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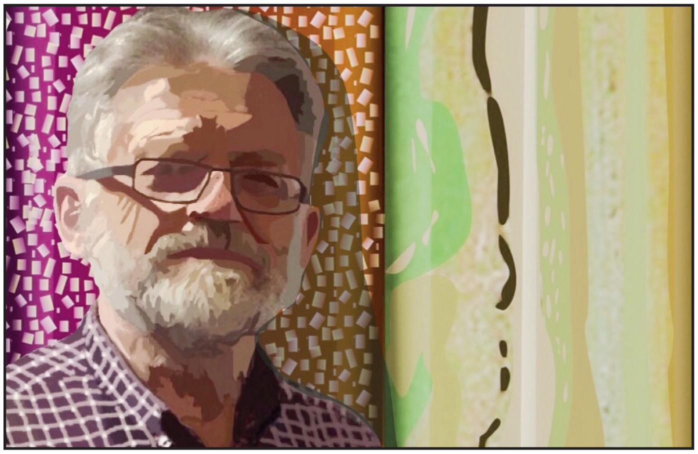

Heritage Stone 3. Degradation Patterns of Stone Used in Historic Buildings in Brazil*

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SUMMARY
Brazil's heritage buildings were built using different types of natural stone, including sandstone, limestone, quartzite, granite, gneiss, steatite (soapstone) and schist. Historic buildings are located in cities such as Recife, Olinda, Salvador, Rio de Janeiro, Congonhas and Ouro Preto; some are over 300 years old. They show evidence of different alteration and decay processes, with the latter leading to a loss of value because of physical and chemical modifications in intrinsic properties of the natural stones used. Consequently, these buildings function as open-air laboratories, and contribute to the study of deterioration in such monuments. On going investigation of alteration and decay reveals that they are affected by a diverse group of processes that are, in part, influenced by lithological factors. This understanding will contribute to the choice of preservation methods that will be applied in order to arrest degradation.

RÉSUMÉ
Les édifices classés brésiliens ont été batis en roches variées. On a employé des grès, des calcaires, quartzites, granites, gneiss, ainsi que la stéatite et des schistes. Les bâtiments historiques, dont certains ont plus de 300 ans, se trouvent dans des villes comme Recife, Olinda, Salvador, Rio de Janeiro, Congonhas et Ouro Preto. Ils présentent les marques de différents processus d'altération et de deterioration, ce dernier conduisant à une perte de valeur, en raison de modifications physiques et chimiques dans les propriétés intrinsèques des pierres naturelles utilisées. De la sorte, ces bâtiments fonctionnent comme des laboratoires à ciel ouvert et contribuent à l'étude des modalités de dégradation des monuments. L'étude en cours des phénomènes d'altération et de décomposition révèle la diversité des processus en cours et leur relation avec la lithologie. La reconnaissance de ces phénomènes aidera à choisir les méthodes de conservation destinées à bloquer la dégradation.

INTRODUCTION
There are currently few studies in Brazil that describe the rocks that make up its built cultural heritage, or provide information on where they come from and how the stone was used in the construction of many monuments. Based on a detailed survey of these materials and other issues related to this heritage (Costa 2009), we present descriptions of the most common alteration processes and forms of decay observed for monuments located in a number of areas of Brazil. Given the variety of stone used for heritage buildings, this is the first step toward recommending adequate preservation methods for each case of observed deterioration.

THE USE OF STONE IN THE CONSTRUCTION OF BRAZIL'S CULTURAL BUILT HERITAGE
Brazil's territory features a diverse geology. Therefore, from north to south, east to west, different types of rocks (Fig. 1) have been used in the construction of the religious, civil, administrative or military buildings that currently constitute the assets of Brazil's Cultural Heritage (Costa et al. 2008; Costa 2009, 2014, 2015). Other rocks can be added to that list of

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Figure 1. Major regions of Brazil showing the location of its most important historical cities and the distribution of different types of natural stone used in monuments built between the 16th and the late 19th century.

materials, especially those brought or imported from Portugal and Italy, particularly in the 17th and 18th centuries.

With regard to timing, a considerable number of these buildings, notably those in Minas Gerais, were constructed between the mid-16th century and the late 19th century, with most in the first half of the 18th century. However, access to and use of rock materials was limited, and not always adequate. Broadly, such restricted rock use to the end of the 19th century, whether in masonry or stonework, was the result of multiple factors: variable rock distribution; a near-total absence of suitable stone in some regions; and lack of a work force skilled in stonework techniques. The people in charge of those constructions frequently found themselves forced to resort to other methods and to use less resistant materials, such as wood, mud or clay (Costa 2013).

