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QUANTITATIVE ASSESSMENT OF PRE- AND POST-RESTORATION WEATHERING RATES OF LIMESTONE MAYAN TEMPLES (UXMAL, YUCATAN)

ABSTRACT: ROUSSEL E. & ANDRÉ M.-F., *Quantitative assessment of pre- and post-restoration weathering rates of limestone Mayan temples (Uxmal, Yucatán)*. (IT ISSN 0391-9838, 2013).

The House of Turtles is one of the Mayan buildings of the Uxmal site in Yucatan. It has been erected during the Terminal Classic Period (AD 890-915), abandoned around AD 1050, and restored between 1969 and 1972. This monument was selected to quantitatively assess the impact of contemporary restoration practices on limestone weathering. Based on archival research and multi-scale photogrammetric surveys, weathering rates were calculated for two periods, covering respectively almost 1000 years (1050-2012) and 50 years (1972-2012). Whatever the spatial scale, whatever the construction choice, post-restoration weathering rates are systematically faster long-term rates: at the scale of the whole façade, stone recession has operated 38 times faster since restoration than on non-restored historical parts of the building (7.6 mm instead of 0.2 mm per century). This general trend is ascribed to the removal of the stucco coating that has protected limestone and delayed deterioration from the Mayan building times until the contemporary clearing and restoration operations. Another factor responsible for accelerated limestone decay is the replacement of wooden lintels by cement lintels, as indicated by the spatial distribution of deterioration hotspots on the façade and by the computed weathering rates obtained for six fine-scale windows taking into account the construction/restoration choices. This quantitative assessment leads to emphasise the need for softer, less intrusive restoration practices and conservation strategies, that should restrict the use of incompatible materials like cement and reinforced concrete, and consider stucco as a protective skin worth being maintained.

KEY WORDS: Rock weathering, Decay assessment, Limestone, Cultural heritage, Conservation strategies, Maya architecture, Yucatán.

CONTEXT AND OBJECTIVES

The singular and irreplaceable value of temples and other ancient buildings is nowadays fully acknowledged, and many monuments have been inscribed by UNESCO on the list of World Heritage Sites (WHS). Appropriate conservation and management strategies are being defined and implemented in order both to preserve this fragile cultural heritage and to open the sites to the public. In this context, the community of geomorphologists has been involved in recent years in the assessment of weathering damages (Pope & *alii*, 2002; Turkington & Paradise, 2005). Many researchers report an overall aggravation of damage since the 19-20th centuries, and pollution has first been blamed as the main driver of accelerated stone decay, due to enhanced salt weathering related to sulfur dioxide emissions (see review in Brimblecombe, 2003, and Watt & *alii*, 2009). In the 2000s, the deleterious effects of four other types of human interventions on the buildings and their environment have been demonstrated. They include: (i) the climatic stress induced by forest clear-cutting around the monuments (André & *alii*, 2012); (ii) the direct impact of touristic frequentation (Paradise, 2005; Honeyborne, 2011); (iii) the use of abrasive or corrosive techniques of stone cleaning (Young & *alii*, 2003); and (iv) the incorporation of incompatible materials such as cement mortar during restoration operations (Quist, 2009; Phalip & *alii*, 2012).

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At the Maya site of Uxmal in Yucatan, which is the focus of the present study, this potential impact of restoration practices on stone deterioration deserves specific investigations for this site has undergone restoration operations from the late 1920s onward. The major restoration campaigns have been coordinated and supervised by INAH (Instituto Nacional de Antropologia e Historia) since its foundation in 1939. The complex history of restorations at Uxmal is well documented (*e.g.*, Sáenz Vargas, 1969; Maldonado, 1981; Barrera, 1987). Both Molina-Montes (1975, 1982) and Schávelzon (1990) emphasise the shift in restoration philosophies and practices that has occurred in the late 1970s. Indeed, the period from the 1940s to the early 1970s had been characterised by important interventions including massive reconstructions; for Molina-Montes (1975, p. 71), «*The pyramid of the Magician [at Uxmal] is a brand new wedding cake that has lost much of its authenticity*». Following benchmark meetings held in Mexico in 1973 and 1974, new restoration practices have been promoted, which are in conformity with the Venice Chart (Diaz-Berrio, 2004); at Uxmal, the anastylosis of the ballcourt by INAH in 1977-1978 is emblematic of the application of these international standards preserving the authenticity of the materials (Maldonado, 1981).

