Decay patterns of granite stones in Braga monuments (NW Portugal)

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ABSTRACT: The decay features of thirty-nine monuments built with granite stones and presenting diverse architectural characteristics, date of construction and environment characteristics (including exposition conditions, traffic intensity, etc) are compare in order to discuss decay patterns and susceptibility of granite types applied in architectural works. Decay patterns of biotite-rich medium to fine-grained (frequently porphyritic) granite stones are related to weathering inherited from the quarry (expressed by yellowing), to the presence of heterogeneous elements (enclaves and phenocrysts) and to grain size variations. Fine-grained leucogranitic stones decay is mainly controlled by tectonic foliation. The characteristics of stone application, including how and where was stone used, influence decay patterns by favouring salt pollution concentration, biological colonisation and fixation of atmospheric pollutants. Erosive decay features (linked mainly to salt pollution) and stone coatings (linked to biological action and atmospheric and organic pollution) are widespread decay forms that affect granite stones on Braga buildings.

1 INTRODUCTION

Granite stone is an important element of the built heritage of Braga (NW Portugal, Fig. 1a,b). Several decay features related to anthropogenic and geogenic factors affect the granite stones of these monuments. The decay aspects discussed in this paper concern surface modifications that affect the aesthetics value of stones. Certain authors have considered natural chromatic alterations of stones as kind of “finishing” (Mostafavi and Leatherbarrow 1993), but, in the present paper, all alterations that occur after employment of the stones will be considered decay features (since the original aspect of the stone is altered).

Although decay processes have been modelled, and several laboratory essays have tried to simulated decay process, only comparison of decay features of diverse buildings may avail the real time and space scale of decay processes and the simultaneous effects and interactions of diverse decay agents (Smith 1996, Lewis and McDonald 1997, Nord and Holenyi 1999).

The main goals of this paper are i) to discuss and identify decay patterns of granites stones on Braga monuments; ii) to discuss stone susceptibility and durability as result of stone characteristics and application aspects.

2 MATERIALS AND METHODS

The decay features of thirty-nine monuments (see location on Fig. 1) are considered, including results of previous studies regarding the Archiepiscopal and Biscainhos Palaces (Alves 1997) and the Idol's Fountain (Aires-Barros *et al.* 1998).

