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QUANTITATIVE ASSESSMENT OF POST-RESTORATION ACCELERATED STONE DECAY DUE TO COMPATIBILITY PROBLEMS (ST. SEBASTIAN'S ABBEY CHURCH, MANGLIEU, FRENCH MASSIF CENTRAL)

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Abstract

Most Romanesque churches of the French Massif Central have been built during the 11-12th centuries and restored between the mid-19th and the mid-20th centuries. Restoration campaigns including stone replacement and cement repointing are assumed to have caused accelerated stone deterioration. A quantitative assessment of this post-restoration accelerated decay is provided by the St. Sebastian's Church at Manglieu (Puy-de-Dôme, France), which displays conspicuous decay forms affecting the medieval stone facings. An interdisciplinary approach involving geoscientists and archaeologists specialized in the medieval period is developed, which combines: (1) the deciphering of the complex history of the facade, (2) the 3D-modeling of stone decay by laser scanning and (3) the analysis of the composition and properties of the building and restoration materials. Laser scanning data reveal that the most severely decayed part of the facade is located between 2 and 3 m a.g.l. i.e. just above the modern granite stones, incorporated at the base of the facade during the underpinning operation conducted in the 1860s. Contact sponge data indicates that these replacement stones, which were chosen because of their esthetic compatibility with the original ones, are four less permeable, and therefore create a major discontinuity zone above which capillary rise is enhanced; this induces an accelerated granular disintegration of the overlying medieval gneiss ashlars. On the whole, the post-restoration stone recession has been 20 mm on average since the 1870s (max. 130 mm). By contrast, on the rest of the facade not affected by restoration, the stone recession has been less than 2 mm since the 12th century as shown by the preservation of the medieval 'fish-bone' finish and mason's marks. It means that the post-restoration stone recession has proceeded up to 100 times faster than the pre-restoration recession. At a local scale, the replacement of lime mortar by Portland cement during the late 19th century repointing operations is an additional factor of accelerated decay.

Keywords accelerated stone decay, restoration practices, compatibility problems, medieval architecture, France

1. Introduction

Selecting the most suitable replacement stone when undertaking monument restoration or repair is a growing concern for many quarries have been mined out or are abandoned and no longer accessible. Atlases and databases are being developed to help restorers to select appropriate replacement stones.

Although the term ‘compatibility’ mainly refers to the mechanical, physical and chemical compatibility of new stones with the historic stone materials (Teutonico et al. 1997), the selection of substitution stones has for long mainly been based on their esthetical compatibility (i.e. their colour and texture) with the original stones. An additional factor considered for selecting replacement stones has often been the stone ‘hardness’, which mainly refers to their compressive strength. In its *Dictionnaire raisonné de l’architecture française du XIe au XVIe siècle* published in 1854, the French architect Viollet-le-Duc already recommended to select ‘better’ materials than the original ones, and high hardness and high density were consequently taken by many restorers as positive properties (cf, for instance the replacement of limestone by trachyte during the restoration of Our Lady in Breda, Netherlands, as reported by Quist 2009). No clear attention was paid to the relations between material properties of replacement stones and those of historic stones.

Since the 1990s, several studies have pointed out the deleterious effects on stone conservation of inadequate stone replacement: the selection of harder stones than the original ones has been reported to create new problems by Blanc (1992), Přikryl and Smith (2007), and Quist (2009), due to differences of water transport properties between new and old stones. The replacement of soft and permeable lime mortar by hard and stiff cement mortar has also been pointed out as a frequent cause of accelerated stone deterioration. Portland cement, patented in England by Joseph Aspdin in 1824, has rapidly supplanted the lime-based mortars, which had been in use since antiquity (Dotter et al. 2009). In Europe, large use of cement in various styles such as ‘ribbon’ and ‘bastard tuck’ was made during the 19th-20th century restoration campaigns. This caused drastic changes in the water balance and the chemistry of masonry stones. The responsibility of cement repointing in the acceleration of stone decay has been incriminated in rural areas of Ireland, based on a national assessment commissioned by the Heritage Council. Of the 112 investigated monuments, 32.5% had been repointed with modern Portland cement, which had reacted chemically with the original masonry, inducing damage in 46% of these cases (Pavia and Bolton 2001).