Following the colonization of the Brazilian coast, inland Brazil was conquered in the late 17th century, the Portuguese focused their efforts on settling a region endowed with abundant gold and diamond mines, which became known as Minas Gerais (General Mines) (Fig. 1). This area later became part of the Brazilian Empire and is currently the State of Minas Gerais. With its rich mines, including iron deposits, it was very important to the economy of 18th and 19th century Brazil, becoming its richest captaincy. Located in the country's interior, it was also the region where the largest number of historic buildings was constructed with the use of natural stone.

The first half of the 18th century, during which Minas Gerais was developed, saw the rise of the state's most important constructions, even in the face of difficulties. Resources became progressively rarer, especially for projects belonging to religious orders, insofar as gold and diamonds were no longer produced in large quantities. In addition, the colonizers themselves lacked interest in spending their resources on very expensive buildings, as they eagerly hoped to return to their homeland with their newly acquired wealth. However, these reasons did not prevent Brazil, and especially Minas Gerais, from producing the beautiful baroque and rococo monuments typical of the 18th century. Eventually, that scenario contributed to the rise of a peculiar, typically mineira constructive art (mineiro being the adjective designating things or people from Minas Gerais).

BUILDING STONES USED IN BRAZILIAN HERITAGE BUILDINGS

The historical buildings were constructed with sedimentary rocks such as limestone and sandstone, metamorphic rocks such as quartzite, schist, steatite (soapstone), marble and gneiss, and igneous rocks such as granite, gabbro and basalt (Fig. 2).

Several types of limestone, sandstone and calcarenitic reef deposits were used during both colonial Brazil — in the north and in villages and towns of northeastern captaincies and provinces — and the imperial period (Carvalho 1942; Costa 2009). These materials, when compared to granite, quartzite and marble, proved to be more suitable for the sculptural arts, inasmuch as the former are softer while the latter are more resistant, making these more suitable for construction in general, and crop out all along Brazil's northeastern coast, from Paraíba south to Bahia state. Within that area, the use of limestone was more frequent in the states of Bahia, Sergipe and Paraíba, whereas sandstone and calcarenite were more widely used in the regions of Pernambuco and Alagoas states (where they could be easily extracted from reefs and beaches). Another type of sandstone, very ferruginous, was widely used in old buildings of Amapá state, located in the extreme north of Brazil.

Gneiss, plutonic igneous rocks such as granite, gabbro (mistakenly called black granite) and several kinds of volcanic rocks were used secondarily in buildings of those old historical centres. In his study on the use of stone in northeastern religious architecture, Carvalho (1942) indicated that "*a great amount of rock used in the adornments of Pernambuco's churches*" might have been extracted from volcanic Santo Aleixo Island, which lies near the coast of Pernambuco.

In João Pessoa (Paraíba state), São Francisco's Convent, Santo Antônio's Church and its fountain, all property of the old Third Order of Saint Francis, were built a few metres away from the quarry that provided the limestone used both in their masonry and for several decorative elements. In Lucena, also in the region of João Pessoa, Nossa Senhora da Guia's Church (Our Lady Who Guides), built between 1763 and 1778 to replace an old chapel dating from the late 16th century, features on its frontispiece an exquisite arrangement of fruit carved out of local limestone, which was likewise used in the construction of the church arches and portals.

In Recife, Pernambuco state, the calcarenitic rock found in coastal reefs and beaches was used in the masonry, stonework and sculptures of its innumerable churches, such as the Igreja dos Prazeres (Church of Pleasures), in São Pedro dos Clérigos' (Saint Peter of Clergymen), in Rosário dos Pretos' (Black People's Rosary), in the Igreja Matriz de Santo Antônio (Mother Church of Saint Anthony), and in the Igreja de Nossa Senhora do Carmo (Church of Our Lady of Carmo).

