This is a post-print of a paper published in the journal Geoheritage, in 2022. Access provided by Consorcio de Bibliotecas Universitarias de Castilla y León (BUCLE)

The Importance of Preserving Small Heritage Sites: the Case of La Tuiza Sanctuary (Zamora, Spain)

Rafael Navarro; r.navarro@igme.es
Serafín Monterrubio; seramp@usal.es
Dolores Pereira; mdp@usal.es

https://doi.org/10.1007/s12371-022-00685-w

Geoheritage (2022) 14:47
https://doi.org/10.1007/s12371-022-00685-w

ORIGINAL ARTICLE

The Importance of Preserving Small Heritage Sites: the Case of La Tuiza Sanctuary (Zamora, Spain)

Rafael Navarro[1] · Serafín Monterrubio[1,2] · Dolores Pereira[1,3]

Received: 27 October 2021 / Accepted: 28 March 2022 / Published online: 8 April 2022

Abstract
For centuries, granite has been one of the most widely used natural stones for building heritage, especially in the north of the Iberian Peninsula. The sanctuary of La Tuiza in Lubian (Zamora, northwest of Spain), built with Calabor granite, dates from the eighteenth century and was declared an Asset of Cultural Interest in 1995. The heritage importance of this site lies in its location, on the Sanabria route (Silver Route) of the Way of St James (Camino de Santiago), attracting visitors from all over the world. This work presents the complete characterisation of the building stone of both the monument and the original quarry and the qualitative description of the main pathologies that have been detected. The capillary water absorption coefficient is twice the value in the sanctuary compared to the quarry; the open porosity, water absorption at atmospheric pressure and sound speed propagation are slightly higher, and the compressive strength value is lower in the stones of the building. These differences reveal the incipient decay processes. In terms of pathologies, biological colonisation is scattered throughout the building, affecting the north face more intensely, and on the exterior, scaling is observed on the west face. Inside the sanctuary, deterioration is related to humidity due to capillary water infiltration, which causes conspicuous stains, efflorescence and biological colonisation in the western sidewalls. The authors recommend that measures be taken to prevent further deterioration and to protect this small site in order to maintain the cultural heritage linked to the local community.

Keywords Biological colonisation · Heritage building · Granite · Natural stone decay · Preservation of a small sanctuary

Introduction

Most of the time, centuries of culture are preserved on the condition that artefacts were built on stone. The same is true for historic buildings. Cultural heritage sites are non-renewable resources linking our generation to a diverse past. Historically significant places can be restored to some of their former glory, but ultimately the original fabric will disappear. Therefore, heritage management aims to preserve heritage places for as long as humanly possible, including the ability to visit those sites, enhancing the cultural and also the economic value of the area. But this option may also lead to the deterioration of the site.

Natural stone has been used as a building material since ancient times. Initially, these expensive and difficult to transport materials were used for temples, tombs, palaces, civic buildings and major infrastructure as well as for decoration and sculptures. Hundreds of temples remain of what were once great social, religious and political centres, such as the magnificent structures and buildings in Egypt from about 4700 BC (Klemm and Klemm 2001; Rovella et al. 2020), the architectural heritage of Greece (Lazzarini 2007; Melfos 2008; Russel 2017) or the temples and palaces across India (Garg et al. 2019). Some of those buildings are splendid constructions, but other humble sites are also well worth preserving in order to transfer knowledge of the past to future generations.

In the northwest of the Iberian Peninsula, granite was traditionally used in construction due to its wide availability. It was especially used in the construction of churches,

This article is part of the Topical Collection on Global Heritage Stone Resource: The sustainable way forward

✉ Rafael Navarro
rafanavarro74@gmail.com

1 CHARROCK Research Group, University of Salamanca, Plaza de los Caídos s/n , Salamanca 37008, Spain

2 Department of Geology, University of Salamanca, Avd. Requejo 33, Zamora 49022, Spain

3 Department of Geology, University of Salamanca, Plaza de los Caídos s/n, Salamanca 37008, Spain

monasteries, sanctuaries, and hermitages, most of them in relation to the Way of St James (Alvarez-Areces et al. 2011), becoming a characteristic element of the region's heritage. One of the most prominent examples of granite used for heritage construction in Spain is the Martiamor granite, widely used in the city of Salamanca (UNESCO World Heritage Site) (Pereira et al. 2015; Pereira 2019). In addition, there are different local granites used in several convents and churches spread all over Galicia and northern Portugal, some of them also used in UNESCO World Heritage Sites (Prieto et al. 1999; Pan et al. 2009, 2011; Sanjurjo Sánchez et al. 2016; Fernández Suárez et al. 2017; Barroso et al. 2020; Tomás et al. 2021).

The sanctuary of La Tuiza (eighteenth century) is an example of traditional architecture. It is a small temple in the Baroque style, located very close to the small village of Lubián (Zamora, Castilla y Leon region, Spain). In fact, it is right on the border with the region of Galicia, which gave a very specific character to the construction. The sanctuary is devoted to the Virgin of Tuiza and, in the past, the most fervent worshippers were the Galicians who went to harvest in the fields of Castilla y Leon during the summer season. Today, many of the visitors to the sanctuary are pilgrims coming back from or going to Santiago de Compostela (Galicia) along the Way of St James, following the Silver Route, passing through Sanabria route, where La Tuiza is located.

The building was declared an Asset of Cultural Interest (BIC, acronym for the Spanish "Bien de Interés Cultural") in 1995. It is in relatively good condition, although a high degree of humidity, both of natural and anthropic origin, has started to deteriorate some parts of the exterior and interior of the building. Because it is a place of pilgrimage to celebrate the Virgin in September, the locals maintain the aesthetic appeal of the lawn around the building, which includes continuously watering it, including the area near the walls of the building, where they have also planted some ornamental lilacs. This part of Spain has long rainy periods and winter temperatures drop to several degrees below zero. The lack of a drainage system in the building means that rainwater comes from above, causing static deterioration of the walls. But capillary absorption is also affecting the interior and exterior walls, as well as biological colonisation (e.g. lichens, mosses and plants) of the façade and even some areas inside. Biological colonisation is one of the most important causes of the deterioration of granite buildings in the northwest of the Iberian Peninsula (Prieto Lamas et al. 1995; Carballal et al. 2001; Pozo-Antonio et al. 2016, 2021; Rivas et al. 2018, 2020; Fuentes et al. 2021). Decay due to biological activity starts with the colonisation of the surface of the stone by microorganisms such as lichens and mosses. These elements produce chemically active compounds (organic acids) and stimulate the extraction of chemicals from the rock minerals, leading to the degradation of the stone (Panova et al. 2016).

Small heritage sites may be modest in appearance, but they are still worthy of conservation. They may not attract large numbers of visitors, but they can provide socio-economic benefits to local communities by including them in routes and other leisure activities. This is an example of heritage that should be protected for cultural but also economic reasons, as it stimulates the local economy by attracting tourists to a rural area that otherwise would not be visited. The preservation of this and other traditional buildings in the region has attracted the interest of the regional government, investing in such examples. Preservation invokes characterisation of the stone, description of decay and advice to correct negative effects that may derive into further deterioration.

The authors of this paper were contracted to characterise the stone of the historic building and to map the different deterioration stages affecting the building stone. This paper summarises the work carried out, including not only the characterisation of the stone of the building but also the stone of the historical quarry where the stone blocks came from; the description of the deterioration detected in the stone, both inside and outside the building; and the recommendations to preserve the building for the next generations, which were the main goal of the regional government for requesting our professional evaluation. This sanctuary is not one of the greatest architectural heritages (Pereira and Marker 2016) but it has the same important cultural value as any other small heritage site (Grimwade and Carter 2000).

Location and Geological Setting

The sanctuary of La Tuiza is located southwest of the municipality of Lubián, in the province of Zamora (Castilla y Leon, Spain), on a terrace over the river Tuela. The main building material is a foliated granite, quarried from nearby outcrops that were never exploited with a commercial view. The roof of the building is made of slate, probably coming from nearby regions where quality slate is quarried.