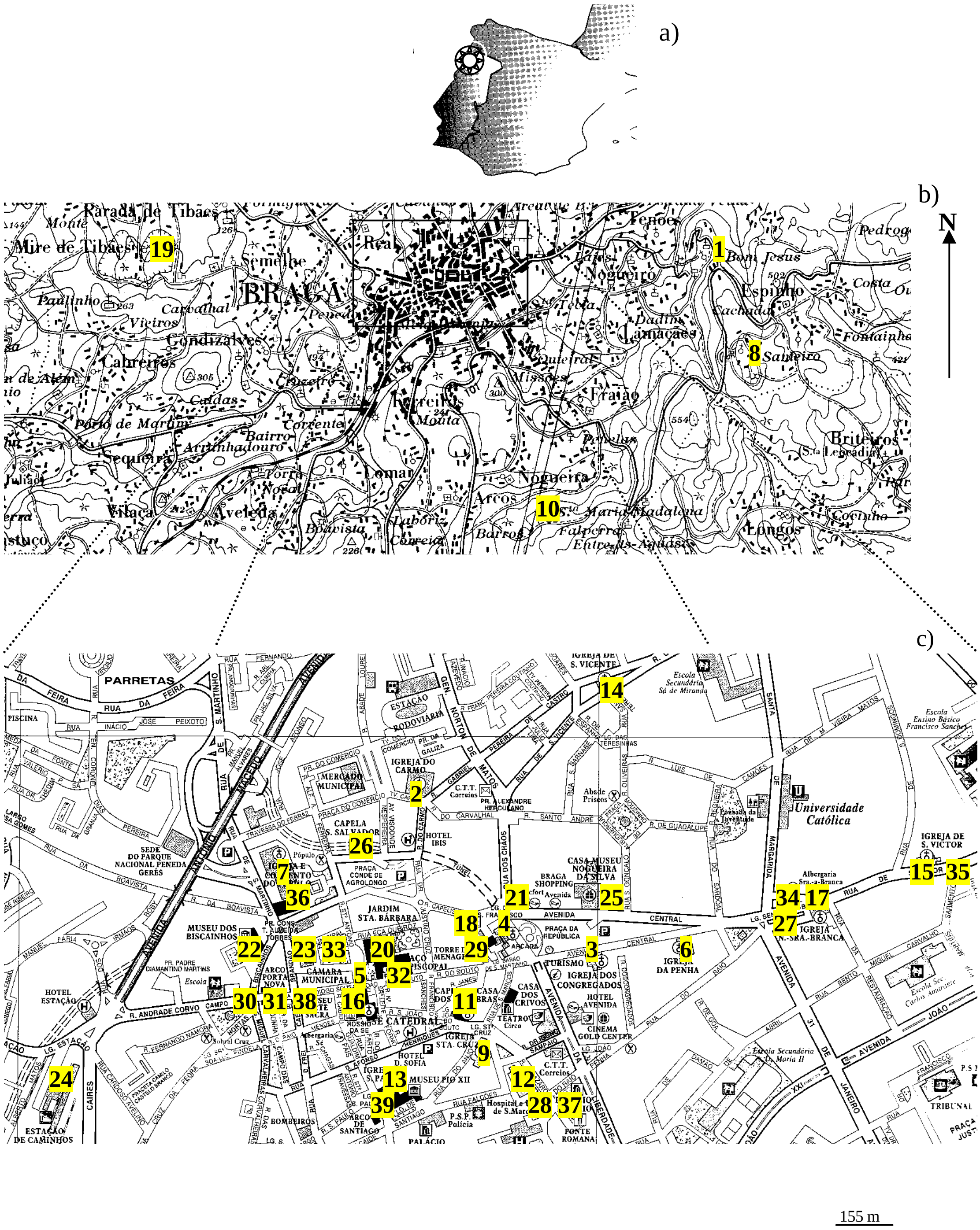

Figure 1 : Location of the town of Braga (a, b) and of the studied monuments (b, c).

These monuments include churches and chapels, civil and military buildings and fountains. The selected monuments (Table 1) were almost all built between the 16th and 20th centuries, but there are older monuments and portions of monuments (Costa 1985, DGEMN 2000, Oliveira 1999). This group of monuments allowed the study decay features of granite used for walls and façades masonry blocks, windows and doors frames elements, ornamental details, paving slabs, columns and arches, and subjected to different environmental conditions (interior/exterior, varied exposition orientation, diverse surroundings, etc). The orientation of the buildings façades is very variable (Fig. 2).

Table 1: Designation and construction centuries of studied monuments (numbers correspond to numbers of Fig. 1).

Typology	Monuments	Age (century AD))
Religious buildings	1- Bom Jesus Sanctuary	18th/19th
	2- Carmo Church	17th/20th
	3- Congregados Church and Convent	17th/18th
	4- Lapa Church / Arcade	18th/20th
	5- Misericórdia Church	16th
	6- Penha de França Chapel	18th
	7- Pópulo Church and Convent	18th
	8- Sameiro Sanctuary Church	19th/20th
	9- Santa Cruz Church	17th/18th
	10- Santa Maria Madalena Chapel	18th
	11- Coimbras Chapel	16th
	12- S. Marcos Church	18th/19th
	13- S. Paulo Church	16th/17th
	14- S. Vicente Church	17th/18th
	15- S. Vítor Church	17th
	16- Braga Cathedral	12th/15th/18th
	17- Senhora-a-Branca Church	14th/18th
	18- Terceiros Church	17th/18th
	19- Tibães Monastery Church	17th
Civil and military buildings	20- Arquiepiscopal palace	14th/15th/16th/17th/18th
	21- Banco de Portugal Building	20th
	22- Biscainhos Palace	17th/18th
	23- City Hall Building	18th/19th
	24- Railway Station Building	19th
	25- INATEL Building	19th
	26- Lar Conde de Agrolongo Building	17th/20th
	27- Matos Graça Palace	19th
	28- Raio Palace	18th
	29- Medieval Donjon	14th
Decorative, Evocative and Functional Monuments	30- Porta Nova Arch	18th
	31- Noble House	16th/17th
	32- Castelos fountain	18th
	33- Pelicano fountain	18th
	34- Square Senhora-a-Branca fountain	20th
	35- D. Pedro V Street Fountain	19th
	36- Cons. Torres de Almeida Square Fountain	19th
	37- Ídol’s fountain	1st or 2nd
	38- Passo da Praça Velha	18th
	39- Door of Santiago	16th

In all the studied monuments was performed a detailed visual survey, in order to distinguish the decay features affecting granite stones and its distribution in the monuments. The decay features detected and the characteristics used for its field distinction are presented in Table 2 (partly following nomenclature suggestions of Fitzner *et al.* 1992 and Dorn 1998). Efflorescences samples were furthermore characterised by optical microscopy (immersion method, using the indications of Arnold 1984) and by X-ray diffraction, since salt efflorescences could be useful fingerprints of salt pollution (Arnold and Zehnder 1989, Arnold 1996, Alves and Sequeira Braga 2000). Some samples of stone coatings (namely patinas) where also studied, using scanning electron microscopy with microanalysis system (SEM/EDS).