Although geomorphologists have developed new methods to quantify stone deterioration (Pope et al. 2002; André et al. 2008; Vautier & Voldoire 2011), little quantitative data are currently available concerning the man-induced acceleration of stone deterioration. Measurements on nine granite churches of Brittany suggest that post-repointing weathering rates are three times faster than pre-repointing rates (Paris 1998), but to date, the accelerated deterioration induced by incorporation of incompatible stone materials has never been quantified. This gap in knowledge motivated the multidisciplinary study of the medieval church of St. Sebastian in Manglieu (French Massif Central), which has been restored in the late 19th century. The aim of the present study is to quantify the impact of restoration (stone replacement and cement repointing) on the activation of stone decay at this monument, which had been exposed for seven centuries to atmospheric attack before restoration. Such a quantitative assessment requires three objectives: (i) to reconstruct the history of the monument and to distinguish the historic from the replaced stones, based on archival research and stone-by-stone surveys ; (ii) to characterize the old and new stone materials, regarding their geochemical and mineralogical composition, and their water transport properties, based on ICP-AES, polarizing light microscopy and the contact sponge method; (iii) to provide a 3D-model of the stone decay at the study site based on long range laser scanning in order to provide estimates of stone recession rates before and after restoration.

2. Study site

The Auvergne region, which is located in the French Massif Central, is characterized by the diversity of its architectural heritage, with a particular mention for hundreds of Romanesque churches mainly dating back to the 11-12th centuries (Figure 1). Since their building, most of these monuments have been subject to modifications, additions and repairs, including a major restoration phase, which started in the mid-19th century.

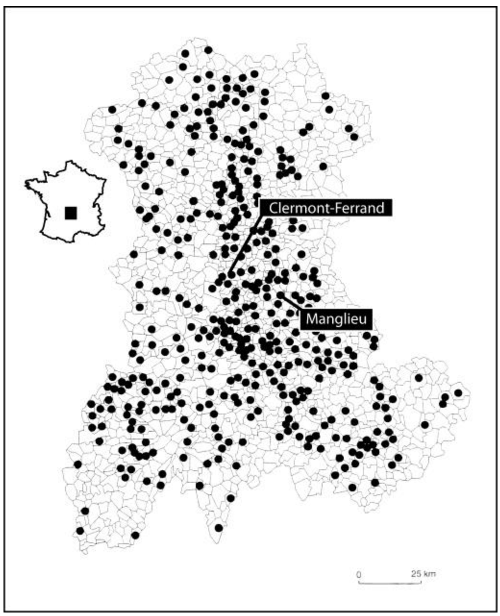

Figure 1. Location of Romanesque churches in the Auvergne region, French Massif Central (after Phalip 2001)

St. Sebastian's abbey church is one of these medieval restored monuments. It is located 44 km south of Clermont-Ferrand, the main city of the Auvergne region (Figure 1). This church is a protected monument, which has been inscribed in 1840 on the national list of historical monuments. It is renowned for the antiquity of its apse, which dates back to the 8th century. Whereas other parts of the church such as the narthex and most of the façade date back to the 12th century, the nave and the quadrangular tower were rebuilt in the 15-16th centuries, and the upper part of the façade was completed in the late 19th century (Cabréro-Ravel 1997; Phalip 2001). The geological setting of St.

Sebastian's abbey church is characterized by the abundance of local building materials associating Paleozoic basement rocks (migmatitic gneisses and granites), and Cenozoic sedimentary rocks mainly represented by arkosic sandstones. This geological diversity is expressed by the multicoloured appearance of St. Sebastian's western façade, which includes grey gneiss and granite, and yellow and red arkosic sandstone. This façade, which is the focus of the present study, illustrates the complex history of St. Sebastian, with four building phases ranging from the 12th to the 19th century (Figure 2). The lower part of this façade, which faces the prevailing winds blowing from the west, is decorated with three semicircular blind arches, four meters wide by five meters high, which mainly display grey ashlar blocks. The inner part of these arches displays conspicuous decay features. Surprisingly, these have not developed within the capillary fringe, but 2.5 meters a.g.l. The severity of decay and the anomalous distribution of decay forms has motivated the present study.

