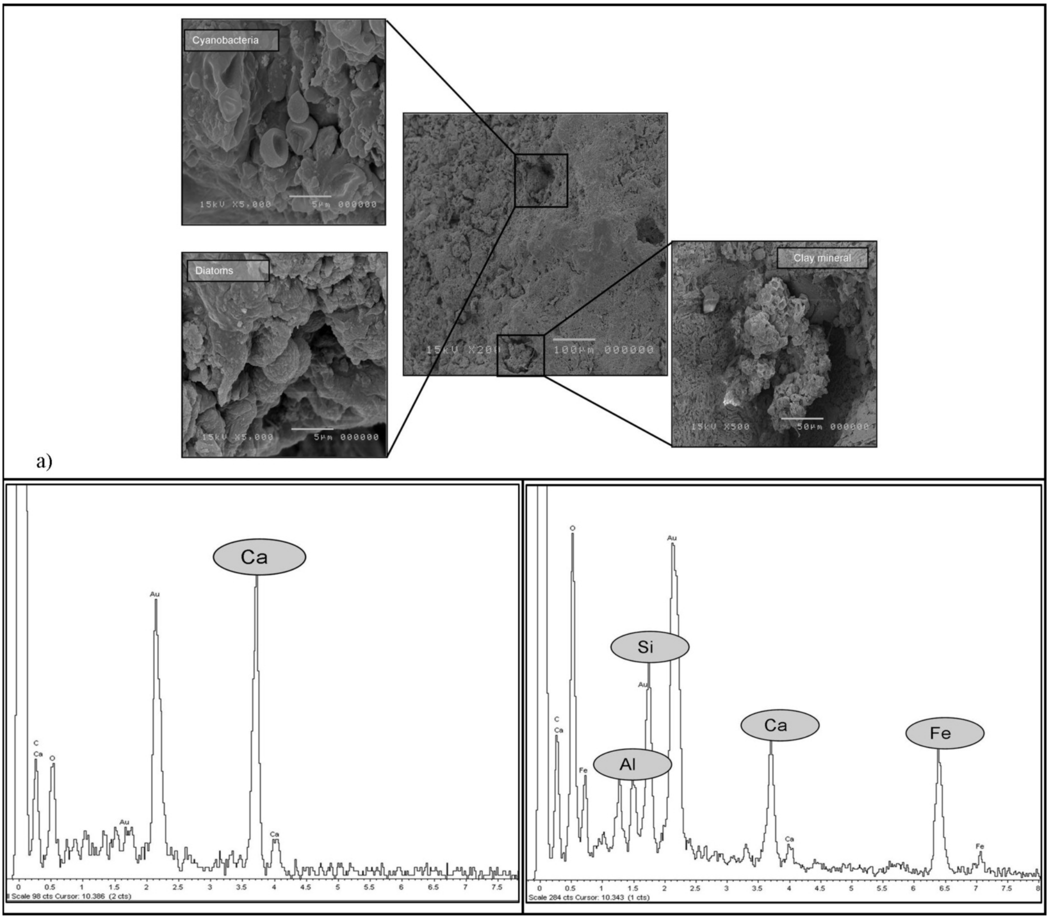
The black crust has been studied under Scanning Electron Microscopy on a small stone fragment from the east basement façade of the bell tower (Fig. 2). Results proved that the black crust on the surface of the sample was composed by calcite (Fig. 2b) and was characterized by some micropits (honeycombed shaped voids) containing biological matter (Cyanobacteria and Diatoms) and clay minerals, as evident from Figure 2a, probably due to previous cleaning treatments on the material and/or presence of atmospheric particulates. The EDS analysis confirmed the presence of clay minerals whose composition is essentially made by silica and alumina (Fig. 2c).

Rating of stone damage

The extent of each decay morphology was estimated in a semi-quantitative way in relation to the total weathered area (Fig. 3).

Three grades of weathering intensity of were defined (Calcaterra *et al.*, 1995): high, moderate and negligible. Based on the criteria proposed b the authors, the weathering of the northern, western and southern bell tower basement façades was moderate; on the contrary, the eastern basement façade showed a strong decay (Table 4) probably connected to its position facing a very trafficked street and/or some particular microenvironmental conditions (type of exposure, variations in temperature and relative humidity).