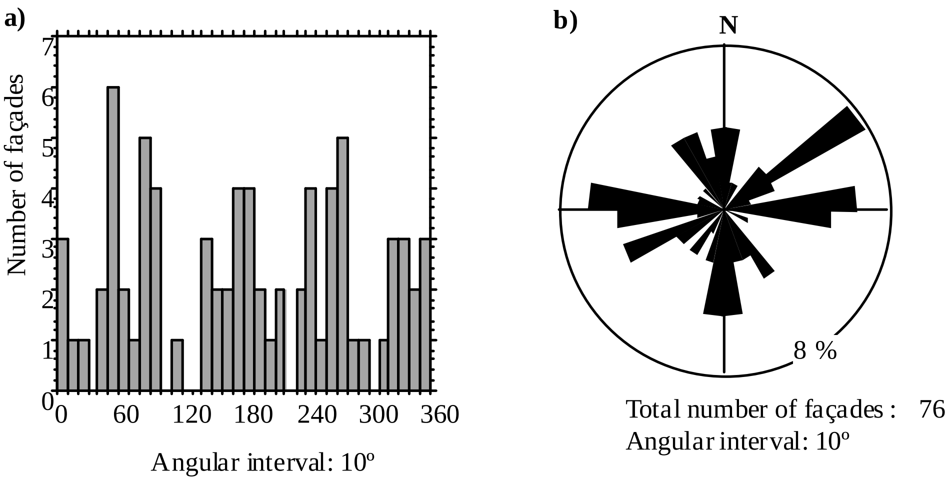

Figure 2 : Histogram (a) and rose diagram (b) of exposition azimuth of surveyed façades (given by the exposition sense of the vector normal to the façade plane).

Table 2 : Decay features on the studied monuments and macroscopic characteristics used for distinction.

Designation	Macroscopic characteristics
Fissures	crack lines at the stone surface
Granular disintegration	detachment of stone grains
Flakes	detachment of small, planar elements parallel to the stone surface
Scales	detachment of large, planar elements parallel to the stone surface
Efflorescences	salt aggregates on stone surface
Black crusts	very dark spongy concretions
Biological colonisation	biological related coatings (including diverse organisms and soiling resulting from biological colonisation)
Patinas	generic term for thin stone coatings without clear genetic evidence

3 RESULTS: DISCUSSION OF DECAY PATTERNS

The comparison of decay features distribution in monuments allows the discussion of decay patterns related, on one hand, to stone characteristics and, on the other hand, to the characteristics of stone application (including the surrounding environment of the monuments where stones are used).

3.1 Granite stones characteristics

The granite stones applied in these monuments present varied petrographic characteristics, but two types are dominants, and, therefore, will be the object of consideration (allowing comparison of different situations). The most frequent stones are of biotite-rich, medium to fine grained, frequently porphyritic, granite, with diverse enclaves, and presenting variable coloration (yellowing). Also frequent, namely on façades of some more recent buildings, are fine-grained leucogranitic stones (with colour index < 5%, as defined in LeMaitre ed. 1989) with tectonic foliation. Decay patterns related to petrographic characteristics of these main granite types are summarised in Table 3.

Table 3 : Decay patterns related to stone characteristics.

Stone Characteristics	Decay patterns
Biotite-rich granite	
coloration (yellowing)	• more yellow stones - - more intense and extensive erosive decay; - higher frequency of black crusts;
heterogeneity - - phenocrysts - granular enclaves - micaceous nodules	• surface irregularities by differential erosion - - positive relief; - positive relief; - negative relief;
grain size	• coarser stones present more intense granular disintegration
Fine-grained leucogranite	• frequent occurrence of patinas
tectonic foliation	• flakes along whole block faces parallel to foliation • fissures and erosion along foliation planes • biological colonisation along fissures

Biotite-rich granite stones decay is clearly dependent on stone coloration (yellowing), which represents weathering inherited from the quarry, being the more yellowed stones less durable, as previously observed by Alves (1997), Begonha (1997) and Delgado Rodrigues (1979, 1996). This inherited weathering that granites suffer in natural massifs affects the properties of the stones applied on monuments, namely through porous media development that favours pollutants absorption and migration (for characterisation of these stones porous media see Alves 1997, Alves *et al.* 1996) and through physical weakening. The higher frequency of black crusts on more yellow stones can also be due to the development of porous media, in a similar to what is referred by Aires-Barros (1991a, b) for marble and limestone. The presence of heterogeneous elements like enclaves and phenocrysts has also a marked effect on these stones performance, with development of surface irregularities, resulting of differential erosion. Decay by granular disintegration is also more pronounced on coarser grained stones.