Geologically, both the sanctuary and the quarry are located in the north of the Central-Iberian zone of the Iberian Hercynian Massif, belonging to the Ollo de Sapo Domain. Both the bedrock material of the sanctuary and the stones used in its construction are made of two-mica synkinematic granitoids belonging to the so-called Calabor granite (Martínez-García 1973; Moral-Crespo et al. 1979) or to the granite from the Hermisende-Padornelo massif (Díez-Montes 2006). The Hermisende-Padornelo massif is a complex made up of two-mica granites, migmatites, and para- and orthogneisses, which can be traced from the southwestern area of Zamora province to northern Portugal. It is a meso-catazonal granitic-migmatitic complex, whose emplacement is partially simultaneous with the Variscan low-pressure metamorphic peak and with the deformation events of the third Variscan phase. The age of the Calabor granitic intrusion is dated to the Upper Carboniferous–Lower Permian (Díez-Montes 2006). Figure 1 shows the geological setting and location of both the sanctuary and the quarry.

The Sanctuary of La Tuiza

The building (Fig. 2a, b) is an example of a very pure Baroque style, with clear Galician-Portuguese influences, in which the tower stands out, with its dome and lanterns adorned with a rich decoration of volutes.

It is recorded that the first emplacement of the sanctuary was done in a place called "Cavados", in the municipality of Chanos (1 km north) in the eighteenth century, but it was soon moved to its present location. Locals claim, without any foundation, that the chapel of the first sanctuary was rebuilt on its square floor, stone by stone; this part would correspond to the current main chapel of La Tuiza; it is also stated that the tower has the same origin. And that some other materials from that same first chapel were reused in the construction of the current sanctuary, which would take place in 1764.

The sanctuary has a cross plan, with a single nave, a straight crossing and a slightly marked transept. The tower rises on the west side and, attached to one of the transepts, there is a small sacristy. In addition, the roof is gabled, made of slate, following the popular pattern of the area. Its tower stands out for its height and greater ornamental details. The exterior follows the same distribution: the building rests on

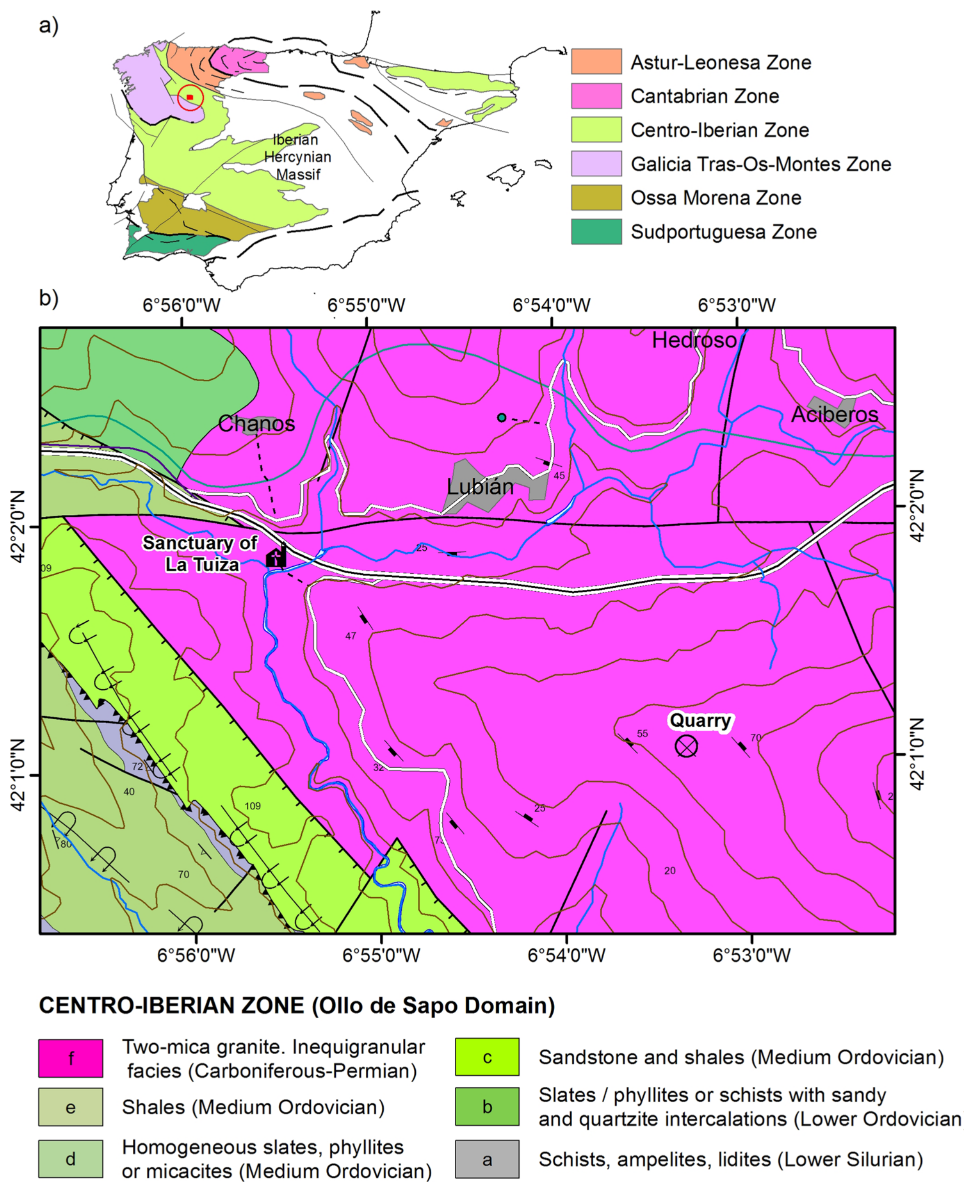

Fig. 1 Geological setting and location of the sanctuary of La Tuiza and the quarry where the granite ashlars were extracted: **a** regional context (modified from Díez-Montes 2006); **b** local geology (modified from GEODE 2021)

Fig. 2 North (**a**) and west (**b**) views of the façade of the sanctuary

a base, protruding from the plane of the wall, with angles topped by a Doric pilaster, separated from the roof by a cornice topped by pinnacles. On the north and south elevations of the nave, there are two lintelled doors, while on the west elevation of the tower there is another semi-circular door; there are numerous lintelled windows on the walls, with crossed or simple frames. The interior is notable for its barrel vaults, built with the same rock and supported by pilasters. At the foot of the sanctuary is the rood screen, and in the main chapel the altarpiece is preserved, contemporary to the rest of the building (JCYL, 2021).

As for the quarry where the stones were extracted, it is located about 2.4 km southeast of the sanctuary, in the "Alto da Penageira" (Fig. 1b), in an extensive granite outcrop. This is not an active quarry, and it is fully covered by vegetation, but still, it is possible to distinguish several historical marks of the masonry works such as wedges, cuts, indentations, abandoned ashlars, etc. (Fig. 3a–c). According to personal communication from the town hall staff, the only use of the quarry was for the construction of the sanctuary at the end of the eighteenth century, with no evidence or any indication suggesting its later use. Regarding transport, it was the locals themselves, with their oxen and carts, who hauled the stones from the quarry to the sanctuary.

With regard to the extraction methods, in this type of quarries the most traditional method was the use of wedges to precut the blocks, although there are no references to whether the material used was wood or metal. In this case, no marks of oxidation of the wedge holes were observed, which leads us to think that wood may have been used (Fig. 3b, c). In

Fig. 3 **a** General view of the granite outcrop where the quarry was opened. **b** Wedge marks on stone. **c** Block cutting marks

ancient times, blocks were fragmented by inserting wooden wedges into cracks and fissures, which were then swollen with water until the rock cracked. The wedge system has been used for thousands of years for all types of stones and it is still used in traditional quarrying today. It consists of making incisions in the stone block where iron or steel wedges will be lodged, which, when hit with the mallet, will divide the stone in two. If done with sufficient expertise, the cut can be very precise, due to the low tensile strength of the stones (Fernandez Suarez et al. 2017).

No drilling marks were found either, so the use of explosives to cut blocks can be also ruled out.

Sampling

Granite samples were taken from both the historic building and the quarry. The sampling of monuments is very restricted, for obvious reasons, and in our case, we followed the recommendations for sampling protected sites. Although the main recommendation is to apply non-destructive techniques (NDTs) for the study of heritage (ICOMOS 1990), when this is not possible, some recommendations are to take the minimum number of samples, that their size is as small as possible to apply the corresponding analytical techniques and that the samples were taken in areas where the aesthetic damage is minimal, or even areas already detached or fractured, whose repair is not possible. The materials related to the main deteriorations were also sampled, namely two small samples of loose material from the sanctuary (Lu-1, dimension 5 × 2 × 2 cm and Lu-3, dimension 13 × 10 × 10 cm, the latter sample was used for a complete characterization); flakes from the west façade (Lu-4; weight about 30 g); dark sample from the exterior façade in the tower area (Lu-5; weight about 10 g); alteration and greenish remains before the staircase leading up to the tower in the vaulted area (Lu-7; weight about 10 g); block from the quarry (Lu-8; dimension 23 × 22 × 22 cm); efflorescence occurring in the small cracks of the stone (Lu-9; weight about 10 g); and one of efflorescence from the contact between the stone and the coating mortar covering the lower part of the interior walls (Lu-10; weight about 20 g). Table 1 shows the origin of the samples and the tests carried out on them.