In the city of Olinda, also in Pernambuco, limestone was more frequently used in the construction of its older buildings. Partly brought from the area of João Pessoa, limestone was employed, among other rocks, in the construction of arches and lateral altar pieces in the Igreja Nossa Senhora das Graças (Our Lady of the Graces Church), located in the city's seminary and built between 1551 and 1592. Limestone from that region was also used in the production of several elements of the Capela de Nossa Senhora do Carmo (Chapel of Our Lady of Carmo), built around 1580. Later, sandstone began to be more frequently employed, as it provided higher resistance compared to limestone, as is the case with Basilica de São Bento (Saint Benedict's Basilica), reconstructed with stone and lime-based mortar between 1688 and 1692. Documents found with the Order of Saint Benedict (Carvalho 1942) in Olinda's Monastery, dedicated to Nossa Senhora dos Prazeres dos Montes Guararapes (Our Lady of Pleasures on the Guararapes Hills), indicate expenses concerning the extraction of sandstone from reefs nearby for the construction of quoins, arches, jambs and cartouches of the chapel. In Igarassú, limestone was used both in masonry and in stonework. In some buildings in Goiana, another important historical site in Pernambuco, calcareous rocks, varying from limestone to calcareous sandstone, were used. Both Carvalho (1942) and Costa (2009) noted that in Serinhaém, Pernambuco, sandstone was also used in the construction of arches, jambs and cyma moldings in the chapel of Santo Antonio's Convent, whereas granite was applied to the so-called ordinary masonry in the same building.

In Santo Amaro das Brotas, as well as in other coastal towns in Sergipe state, limestone was used in the production of quoins, cyma moldings, staircases, sills and transept arches. However, in the city of Gerú, located in the countryside, gneissic rocks crop out more frequently and were thus used by Jesuit priests both in the construction of their church and in elements of the doorway of another important historical site called Engenho Retiro.

In the town of Penedo, Alagoas state, sandstone appears along the bay of the Rio São Francisco, and was also used in the production of ornaments and stonework. In the Igreja de São Gonçalo Garcia (Church of São Gonçalo Garcia), in addition to its portals and quoins, tracery details made from arenitic sandstone are present. Despite the greater hardness of this material, these tracery details are identical to steatite tracery observed in Minas Gerais, as well as those produced in limestone at Santo Amaro.

In Salvador, Bahia state, the frontispiece at the Capela da Ordem Terceira de São Francisco (Chapel of The Third Order of Saint Francis) (Fig. 2a) is built partly of limestone, but also in sandstone. The frontispiece is covered from its base to its

Figure 2. Selected uses of stone in the construction of Brazil's cultural built heritage. a) Limestone and sandstone in the frontispiece at the Chapel of The Third Order of Saint Francis, Salvador, Bahia; b) gneiss in a building in the city of Rio de Janeiro; c) quartzite in the old Casa de Câmara e Cadeia (Chamber and Prison House), located in Ouro Preto; and d) quartzite and steatite in the frontispiece of the Chapel of The Third Order of Saint Francis, Ouro Preto, Minas Gerais.

ridge with countless figures and decorations which, according to Bazin (1956), resemble an architectural style typical of overly-decorated façades, associated with the Spanish Renaissance and known as 'Plateresco.'

After considering the use of soft or barely consolidated rocks, such as limestone and sandstone, widely used in historical buildings in northern and northeastern Brazil, our focus goes on to gneisses and granites. These rocks are aesthetically very similar, and constitute the bedrock on which several historical sites were established during the period of Portuguese America in the coastal zones of old captaincies and in the provinces of Brazil's southeastern and southern regions. They were widely used in several constructions, particularly those in the former Captaincy of Rio de Janeiro (Fig. 2b). Such frequent applications can be observed in buildings and monuments of cities such as Rio de Janeiro, Paraty, Cabo Frio and Angra dos Reis, as well as in the old Village of Nossa Senhora do Desterro in the Isle of Santa Catarina, currently Florianópolis, which at that time was part of the aforementioned captaincy. In the city of Rio de Janeiro, several churches, chapels, convents, residences, fortresses and palaces were built with different types of granite and, more commonly, gneiss. The latter, whether finely banded or not, normally contains fine- to coarse-grained crystals of feldspar and quartz, the latter resembling large eyes because of the difference in size between these grains and other minerals. Usually speckled with reddish garnet crystals in a whitish-grey matrix, these materials were worked by craftsmen who came mostly from Portugal. Examples can be found in cornices, portals, columns, quoins, jambs, lintels and sills installed in churches, such as those of São Francisco de Paula, Carmo and Nossa Senhora da Candelária. Gneisses were also used in the construction of different arches, such as the well-known Arco do Telles, in administrative buildings such as the Paço dos Vice Reis (Viceroy's Paço or Palace), as well as in the Santa Cruz Fort and the Fiscal Island palace.