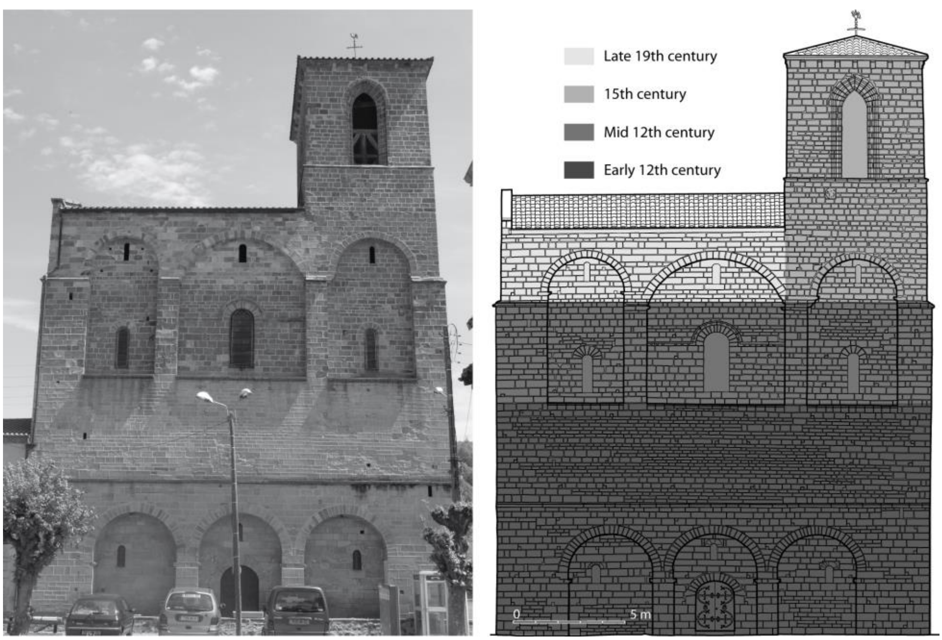

Figure. 2. Multi-phased façade of St. Sebastian's abbey church. © M.F. André (left) and David Morel (right)

3. Methods

Methods combine approaches from various disciplinary fields including art history, archeology, geomorphology, geology and geomatics.

Archival research in various documentary sources (including the Mérimée architecture database of the French Ministry of Culture) and on-site stone-by-stone surveys were carried out to precise the chronology of building and restoration periods, and to discriminate the original from the restored parts of the blind arches, mainly based on the presence or absence of medieval mason's marks and 'fishbone' tooling marks. These marks were also used to reconstruct a secure reference surface (i.e. dated 'zero-datum level') to be able to quantitatively assess stone decay (André and Phalip 2010). Stone-by-stone surveys aimed also to determine the petrography of every ashlar block.

Visual categorization of stone decay forms (such as flaking, scaling and alveolar weathering) was then carried out based on the existing nomenclatures (Fitzner and Heinrichs, 2002; Vergès-Belmin, 2008). Quantitative assessment of stone decay was based on 3D-modeling of stone decay by laser scanning. Scans were obtained with the Optech Ilris 3D laser scanner, which is long range, accurate and fast, and provides a comprehensive view of the stonework conditions. Polyworks and Geomagic sofwares were used to obtain 3D models of the decayed surfaces to be compared with the reconstructed 'zero-datum level' in order to calculate stone recession rates.

Petrographical characterization was carried out based on laboratory analyses of small pieces of stone materials fallen from the monument. Geochemical composition was determined by using ICP spectrometry (Murray et al. 2000). Each sample aliquot (100 mg) was mixed with $LiBO_2$ flux and fused for 5 min at about 1050° in 2000 W induction furnace. The melt was poured into a disposable polystyrene beaker containing 50 ml of 2 M HNO_3 stirred by a magnetic bar, and after complete dissolution, the solution was passed through a filter paper to remove graphite particles. Major element compositions of rock samples were measured on ULTIMA C Horiba-Jobin-Yvon ICP-AES, based on the ICP-AES analytical techniques described in Cantagrel & Pin (1994). Mineralogical identification was performed based on polarizing light microscopy. Stone samples were cut to fit a 45×30 mm glass slide and due to their friability, impregnated with an epoxy resin under vacuum. Thin sections were examined using an optical polarizing light microscope (LEICA DMLP) equipped with a camera (LEICA DFC295).

