Rates of stone recession on Mediaeval monuments: some thoughts and methodological perspectives

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Abstract

Studies of stone decay contribute significantly to an understanding of weathering processes and landform development. However, compared to tombstones, coastal defensive structures and Roman temples, Mediaeval monuments appear to be underrepresented in quantitative assessments of historical stone decay. As a result of the close cooperation between geomorphologists and archaeologists of the Mediaeval period, it has proved possible to improve the chronological control of stone recession measurements, to reconstruct the rates of stone decay, and to investigate some of its causes.

Key words: Rock weathering, stone decay, weathering rates, Mediaeval monuments, Romanesque churches, Angkor temples

INTRODUCTION

Over the last several years studies of weathering acquired considerable status within physical geography. Though most progress has resulted from field investigations in natural environments and laboratory simulations, stone decay studies have also made valuable contributions. More than one century after Geikie's pioneer investigations of stone decay in Edinburgh churchyards (GEIKIE, 1880), a considerable international and multidisciplinary research effort has been made in cultural stone weathering research (see reviews in POPE et al., 2002 and TURKINGTON and PARADISE, 2005). Various descriptive schemes have been developed for classifying and mapping weathering forms (e.g. FITZNER, 1990; WARKE et al., 2003).

Based on less integrated though still effective methodologies, monuments have been used by geomorphologists as 'natural laboratories' to assess rates of long-term surface back-wearing in various lithologies and environments. As noted by POPE et al. (2002, p. 216), "through measurement of surface recession in various contexts, a very large database is available now for weathering rates". However, this database is not homogeneous. Some monument types are overrepresented (e.g. ≤200 yr marble tombstones, see MEIERDING, 1981; BAER and BERMAN, 1983; DRAGOVICH, 1986; NEIL, 1989; INKPEN and JACKSON, 2000), whereas others have not been given enough attention (e.g. Mediaeval sandstone monuments, see ROBINSON and WILLIAMS, 1996). Between these extremes, ancient monuments (>2000 yr) have received

increasing attention during the last fifteen years, with special reference to Jordan temples and theatres (PARADISE, 1998, 2005) and Brittany megaliths (SELLIER, 1991, 1997). The same is true of the 500 yr-old coastal defensive structures of the British Isles, which have been thoroughly investigated (MOTTERSHEAD, 1997, 2000a).

The main reason for this database heterogeneity is that tombstones, coastal defensive structures and ancient monuments usually offer a much more uniform *corpus* for stone recession measurements than Mediaeval (i.e. 5th-15th centuries CE) monuments. Many of these, especially in Europe, have been subject to several building and/or restoration phases, and look like giant jig-saw puzzles (figure 1). In parts of some so-called 'Romanesque' churches, constructed of rock types susceptible to frost action (e.g. the Saint-Etienne church of Nevers), up to 50% of the stones date back to post-Romanesque periods. Such a complexity renders difficult any quantification of weathering rates. Even in the same wall bricks of essentially similar composition and texture display strongly contrasted rates of weathering (IKEDA, 2004). However, apart from stone by stone assessments of percentage areas of decayed surfaces (ROBINSON and WILLIAMS, 1996), some attempts have been made to measure surficial stone recession. Most of this exploratory work has been conducted in France on Romanesque and Gothic churches of Brittany and the Massif Central, using basic tools such as steel tapes, callipers and profile gauges. The resulting weathering rates, which are summarized on Table 1, are at this stage provisional.

Fig. 1. Polygenetic origin of 'Mediaeval' European churches. © M. F. André

A. Mid-12th century Gothic arch inserted in late 11th century Romanesque arch (Saint-Front Cathedral, Périgueux, Dordogne, 21-11-08). B. Decayed and replaced sandstone elements in early 13th century portal (Saint-Magnus Cathedral, Kirkwall, Orkney Islands, 27-7-1987). C. Intriguing weathering pattern on a Mediaeval column (Sainte-Foy abbey church, Conques, Aveyron, 18-6-00). D. Contemporary restoration site (Sainte-Valérie abbey church, Chambon-sur-Voueize, Creuse, 19-10-08). E. Late 12th century whitewashed portal columns (Notre-Dame church, Fleuriel, Allier, 15-10-08). F. Polychrome apsidiole, restored in mid-19th c. and cleaned in the early 2000s. (Notre-Dame du Port church, Clermont-Ferrand, Puy-de-Dôme, 31-1-06). G. Original limestones and darker arkosic sandstones incorporated during the 1995-2000 restoration (Sainte-Martine church, Pont-du-Château, Puy-de-Dôme, 4-10-08).

Monument location	Monument corpus	Building century	Lithology	Stone recession rate in mm per century	Source
FRENCH CHURCHES					
West and South Brittany	6	15-16th	Granite	3.1 – 6.5	Sellier 1998
South Brittany	29	11-17th	Granite	2.6 – 4.5	Paris 1998
South Brittany	35	11-17th	Granite	1.6 – 3.9	Magré et al. 2007
French Massif Central	133	11-15th	Various including: • Leucocratic granite • Basalt, Trachyandesite • Oolitic & bioconstructed limestones • Marble • Biotite/chlorite-rich granite • Soft limestones • Sandstones	 <1 <1 <1 <1 3 – 5 6 – 7 0.3 - 16	Bonneau 2001 Robert 2002 André et al. 2007
KHMER TEMPLES					
Angkor temples	11	10-13th	Sandstone	0.2 – 5.0	André 2006
Ta Keo temple (Angkor)	1	11th	Sandstone	0.0 – 5.5	André et al. 2008

Table 1. Tentative rates of stone recession on Mediaeval French churches and Khmer temples.

Based on this reconnaissance work involving more than 200 churches, it is clear that further use of Mediaeval monuments with the assessment of historical weathering rates in mind requires collaboration. Of special interest is the current tightening of links between French geomorphologists, archaeologists concerned with Mediaeval buildings and art historians, architects, restorers and stonemasons. Such a collaborative approach is being developed to ensure that stone recession measurements are representative and reliable. This will improve the current knowledge and understanding of the spatial and temporal variability of stone decay rates since the Middle Ages. The two main study areas presently investigated by this interdisciplinary network are the Mediaeval churches of the Massif Central and the Khmer temples of the Angkor site (ANDRÉ et al., 2007a, 2007b; ANDRÉ et al., 2008; PHALIP and ANDRÉ, 2008; ANDRÉ and PHALIP, in press).

The main objective of this paper, which is based on these current interdisciplinary exchanges, is to suggest research that addresses the following questions:

1. How to improve the chronological control of stone recession measurements in Mediaeval monuments?
2. How to reconstruct the *tempo* of stone decay in such monuments?
3. What specific causes of stone decay deserve further investigations?

The examination of the crucial question of the mapping methods and sampling strategies is beyond the scope of this paper. Insights of special interest are provided by previous reviews and discussions (e.g. MOTTERSHEAD, 2000b; WILLIAMS and SWANTES-

SON, 2000; INKPEN et al., 2004) and recent case studies (INKPEN et al., 2001; TURK-INGTON and SMITH, 2004; PARADISE, 2005; McCABE et al., 2007a; ANDRÉ et al. 2008; HEINRICHS, 2008).