Analytical Methods

For the petrographic analysis, a Leica DM2500P optical polarised microscope with Leica Microsystem DF420T-wain and Leica Application suite V.3.50 software was used for the acquisition of images. The qualitative analysis of the mineralogy was obtained by X-ray diffraction (XRD) with a Bruker D8 Advance diffractometer. Semi-quantitative mineral ratios were determined according to the reflection power method (Chung 1974). Geochemical characterisation was performed by X-ray fluorescence (XRF) with Thermo Fisher Scientific ARL Optim'X WDXRF equipment with a rhodium anode X-ray tube (50 kV, 150 mA) and LiF200, InSb and AX06 analyser crystals. For the interpretation of spectra, the Uniquant software from Thermo Fisher Sci was used. The loss on ignition (LOI) was determined in a muffle furnace for 4 h at 550 °C and 2 h at 1000 °C.

With respect to the physical and mechanical properties, the following parameters were determined at INTROMAC Laboratory (Cáceres, Spain) on cylindrical cores of 40 mm length and 40 mm diameter, following the European normative: water absorption coefficient by capillarity (UNE-EN 1925:1999), apparent density and open porosity (UNE-EN 1936:2007), water absorption at atmospheric pressure (UNE-EN 13,755:2008), sound speed propagation (UNE-EN 14,579:2005), and uniaxial compressive strength (UNE-EN 1926:2007).

The identification and characterisation of deterioration were carried out visually in the field, and also through the analysis of samples (Table 1). For this task, the nomenclature and descriptions of the document "Illustrated glossary on stone deterioration patterns" by the ICOMOS (International Council on Monuments and Sites—International Scientific Committee for Stone) (Vergès-Belmin 2011) were followed. The deterioration mapping was carried out by plotting the observations on the photogrammetric reconstruction of the building, provided by the architects of the Junta de Castilla y Leon (regional government).

Table 1 Samples and tests. OM, optical microscopy; XRD, X-ray diffraction; XRF, X-ray fluorescence; PMT, physical and mechanical test

Sample	Description	Source	OM	XRD	XRF	PMT
Lu-1	Loose sample from the façade	Façade		X	X	
Lu-3	Loose block from the building	Façade	X	X	X	X
Lu-4	Façade stone scales	Façade		X	X	
Lu-6	Dark sample from exterior façade in the tower area	Façade		X		
Lu-7	Alteration and greenish remains before the staircase leading up to the tower. Vaulted area	Inside		X		
Lu-8	Quarry block	Quarry	X	X	X	X
Lu-9	Fissure with efflorescence (west side)	Inside		X		
Lu-10	Interface of the granite with the coating mortar (south side)	Inside		X		

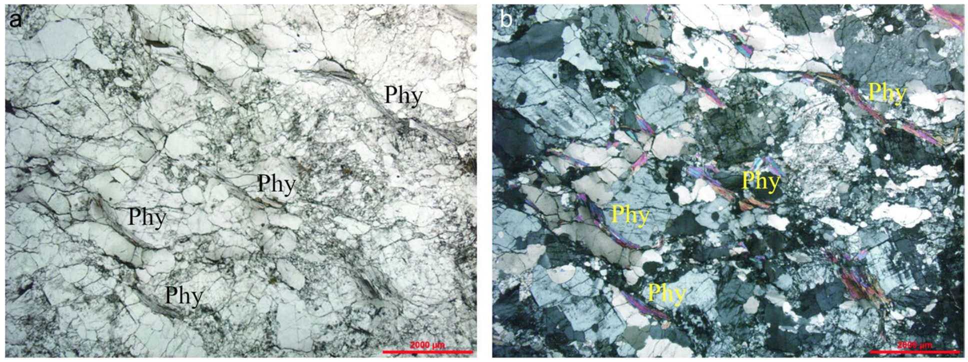

Fig. 4 Microscopic aspect of the granite sampled in the quarry. The orientation of the phyllosilicates (Phy) marks a conspicuous foliation. **a** Parallel Nicols. **b** Crossed Nicols

Results

Mineralogy

The samples taken from the sanctuary (Lu-3) and the quarry (Lu-8) are very similar on a microscopic scale. They belong to a granite composed mainly of quartz, K-feldspar (orthoclase and microcline) and plagioclase. The most important accessories are biotite, muscovite and opaque minerals, and as secondary phases, phyllosilicates. The size of the main crystals is several millimetres in length, up to about 3 mm, while the smaller crystals are 0.1 mm in size. The crystals show idiomorphic, subidiomorphic and allotriomorphic morphology, with straight to somewhat irregular edges. The rocks have inequigranular, holocrystalline phaneritic granitic texture, with a fine to medium grain size resulting in a homogeneous rock, with an alignment of biotite and muscovite crystals. The single, polycrystalline quartz has a fine to medium grain size, ranging from 0.64 to 2.17 mm in Lu-3 and 0.89 to 1.92 mm in Lu-8. Alkali feldspar occurs mostly as potassium feldspar, in the form of orthoclase and microcline with a medium grain size, greater than 1 up to 2.56 mm in Lu-3 and 0.51 to 2.94 mm in Lu-8, with the occasional presence of perthitic exolution textures due to the presence of albite veinlets, probably as a consequence of syncrystallisation of the two minerals. Plagioclase has a fine to medium grain size, varying between 0.64–2.56 mm (Lu-3) and 0.25–0.51 mm (Lu-8) and is characterised by polysynthetic twinning and zoned texture. Micas have a fine to medium grain size, ranging from 1.02 to 2.17 mm (Lu-3) and 0.51 to 2.56 mm (Lu-8). The opaque minerals have a fine grain size of 0.12–0.51 mm. (Lu-3) and 0.12–0.19 mm (Lu-8). The phyllosilicates show a pronounced foliation of the granite which may influence the physical and mechanical behaviour of the stone once emplaced in the building (Fig. 4a, b).

With respect to the mineralogical characterisation by XRD, Table 2 shows the different phases detected in the analysed samples. Quartz, phyllosilicates and microcline are the most abundant phases, as could also be verified by optical microscope. Albite is also present, and the main secondary minerals are kaolinite and chlorite. The amount of salts such as gypsum (CaSO3), epsomite ($MgSO_4 \cdot 7H_2O$), nesquehonite ($MgCO_3 \cdot 3H_2O$) or hydrocalumite ($Ca_4Al_2(OH)_{12}(Cl,CO_3,OH)_2 \cdot 4H_2O$) in the alteration products (Lu-7, Lu-9 and Lu-10) is remarkable.

Table 2 Mineralogical composition by XRD (% weight). Abbreviations: Qz, quartz; Ms, micas; Mc, microcline; Ab, albite; Kln, kaolinite; Nsq, nesquehonite; Eps, epsomite; Gp, gypsum; Hclm, hydrocalumite; Chl, chlorite; Cal, calcite

Sample	Description	Qz	Ms	Mc	Ab	Kln	Nsq	Eps	Gp	Hclm	Chl	Cal
Lu-1	Loose sample from the façade	8	10	40	40	1					1	
Lu-3	Loose block from the building	8	11	26	55							
Lu-4	Façade stone scales	9	19	22	50							
Lu-6	Dark sample from exterior façade in the tower area	16	18	36	29	1						
Lu-7	Alteration and greenish remains before the staircase leading up to the tower. Vaulted area		2				91	5	1	1		
Lu-8	Quarry block	7	16	28	48						1	
Lu-9	Fissure with efflorescence (west side)	55	21	10		8			6			
Lu-10	Interface of the granite with the coating mortar (south side)	5	12	9		4			54			16

Chemical Composition

The chemical composition (main elements) is shown in Table 3.

As shown in Table 3, the silica, aluminium and potassium content is quite similar in all samples, as expected. The façade scales (Lu-4) show a slight variation in chemical composition with respect to the original material, especially in LOI, calcium, magnesium and iron, which may be indicative of an incipient decay process.