On fine-grained leucogranitic stones, tectonic foliation controls development of flakes and fissures, according to the orientation of stones faces to foliation (Fig. 3), since foliation constitutes planes of weakness. While on biotite-rich granite stones flakes tend to occur near mortar joints and corners, flakes on leucogranitic stones tend to affect the whole stone face. Curiously, the development of scales on leucogranitic stones does not seem to be directly related to the orientation of foliation and tend to concentrate near mortar joints and corners.

It is noted that leucogranitic stones are frequently affected by patinas (being these patinas, perhaps, more noticeable on account of these stones lighter coloration). Black crusts are only observed on biotite-rich granite stones, but whether this pattern is related to stones characteristics or to the monuments location (and surrounding environment) is not yet clear.

3.2 Granite stones application

In this subject (Table 4) are considered decay patterns related to the influence of exposition, height, mode of application, use given, and the monuments surrounding environment (including traffic intensity, presence of other buildings and trees, etc).

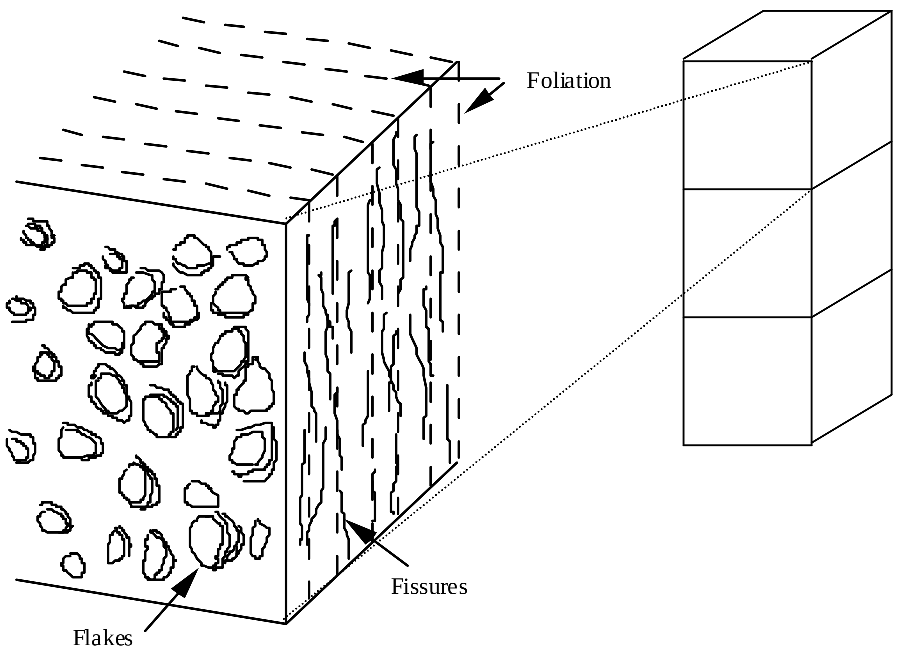

Figure 3 : Effects of foliation on fine-grained leucogranitic stones decay.

According to the survey performed, architectural characteristics of façades have a bigger influence on the occurrence and distribution of decay features than orientation, namely by the presence of places that cause accumulation of solutions, like balconies, cornices, etc; places that have been considered as, potentially, presenting a higher salt regime (Duffy and O'Brien 1996). Accentuated decay associated with concentration of solutions is also observed at the sheltered portions of arcades and, occasionally, borders of pavement slabs (linked to presence of buried corpses). The effect of façades orientation is also countered by the sheltering effect of trees and/or buildings in the surroundings. Nevertheless, it is observed that north façades are more susceptible to soiling by biological colonisation and that south façades, sunnier and windier, tend to present more intense development of flakes (also observed on some west façades).

The base of buildings walls is frequently the most affected zone, both by erosive decay (associated with saline pollution ascension) that affect both interior and exterior elements, and by the development of patinas (affecting façades). However, it must be referred that discoloration by patinas affects entire façades made with leucogranitic stones.

Discoloration resulting from the diverse stone coatings is a major problem affecting outside features. Biological colonisation distribution is clearly related to moisture and sun exposition balance and black crusts show characteristics elements, namely gypsum aggregates and flying ashes (LeFèvre 1992), of association with atmospheric pollution.. The coatings generically designed by patinas show evidences of a more complex and varied genesis, related to pollution (atmospheric and organic), moisture balance and influence of microbiological activities.