CHRONOLOGICAL CONTROL OF STONE RECESSION MEASUREMENTS

Deciphering the monument history

In spite of the development of the technology involved in methods such as laser scanning, the stone by stone survey is still considered by the archaeologists as the most efficient and informative method by which to decipher the intricate history of Mediaeval monuments (PARRON-KON-TIS, 2005). The resulting maps, such as the one recently obtained of the southern wall of Notre-Dame du Port church in Clermont-Ferrand by Phalip and Morel (figure 2), are a first-class data source for the geomorphologist. Not only do they help in the selection of chronologically homogeneous surfaces for quantifying purposes, but the accompanying descriptions of stone facings (e.g. stone dressing marks, lime and cement mortars, etc.) provide valuable indicators by which to identify zero datum levels (REVEYRON, 2005).
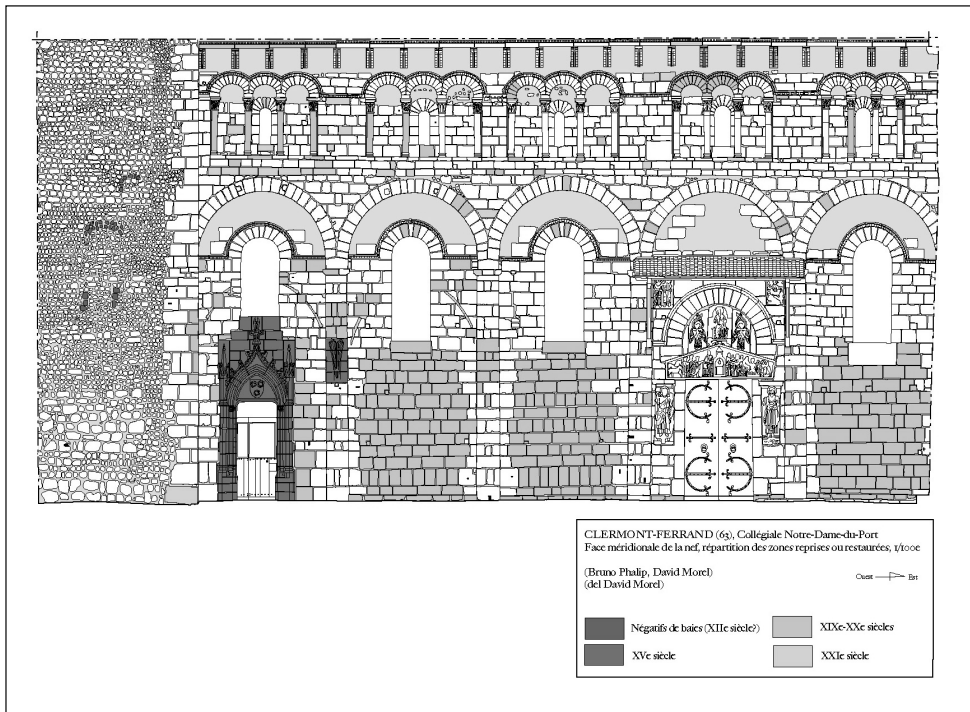

Fig. 2. Stone by stone map of the restored parts of the southern façade of the nave of Notre-Dame du Port church (Clermont-Ferrand, Puy-de-Dôme, 2006). © B. Phalip and D. Morel

Searching for secure zero-datum levels

Reliability of reference surfaces (i.e. dated 'zero-datum levels') is a pre-requisite to ensure the validity of any weathering/decay rates, that may be obtained either in natural or cultural contexts. The question of the reference surfaces has long been addressed by cold-climate geomorphologists who have made extensive use of protruding ice-polished quartz veins to assess Postglacial weathering rates (e.g. DAHL, 1967; ANDRÉ, 1995; NICHOLSON, 2008), and, indeed in previous studies on cultural stone (e.g. LIVINGSTON and BAER, 1986; WINKLER, 1986; INKPEN, 1998; MOTTERSHEAD, 2000b). Of special interest to the inventory of reference surfaces provided by Mediaeval monuments, are four exploratory studies conducted in Brittany and Auvergne, France (PARIS, 1998; MAGRÉ, 1999; BONNEAU, 2001; ROBERT, 2002; see also SELLIER, 1998, and MAGRÉ et al., 2007). Based on these studies, and on complementary fieldwork by the authors in the Massif Central (PHALIP, 2001; ANDRÉ et al., 2007b) and in Cambodia (ANDRÉ, 2006; ANDRÉ et al., 2008), a variety of zero datum levels can be listed (Table 2, figures 3 and 4).

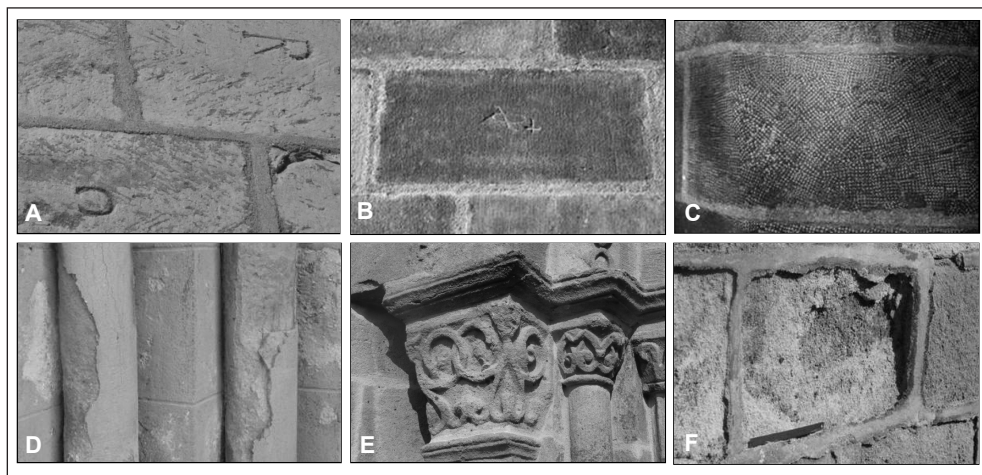| Zero-datum levels	Mediaeval churches (Central and West France)	Khmer temples (Angkor, Cambodia)
Stone-dressing marks	++++	++
Mason's marks	++	
Inscriptions	+	++
Moulded surfaces	++	+++
Columns and pillars	++	+++
Ornamentation (carved details)	+	+++++
Mortar joints (lime and cement)	+++	
Slate wedges	+	
More resistant stones (polychrome monuments)	++	

Fig. 3. Zero-datum levels provided by Mediaeval churches of the Massif Central. © M.-F. André