Due to sampling restrictions, porosity analyses could not be carried out, but the comparative assessment of water transport properties between the replacement and original stones was performed based on on-site contact sponge tests. This recently developed method (Pardini and Tiano 2004) complements the Karsten pipe and capillary rise methods (Vandervoorde et al. 2009). It is a non-destructive and portable method, which can be employed *in situ* as well as in laboratory to measure the water uptake by stone materials. This method consists of a 1034 Rodac contact-plate, 5.6 cm in diameter, containing a Calypso sponge. After filling the sponge with approximately 7 g of water, the contact-plate is pressed manually against the stone surface during a given time (30 or 60 seconds), and the sponge is weighed on a precision balance before and after contact with the stone surface. The difference between weights corresponds with the amount of water absorbed by the stone surface under test. Water absorption is expressed in $g/cm^2.min$. Overall, 90 contact sponge tests were carried out at the investigated site in order to compare the water absorption by historical and replacement ashlars.

4. Results

4.1. Monument history

The historical documentation provided by the Mérimée national database and the Conservation of Historical Monuments in Clermont-Ferrand indicates a major restoration operation undertaken between 1868 and 1888 at the base of St. Sebastian's façade, which has affected the three investigated blind arches. Probably due to a severe deterioration caused by capillary rise, the façade was underpinned up to 2.5 m above the ground level. The decayed medieval gneisses were replaced by new granitic ashlar blocks, and both the new granites and old gneisses were (re)pointed with cement mortar instead of the original lime mortar. This operation is documented by architectural surveys conducted by the architect Louis-Clémentin Bruyerre in 1870, and by the photographs taken by the architect Gabriel Ruprich-Robert in 1909, i.e. after restoration.

Stone-by-stone surveys provided maps of the original and restored parts (Figure 3), and of the lithological nature of stone materials (Figure 4). The esthetic compatibility of the granitic replacement stones with the historic gneissic ashlars was considered by the restorers: the grey colour of the granite matches perfectly with the colour of the medieval gneiss to such an extent that at first sight, they are hardly distinguishable. However, closer examination reveals substantial textural differences between them. The gneiss, which is a migmatitic gneiss ('nebulite'), displays a foliated organization, with alternating layers of leucocratic minerals (mainly quartz and potassic feldspars) and melanocratic minerals (mainly biotite). The granite, which is medium-grained, displays the same minerals but its texture is homogeneous and equant. The arkosic sandstones, which are mainly represented in the upper part of the arches, include various lithotypes, due to their variable quartz and mica content.

4.2. Qualitative and quantitative assessment of stone decay

The stone-by-stone survey of the three blind arches reveals that the state of deterioration of the ashlar blocks varies highly according to their lithology and their height above the ground level. The granite ashlars, which were inserted at the base of the wall during the 19th c. restoration, are invariably sound and fresh. The 12th c. arkosic sandstones, which are located in the highest part of the arches, are moderately affected by a very superficial (<3 mm) granular disintegration; some are fresh and completely free of weathering; a single arkosic ashlar, which is located above the window of the left arc is more severely affected and has receded by 1.5 cm due to granular disintegration. As to the 12th c. gneiss ashlars, their behaviour differs drastically according to their position on the wall. In the highest parts, they are perfectly preserved and still display the medieval 'fishbone' finish and mason's marks of the original surface; by contrast, in the middle part of the wall, they display a very irregular topography due to granular disintegration and alveolar weathering; 'caves' in gneiss reach up to 10 cm deep, especially when surrounded by sound granite ashlars.