The present contribution deals with the «House of the Turtles», another of the Uxmal monuments, which displays both original parts dating back to the early 900s and restored parts dating back to the early 1970s, all made of the same limestone. It provides the opportunity to quantitatively compare the recent (post-restoration) stone degradation to the long-term historical stone deterioration, and to study the effects of construction choices on decay rates. Based on historical research, field observations and multiscale photogrammetric analysis, the objectives of the present study are threefold: (i) to compare the pre- and post-restoration weathering rates; (ii) to compare the weathering rates depending on different construction choices; and (iii) to identify the drivers of both accelerated and delayed weathering, with potential implications for future conservation strategies.

STUDY AREA

Uxmal is a Late Classic Mayan site located in the Northern Yucatán peninsula, 78 km south of Merida (fig. 1A). In this tropical environment, the average annual temperature is 25.4 °C and the amount of precipitation is 1155 mm, with the wet season extending from May to October. The whole site covers about 60 ha and includes architectural complexes and single monuments associating vertical pyramids and flat buildings (fig. 1B). The monuments of Uxmal region have been extensively excavated, studied and restored (*e.g.*, Sáenz Vargas, 1969; Barrera, 1987; Huchim Herrera & Hernández, 1998; Michelet & *alii*, 2000; Grube, 2007). In 1996, Uxmal was inscribed by UNESCO on the list of WHS, together with the nearby Puuc sites of Kabah, Labna and Sayil.

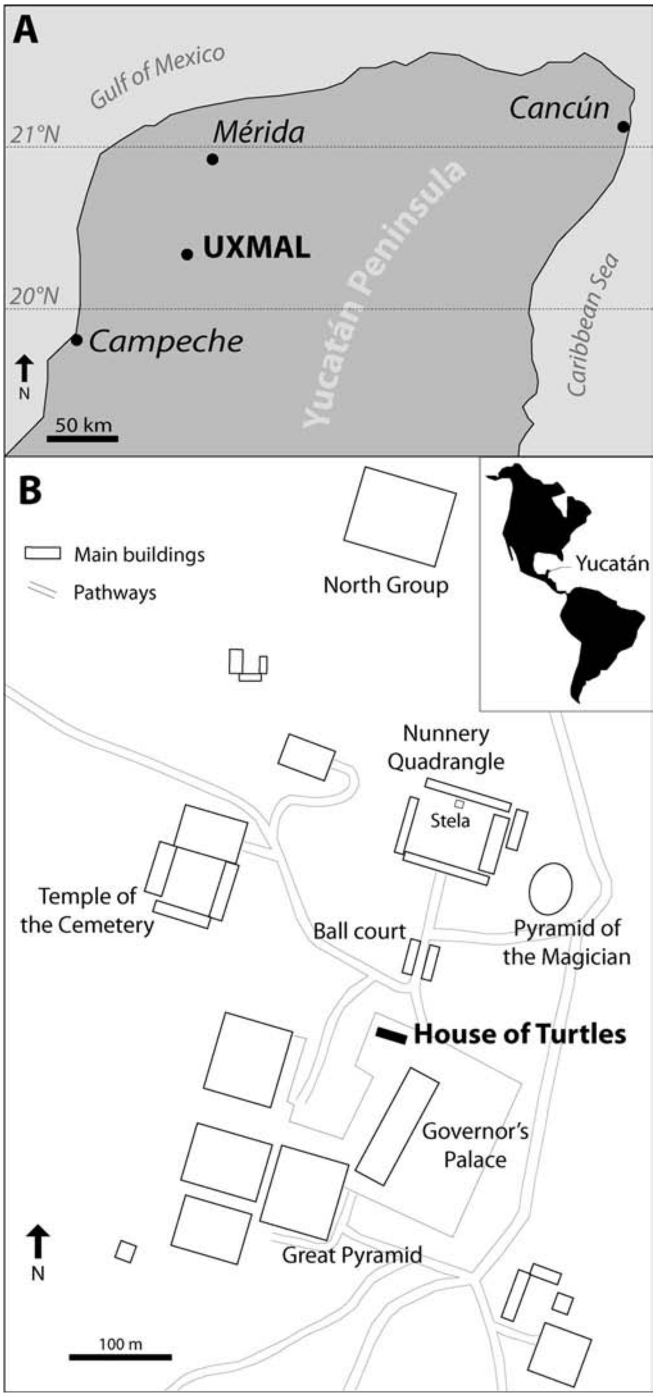

FIG. 1 - Location of Uxmal in the Yucatán peninsula (A) and map of the main buildings of the Uxmal archaeological site (B). The investigated monument appears in bold.