Physical and Mechanical Properties

Table 4 shows the results of the physical and mechanical tests that were carried out on the samples from the historic building and the quarry. The standard deviation is included.

As for the capillary water absorption coefficient, it is noteworthy that the value of the sample from the monument doubled that of the sample from the quarry. In terms of apparent density, open porosity, and water absorption at atmospheric pressure, the monument samples showed values only slightly higher than those of the quarry. The values of sound speed propagation and uniaxial compressive strength were higher in the quarry samples.

Decay Characterization

Sanctuary Façade

Figure 5 shows the mapping of the degradation forms of the north (a) and south (b) façade; Fig. 6 shows the east (a) and west (b) façade; and Fig. 7 (a–f) shows some examples of decay elements.

The sanctuary presents different states of conservation depending on observations of the different orientations of the building, with the north and west sides being the most affected. The most common and abundant recognisable forms of deterioration are due to biological colonisation, including lichens, mosses, and vascular plants (ferns, ivies, etc.). The intensity of the biological colonisation varies from one area to another, with the greatest affection on the north side. It is more frequently located in the joints between ashlars, on the upper surface of the cornices, all around the base of the building (ranging in height from 1.5 m in the north to 0.8 m in the south) which is affected by capillary rise, and on the bell tower, where this intense biological colonisation blackens the stone (Fig. 7a). Once the XRD analyses (Lu-6, Table 2) ruled out that all the blackish tones could be due to the formation of a black crust, which would have been interpreted as due to the development of salts such as gypsum (Pozo-Antonio et al. 2019), it can be deduced that these discolourations are due to the presence of organisms, such as lichens and/or mosses. Other areas where biological colonisation is concentrated are the intersection between the walls and the roof slate in the transept, both on the north side (Fig. 7b) and on the east side. Additionally, the north façade is also covered by green-yellow lichens (Fig. 7c). On the west façade and on the west area of the north and south façade, together with the presence of vascular plants (Fig. 7d), intense detachment, accompanied by scaling, also with varying intensity, should be noted, with the west façade being the most affected (Fig. 7d, e). Some of these scales were sampled (Lu-4) and analysed by XRD, but no salts were found; only the same mineral components characteristic of granites, as illustrated in Table 2. Occasionally, it is also possible to observe cracks and deformation, that is, fractures (Fig. 7f), mainly in the areas close to the doors

Table 3 Main elements obtained by XRF (% weight) and LOI

Sample	Description	Si	Ti	Al	Ca	Mg	Fe	Na	K	PO_4^{3-}	LOI (1000 °C)
Lu-1	Loose sample from the façade	61.5	0.0	22.1	1.0	0.5	0.9	7.1	6.6	0.2	1.5%
Lu-3	Loose block from the building	59.9	0.0	22.4	0.9	0.4	0.9	9.3	5.5	0.4	1.3%
Lu-4	Façade stone scales	58.5	0.1	22.4	1.7	1.8	1.5	8.4	5.1	0.2	3.4%
Lu-8	Quarry block	60.6	0.1	21.4	1.1	0.5	1.2	7.4	6.1	0.3	1.5%

Table 4 Physical and mechanical properties

Test	Standard	LU-3 (monument)	LU-8 (quarry)
Water absorption coefficient by capillarity ($g/m^2s^{0.5}$)	UNE-EN 1925:1999	47.95 ± 6.35	23.02 ± 12.79
Apparent density (kg/m^3)	UNE-EN 1936:2007	2500 ± 28	2480 ± 39
Open porosity (%)	UNE-EN 1936:2007	6.45 ± 0.07	6.07 ± 1.54
Water absorption at atmospheric pressure (%)	UNE-EN 13,755:2008	2.35 ± 0.07	2.15 ± 0.39
Sound speed propagation (Vp) (km/s)	UNE-EN 14,579:2005	1336 ± 34	1807 ± 457
Uniaxial compressive strength (MPa)	UNE-EN 1926:2007	37 ± 5	43 ± 8

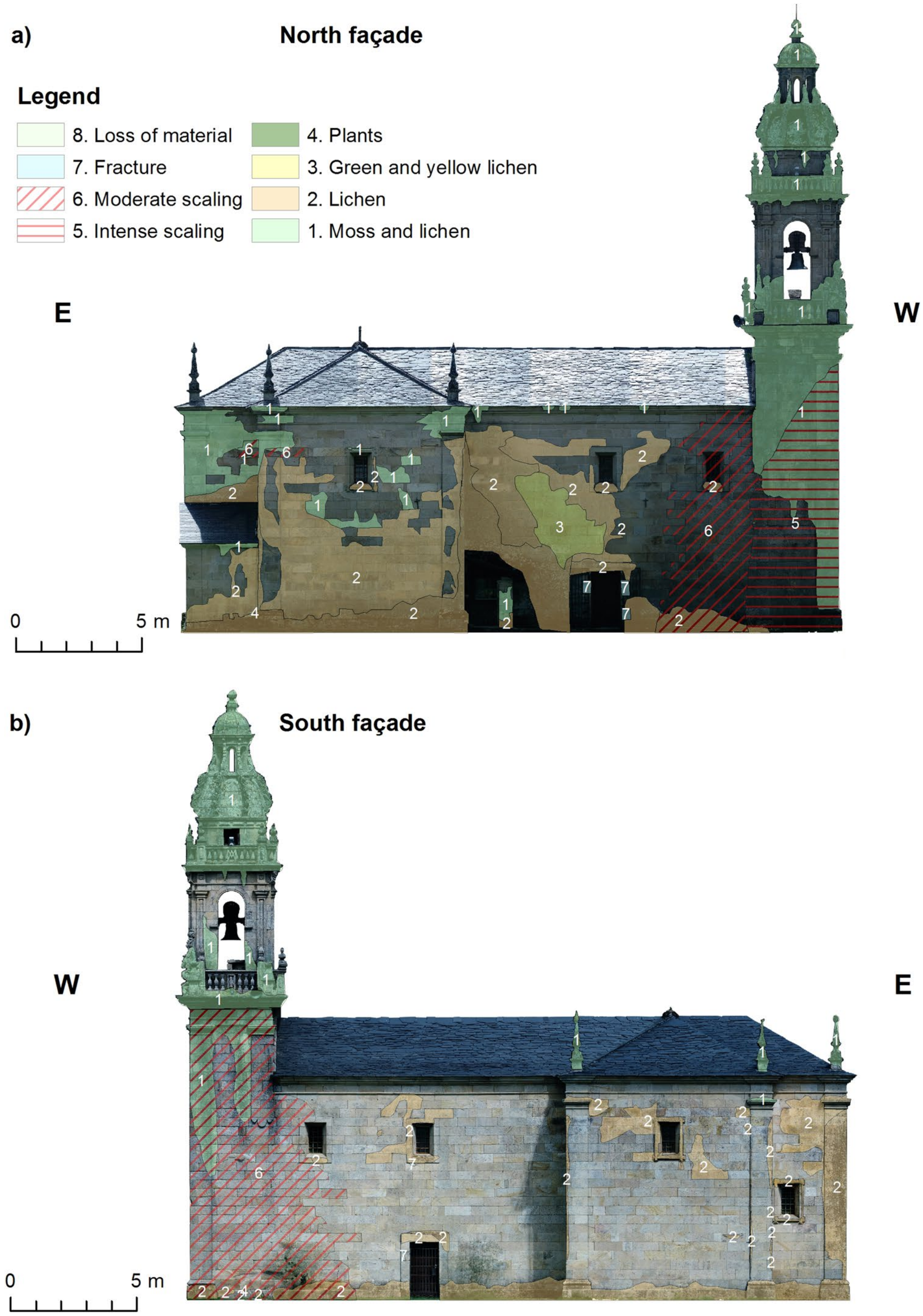

Fig. 5 Orthophoto mapping of the main forms of degradation observed on the north (**a**) and south (**b**) façade

and windows of the building, where there are metallic elements for fixing them to the ashlars. Another form of decay observed only in some points of the façade is the loss of components due to anthropic actions.

Interior of the Sanctuary

Inside the sanctuary, the main alteration on the ground floor is due to the infiltration of water by capillarity from the base, which has generated efflorescence and sub-florescence processes, mainly composed of gypsum (Lu-9 and Lu-10, Table 2). This is especially evident in the product (apparently a kind of mortar) covering the north and south walls of the building. On the north side, the moisture front has reached more than 3 m in height in the past (Fig. 8a). In the areas where no plaster covering was added, dampness is lower and the height of moisture reaches only up to 40 cm, although some efflorescence is also detectable.