Contrary to observations regarding other locals with granite stone monuments (Urquhart *et al.* 1996), biological soiling is a major problem affecting outside granite stone elements, which is supposed results from high precipitation observed in Braga (1514.5 mm/year, mean value for the 1961-1990 series, data from the Portuguese Meteorological Institute).

There seems to be an association between some stone coatings (namely black crusts and some dark patinas) and intensity of traffic surrounding the monument.

Table 4 : Decay patterns related to the characteristics of stone application (including surroundings).

Stones applications	Decay pattern
Façades	
orientation	• frequent and extensive biological colonisation on north façades • more intense and frequent flaking on south façades
height	• lower zones present more frequent occurrence of - - erosive decay features; - dark patinas; • erosive decay features at higher portions depends on architectural characteristics • biological colonisation and some patinas (leucogranitic stones) along the whole height of façades
architectural characteristics	• regardless of height, places where moisture and solutions accumulated (balconies, cornices, etc) present more - - intense erosion; - black crust formation; - biological colonisation; • scales and flakes tend to concentrate near mortar joints and corners • projecting and artistic details are more affected by erosion
surroundings	• biological colonisation increased by sun sheltering effects of other buildings and threes • dark patinas and black crusts associated with narrow streets and intense traffic
Fountains	• frequent occurrence of patinas with diverse tonalities • scarce occurrence of erosive aspects
Pavements and stairs (exterior)	• surface irregularities linked to differential erosion • occasionally, erosion near joints (linked to pollution concentration)
Arches and arcades	• erosive decay and biological colonisation more frequent at the base of piers • more intense erosive decay at the sheltered portions of arches
Interior rooms	• erosive decay occurs at the floor and at the base of walls and pillars; • scales and flakes more frequently near mortar joints and corners • projecting corners are more susceptible to erosion • more intense erosive decay associated with occurrence of efflorescence of diverse soluble salts

Inside the monuments, decay is mostly associated with saline pollution and frequently is limited to the portions nearer the ground. The most intense decay is usually associated with salt efflorescences occurrence (representing a more intense saline pollution). These salt efflorescences show varied mineralogy (Table 5), with predominance of sulphates and nitrates. Biological colonisation is almost absent inside the monuments, and the rare situations observed seem to be associated with infiltration.

Table 5 : Soluble salts detected on efflorescences of the studied monuments.

Monuments	Soluble salts
Arquiepiscopal Palace	Halite, Nitratine, Niter, Trona, Thenardite, Hexahydrite, Epsomite, Gypsum, Aphthitalite, Syngenite
Biscainhos palace	Halite, Nitratine, Niter, Calcite, Trona, Thenardite, Mirabilite Gypsum, Aphthitalite, Syngenite, Darapskite
Carmo Church	Niter, Thermonatrite, Thenardite, Gypsum
Congregados Church and Convent	Halite, Niter, Thenardite, Gypsum
Lapa Church	Nitratine, Niter, Gypsum
Terceiros Church	Gypsum
City Hall Building	Halite, Nitratine, Niter, Trona, Thenardite, Gypsum, Aphthitalite
Railway Station Building	Halite, Nitratine, Trona Thenardite, Gypsum
Raio Palace	Niter, Gypsum

4 CONCLUSIONS

Study of decay features allows identification of the main decay patterns that affect granite monuments of Braga.

For biotite-rich, medium to fine-grained, frequently porphyritic, granite stones, decay is related to yellowing (with more pronounced and extensive erosive decay and also more frequent black crust formation on more yellowed stones), grain size variation (coarser grain stones show more intense erosive decay) and the presence of heterogeneous elements (differential erosion of phenocrysts and enclaves). Tectonic foliation of fine-grained leucogranitic stones conditions the distribution of fissures, flakes and biological colonisation on these stones.

Erosive decay is strongly linked to salt pollution, being favoured by features that allow solutions accumulation and circulation (architectural details and mortar joints). Intensity of salt pollution resulting from local characteristics also affects erosive decay, as is shown by more intense decay inside buildings, associated with salt efflorescences and by decay of pavement slabs, associated with buried corpses.

Chromatic modifications (related to biological colonisation, black crusts and patinas) are a major problem affecting stone applied at exterior elements. Biological colonisation shows a widespread occurrence on these monuments stones and constitutes the main discoloration factor, being its distribution related to substrate moisture and sun exposure. Black crusts are related to atmospheric pollution and its distribution seems related to the intensity of surrounding traffic. The studied patinas show varied characteristics and genesis related to diverse agents.

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