If the Uxmal site includes monuments built between the 6th and the 10th century, the main buildings belong to the Terminal Classic Period (AD 800-950), and more precisely to the period between AD 890 and 915, during the reign of the King Chan Chak K'ak'nal Ajaw. It is the case of the Governor's Palace and the Nunnery Quadrangle (fig. 2), which are typical of the elegant Puuc architectural style. The lower part of the façades displays bare walls with undecorated ashlar blocks separated by doorways, whereas the upper part is characterised by friezes and cornices richly decorated with stone mosaics and masks of the long-nosed God Chac. These monuments are built with local limestone, originally covered with stucco. This stucco layer was made of burnt limestone, fine sand and bark extracts, and often painted in blood red (Littmann, 1959). The Uxmal monuments have been abandoned soon after the city began to decline, when Chichén Itza became the most powerful city of Yucatán. This decline occurred around AD 1050, hence long before the arrival of the conquistadors. From the mid 11th to the early 19th century, the Uxmal monuments have been extensively covered with vegetation: the Franciscan priest Alonso Ponce who visited the site in 1588 described it as completed ruined and densely wooded (Saville, 1921).

The House of Turtles («Casa de las Tortugas») was selected for comparative study for it comprises both original and restored parts. This rectangular building of simple design, 29 m long and 11 m wide, is located behind the Governor's Palace and belongs to the same period (AD 890-915). Its name was inspired in the 1830s to the Franciscan priest Padre Carillo by the row of turtles forming the main decoration of the upper cornice. This building is made of ochre Eocene limestones, either fine-grained or nodular, which display more or less pronounced micro-karst features resulting in pitted if not honeycombed surfaces.

METHODS

Methods used to assess pre- and post-restoration weathering rates at the House of Turtles combine archival research, field observations, photogrammetric surveys and 3-D modelling of weathered surfaces. We followed a methodological workflow which allowed to map the original and restored parts of the south facing wall, based on photogrammetric surveys of the whole façade and geometric correction of the most relevant old photograph (fig. 3). Then, three fine-scale windows were selected in each part (original *vs.* restored) of the south façade for detailed photogrammetric measurements. All the collected and produced data were stored in a GIS software (ArcGIS 10) for further analysis.

Archival research

Documentary search was carried out in order to reconstruct the history of the House of the Turtles from its rediscovery in the 1830s to the Present, and to distinguish the original from the restored parts. Four main sources were used depending on the period: (i) 1839-1841: drawings of the English architect Frederick Catherwood, who visited the Mayan ruins of Yucatan with the American explorer and diplomat John Lloyd Stephens (Catherwood, 1844); (ii) 1859-1860: photographs taken by the French explorer Désiré Charnay (Charnay, 1863; Brunet & *alii*, 2007); (iii) 1913-1957: photographs and documents gathered by the Carnegie Institution of Washington, which sponsored Maya excavations in the Uxmal region; this collection is currently stored at the Peabody Museum in Harvard (http://www.peabody.harvard.edu/col/default.cfm); (iv) 1970-1997: photographs and drawings of the American epigraphist Linda Schele, which are preserved at the Foundation for the Advancement of Mesoamerican Studies (http://research.famsi.org/schele.html). Last but not least, an abundant iconographic and bibliographic documentation was used, which was compiled by the American art historian Charles S. Rhyne (Reed College). It covers the period from the early 19th century onward and is available online (http://academic.reed.edu/uxmal/).

Photogrammetric surveys and mapping of the whole façade

Photogrammetric methods are now recognised as efficient procedures to capture accurate 3-D scenes for

FIG. 2 - View from the south of three famous buildings of the Uxmal archaeological site. From left to right: the Nunnery Quadrangle, the House of Turtles, and the Pyramid of the Magician.