The bell tower is accessed through a narrow staircase, and right at the entrance wall to the staircase, on the west side

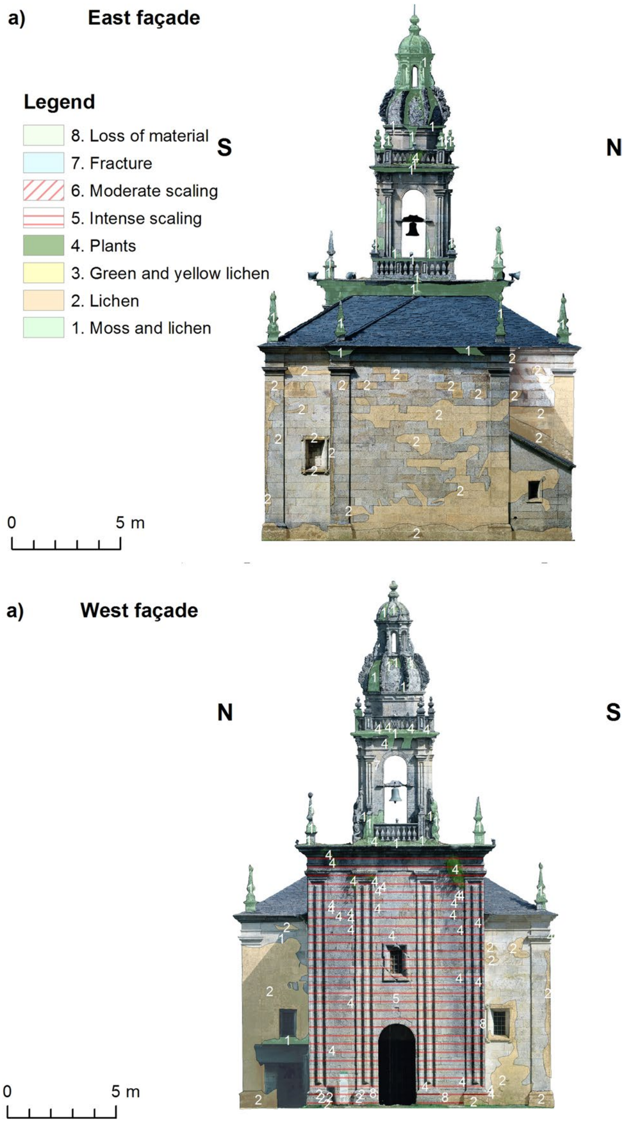

Fig. 6 Orthophoto mapping of the main forms of degradation observed on the east (**a**) and west (**b**) façade

of the building, there is a complete green covering due to biological colonisation (Fig. 8b), affecting more evidently the mortar between the stone blocks. The ceiling in that area is also affected, although to a lesser extent. Efflorescences composed of magnesium carbonates and calcium and magnesium sulphates are observed (Lu-7, Table 2).

Discussion

After the complete characterisation of the Calabor granite, sampled both in the historic building and in the quarry, it is important to highlight the differences found between them. All the physical and mechanical tests returned higher values for the stone in the historic building, except for the sound speed propagation and the compression test. The most significant differences are in the water absorption coefficient (the stone from the sanctuary doubles the value of the one sampled in the quarry), and the compressive strength testing gave higher values in the stone from the quarry. The porosity is slightly higher in the stone from the building and the interpretation is based on the increased volume and connectivity among the pores inside the stone, due to the increased microcracking (Vázquez et al. 2010; Junique et al. 2021). This slight increase in porosity is also connected to the increase of the water absorption coefficient by capillarity, one of the most important parameters to measure the deterioration process of building stones (Mosquera et al. 2000; İnce et al. 2021). In addition, the sound speed propagation (Vp) is directly related to the mechanical strength of the stone and it is inversely proportional to its decay and, consequently, to its porosity (Martínez-Martínez 2008; Sousa et al. 2005; Vázquez et al. 2010; Zalooli et al. 2020). This parameter decreases exponentially with the increase of salt crystallization cycles. The increase in microcracking is caused by the precipitation/dissolution of salts within the stone (Zalooli et al. 2020). The origin of this process can be explained as due to a synergic action of biological activity and water coming from outside the building, which in this case, in addition to the rain and occasional snow, comes from a continuous supply of irrigation water for the grass surrounding the sanctuary. Water penetrates through the porous system of the stone, causing the crystallization of the salts carried by the water in solution. These salts can cause pressure inside the stone, which will increase microcracks, also causing a further reduction in the uniaxial compressive strength of the stone (Rodriguez-Navarro and Doehne 1999; Sousa et al. 2005; Momeni et al. 2015; Zalooli et al 2020). On the outer façade of the north side of the sanctuary, the capillary rise can reach, at least, 1.5 m, based on the limit marked by the presence of lichens, which only grow in the most humid areas. Inside the sanctuary, there is a significant drainage problem, mainly due to the covering of the north and south walls with mortar. In this context, the capillary rise is higher than 3 m on the north side (Fig. 7a), also producing damp stains, affecting, in principle, the aesthetic of the building, although greater consequences can be derived from them. These damp stains can also be observed in areas where the granite is directly exposed, without the plaster coating, such as in the columns and transepts of the sanctuary. However, although the presence of saline efflorescence is also observed, the aesthetic damage seems significantly lower, as the capillary affected height is much lower (approximately 40 cm). In addition, the coating mortar is an inexhaustible source of salts, triggering the formation of efflorescence (Fig. 9a, b). All these salts formed in the contact between the granite and the mortar have also caused some granular disintegration in the granite (sanding). The salts are mainly

Fig. 7 Main deterioration forms. **a** Lichens, moss and vascular plants growing on the bell tower blackening the stone. **b** Moss and lichens on and above a slate roof. **c** Green and yellow lichens on the north façade. **d** Vascular plants and general view of the scaling on the west side façade. **e** Detail of the scaling. **f** fracture by the anchors of an iron fence

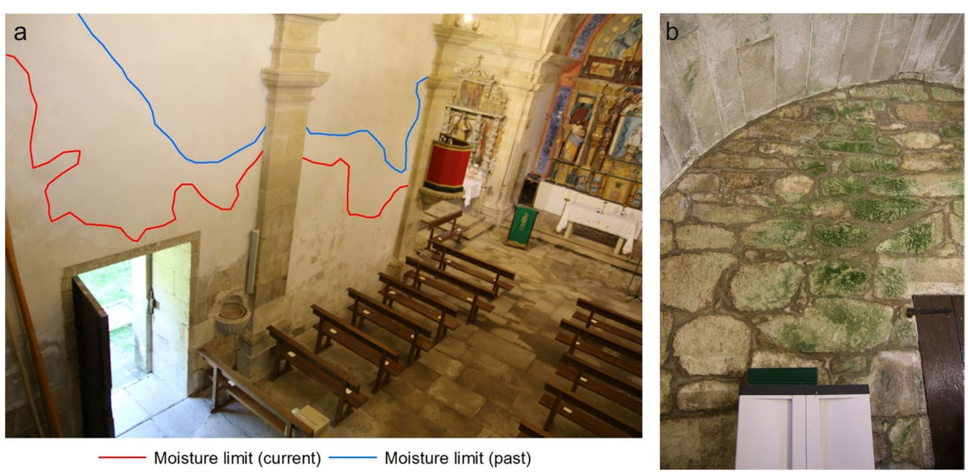

Fig. 8 **a** Moisture advance on the walls of the north side of the building. **b** Biological colonisation on the wall of the west side of the building, which gives access to the bell tower staircase

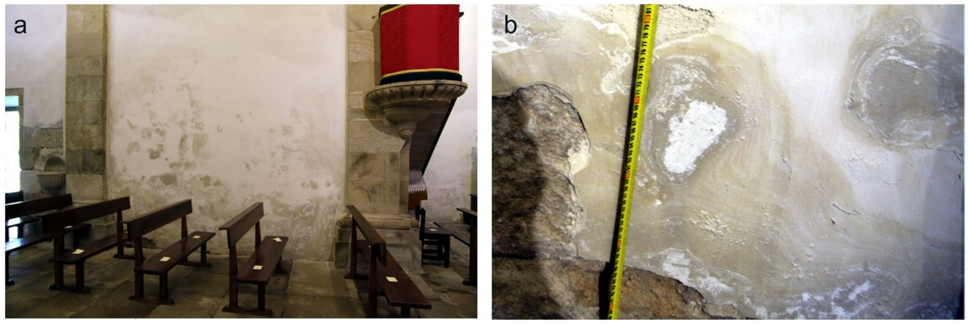

Fig. 9 **a** Humidity stains on the north wall inside the sanctuary. **b** Efflorescence formed in the coating mortar

composed of gypsum, but epsomite and nesquehonite were also detected (samples Lu-7, Lu-9 and Lu-10; Table 2). These salts are common phases in the deterioration stages of granite, as has been pointed out by several authors (e.g. Winkler 1975; Arnold y Zehnder 1990; Siedel 2013; Steiger et al. 2014; Vereshchagin et al. 2018).