As for Minas Gerais, also located in southeastern Brazil, its villages and towns, although inland, were established with the use of other materials, such as quartzite (Fig. 2c), a variety of schist, iron-rich rocks and steatite (Fig. 2d). In this captaincy, limestone, gneiss and even granite were also used, albeit infrequently. Minas Gerais features geological diversity and an abundance of stone occurrences, except for calcareous rocks, which were always rare and, in general, improper for the art of stonework. Nevertheless, the location of the mining areas, the extraction and processing technologies available at the time, and the geomorphic features of the mineiro territory, all influenced the choice of materials and construction techniques, and did not always favour the use of stone. The utilization of stone was, therefore, sometimes limited or even nonexistent.

Finally, in the southernmost area of the country, the abundance of basalt, as well as the occurrence of sandstone, determined the prominent use of these materials, as for example in the Jesuitical constructions in the territory of Sete Povos das Missões (Seven Peoples of the Missions).

In spite of this rock variety, limestone brought from Portugal, and, more rarely, from Italy, was also widely used in Brazilian constructions. Examples of such applications can be found in several villages and towns lying along the Brazilian coast, mainly those in the northern and northeastern regions, from the state of Pará to Bahia. In Minas Gerais, however, no significant quantity of rock from Portugal or other foreign regions was used in the construction of monuments, edifices, and sculptures between the early 18th century (when used in the construction of the city of Vila Rica), and the end of the 19th century (when used in the construction of the city of Belo Horizonte). This is likely because of the distance between the province's urban centres and the coast; that is, the great distances and lack of suitable roads meant higher transportation costs, forcing the use of local products.

STONE DEGRADATION AND DETERIORATION IN HERITAGE BUILDINGS OF BRAZIL

Based on the examination of various types of stone used in the production of Brazil's built cultural heritage, it has been possible to identify several forms of damage caused by processes leading to the decay or alteration of these materials. In some cases, the decay or alteration has resulted in a serious decline of the site's degree of preservation, as pointed out by the ICOMOS-ISCS (2008) Glossary. Some of these processes are natural and occur continuously at geological rates, starting with the actual genesis of the rocks that have been crafted into the architectural pieces, and influence the type of damage the stone may incur. Deuteric alteration occurs soon after crystallization of igneous rocks, and additional secondary changes include transformations related to weathering processes. However, other transformations can lead to the deterioration of historical monuments within a human time scale, affecting their use in architectural projects (Fig. 3). These transformations normally result from an interaction between factors related to the characteristics of the rock and those related to the environment. They can also be induced by extraction, processing and application methods at the time the monuments are constructed. There is consensus that extraction methods used in the past, such as impacts and vibrations inflicted by tools, have caused the appearance of cracks and microfissures. In addition, processing can equally contribute to rock alteration or decay, insofar as some methods allow the fixation and accumulation of particles, mainly from the atmosphere. Alteration processes have also been influenced by the action of fixation materials, such as mortars and cements, applied at the time of construction. Such materials have contributed to the emergence of stains and efflorescence that depend on the level of humidity or on significant evaporation.

An ongoing investigation of rocks such as steatite, quartzite, schist, gneiss and granite, all used in the construction of edifices belonging to Brazil's cultural heritage, especially in the state of Minas Gerais, indicates that the visual effects of such processes may compromise the aesthetics of heritage buildings to varying degrees. This may lead to a decrease in their value or prevent them from being used in some way, according to the indications in the illustrated glossary on deterioration patterns proposed by ICOMOS-ISCS (2008). Macroscopically, stone degradation may include: development of numerous fissures, swelling and detachment of outer layers in some rocks, separation of layers, disintegration of individual grains or grain aggregates, and loss of material. All of these lead to changes in the original stone surface, such as smooth shapes, resulting from partial or selective weathering, or to mechanical action. Missing parts, crumbling sculptures and the presence of

Figure 3. Examples of damage that attest to some of the processes responsible for decay or alteration of the stone in some historic monuments built in Brazil. a) Biological colonization and black crust on limestone in the São Francisco's Convent in João Pessoa (state of Paraíba); b) crack and alveolization of limestone in the Church of São Pedro dos Clérigos in Recife (Pernambuco); c) disintegration of calcarenite in São Francisco's Convent in João Pessoa (state of Paraíba); d) encrustation associated with gneiss in the Palacete Laje in Rio de Janeiro (state of Rio de Janeiro); e) missing part on one of the prophet statues at the Bom Jesus Sanctuary of Congonhas (state of Minas Gerais); f) graffiti on the Church of Santíssimo Sacramento in Rio de Janeiro (state of Rio de Janeiro); g) patina formed on quartzite in the old Chamber and Prison House in Ouro Preto (state of Minas Gerais).

cavities or alveoli formed on the rock surface have also been observed. Other degradation patterns were noted, such as fragmentation of the stone surface, blistering, presence of crusts associated with deposits of soot and dust (representing the accumulation of both foreign material and that produced by the rock itself), changes in colour, efflorescence, sub-efflorescence, encrustations interfering with surface morphology and with the colouration of the rocks involved, patinas, graffiti, and varying degrees of biological colonization by mold, lichen, algae and plants.