A. Late 12th century 'fern-leaved' or 'fishbone' finish and mason's marks on arkosic sandstone (Saint-Austremoine abbey church of Issoire, Puy-de-Dôme, 18-10-08). B. 14th century brettelé finish and mason mark on trachyandesite (Clermont-Ferrand Cathedral, Puy-de-Dôme, 31-1-06). C. Bush-hammered trachy-andesite stone, 19th century (Michel de l'Hospital's Place, Clermont-Ferrand, Puy-de-Dôme, 31-1-06); in a Mediaeval monument, a bush-hammered stone surface indicates a post-late 18th century, often 19th century, restoration. D. Late 12th century sandstone door jambs affected by scaling (Saint-Martin church, Besson, Allier, 29-09-08). E. Mid-12th century ornamented capitals in arkosic sandstones (Saint-Pierre church, Gipcy, Allier, 29-9-08). F. Cement mortar joints in arkosic sandstones (Saint-Marc church, Souvigny, Allier, 29-9-08).
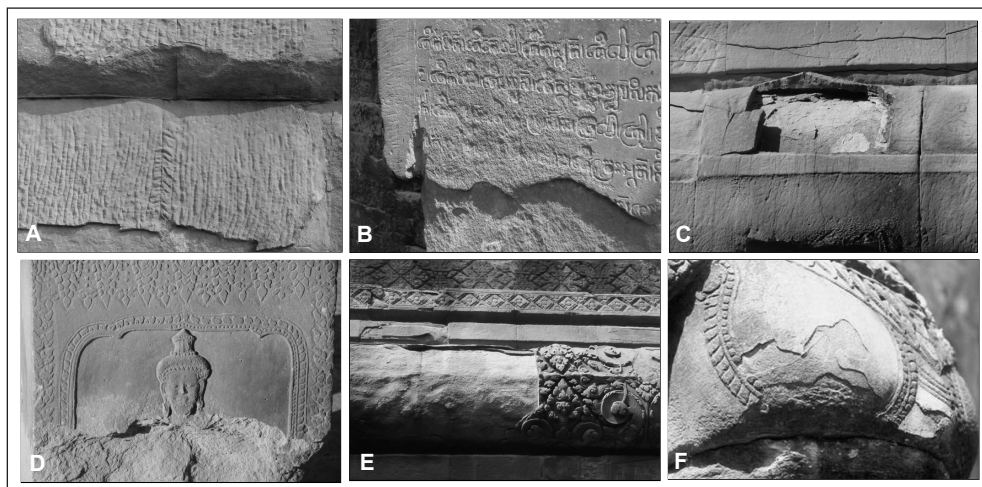

Fig. 4. Zero-datum levels provided by sandstone Khmer temples to evaluate recession depth from scaling and flaking (Angkor, Cambodia). © M.-F. André

A. Stone dressing marks (Ta Keo temple, South face, second tier, early 11th century, 7-2-08). B. Stele with inscriptions (Lolei temple, 9th century, 20-3-08). C. Moulded surface (Ta Keo temple, South face, first tier, early 11th century, 6-12-08). D. Ornamented pillar (west gallery, Angkor Wat, 12th century, 6-12-08). E. Scaling decorated toric rib (eastern face, Ta Keo temple, early 11th century, 6-2-08). F. Flaking sandstone on the polished surface of a garuda statue (terrace of the elephants, Late 12th century, 28-12-04).

Stone-dressing marks

Stone-dressing marks provide authentic reference surfaces on the wall facings of churches and temples dating back as far as the Antiquity (e.g. BESSAC, 1986, 1993; PARADISE, 1998, 2005). Good inscription and dressing marks are more likely to survive on sandstones, limestones, marbles, and hard volcanic rocks, than on for example conglomerates and coarse-grained granites. In Mediaeval churches, stone-dressing marks can be classified in three major categories: (1) 12th century stones with their mason marks and fern-leaved or 'fish-bone' finish, with irregular and obliterated furrows every 5 mm (see figure 3a); (2) 13-15th century *brettelé* finish (see figure 3b); (3) 19th century bush-hammered finish (see figure 3c). This chronological succession provides a general framework whereby reference surfaces can be identified, but the reliability varies according to regions and monuments. Close cooperation with archaeologists of the Mediaeval period is required to ensure the chronology of stone-dressing marks, as it is to detect Mediaeval re-cuts of Gallo-Roman stones and 19th-21st century imitations of Mediaeval stone dressing techniques, with very sharp 1-2 mm-spaced tooling marks. In Cambodian sandstones, stone-dressing marks are mostly represented in the least ornamented or unfinished parts of temples (figure 4a).

Mason marks and inscriptions

Mason marks are widespread on building stones of Mediaeval churches of the Massif Central, where they have been thoroughly studied and classified (e.g. MOREL, 2004). They are present both on Roman and Gothic churches (figures 3a and 3b), and have various forms such as swirls, triangles, stars, keys, and letters from the Latin and Greek alphabets, sometimes used in reverse. As to the Khmer temples of Cambodia, they provide plenty of steles bearing inscriptions (figure 4b), of which thousands have been translated from Sanskrit and ancient Khmer by COEDÈS (1937-1966). They frequently provide information on the building or consecration date of the monument, but some may postdate the temple itself, a factor that must be taken into account when using them as datum surfaces to assess weathering rates.

Mouldings and columns

In Romanesque churches, moulded surfaces are present in cornices, drips and portals, with polychrome archivolt of special interest when quantifying selective weathering (as long as stones have not been replaced). In portals of Mediaeval churches, door jambs can be systematically used to measure stone recession, for they display standardized sections, either cylindrical (in Romanesque style, cf. figure 3d) and/or polygonal section (in Gothic style). The polished surface of door jambs and columns can be preserved, particularly in marble, but this material often comes from Gallo-Roman columns, reused during the Middle Ages. Therefore, the chronological control of the datum is not easy to establish precisely. Edges of cornerstones can be used to quantify stone recession, though because of the sensitivity to weathering of their sharp edge, their use leads to over-estimations of the amount of weathering (as do, the measurements taken at the base of monuments, where accelerated weathering operates within the capillary fringe). In Cambodia, the numerous pillars of the Khmer temple galleries can be used to quantify historical weathering, together with horizontal mouldings such as toric ribs which are affected by scaling (figure 4c).

Decorative carved elements

Romanesque churches do not display abundant ornamentation, except for delicately chiselled capitals (figure 3e), modillions and tympanums, which provide good zero datum levels, provided they were not repeatedly restored or hammered during the French Revolution. Gothic cathedrals and later monuments partly inspired by the Late Gothic style (e.g. during the 16th century in Brittany) are richer in carved elements such as gargoyles and pinnacles, but they do not provide good datum surfaces in all sites. For instance, in coarse-grained granite located in coastal regions (e.g. Brittany), they have often been too severely affected by salt weathering for their initial shape to be reconstructed (SELLIER, 1998). Nevertheless, based on a scale of ornamentation legibility inspired from the scales of inscription legibility proposed by RAHN (1971) and MEIERDING (1993), they provide valuable information for purposes of comparison (PARIS, 1998).

In contrast to Romanesque churches, the Khmer temples of the Angkor site are richly ornamented, offering almost everywhere, zero-datum levels by which to assess sandstone recession rates: at the base of pillars in the Angkor Wat galleries, on the sculpted facings of the Ta Keo temple-mountain, and on the bas-reliefs of the Terrace of Elephants (figures 4d–4f). Carved details are particularly secure datum surfaces in monuments or parts of monuments that have never been restored. Thus, the ornamented patterns in Khmer architecture provide large, statistically significant, datasets, on stone recession.