Figures 4, 5, 6 and 7 show the stone weathering patterns of all the façades of the Santa Chiara bell tower basement. Each deterioration morphology is given in a different colour. The black crust is very common on the top and on the basis of all



b) c)

Fig. 2 - Black crust: a) black crust SEM micrograph; b) black crust EDS analysis; c) alveolar clay mineral EDS Analysis.

the basement façades while efflorescence and stain are concentrated in the middle sectors. The greatest number of detachments are observed on the eastern basement façade.

DISCUSSION AND CONCLUSIONS

The present research brings new data on the durability of the Cusano limestones (through freeze-thaw and salt crystallization laboratory tests), and on the main deterioration morphologies involving the stone when used in exterior locations.

The artificial weathering of the Cusano limestones proved that it must be classified as frost-proof; the salt crystallization action is negligible because of the low porosity of the rock.

The weathering features were surveyed and mapped in a semi-quantitative way on the basement of the bell tower of the Santa Chiara Monastery, which was studied as a case history.

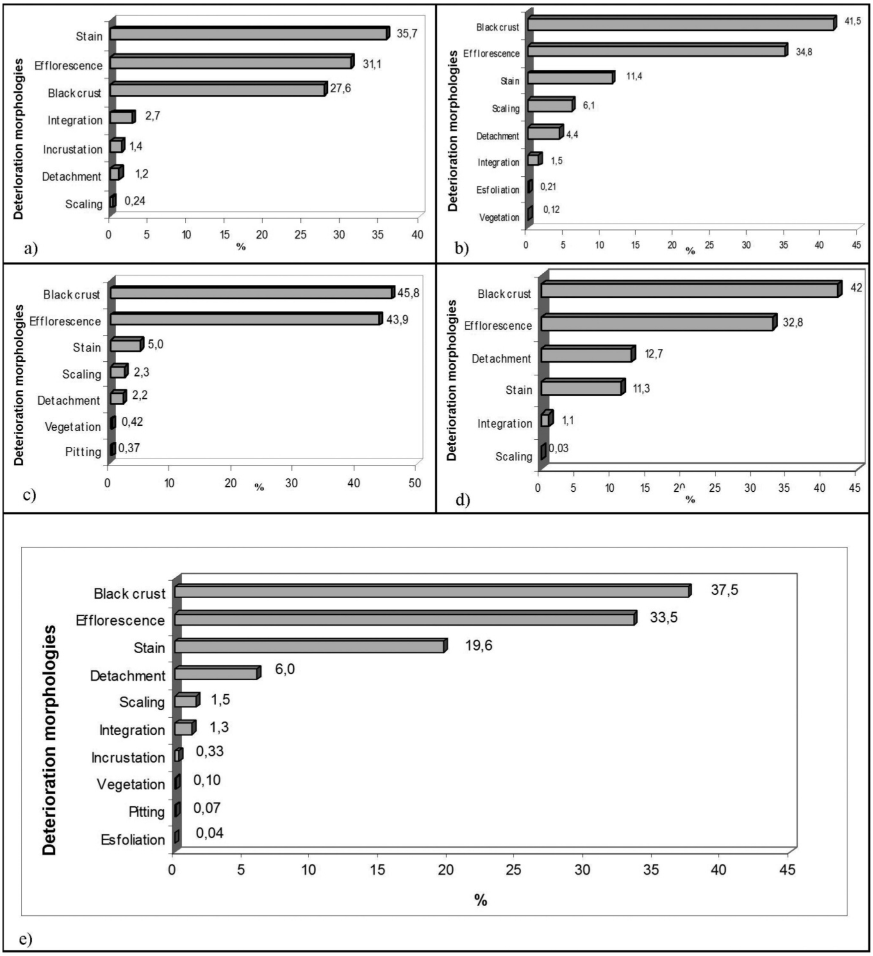


Fig. 3 - Deterioration morphologies of the Santa Chiara monastery bell tower basement expressed in percentage of involved surface: a) Northern façade; b) Western façade; c) Southern façade; d) Eastern façade; e) Bell tower total area.

TABLE 4

Weathered area of the façades of the Santa Chiara Monastery bell tower.