Some types of degradation were directly influenced by the textures and structures present in the stone employed. The presence or absence of a foliation, as well as variations in mineral content, are important factors. For example, where foliated rocks such as schist have been used, decay processes occur faster. Depending on the content of mica, planar structures may develop, and detachments ranging from delamination to exfoliation parallel to the stone structure demonstrate the strong influence of the rock's anisotropy.

Susceptibility is also associated with the type of rock-cutting method employed: blocks have been cut indiscriminately both parallel and perpendicular to rock foliation planes with concern for matching the type of cut with the requirements in each of those applications. Thus, in the parallel-cut blocks, where foliation planes lie vertically (Fig. 4), decay occurs rapidly as a result of surface delamination or exfoliation and separation of one or more layers. In some cases of detachment, separation involves submillimetric to centimetric elements such as flakes or scales parallel to the stone surface, although not following the stone structure. In such cases, as is observed at the external and flat wedges of the Capela de Nossa Senhora do Carmo (Chapel of Our Lady of Carmo) in Ouro Preto (Minas Gerais state), the process was identified as spalling (Fig. 5).

The presence of sedimentary structures inherited in metamorphic rocks may influence processes of degradation, such as in some of the quartzite used. Banding by compositional variation, or cross-bedding, occurring alone or in combinations, can lead to different degrees of degradation, and the effect of these structures may be enhanced by differential erosion. Some of the processes observed were strongly influenced by the mineralogical composition of the rocks employed, as in the case of steatite. Although prone to scratching because of the softness of its main mineralogical component, steatites contain a significant number of different minerals, and each mineral phase has its own coefficient of thermal expansion, contributing to the appearance of fissures and cracks. Broadly speaking, however, the main types of damage observed in steatite applications involve the appearance of cavities, because minerals formed from local enrichment of iron oxide or sulfide (pyrite) are easily removed by alteration/weathering. The common presence of carbonate crystals, usually dolomite, also contributes to the formation of such cavities through dissolution, accelerated in part by acid rain. An instructive example of the process of cavity or alveoli formation in steatite is seen in the statues of the prophets installed in the churchyard of the Santuário do Bom Jesus (Good Jesus Sanctuary) in Congonhas, Minas Gerais. Visual examination over the past 15 years has showed that, within the last 7 years, the process has accelerated. Throughout this period, it was noted that stains gave rise to cavities, some of which were 0.5 to 1.0 cm deep (Fig. 6).

In many of the applications studied, the stone consists almost exclusively of a single mineral, such as quartz in the case of the quartzite. But these stones may contain many different accessory minerals such as mica, kyanite and opaque minerals (iron oxides). The presence of iron-rich accessory minerals contributed, in some cases, to extensive oxidation, resulting in a great variety of rock hues. Because of these chromatic modifications (patina), quartzite and other rocks such as granite show colour variations ranging from white to yellow, red or orange tones. On the other hand, quartzite, consisting essentially of quartz grains, usually has a granoblastic texture, and contacts between the grains can be serrated, lobed or straight (polygonal arrangement). Depending on how these grains are juxtaposed, the type of degradation most frequently observed may consist of granular disintegration, the intensity and extent of which are quite variable. In several buildings, arenization (sand formation) and hydrolysis of varying amounts of micaceous material, if present, have occurred, as with the doors leading to the pulpit inside the Capela de Nossa Senhora do Carmo (Chapel of Our Lady of Carmo) in Ouro Preto.