Lime and cement mortar joints

Mortar joints can be used, frequently in association with other datum surfaces, to assess rates of stone recession (figure 3f).

It should be done with caution, for joints belong to several generations and are not always incorporated into the walls at the same level as building stones. Lime mortars have been used from the 3-4th century BC to the middle of the 19th century. Those which date back to the 12th century are usually very lumpy, lime-rich, with non sieved coarse sands. From the 13th century onwards, mortar joints are less lime-rich, they contain more and more sieved sands, and their water content is higher. This frequently makes it necessary to use wedges to keep constant the spacing between the stones. Most Portland cement joints indicate repointing operations having taking place from the 1860s to 1950. Cement joints contain fine-grained sieved sands, and often protrude some 2 mm out from the stone surface. At places, these joints follow the shape of pre-existing irregularities and can be used, jointly with older datum surfaces such as dressing marks, to assess both pre- and post-repointing recession rates.

Slate wedges

Up to c. 3 cm thick slate wedges incorporated in mortars during building are widespread in churches of western France, and that used in Brittany tends to be more resistant than the granite building material. Therefore these protruding slate wedges can be used to assess rates of granite stone recession since the 15th century, though they only provide minimum rates for they are commonly affected by flaking (see Fig. 58 in PARIS, 1998, and Fig. 2a in SELLIER, 1998). In the Massif Central, wedges are of 11-12th century broken tile except for the Saint-Pierre church of Souvigny, where slate wedges were used.

More resistant stones

The polychrome Romanesque churches of the Massif Central display many examples of resistant building materials, providing reference surfaces to assess rates of stone recession in less resistant lithologies such as sandstones. Among these resistant stones are such magmatic rocks as leucocratic granite, basalt and trachyandesite, and some sedimentary materials as siliceous nodules or recrystallized layers in limestone, laterite and brick. This last material is more resistant than chlorite-rich granite in the Massif Central (e.g. in the Merovingian wall at Neris-les-Bains) and the volcanic tuffs in Roman sites like Herculaneum and Pompeii. In Brittany, building stone materials are less diversified. Most Mediaeval and later churches are made of granite, which displays protruding quartz and feldspar veins or phenocrysts, that can be used to reconstruct the initial stone surface; of special interest are the remnants of vein walls many of which have remained intact since granite extraction (PARIS, 1998; SELLIER, 1998; MAGRÉ, 1999; MAGRÉ et al., 2007).

Although resistant rock types do not provide as precise reference surfaces as do dressing marks, they are frequently considered as particularly reliable when reconstructing the position of the original stone surface (e.g. WINKLER, 1986). However, as they have been subjected to scaling, the measurements of stone recession made should be regarded as providing minimum values.

RECONSTRUCTING THE *TEMPO* OF STONE DECAY: THE DIACHRONOUS AND HETEROCHRONOUS APPROACH

Average rates of stone recession expressed in millimetres per century or millennium are relevant for comparison purposes between different lithologies or environments, but the mean values derived pertain to a suite of weathering processes and frequently mask the non-linear nature of weathering rates over time (POPE et al., 2002). At the centennial to millennial scales, previous weathering studies have suggested constant rates over time (e.g. PETUSKEY et al., 1995; MOTTERSHEAD, 1997), decreasing rates (e.g. WINKLER, 1973; MATSUKURA and MATSUOKA, 1991; ROBINSON AND WILLIAMS, 1996, see Fig. 6A; MAGRÉ, 1999), and increasing rates (e.g. KLEIN, 1984; NEIL, 1989; WELLS et al., 2008). In fact, it seems that nonlinearity prevails in stone decay/rock weathering systems, which operate in an episodic rather than gradual mode, in a 'stepwise' fashion; brief decay episodes follow the crossing of thresholds associated with intrinsic or extrinsic variables, separated by often prolonged intervening periods of relative or apparent quiescence (SMITH et al., 1992, 1994; cf. figure 5). Extrinsic triggering factors of accelerated decay can be climatic (e.g. severe frost) or anthropogenic (e.g. stone cleaning). In some instances, building stone materials suffer catastrophic decay, and conceptual models of such decay have been recently proposed for sandstone and limestone (SMITH AND VILES, 2006). It has even been suggested that stone decay is an erratic, random or chaotic process (e.g. ROBINSON and WILLIAMS, 1996; VILES, 2005).
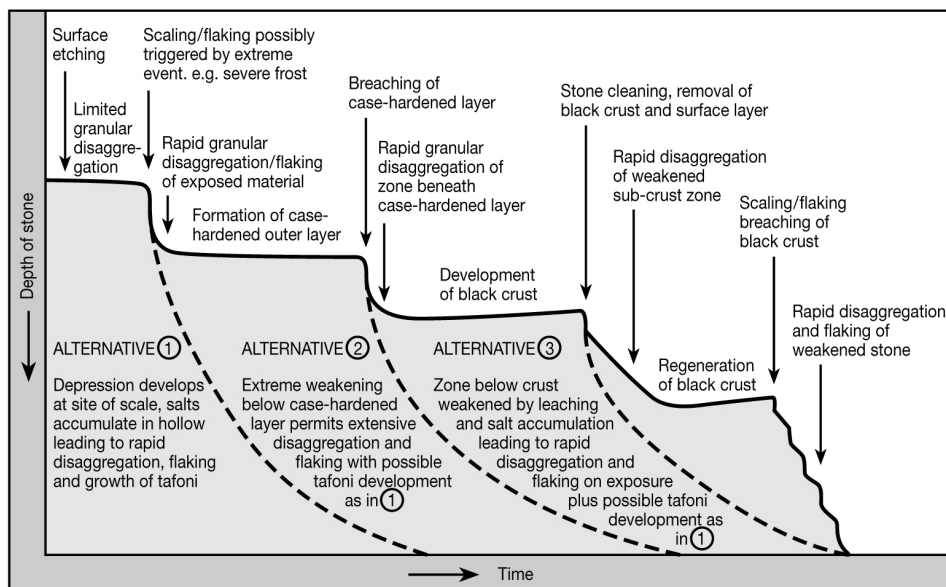
Fig. 5. Stone decay: a pulsatory process (SMITH et al. 1994).

Addressing the episodicity of stone decay calls for research strategies extending back in time. Anamnesis (FITZNER et al., 1992), inheritance effects (WARKE, 1994), the history of monuments, building materials, and their environment are considered essential in the assessment of present-day stone decay. In Mediaeval monuments, the episodicity of stone recession can be investigated using diachronic photogrammetry, stepped datum surfaces, and comparative studies of stone recession in younger and older monuments in similar lithologies as those found in Mediaeval constructions.