Façade	Weathered area (%)	Intensity
Northern	49.59	Moderate
Western	34.19	Moderate
Southern	38.56	Moderate
Eastern	70.88	High

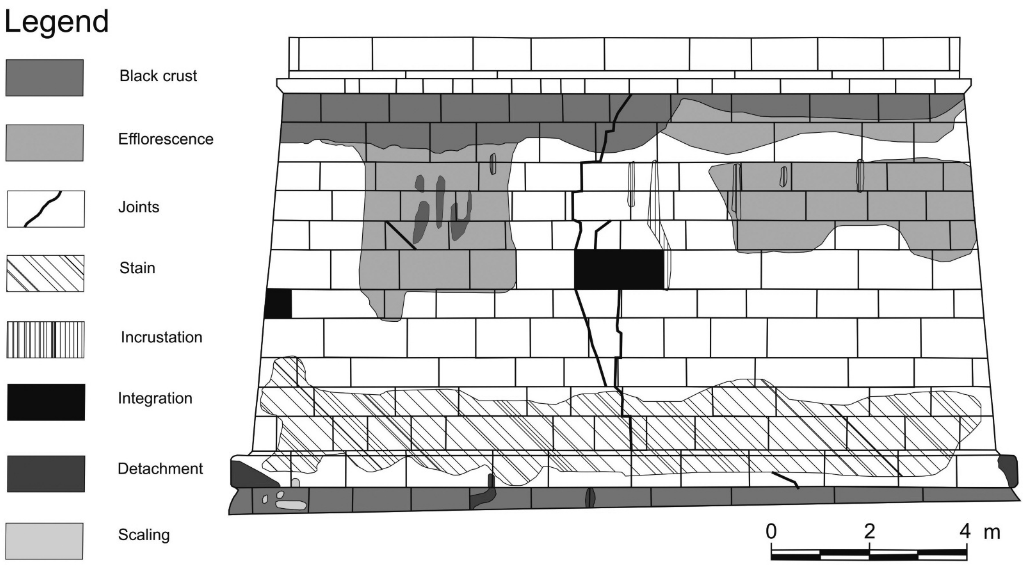


Fig. 4 - Deterioration morphologies of the Northern Santa Chiara bell tower basement façade.

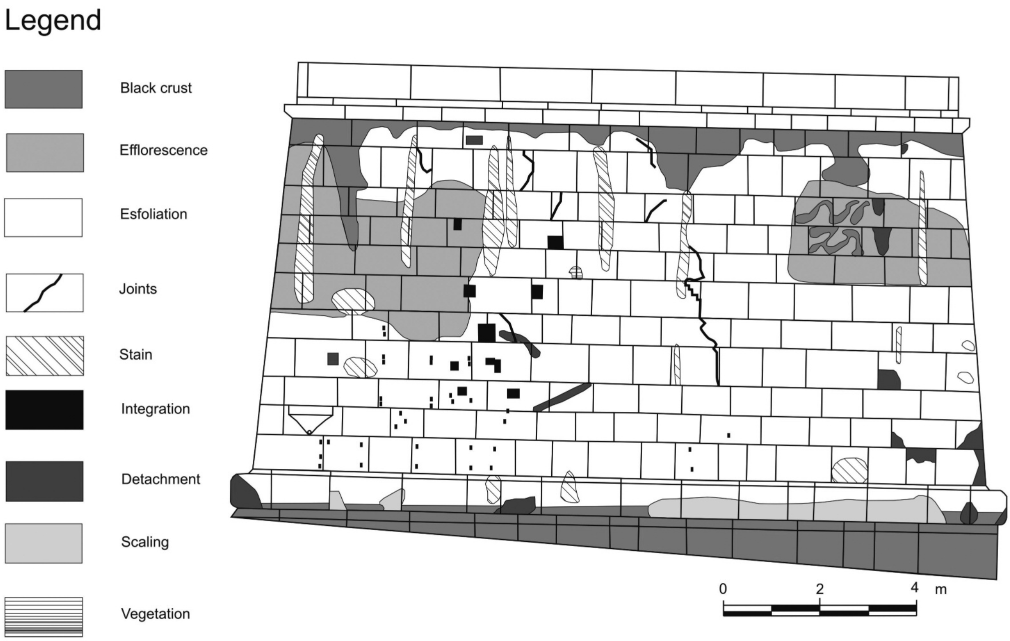


Fig. 5 - Deterioration morphologies of the Western Santa Chiara bell tower basement façade.