Despite the above interpretation of the decay, the main cause of the deterioration of the building is biological colonisation, mainly due to lichens but also moss and vascular plants. Their presence varies in intensity in the different areas of the building and reaches its greatest development in the base of the building of the north side, reaching up to 1.5 m in height, on the bell tower, where the presence of moisture is greater, on the cornices, and on the roof on the top of the transepts. In the first-mentioned area, because of the continuous supply of water from the ground due to the continuous watering of the lawn, as described above. In the other areas, due to poor drainage of rainwater, which causes moisture accumulation, especially in the joints between the roof slate and the granite of the ashlars and in the horizontal platform of the tower, which is limited by the balustrade. The latter area is most affected by growth of vascular plants (e.g. berry bushes) and the blackish colouring affects the stone. XRD analysis of the sample taken from this area (Lu-6) did not show the presence of salts, necessary for the formation of black crust (Pozo-Antonio et al. 2019). The development of vascular plants in the tower area (Fig. 10), as in the west façade (Fig. 7d), favours the mechanical breakage of the granite, either by development of microfractures, or by the joint with the fixing mortar between the granite blocks, increasing the porosity, and therefore the infiltration of water into the sanctuary. As with the vascular plants, the presence of moss, in addition to indicating higher humidity, causes greater alteration in the stone surface. The rhizoids penetrate through the ashlar joints increasing the physical damage by the creation of microcracks and the chemical damage by the production of carbonic acid, causing progressive deterioration of the stone, besides the aesthetic damage (Di Carlo et al. 2017).

As for the lichens, their presence varies from one area of the façades to another, with the north side being the most affected. In addition to the black patina that covers all the affected areas, there is a large development of green/yellowish lichens (Fig. 7c) just above the entrance door of the north side. Biological colonisation is conspicuous inside the building, mainly on the first floor, on the west wall, and in a vaulted area below the bell tower (Fig. 8b). The continuous infiltration of water from the tower through the joint between the wall and the ceiling and the lack of adequate drainage has caused the west wall and the surrounding ceiling to become covered by green lichen, resulting in an aesthetic damage to the wall. The effect that lichens can have on the stone can be, on the one hand, physical changes caused by penetration of fungal hyphae (filaments), through fissures that cause disaggregation and fragmentation of the mineral surface, and on the other hand, chemical changes in relation to the substances secreted or excreted by mycobionts and photobionts, and which may be the cause of blackening (Di Carlo et al. 2017; Pozo-Antonio et al. 2021). The neoformation

Fig. 10 View of the biological colonisation on the upper platform of the bell tower

of minerals such as kaolinite due to lichen activity, as was found in samples Lu-1, Lu-6, Lu-9 and Lu-10 (Table 2) has been described by several authors (Prieto Lamas et al. 1995; Adamo and Violante 2000; Chen et al. 2000; Rivas et al. 2020).

The other major deterioration is scaling. It affects mainly the west side of the sanctuary (Fig. 7d, e). This scaling on the granites can be caused by several factors acting synergistically (Freire Lista and Fort 2016). These factors include the presence of salts, such as calcium sulphate (Silva Hermo et al. 2010), the combination of hygric or hydric swelling and thermal dilatation processes (Siegesmund and Dürrast 2014) or by petrophysical factors including total porosity change, capillary water absorption kinetics, evaporation kinetics, air permeability and water vapour conductivity (Bromblet et al. 1996). Although no salts were directly reported in scale sample Lu-4, an increase in calcium and magnesium and LOI was observed in the chemical analysis (Table 3), which may be indicative of the presence of calcium and magnesium salts (such as gypsum, epsomite or nesquehonite), as observed in samples Lu-7, Lu-9 and Lu-10, effloresces from the interior of the building. The preferential development of scales in the western part of the sanctuary can be due to the climatic characteristics of the area. In this region of Spain, the predominant wind gusts are from the NNE, W and S directions,, with those from the west reaching speeds over 60 km/h, especially during the winter season (Martí Ezpeleta et al. 1998).

The identification and study of the original quarries that provided the stones used in the monuments is of great importance from several points of view. On the one hand, it can be used as source of original material in case that a restoration of the monument is necessary, avoiding problems of incompatibilities and aesthetic damage. On the other hand, the studies on the original quarries and their associated monuments increase the historical value of the region and scientific knowledge. This includes several aspects such as the resource in term of economic value; the remains such as tools, discarded or broken pieces; the logistical system, such as the organization of the quarry or the transport system from the quarry to the monument; and the social aspect in relation to the workers, the economic development of the region, etc. (Bloxan 2011). Furthermore, the correct management and promotion of the historical quarry can offer new perspectives for the promotion of cultural and nature tourism (Navarro et al. 2022).

In this case study, and as future perspective, we advise the dissemination of the site through the creation of a properly signposted hiking route and the placement of didactic panels, both at the quarry and at the monument sites. The traditional heritage would be integrated with the natural environment. This would help considerably in the dissemination of the environment, geological sciences, and a better knowledge of the local architectural heritage, and therefore its conservation.

These measures for the dissemination of local heritage should be accompanied by the protection of the historic quarry and its landscape under some kind of administrative figure (at local or regional level) that ensures its future conservation, guaranteeing, in turn, the availability of the same material used in the construction of the sanctuary.

Conclusions

The climatic characteristics of the area where the Tuiza sanctuary is located mean that the building is exposed to wind, rain and freeze–thaw actions. These, together with the leaking from the base of the bell tower, mean that the northern and western parts of the sanctuary are the areas most affected (both the exterior façade and the interior of the building). The most important deterioration problems are those generated by humidity, both from the continuous watering of the lawn and from the discharge of water from the bell tower platform. Our advice is to stop, or at least move the irrigation system several metres away from the building, making sure that the sprinklers do not reach the façade, and to build a perimetral margin of, at least, 0.5 m around the building to prevent the growth of grass and/or other plants, filling it with gravel material that allows for breathing at the base of the building. These actions will allow the evacuation of moisture from the base through the area in contact with the ground. It is also advisable to waterproof the platform of the bell tower, as well as the water drains, such as the gargoyles, allowing the expulsion of excess water from the upper roofs, and preventing the leakage through the roofs and façade, clearing away biological activity.

With regard to the interior of the sanctuary, the high humidity is due to increased capillarity and water retention by the mortar covering the stone. To allow the building to dry out, or at least to diminish dampness, we advise to remove the coating mortar and leave the stone bare. Likewise, it would be advisable to install dehumidifiers to remove the current humidity and ventilate the space effectively since some windows are permanently closed or even blocked with wooden panels.

Looking to the future, although this monument does not present critical pathologies, it would be advisable to adopt some measures to correct some of those observed, preventing further deterioration.

In the case of opting to restore the affected areas, it is recommended to follow the experiences and research published in various papers that describe mechanical cleaning works (Rivas et al. 2018; Pozo-Antonio et al. 2021), laser cleaning (Pozo-Antonio et al. 2018; Rivas et al. 2018), cleaning using natural light and ultraviolet light (Pozo-Antonio and Sanmartín 2018; Rivas et al. 2020; Sanmartin et al. 2021), before proceeding with biocides (authorised by the European Union in in architectural heritage conservation and restoration works). A more detailed study on the different species of lichens and mosses present in the building could help to design the most effective strategy for their correct removal.

Acknowledgements The authors thank two anonymous reviewers for their comments and suggestions to improve this manuscript.

Author Contribution All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Rafael Navarro, Serafin Monterrubio and Dolores Pereira. The first draft of the manuscript was written by Rafael Navarro, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding The research was conducted in the frame of the European Region Development Funding (FEDER) to the Territorial Service of Culture and Tourism of Zamora, Junta de Castilla y Leon (Regional Government).