Diachronous photogrammetry

The value of historical photographs as a means of documenting the extent and timing of stone decay have been illustrated in many studies (e.g. VILES, 1993). Time se-quences of old photographs have been used by INKPEN et al. (2001) to plot changes in the extent of weathering forms on an Oxford building over the 1892-1932 period. The abundance and relevance of documentation for Mediaeval monuments of the Massif Central varies. A long search can be necessary, both at the national and local levels, to discover key illustrations. On the other hand, there is an abundant iconographic documentation covering the last century for Khmer temples, due to the conservation and restoration work carried out by the *Ecole Française d'Extrême-Orient* and the *Conservation d'Angkor*. For example, just for the 1930s, some 5300 photographs document the deterioration of the Angkor monuments and the conservation and restoration operations (POTTIER, 2008). However, the crucial archival documents are held by various research centres, museums and private col-

lections, and a methodical and determined photographic hunt is needed. For example, figure 6 documents the formation and development of an 'erosion' scar during at least six scaling episodes over the 1905-2006 period, on a toric rib of Ta Keo temple. More extensive photogrammetry being undertaken on the sculpted facings of the central pyramid of this temple-mountain, is based on integra-

tion of orthorectified photographs with the MapInfo GIS (ANDRÉ et al., 2008). This diachronic approach is useful both in the reconstruction of the calendar of decay and in the tentative prediction of future damage, or at least the delineation of risk zones (based on scenarios of degradation, which differ according to the sculpted levels).
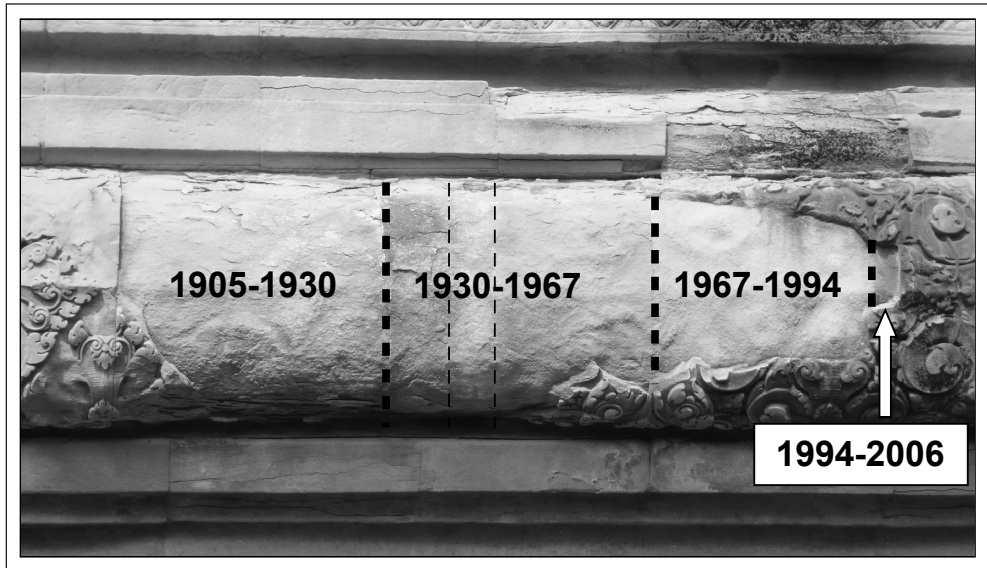

Fig. 6. Scenario of formation and development of an 'erosion' scar on an ornamented sandstone toric rib, reconstructed after a collection of old photographs (first tier of the eastern face of the central pyramid of Ta Keo temple, early 11th century, 19-3-08). © M.-F. André

Stepped datum surfaces

In Romanesque and Gothic churches, two generations of zero-datum levels are often present on the stone facings: one dating back to the Middle Ages, the other to the 19th or 20th century. The old datum consists either of Mediaeval stone-dressing marks or masons' marks, or of resistant protruding stones or nodules, or of carved elements, whereas the recent one generally consists

of Portland cement joints (see Fig 55 in PARIS, 1998, p. 96). These heterochronous datum surfaces can be used to discriminate the 'modern' (i.e. post-repointing) stone recession depth from the previous one (i.e. pre-repointing). Preliminary observations by PARIS (1998) in Brittany and by the authors in the Massif Central suggest accelerated weathering rates in the last 150 years, that are possibly a consequence of the Portland cement repointing, although

atmospheric pollution may also have played a role in the accelerated stone decay seen in Rodez's Cathedral.

Comparison of stone recession depths in heterochronous monuments

In Brittany, SELLIER (1998) and MA-GRÉ (1999) have collected data on rates of granite weathering on heterochronous monuments such as 500 yr-old churches and 5000 yr-old megaliths. As a result, MAGRÉ (1999, p. 109) suggests that weathering was more rapid in the first centuries, and then slowed down, possibly because the deeper the weathering proceeds the more sound the stone is. Interestingly, SELLIER (2007) has also described substitutions of weathering forms over time in the granite of Brittany.

In England, ROBINSON and WIL-LIAMS (1996) have investigated hetero-chronous Wealden sandstone churches and question the significance of the resulting curve (figure 7). This suggests either a gradual decrease of decay due to the formation of protective crusts or patinas over time, or a contemporary acceleration of decay, possibly due to pollution and acid deposition. Such an acceleration is also suggested by BONNEAU (2001) in a preliminary study on the Romanesque and Neo-romanesque sandstone churches of the French Massif Central.
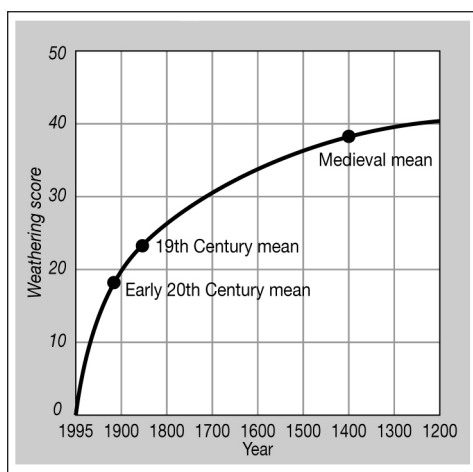

Fig. 7. Graph showing mean weathering scores for churches of different ages in Hastings Beds sandstones of central Weald, SE England (ROBINSON and WILLIAMS, 1996, Fig. 12.7 p. 144).

INVESTIGATING SOME CAUSES OF ACCELERATED STONE DECAY

Accelerated stone decay of cultural stone is due to a suite of weathering processes resulting from the interplay of various extrinsic and intrinsic factors. For instance, in Strasburg's cathedral (France) the contemporary accelerated decay observed in the second half of the 20th century is due to the disastrous impact of air pollution on the calcium-rich building sandstone, and the recent improvement of the situation is due both to the reduction of air pollution and the replacement of calcium-rich sandstones ('grès à meules') by calcium-free sandstones ('grès vosgien').

Intrinsic causes: low durability of stone

There is a persistent contemporary trend to emphasize the role of external factors such as environmental stress in accelerated stone decay. However, a recent assessment of 112 Irish monuments under the auspices of the Heritage Council points to stone properties as the main control on stone decay: 'Only in aggressive polluted atmospheres is the environment more determinant on the type and rate of decay than the nature of the stone itself' (PAVIA and BOLTON, 2001).