Rock decay in monuments is also caused by differential erosion, such as that observed at the pillar bases in Mariana's Capitular House (Minas Gerais state), between parts constructed of quartzite and of schist, which respond differently to alteration processes. This decay was also seen in the wear found at the base of the old Casa de Câmara e Cadeia (Chamber and Prison House), located in Ouro Preto. Many of these irregularities and wear are a result of one or a combination of factors such as so-called eolian erosion and abrasive wear, including that caused by water erosion, for example, which is present on the stair steps of the Capitular House or on the stairway leading to the churchyard in the Congonhas Sanctuary, both in Minas Gerais state. Furthermore, the locations of some of the constructions in Minas Gerais, such as the Capela de Santo Antônio (Chapel of Santo Antonio) in the Itatiaia district, the Igreja de Santo Antônio (Church of Santo Antonio) in Tiradentes and the Santuário do Bom Jesus de Congonhas (Good Jesus Sanctuary), relative to wind currents, solar radiation and humidity levels, explains oxidation phenomena and differential development of patina and colonies of algae and lichen (Fig. 7). In the Congonhas complex, the increasingly common presence of orange-yellow patinas can be observed. They are concentrated in certain areas, especially those that are better protected from rain, and are difficult to remove. Biological colonization is equally frequent and has been the only reason for official interventions in recent years.

Fissures and oblique cracks, resulting in part from accidental ruptures or those caused by improper handling during application, are also present. Therefore, mechanical action might have contributed to the damage observed in some structures, as some blocks are both less resistant to compression effects and more prone to rupture. Pre-existing or induced microfissures were also observed to have evolved, causing parts of the same block to separate, with significant loss of mass, as shown in several of the Congonhas' prophet statues and in many of the sculptures set in innumerable medallions and portals of a variety of chapels. Examples include fissures and chipping in the winged seraphs and on the low-relief che-

Figure 4. Detachment processes observed in parallel-cut blocks in which surface exfoliation is parallel to vertical foliation planes (schistosity) in a) a sericite-quartzite application in Ouro Preto, Minas Gerais, and b) a garnet gneiss application in the city of Rio de Janeiro.