Data Availability The datasets used or analysed during current study are available from the corresponding author upon reasonable request, and all data generated or analysed during this study are included in this article.

Declarations

Conflict of Interest The authors declare no competing interests.

References

Adamo P, Violante P (2000) Weathering of rocks and neogenesis of minerals associated with lichen activity. Appl Clay Sci 16:229–256. https://doi.org/10.1016/S0169-1317(99)00056-3

Alvarez-Areces E, Jiménez Martínez R, Menduiña-Fernández J (2011) La expresión de la piedra: singularidad arquitectónica en el patrimonio histórico del Camino de Santiago. De Re Metallica 16:53–61

Arnold A, Zehnder K Monitoring wall paintings affected by soluble salts. The conservation of wall paintings. In: Symposium organized by the Courtauld Institute of Art and the Getty Conservation Institute, London (UK), July 13–16, 1987 1991. The Getty Conservation Institute, 103–135.

Barroso CE, Oliveira DV, Ramos LF (2020) Physical and mechanical characterization of vernacular dry stone heritage materials: schist and granite from Northwest Portugal. Constr Build Mater 259:119705. https://doi.org/10.1016/j.conbuildmat.2020.119705

Bloxam E (2011) Ancient quarries in mind: pathways to a more accessible significance. World Archaeol 43:149–166. https://doi.org/10.1080/00438243.2011.579481

Bromblet P, Bernabé E, Vergès-Belmin V (1996) Petrophysical investigation on the origin of scaling of a microgranular magmatic rock associated to granite in the monuments from Brittany (France). In: Commission E (ed) Environmental Protection and Conservation of the European Cultural Heritage-Degradation and Conservation of Granitic Rocks. European Commission, Bruxelles (Belgium), 73–78

Carballal R, Paz-Bermúdez G, Sánchez-Biezma MJ, Prieto B (2001) Lichen colonization of coastal churches in Galicia: biodeterioration implications. Int Biodeterior Biodegradation 47:157–163. https://doi.org/10.1016/S0964-8305(01)00044-0

Chen J, Blume H-P, Beyer L (2000) Weathering of rocks induced by lichen colonization — a review. CATENA 39:121–146. https://doi.org/10.1016/S0341-8162(99)00085-5

Chung FH (1974) Quantitative interpretation of X-ray diffraction patterns. I. Matrix flushing method of quantitative multicomponent analysis. J Appl Crystallogr 7:519–525

Di Carlo E, Barresi G, Palla F (2017) Biodeterioration. In: Palla F, Barresi G (eds) Biotechnology and Conservation of Cultural Heritage. Springer, Cham, 1–30 https://doi.org/10.1007/978-3-319-46168-7_1

Diez-Montes A (2006) La Geología del Dominio "Ollo de Sapo" en las comarcas de Sanabria y Terra do Bolo. University of Salamanca, Ph.D.

Fernández-Suarez J, Álvarez-Areces E, Baltuille-Martín JM, Martínez-Martínez J (2017) Identificación, estudio preliminar y puesta en valor de las canteras históricas de San Ciprián (Lugo). Bol Geol Min 128:485–498. https://doi.org/10.21701/bolgeomin.128.2.014

Freire-Lista DM, Fort R (2016) Causes of scaling on bush-hammered heritage ashlars: a case study—Plaza Mayor of Madrid (Spain). Environ Earth Sci 75:932. https://doi.org/10.1007/s12665-016-5688-0

Fuentes E, Carballeira R, Prieto B (2021) Role of Exposure on the Microbial Consortiums on Historical Rural Granite Buildings. Appl Sci 11:3786. https://doi.org/10.3390/app11093786

Garg S, Kaur P, Pandit M, Fareeduddin KG, Kamboj A, Thakur SN (2019) Makrana Marble: a Popular Heritage Stone Resource from NW India. Geoheritage 11:909–925. https://doi.org/10.1007/s12371-018-00343-0

GEODE (2021) Mapa Geológico Digital continuo de España (en línea). Instituto Geológico y Minero de España. https://mapas.igme.es/gis/services/Cartografia_Geologica/IGME_Geode_50/MapServer/WMSServer? Accessed 10/10/2021

Grimwade G, Carter B (2000) Managing Small Heritage Sites with Interpretation and Community Involvement. Int J Herit Stud 6:33–48. https://doi.org/10.1080/135272500363724

ICOMOS (1990) Charter for the Protection and Management of the Archaeological Heritage, https://www.icomos.org/images/DOCUMENTS/Charters/arch_e.pdf. Accessed 07/07/2021

İnce İ, Bozdağ A, Mb B, Mc F (2021) Evaluation of the relationship between the physical properties and capillary water absorption values of building stones by regression analysis and artificial neural networks. J Build Eng 42:103055. https://doi.org/10.1016/j.jobe.2021.103055

JCYL (Junta de Castilla y Leon) (2021) Catálogo de Bienes Protegidos. https://servicios.jcyl.es/pweb/datosGIS.do?tipo=inmueble&numero=16718. Accessed 09/02/2021

Junique T, Vazquez P, Benavente D, Thomachot-Schneider C, Géraud Y (2021) Experimental investigation of the effect of quenching cycles on the physico-chemical properties of granites. Geothermics 97:102235. https://doi.org/10.1016/j.geothermics.2021.102235

Klemm D, Klemm R (2001) The building stones of ancient Egypt - a gift of its geology. J Afr Earth Sci mid East 33:631–642. https://doi.org/10.1016/S0899-5362(01)00085-9

Lazzarini L (2007) Poikiloi Lithoi, versiculores maculae : marmi colorati della Grecia antica : storia, uso, diffusione, cave, geologia, caratterizzazione scientifica, archeometria, deterioramento. Fabrizio Serra, Pisa (Italy)

Martí Ezpeleta A, García Martínez E, MiragayaVeras A (1998) Rachas máximas y temporales de viento en Galicia. Revista Lurralde 21:262–280

Martínez-García E (1973) Deformación y metamorfismo en la zona de Sanabria. Stvdia Geológica Salmanticensia V:7–106

Martínez-Martínez J (2008) Influencia de la alteración sobre las propiedades mecánicas de calizas, dolomías y mármoles: evaluación mediante estimadores no destructivos (ultrasonidos). University of Alicante, Ph.D.

Melfos V (2008) Green Thessalian stone: the byzantine quarries and the use of a unique architectural material from the Larisa area, Greece. Petrographic and geochemical characterization. Oxf J Archaeol 27:387–405. https://doi.org/10.1111/j.1468-0092.2008.00313.x

Momeni A, Khanlari GR, Heidari M, Bagheri R, Bazvand E (2015) Assessment of physical weathering effects on granitic ancient monuments, Hamedan. Iran Environ Earth Sci 74:5181–5190. https://doi.org/10.1007/s12665-015-4536-y

Moral Crespo J, López Prado J, Arce Duarte JM (1979) Mapa geológico de la Hoja nº 266 (La Gudiña). Mapa geológico de España E. 1:50.000. Segunda Serie (MAGNA), Primera edición. Instituto Geológico y Minero de España, Madrid (Spain)

Mosquera MJ, Rivas T, Prieto B, Silva B (2000) Capillary rise in granitic rocks: interpretation of kinetics on the basis of pore structure. J Colloid Interf Sci 222:41–45. https://doi.org/10.1006/jcis.1999.6612

Navarro R, Martínez-Martínez J, Fernández Suárez J, ArecesÁlvárez E, Baltuille Martín JM (2022) Comparative analysis of the current uneven situation of historical quarries associated with the UNESCO world heritage sites in Spain. Resour Policy 75:102471. https://doi.org/10.1016/j.resourpol.2021.102471

Pan A, Chiussi S, Serra J, González P, León B (2009) Excimer laser removal of beeswax from Galician granite monuments. J Cult Herit 10:48–52. https://doi.org/10.1016/j.culher.2008.04.004

Pan A, Rebollar E, Chiussi S, Serra J, González P, León B (2011) Optimisation of Raman analysis of walnut oil used as protective coating of Galician granite monuments. J Raman Spectrosc 41:1449–1454. https://doi.org/10.1002/jrs.2686

Panova EG, Vlasov DY, Luodes H, Vlasov AD, Popova TA, Zelenskaya MS (2016) Granite weathering in urban environments. In: Frank-Kamenetskaya OV, Panova EG, Vlasov DY (eds) Biogenic—abiogenic interactions in natural and anthropogenic systems. Springer International Publishing, Cham, 345–356 https://doi.org/10.1007/978-3-319-24987-2_27