The 'durability' of a stone, which is defined as 'a measure of its ability to resist weathering' (BELL, 1993), is a complex phenomenon. The significance and relevance of this term have been extensively discussed in the literature (see review in INKPEN et al., 2004). CARR et al. (1996) have suggested that proven use over time is the best test of durability. It is therefore of interest to try and evaluate the behaviour over time of various building stones by carrying out on-site comparative studies of stone recession in a given environment. Such field studies, which should take into account the history of the monument, are complemented by laboratory simulations.

Of special interest is the '500 year stone durability trial' carried out by MOTTERSHEAD (2000a) on sixteen coastal defensive structures embracing a wide range of lithologies. Based on measurements of stone recession at selected representative sites, rank ordering of weathering rates values are provided, which suggest controls on high versus low durability (e.g. high quartz and muscovite content versus high feldspar and chlorite content).

The polychrome Romanesque churches of the Massif Central are particularly suitable for comparative measurements of stone recession (figure 8a–8d). These monuments are particularly abundant in the sandstone-rich Brive, Espalion and Limagne basins, which are surrounded by basement rocks and/or limestones or volcanics. Studies are in progress, but as a working hypothesis, the following scale of increasing durability can be suggested (Table 1; see also ANDRÉ et al., 2007b): (1) weak limestones, (2) chlorite/biotite-rich granites, (3) oolitic and bioconstructed limestones, and magmatic rocks such as basalt, trachyandesite and leucocratic granite. The behaviour of sandstones is highly variable, with some arkosic sandstones as the most durable building stones, that display well preserved Mediaeval builder's and dressing marks (Issoire abbey church, Puy-de-Dôme, cf. MOREL, 2003), and some psammitic sandstones as the least resistant (Estivals church, Corrèze, cf. figure 8b). This last example of heavily weathered sandstone is comparable with 'the most severe cases of stone decay' and 'loss of carved detail' reported from the recent assessment of sandstone Irish monuments (PAVIA and BOLTON, 2001).
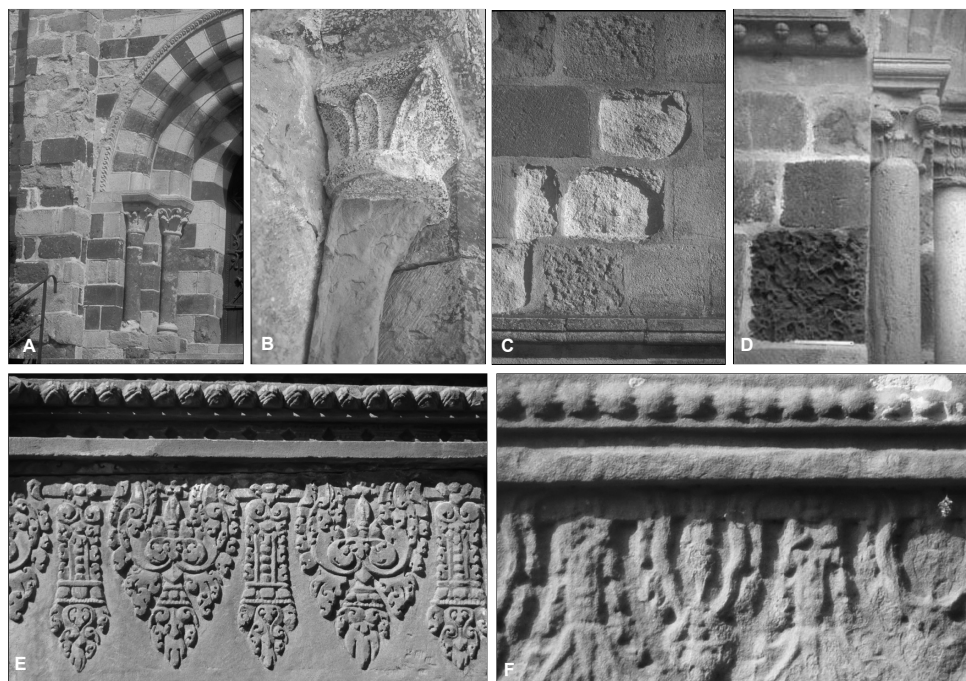
Fig. 8. Selective weathering in Mediaeval monuments: examples from Massif Central churches and Angkor temples. © M.-F. André

A. Well preserved laterite blocks and decayed light-coloured granites on the left (Saint-Didier church, Saint-Dier-d'Auvergne, Puy-de-Dôme, 22-4-01). B. Well preserved limestone capital and severely decayed psammitic sandstone door jamb (Saint-Barthélémy church, Estivals, Corrèze, 16-6-00). C. Well preserved iron-rich sandstones and decayed white sandstones (Saint-Prejet church, Malicorne, Allier, 10-1-01). D. Enigmatic alveolized reddish sandstone block (Saint-Jacques-le-Majeur church, Villefranche-d'Allier, Allier, 10-1-01). E. Well preserved decorative pattern in pink sandstone (Banteay Srei temple, 10th century, 7-12-08). F. Decayed decorative pattern in grey sandstone (East Mebon temple, 10th century, 7-12-08).

In the French Massif Central, the highly variable durability of sandstones stimulated an ongoing study carried out in the Limagne Basin north and south of Clermont-Ferrand to investigate the main controls of sandstone decay in similar environmental conditions. At first glance, the nature of the cement seems to be crucial for high or low durability (e.g. siliceous/ferruginous versus argillaceous/calcitic cements). The presence or abundance of certain minerals (e.g. bi-otite, glauconite) is also involved in the decay. Grain size is not as important as other textural characteristics and mineralogy, but it is not uncommon to observe fine-grained sandstones that are more decayed than coarse equivalents. Similar observations have been made on granite in west Wicklow (Ireland), where the finely textured granite of the Mediaeval Baltinglas Abbey is much more severely affected by stone decay than the coarser grained granite at the Early

Bronze Age Athgreany stone circle to the north of Baltinglas (PAVIA and BOLTON, 2001). Similarly, in nordic environments, granite weathering rates are known to be primarily controlled by the biotite content, with pegmatite veins lacking biotite being more resistant than fine-grained granite (e.g. ANDRÉ, 1995). The only example of grain size influencing stone decay in the Massif Central is found in conglomeratic sandstones, with accelerated decay due to the detachment of gravels (e.g. Charroux church, Allier). Documentation on the monument history can be crucial to interpret properly contrasting patterns and rates of weathering between different sandstones. For instance, in figure 8d, the selective weathering between white and darker sandstones corresponds to concomitant decay, whereas in figure 8d, the alveolized stone might have been incorporated just as it is during restoration, and the honeycombing being an inherited feature.

In Cambodia, the opportunities to quantify differential weathering on a single monument are rare, for most Khmer temples are made of a unique sandstone type. However, it is of interest to compare the states of preservation of similar decorative patterns in monuments of the same date but of differing lithotypes (figures 8e and 8f).