Post-processing of laser scanner data and overlapping of the 3D-models of the decayed surface and the reference surface provided a spatialized view of stone recession rates since the 12th century (in the unrestored parts) and since the 19th century (near the restored parts). Both the upper part of the arches, which still displays the 12th c. mason's marks, and the lower part, which consists of new granite, appear almost free of deterioration. By contrast, the middle part, which lies just above the restored part, is severely decayed (Figure 5), with stone recession values ranging from 10 to 60 mm, with extreme values of almost 130 mm obtained on single medieval gneissic stones completely surrounded by new granitic stones. This implies that in areas impacted by the 19th c. underpinning operation, stone decay of historical gneissic stones has proceeded very fast (0.2 mm per year on average and up to almost 1 mm per year). By contrast, most of the same historic gneissic stones located higher on the wall, which have been exposed for almost nine centuries to the atmospheric attacks but have not been impacted by the 19th c. restoration, still display their medieval 'fishbone finish': the overall decay has affected less than 2 mm, with resulting stone recession rates lower than 0.002 mm per year.

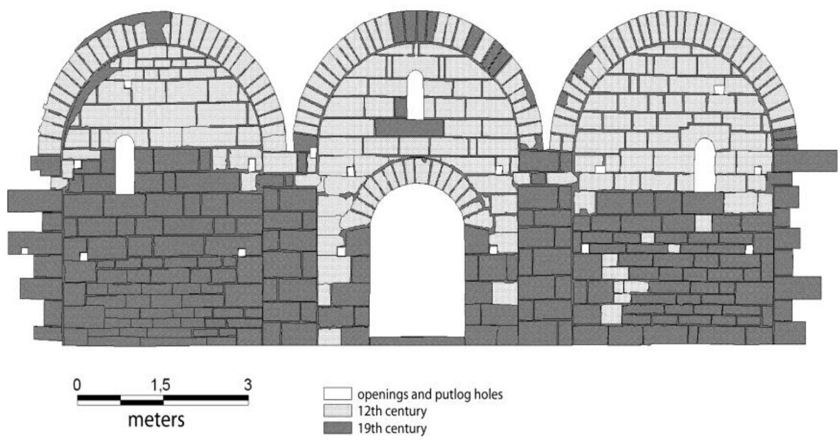

Figure 3. Differentiation between historic and replaced stones based on stone-by-stone surveys. © Bruno Phalip / Olivier Voldoire

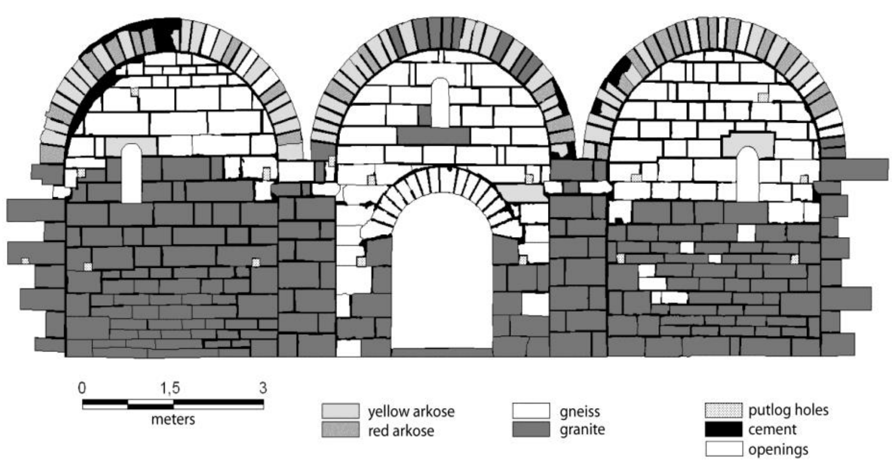

Figure 4. Lithological nature of stones based on stone-by-stone surveys.
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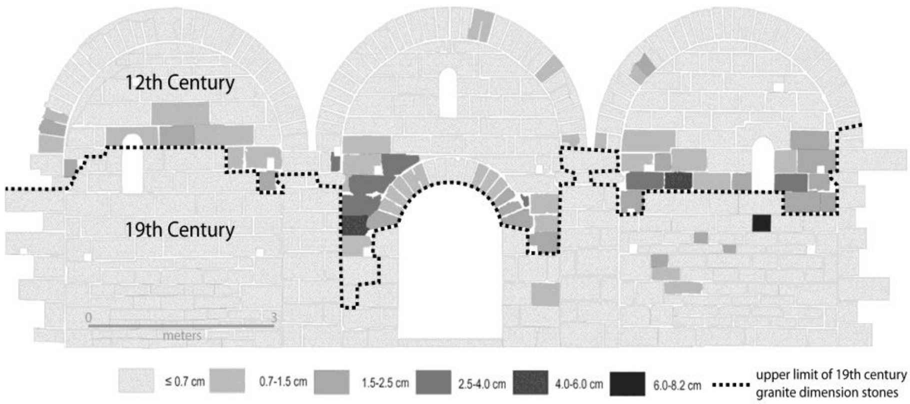