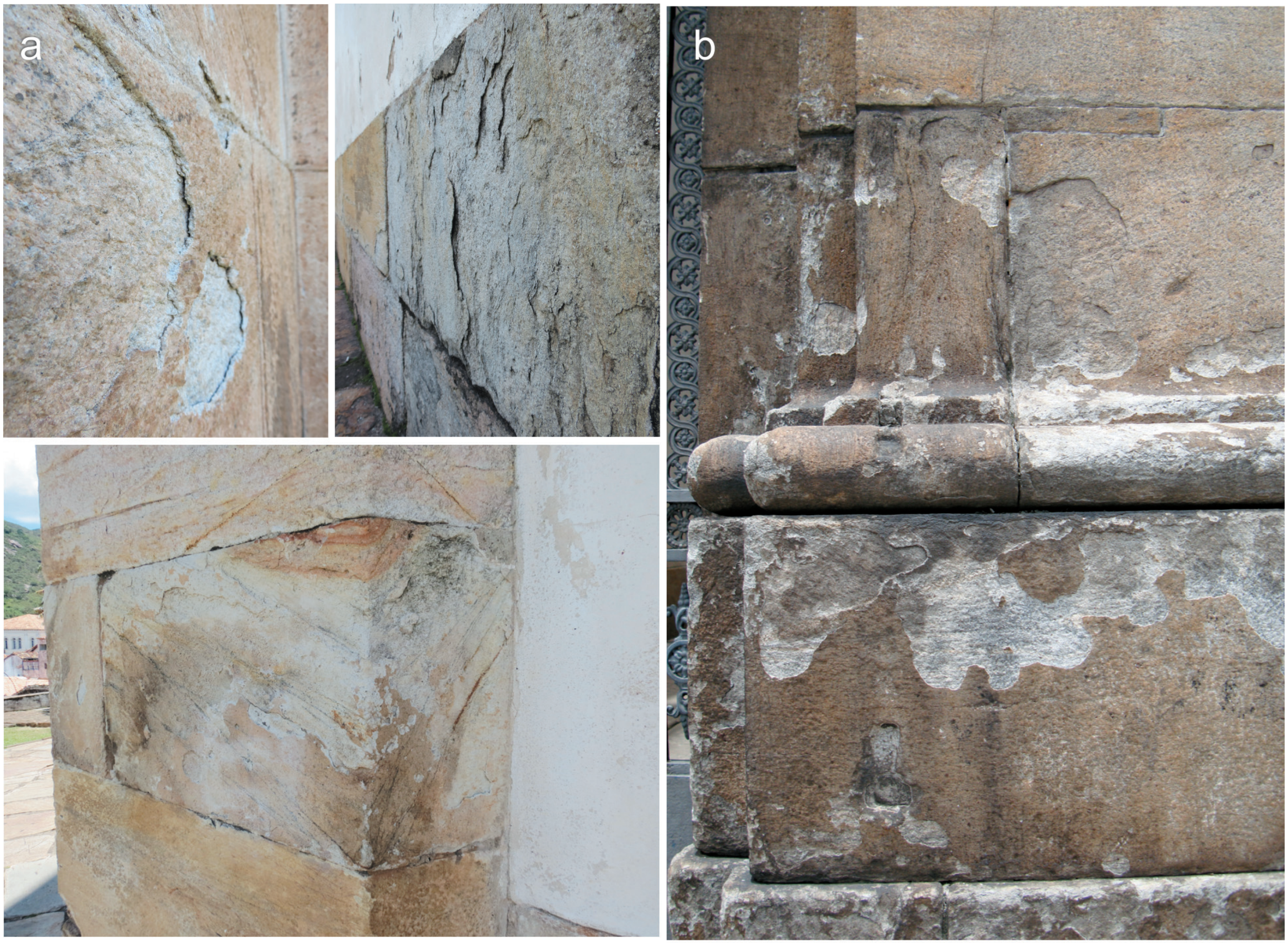

Figure 5. Example of stone detachment as flakes or scales (spalling). In this case, detachment is parallel to the block surface but not to the rock structure, as observed in a) the external and flat wedges of quartzite at the Carmelite Chapelin, Ouro Preto, Minas Gerais, and b) gneiss at the Carmelite Church in Rio de Janeiro.

rubim faces that compose the São Francisco de Assis Church frontispiece, in Ouro Preto.

Finally, in historic sites located in urban centres heavily affected by air pollution, such as in Rio de Janeiro and São Paulo, external surfaces are commonly covered by grey to black deposits of varying consistencies and degrees of adhesion to the substrate. In some cases, these deposits occur in areas protected from the rain; in others they are in areas exposed to open air and may be directly affected by rain water. The deposits differ in thickness and shape, ranging from inconsistent layers of pulverulent (powdery) material on horizontal surfaces, to surface deposits well adhered to the substrates. As black crusts, they are frequently associated with serious problems of stone degradation, manifested as exfoliation or blistering (Fig. 8).

Apart from these and other decay processes that have led to the deterioration of some of the monuments identified herein, many structures have been overlooked and left 'to their fate.' Some have been totally destroyed and others were affected by uncontrolled urban development, such as old constructions on Ouro Preto's hills, whereas others suffered intense and irreversible deterioration, especially in the past thirty years. Currently, they lie lost among new urban facilities, evidence of a lack of commitment towards the preservation of heritage and historical memory.

STEPS TOWARD CONSERVATION

Several technological characterizations of the physical and mechanical characteristics and petrographic features of the materials have been carried out. When possible, these investigations were made both in the quarry and on the monument. Accelerated weathering tests were carried out on all the rocks herein considered; more recently, these have been performed in the LABTECRochas laboratory at CPMTC/UFMG (Costa 2009), and involved simulation of natural processes including sharp drops in temperature, the influence of corrosive material, and variations in oxidation conditions, among others. Consequently, verification was obtained of the deleterious effects of several factors contributing to chromatic alterations, decrease in resistance and to compromised aesthetic standards.

The observations show that the most damaging activities were and still are: (1) interventions made without proper knowledge of rock characteristics and without regard to its texture and structure; (2) interventions that interrupted the

Figure 6. Deterioration of steatite (soapstone) works produced in the late 18th century, such as those shown here in Congonhas Sanctuary, mainly caused by weak rock resistance, and by biological and anthropological factors leading to cavity or alveoli formation.

history of some of these monuments in an unacceptable and irreversible way; (3) the abandonment and degradation of areas surrounding the monument that have been swollen by uncontrolled urban development/sprawl, as observed in almost all major historical sites both in Minas Gerais state and in the whole of Brazil; and (4) extensive vandalism, which remains unpunished in most cases and which arises from lack of information concerning the need for preservation of such rich heritage.

Figure 7. Example of patina formation (oxidation), deposition of particles, and biological colonization on the surface of granite blocks with whitish-grey original colour, on the frontispiece of the Congonhas Sanctuary of Bom Jesus church. The current brownish colour (patina) results from the position of these (outer) blocks facing the action of wind currents and variations in moisture content. In areas unaffected by such currents, the granite retains its original whitish-grey colour, although it is susceptible to intense biological colonization.