Extrinsic causes: environmental and anthropogenic stresses

The variety of environmental stresses conducive to decay has been examined in previous studies (e.g. WARKE, 1996). There is no doubt that enhanced temperature/humidity fluctuations (both in magnitude and frequency) can trigger or accelerate stone deterioration. The influence of pollution has also been extensively studied (e.g. BRIM-BLECOMBE, 2003), but other controls call for further investigation, and with regard to the cultural heritage of rural and 'natural' areas, for instance the impact of forest clearing and tourism pressure in Cambodia, the maintenance and restoration procedures in France, and the stone processing in both countries.

Impact of forest clearing on stone decay in Khmer temples

Following an exploratory survey of 17 Angkor temples (ANDRÉ, 2006), the main objective of the ongoing Ta Keo research project is to assess the pre- and post-clearing rates of stone decay on the central pyramid of this temple-mountain (ANDRÉ et al., 2007a). Ta Keo temple has remained practically untouched since building (c. 1000 A.D.). It was surrounded by forest for some five centuries before the forest clearing of the 1920s. The history of the contemporary stone decay at the surface of its sandstone facings is documented by photographs covering the period 1905-2008 (figure 6). Therefore, it provides a rare opportunity to evaluate the impact of recent forest clearance on stone decay. Various sampling strategies were developed to assess weathering rates, based on a combination of methods such as photogrammetry, laser scanning and manual measurements of stone recession. Comparisons were made with Ta Nei, a neighbouring temple still located in a forested environment (figure 9), regarding both the state of deterioration of similar decorative patterns and the climatic conditions (meteorological monitoring in progress). The first results point to a contemporary acceleration of stone decay, with the area of deteriorated surfaces having tripled between 1963 and 2008 on the investigated test-zone

(ANDRÉ et al., 2008). Touristic pressure has been shown to be an accelerating factor of stone decay at world heritage sites (e.g. in Petra, Jordan; see PARADISE, 2005). No doubt that it has played a role in Angkor since the 2000s, but at Ta Keo temple, apart from some obvious anthropogenic impacts, it is at this stage difficult to discriminate the role of direct human impact from that of the consequences of forest clearing.

Fig. 9. Forested environment at Ta Nei temple (A) and non forested environment at Ta Keo temple, cleared from the forest in the 1920s (B). © M.-F. André (left: 8-12-08; right: 4-12-08).

Influence of conservation and restoration measures in European Mediaeval monuments

Restoration campaigns have flourished in Europe over the last two centuries, and the negative effects of some restoration practices were adversely criticised early on (e.g. in France in the 1830s Prosper Mérimée and Charles de Montalembert denounced 'vandalism' in restorations as well as in destructions). Among the restoration/conservation measures, it seems of particular interest to investigate the effects on stone decay of Portland cement repointing and cleaning methods which have taken place between the mid-19th and the mid-20th century.

Portland cement repointing

In the Middle Ages, the builders of the Romanesque churches had found various solutions to ensure the ventilation and drainage of masonry stones, such as the use of putlog holes across the walls and of porous lime mortars for jointing (PHALIP, 2001; PHALIP and ANDRÉ, 2008). The

introduction of watertight Portland cement and the blocking of putlog holes (figure 10) caused drastic changes in the water balance and the chemistry of masonry stones (e.g. HERNÁNDEZ, BALLESTEROS AND ARNAU, 1993). They caused accelerated granular disintegration (e.g. GRUNAU, 1971; COLLOMBET, 1989). In rural areas of the Massif Central, the most severe damage occurred from the end of the 19th century to the middle of the 20th, due to the replacement of lime mortars by cement mortars, e.g. on Saint-Nectaire church, Puy-de-Dôme (PHALIP and ANDRÉ, 2008). In Brittany, measurements on nine granite churches located in non polluted environments suggest that post-repointing weather-ing rates are three times faster than pre-repointing rates (PARIS, 1998). The acceleration of stone decay in rural areas of Ireland has been blamed on repointing, 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). In the Massif Central, preliminary studies suggest that post-repointing weathering rates are two to three times faster than pre-repointing rates, but in churches located in urban areas, it is difficult to distinguish the responsibility of repointing itself from the one of pollution.
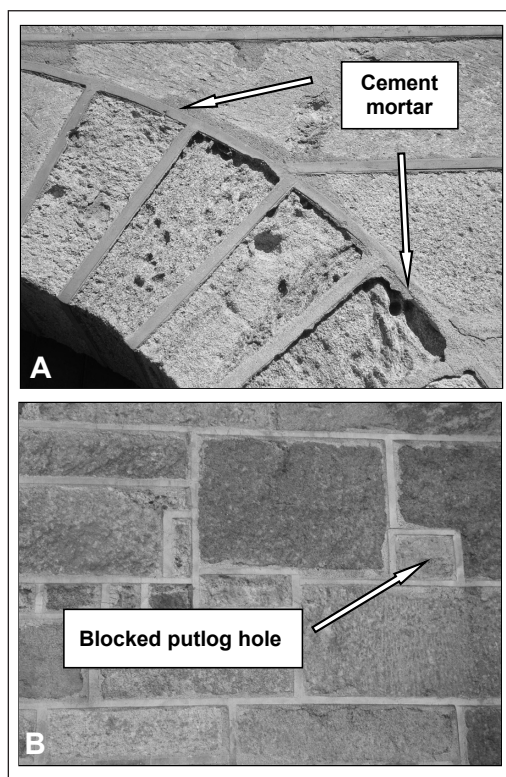

Fig. 10. Repointing with cement mortar and obturation of putlog hogs: a widespread practice between 1860 and 1950 in the Mediaeval churches of the French Massif Central. Examples are from two Puy-de-Dôme abbey churches: Saint-Sébastien of Manglieu (A) and Saint-Austremoine of Issoire (B). © N. Duracka / M.-F. André.

Cleaning methods

Cleaning and resurfacing can destroy crusts and patinas (biogenic or not), which act as a natural protection against rainfall dissolution, wind abrasion, atmospheric pollution and salt weathering. Such effects have been demonstrated in the British Isles, in the late 1980s in Scotland (WEBSTER, 1992) and in the late 1990s in Ireland, where the rate of particle removal by lichens is lower than the one by the atmospheric agents, especially in the exposed environments of the west coast (PAVIA and BOLTON, 2001). In France, the acceleration of stone decay during and after cleaning operations has been recognised, mostly based on qualitative observations. For example, on Brittany granite churches affected by scaling, the systematic removal of scales during 'conservation' operations is evidently common practice (MAGRÉ et al., 2007). Unfortunately it induces a much faster rate of decay than previous biogenic granular disintegration due to lichen colonization. Repeated short range laser scanning of test-zones would be helpful in the evaluation of the short term and long term impact of various cleaning procedures on a range of lithologies. But at this stage, despite recent progress, the implementation of such standardized procedures is somewhat difficult due to institutional barriers.