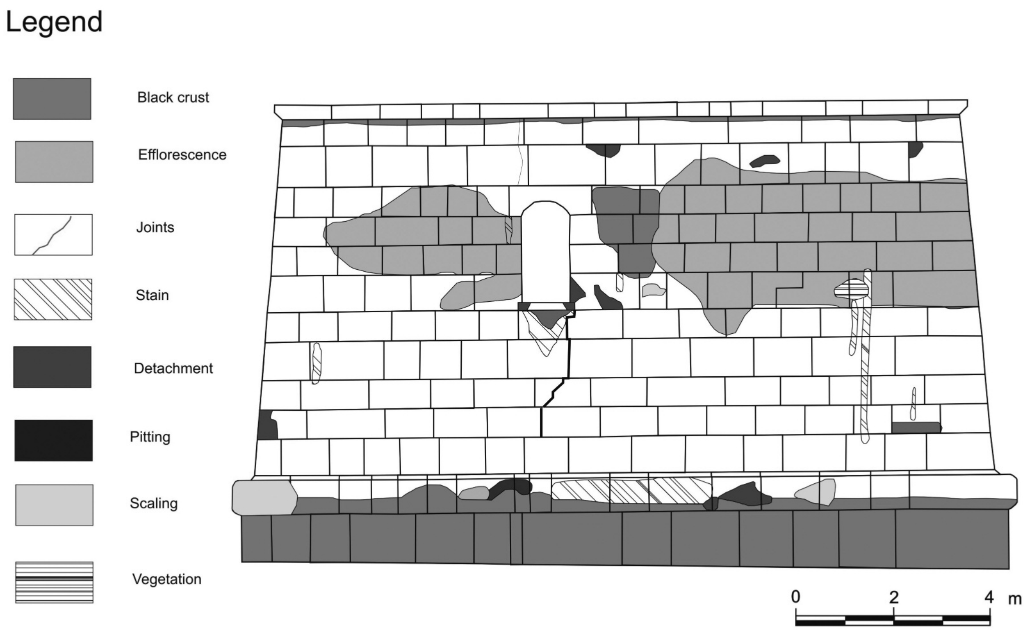


Fig. 6 - Deterioration morphologies of the Southern Santa Chiara bell tower basement façade.

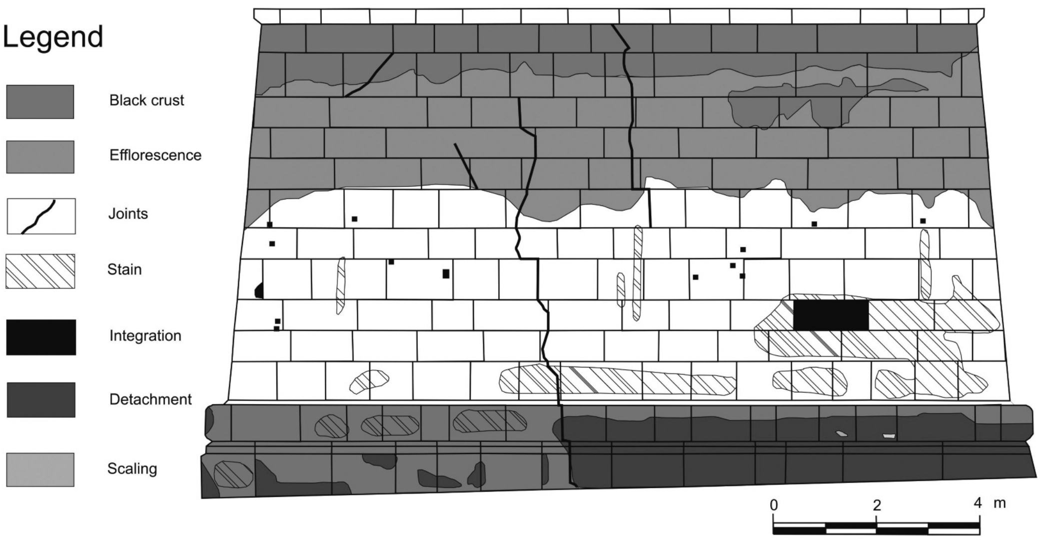


Fig. 7 - Deterioration morphologies of the Eastern Santa Chiara bell tower basement façade.

A deep knowledge of the state of conservation of the building material is in fact useful to provide a substantial contribution to the restoration of the monuments.

As all the façades of the exposed surfaces show moderate to strong deterioration grade, restoration and conservation works such as cleaning and replacement of badly damaged blocks and filling of joints need to be implemented in order to protect the original stone surface from further decay.

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