Figure 5. Accelerated stone recession just above the underpinned part of the arches based on 3D-modeling of stone decay by laser scanning.
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4.3. Geochemical and mineralogical composition of stone materials

ICP-analyses reveal the similarity of geochemical composition of the medieval gneiss and new granite incorporated at the base of the monument in the 1870s: gneiss and granite respectively comprise 67 and 65% SiO_2, 17 and 16% Al_2O_3, and 3 and 4% Fe_2O_3. The arkosic sandstones appear more silica-rich (mean 74%, maximum 87.6%).

Unlike geochemical analyses, microscopical observations reveal a sharp contrast between the original gneiss and the new granite ashlars. The 12th c. gneiss displays completely pulverized biotites, microcracked quartz grains and argilized feldspars; muscovite is the only intact mineral. By contrast, although the least quartz-rich (65% SiO_2) and the richest in Fe-Mg (> 6%) and Ca-Na (> 7%) minerals, the 19th c. granite appears very fresh and display sealed grain contacts. Quartz grains and biotite flakes are intact. Feldspars, though slightly misty, are perfectly recognisable, based on their Carlsbad twins (orthoclase) and polysynthetic twins (plagioclase). Thin sections also indicate a high variability of the arkosic lithotypes, which are a minor constitutive material of the blind arches. Whereas the high quartz content and the low feldspar and mica content of the siliceous arkose subtype makes it close to a quartzitic sandstone, the yellow micaceous arkose is characterized by its mineralogical heterogeneity (quartz, orthoclase, plagioclase, biotite, muscovite, epidote, etc.), its weathered feldspars, and its cracked or pulverized quartz grains and biotite flakes. The red arkose is rather similar to this yellow micaceous arkose but is richer in iron oxides and slightly laminated.

4.4. Water absorption of original and new stone materials

The results of contact sponge tests reveal a high contrast in water absorption between the historical and the replacement stones. Water absorption is 0.056 and 0.052 g/cm².min for the medieval gneissic and arkosic ashlars, and only 0.016 g/cm².min for the granitic replacement stones. These granites inserted in the lower part of the façade in the 1870s are therefore three to four times less permeable than the original gneissic stone materials.

5. Discussion and conclusions

The St. Sebastian case study illustrates the severity of damages caused to ashlar masonry by inappropriate stone replacement based on a quantitative assessment of the man-induced acceleration of stone deterioration. In the middle part of the arches impacted by the underpinning operations, the stone recession has proceeded 100 times faster during the 140 year post-restoration period than during the 700 preceding years of atmospheric attacks. The main cause of this accelerated decay is obviously the incorporation of granite at the base of the façade. Although esthetically compatible with the original stone, this replacement stone is four time less permeable and creates a floor above which capillary rise conducive to granular disintegration is enhanced. The present study emphasizes the absolute necessity to take into account before selecting substitution stones not only their petrochemical compatibility with the original stones but most importantly their petrophysical compatibility, water transport properties being the key driver of stone deterioration (Rozenbaum et al. 2008). It also confirms that cement repointing represents an additional cause of accelerated decay due to its low permeability, which prevents the joints from acting as a drainage network for the historical monuments, and drives moisture to the stonework (Grunau 1971; Collombet 1989; Dotter et al. 2009). From a methodological point of view, this case study demonstrates both the interest of long-term natural exposure trials as reliable durability tests (Doehne & Price 2010) and of the contact sponge as a non-destructive and portable method for *in situ* assessments of water absorption by stone materials (Pardini and Tiano 2004; Vandervoorde et al. 2009).

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