CONCLUSIONS

Stone decay increases over time because, from that moment of its installation and exposure in monuments, the rock finds itself in a foreign environment and is subject to thermodynamic conditions very different from those present where it was formed. Corrosion, disaggregation, crust formation and exfoliation of stone materials, among other forms of decay, can be kept under control or monitored, but can never be completely prevented. On the other hand, it is possible, via education, to reduce or eliminate the impacts of factors deriving from human influence.

It is recommended that cleaning processes using abrasive materials be avoided, especially on steatite, schist and limestone. As for the monuments that feature exposed stone or any stone sculptures kept outdoors, it is recommended that their respective patinas and crusts be preserved, in spite of it being possible to remove the original statues and replace them with copies. The presence of these coatings will probably not lead to further deterioration, nor aesthetically affect monuments or sculptures. Instead, they will function as protective elements and even consolidate their altered parts. Besides, their presence can prevent new losses or wear deriving from continuous attacks by external agents on the monuments. Because of this, removing the effects of alteration or decay is not always the best approach to conservation. Still, while patinas and crusts can prevent or reduce the absorption of fluid, whether or not carrying dissolved salts or other particles, they can also hinder or prevent the release of fluids through evaporation. Depending on climatic conditions, this can compromise the stone. In such cases, the recommended strategy is a gentle cleaning aimed at removing biological contamination and crusts. It is also worth noting that microbiological colonization, for example, does not always cause damage to the rocks used in monuments, especially if it is kept under control.

Each situation therefore deserves careful analysis, and any and all decisions, either towards maintenance or restoration, must be preceded by investigations aimed at collecting data on the environmental conditions affecting the monument, on the characteristics of the materials used in its construction, and on the types and extent of potential damage.

Figure 8. Degradation observed in historical buildings and identified as black crust. Formed by the accumulation of particles deposited on the flat surface of fine-grained garnet gneiss, the crust is associated with a blistering process on the façade of the Carmelite church, Rio de Janeiro.

It is hoped that, on the basis of the data collected for this study, it will be possible to indicate the most suitable preservation and maintenance methods for each case of alteration or decay observed in such stone monuments. On the other hand, considering that most of these monuments remain exposed and in direct contact with adverse conditions, all efforts in the area of preventive conservation will serve only to delay the impacts and minimize the effects of these degradation processes. These will, with time, inexorably cause the deterioration of the cultural heritage of Brazil, as they will elsewhere.

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REFERENCES

Bazin, G., 1956, A Escultura Monumental do Nordeste, *in* Nunes, G.L., *ed.,* Arquitetura Religiosa no Brasil, Editora Record, Rio de Janeiro, 1981, v. I, p. 189.

Carvalho, A., 1942, Algumas notas sobre o uso da Pedra na Arquitetura Religiosa do Nordeste: Revista do Serviço do Patrimônio Histórico e Artístico Nacional, No. 6, p. 277–294.

Costa, A.G., 2009, Rochas e Histórias do Patrimônio Cultural do Brasil e de Minas Gerais: Editora UFMG, Belo Horizonte, 292 p.

Costa, A.G., 2013, Stone materials, constructions techniques and alterations in historic buildings: Examples from Minas Gerais, in Brazil and from the Braga and Viseu districts in Portugal: Key Engineering Materials, v. 548, p. 336–347, http://dx.doi.org/10.4028/www.scientific.net/KEM.548.336.

Costa, A.G., 2014, Natural stone in the built heritage of the interior of Brazil: the use of stone in Minas Gerais, *in* Pereira, D., Marker B.R., Kramar, S., Cooper, B.J., and Schouenborg, B.E., *eds.,* Global Heritage Stone: Towards International Recognition of Building and Ornamental Stones: Geological Society, London, Special Publications, v. 407, p. 253–261, http://dx.doi.org/10.1144/SP407.13.

Costa, A.G., 2015, Quartzite of historic buildings in Brazil: designations and degradation patterns (Abstract): Geophysical Research Abstracts, v. 17, EGU2015-7947, 2015.

Costa, A.G., Bruno, R., and Becerra-Becerra, J., 2008, Ornamental stones in monuments: a guide for the characterisation and evaluation: Dimension Stones ICPS XXI, Century Challenges Proceedings of the Second International Congress, Carrara, Italy, p. 331–335.

ICOMOS-ISCS, 2008, International Scientific Committee for Stone: Monuments and Sites XV. Illustrated glossary on stone deterioration patterns: International Council on Monuments and Sites (ICOMOS), Paris, 78 p.

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