Role of inheritance effects related to stone processing: from quarrying to carving

The importance of inheritance effects in patterns and rates of stone decay have been emphasized by WARKE (e.g. WARKE 1994, 1996), and recently investigated by McCABE et al. (2007b), based partly on laboratory simulations. Among the wide range of inheritance effects, stone processing was identified long ago as a major control on patterns and rates of stone decay (e.g. SCHAFFER, 1932). Quarrying, dressing and carving of stone can induce or reveal structural weaknesses in the building stone material. For example, the use of explosives for stone extraction and of bush hammers for stone dressing can induce macrofracturing or microcracking, paving the way to further weathering processes. Of course, the sensitivity of stone to such operations depends on its inherent properties. The impact of the Mediaeval and recent stonemasonry techniques on European monuments deserves further investigations, as does the mode of incorporation of stones into the structure. For instance, checked weathering patterns in Romanesque churches are frequently linked with the alternating placement of stones in parallel and perpendicular to bedding planes (e.g. in the Escurolles church, Allier – see photo 52 in BONNEAU, 2001 p. 117). In Cambodia, accelerated decay due to vertical stone placement is widespread at the base of pillars in the Angkor Wat galleries (ANDRÉ, 2006). The unfinished Ta Keo temple offers exceptional conditions whereby to assess the role of stone processing in the amount and forms of stone decay, and comparative studies of dressed, moulded and delicately ornamented sandstones are in progress (figure 11).
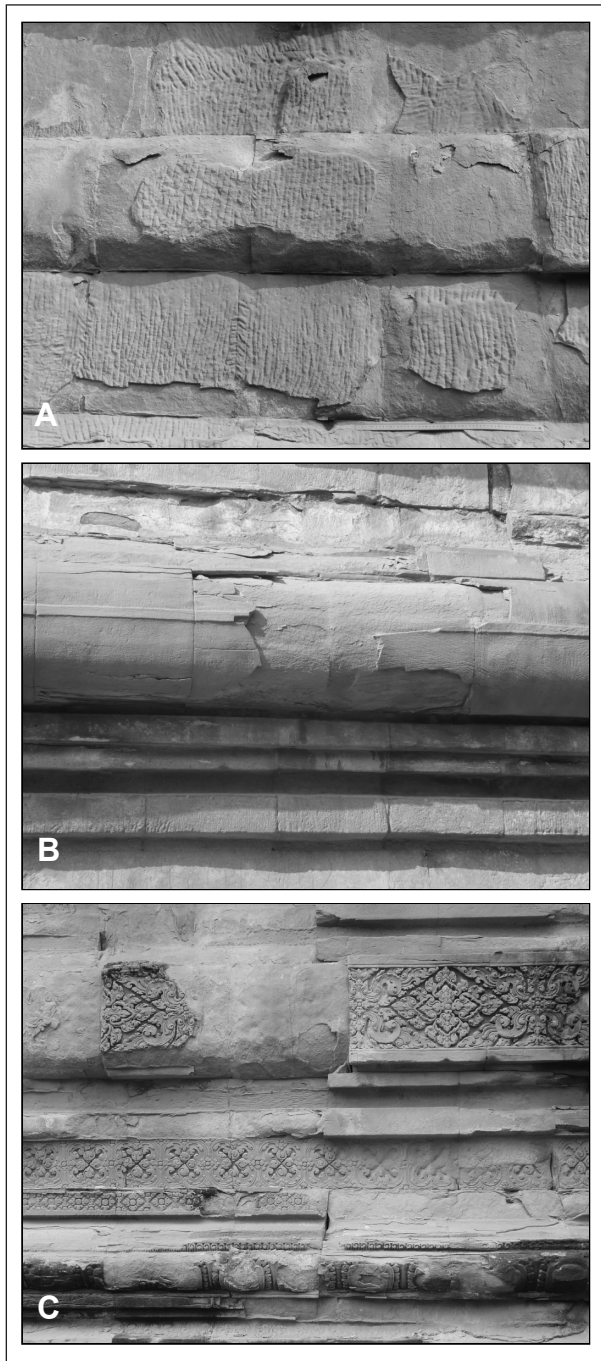
Fig. 11. Three types of stone finish on sandstone facings of the central pyramid of Ta Keo temple, Angkor. © M.-F. André.

A. Rough-hewed stones. B. Moulded stones. C. Chiselled stones.

CONCLUSIONS

Stone decay is a particularly exciting topic for geomorphologists because it provides opportunities to address a range of fundamental questions such as: (1) the rhythm of weathering and erosion, (2) the process/form linkages, (3) the interplay between intrinsic and extrinsic controls, (4) the importance of microenvironmental conditions, (5) the evaluation of the human impact, and (6) the assessment of the destructive versus the protective role played by living organisms. Working on cultural stone encourages the 'cross-pollination of ideas' between disciplines (POPE et al., 2002, p. 215). There is a crucial need for further cooperation with archaeologists of the Mediaeval period, who have developed specific methods for understanding the multiphase history of monuments, and with stonemasons, who have a highly valuable practical experience and documentation (e.g. CONNIER, 2000; see figure 12). This is necessary in order to ensure the reliability and validity of stone decay assessments carried out by geomorphologists, who while pursuing their own objectives, share their views with archaeologists, and provide data to contribute to the determination of conservation strategies. Informal interdisciplinary cooperations and institutional research groups such as the Oxford Preserving Our Past research cluster (that includes fields ranging from synchrotron radiation applications to video art), are crucial for further progress in the assessment of stone decay rates.
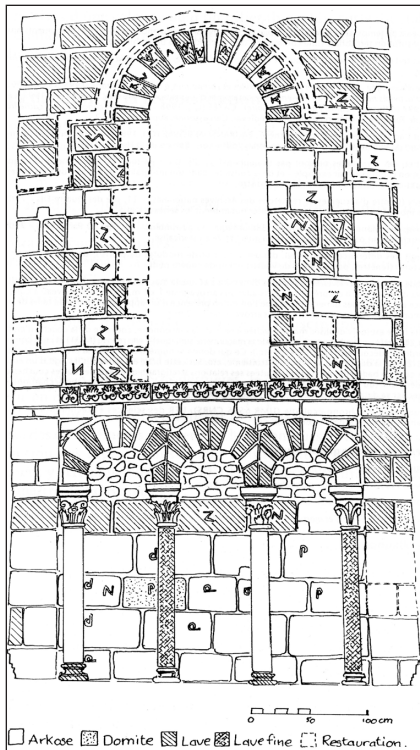

Fig. 12. Stone by stone mapping of the axial ambulatory window of Chamalières church, Puy-de-Dôme, by Yves Connier, stonemason (CONNIER, 2000, Fig. 1 p. 266).

Domite = Puy-de-Dôme trachyte; Lave = Vesicular lava; Lave fine = Close-grained lava; Restauration = Restoration.

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Appendix: Glossary of Mediaeval architecture

APSIDIOLE. Small apsidal chapel, especially one projecting from an apse.

ARCHIVOLT. Bands or mouldings surrounding an arched opening.

CAPITAL. Decorative element that divides a column or pier from the masonry which it supports.

LINTEL. Horizontal beam spanning an opening, as over a door or portal.

MODILLION. Ornamental bracket used in series under a cornice.

PUTLOG HOLE. Hole left in a masonry wall to provide support for a horizontal framing member of scaffolding.

STELE. Upright stone or slab with an inscribed or sculptured surface.

TYMPANUM. Area above a door enclosed by an arch and a lintel, frequently decorated with relief sculpture (e.g. Christ in majesty and Judgment day).