Pereira D (2019) Natural Stone and World Heritage: Salamanca (Spain). CRC Press, Leiden (The Netherlands) https://doi.org/10.1201/9781351013352

Pereira D, Gimeno A, Del Barrio S (2015) Piedra Pajarilla: a candidacy as a global heritage stone resource for Martinamor granite. In: Pereira D, Marker B, Kramar S, Cooper B, Schouenborg B (eds) Global Heritage Stone: Towards International Recognition of Building and Ornamental Stones. Geological Society, London, United Kingdom, 93–100 https://doi.org/10.1144/SP407.7

Pereira D, Marker B (2016) The value of original natural stone in the context of architectural heritage. Geosci 6:13. https://doi.org/10.3390/geosciences6010013

Pozo-Antonio JS, Alonso-Villar EM, Rivas T (2021) Efficacy of mechanical procedures for removal of a lichen and a gypsum black crust from granite. J Build Eng 44:102986. https://doi.org/10.1016/j.jobe.2021.102986

Pozo-Antonio JS, Papanikolaou A, Philippidis A, Melessanaki K, Rivas T, Pouli P (2019) Cleaning of gypsum-rich black crusts on granite using a dual wavelength Q-Switched Nd:YAG laser. Constr Build Mater 226:721–733. https://doi.org/10.1016/j.conbuildmat.2019.07.298

Pozo-Antonio JS, Rivas T, Carrera F, García L (2018) Deterioration processes affecting prehistoric rock art engravings in granite in NW Spain. Earth Surf Processes Landforms 43:2435–2448. https://doi.org/10.1002/esp.4406

Pozo-Antonio JS, Rivas T, López AJ, Fiorucci MP, Ramil A (2016) Effectiveness of granite cleaning procedures in cultural heritage: A review. Sci Total Environ 571:1017–1028. https://doi.org/10.1016/j.scitotenv.2016.07.090

Pozo-Antonio JS, Sanmartín P (2018) Exposure to artificial daylight or UV irradiation (A, B or C) prior to chemical cleaning: an effective combination for removing phototrophs from granite. Biofouling 34:851–869. https://doi.org/10.1080/08927014.2018.1512103

Prieto B, Seaward MRD, Edwards HGM, Rivas T, Silva B (1999) Biodeterioration of granite monuments by Ochrolechia parella (L.) mass: An FT Raman spectroscopic study. Biospectroscopy 5:53–59. https://doi.org/10.1002/(SICI)1520-6343(1999)5:1%3c53::AID-BSPY7%3e3.0.CO;2-/23

Prieto Lamas B, Rivas Brea MT, Silva Hermo BM (1995) Colonization by lichens of granite churches in Galicia (northwest Spain). Sci Total Environ 167:343–351. https://doi.org/10.1016/0048-9697(95)04594-Q

Rivas T, Pozo-Antonio JS, López de Silanes ME, Ramil A, López AJ (2018) Laser versus scalpel cleaning of crustose lichens on granite. Appl Surf Sci 440:467–476. https://doi.org/10.1016/j.apsusc.2018.01.167

Rivas T, Pozo-Antonio JS, Ramil A, López AJ (2020) Influence of the weathering rate on the response of granite to nanosecond UV laser irradiation. Sci Total Environ 706:135999. https://doi.org/10.1016/j.scitotenv.2019.135999

Rodríguez-Navarro C, Doehne E (1999) Salt weathering: influence of evaporation rate, supersaturation and crystallization pattern. Earth Surf Processes Landforms 24:191–209. https://doi.org/10.1002/(SICI)1096-9837(199903)24:3%3c191::AID-ESP942%3e3.0.CO;2-G

Rovella N, Aly N, Comite V, Ruffolo SA, Ricca M, Fermo P, Alvarez de Buergo M, La Russa MF (2020) A methodological approach to define the state of conservation of the stone materials used in the Cairo historical heritage (Egypt). Archaeol Anthropol Sci 12:178. https://doi.org/10.1007/s12520-020-01126-x

Russell B (2017) Stone quarrying in Greece: Ten years of research. Archaeol Rep 63:77–88. https://doi.org/10.1017/S0570608418000078

Sanjurjo Sánchez J, Alves C, Vidal Romaní JR (2016) Assessing the weathering of granitic stones on historical urban buildings by geochemical indices. Earth Sci Res J 20:F1–F13. https://doi.org/10.15446/esrj.v20n2.49560

Sanmartín P, Méndez A, Carballeira R, López E (2021) New insights into the growth and diversity of subaerial biofilms colonizing granite-built heritage exposed to UV-A or UV-B radiation plus red LED light. Int Biodeterior Biodegradation 161:105225. https://doi.org/10.1016/j.ibiod.2021.105225

Siedel H (2013) Magnesium sulphate salts on monuments in Saxony (Germany): regional geological and environmental causes. Environ Earth Sci 69:1249–1261. https://doi.org/10.1007/s12665-012-2034-z

Siegesmund S, Dürrast H (2014) Physical and mechanical properties of rocks. In: Siegesmund S, Snethlage R (eds) Stone in Architecture: Properties, Durability. 5th ed. Springer-Verlag Berlin Heidelberg, Berlin (Germany), 97–224 https://doi.org/10.1007/978-3-642-45155-3

Silva Hermo B, Prieto Lamas B, Rivas Brea T, Pereira Pardo L (2010) Gypsum-induced decay in granite monuments in Northwestern Spain. Mater Construcc 60:97–110. https://doi.org/10.3989/mc.2010.46808

Sousa LMO, Suarez del Río LMS, Calleja L, Ruiz de Argandona VGR, Rey AR (2005) Influence of microcracks and porosity on the physico-mechanical properties and weathering of ornamental granites. Eng Geol 77:153–168. https://doi.org/10.1016/j.enggeo.2004.10.001

Steiger M, Charola AE, Sterflinger K (2014) Weathering and deterioration. In: Siegesmund S, Snethlage R (eds) Stone in Architecture: Properties, Durability. 5th ed. Springer-Verlag Berlin Heidelberg, Berlin (Germany), 225–316 https://doi.org/10.1007/978-3-642-45155-3

Tomás R, Cano R, Pulgarín LF, Brotóns V, Benavente D, Miranda T, Vasconcelos G (2021) Thermal effect of high temperatures on the physical and mechanical properties of a granite used in UNESCO World Heritage sites in north Portugal. J Build Eng 43:102823. https://doi.org/10.1016/j.jobe.2021.102823

UNE-EN 1925 (1999) Natural stone test methods - Determination of water absorption coefficient by capillarity. Asociación Española de Normalización y Certificación (AENOR), Madrid

UNE-EN 1926 (2007) Natural stone test methods - Determination of uniaxial compressive strength. Asociación Española de Normalización y Certificación (AENOR), Madrid

UNE-EN 1936 (2007) Natural stone test methods - Determination of real density and apparent density, and of total and open porosity. Asociación Española de Normalización y Certificación (AENOR), Madrid

UNE-EN 13755 (2008) Natural stone test methods - Determination of water absorption at atmospheric pressure. Asociación Española de Normalización y Certificación (AENOR), Madrid

UNE-EN 14579 (2005) Natural stone test methods - Determination of sound speed propagation. Asociación Española de Normalización y Certificación (AENOR), Madrid

Vázquez P, Alonso FJ, Esbert RM, Ordaz J (2010) Ornamental granites: relationships between p-waves velocity, water capillary absorption and the crack network. Constr Build Mater 24:2536–2541. https://doi.org/10.1016/j.conbuildmat.2010.06.002

Vereshchagin OS, Frank-Kamenetskaya OV, Shumilova KV, Khadeeva NY (2018) Carbonate sediments on decorative fountains in Peterhof. Russia Environ Earth Sci 77:56. https://doi.org/10.1007/s12665-018-7243-7

Vergès-Belmin V (ed) (2011) Illustrated glossary on stone deterioration patterns. vol XV. Monuments & Sites. ICOMOS-ISCS, Paris

Winkler EM (1975) Stone: properties, durability in man's environment. Springer-Verlag, Wien-New York

Zalooli A, Khamehchiyan M, Nikudel MR, Freire-Lista DM, Fort R, Ghasemi S (2020) Artificial microcracking of granites subjected to salt crystallization aging test. Bull Eng Geol Environ 79:5499–5515. https://doi.org/10.1007/s10064-020-01891-y