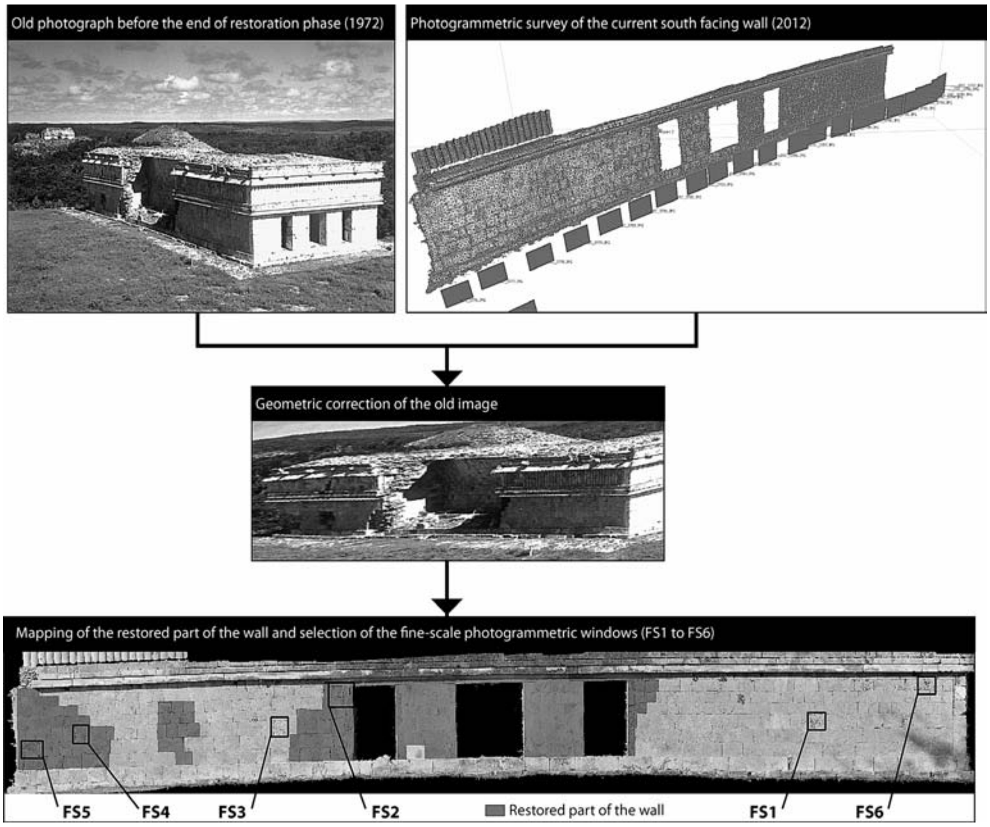

FIG. 3 - Methodological workflow for the delineation of the restored and original parts of the south façade of the House of Turtles and the selection of fine-scale photogrammetric windows.

stone decay assessment (Arias & *alii*, 2007; Vautier & Voldoire, 2011; Calabrò, 2012). Moreover, software based on the so-called SFM (structure from motion) algorithms are widely used in various geoscientific and archaeological settings (Bennett & Evans, 2012; James & Robston, 2012; Fonstad & *alii*, 2013). The 3-D reconstruction of the south-facing wall of the House of Turtles was performed using twenty-four convergent photographs collected in the field. These photographs were compiled in the Agisoft PhotoScan software, which combined SFM sparse points cloud calculation and multi-view stereo-reconstruction (Verhoeven, 2011). Thereby, Photoscan produces a dense coloured point cloud and subsequent 3-D mesh models. As a result, we were able to simplify the model scaling step using only six reference distances measured in the field between twelve fixed markers visible on the 3-D model. Finally, orthophoto and DEM (Digital Elevation Models) of the whole façade with respectively 1 mm and 10 mm pixel resolution were produced and exported to the ArcGIS 10 solution. The precision of the orthophoto and the DEM is about 2 mm (RMSE = 1.92 mm). A spline geometric correction of the digital copy of the old photograph was performed using the ArcGIS georeferencing toolbar and the orthophoto produced with our photogrammetric survey as the reference image. Then, the original and restored sections of the south wall have been mapped using the ArcGIS editing tools (fig. 3).

Selection of six fine-scale windows based on construction choices

Three fine-scale windows (35 x 35 cm) were selected in each delimited section of the south façade (fig. 3). The selection was performed in order to test the effect of similar construction choices on pre- and post-restoration weathering rates (tab. 1). Based on a visual inspection of the south façade of the House of Turtles, three different types of construction choice have been observed: (i) the first type involves the use of nodular limestone as constitutive materials of façade blocks; (ii) the second type is the arrangement of limestone blocks perpendicularly to the natural bedding plane; (iii) the third type is the introduction of heterogeneity in the wall due to incorporation of compact limestone or hard cement. Based on the methods described above, a photogrammetric survey of each fine-scale window has been performed. Subsequent orthophotos and DEMs for each fine-scale window were produced with a pixel resolution and precision of 1 mm.

TABLE 1 - Types of construction choices and corresponding fine-scale windows on restored and original parts of the south façade of the House of Turtles

	Fine scale windows	
Type of construction choice	*Original wall*	*Restored wall*
(i) Using nodular limestone	FS1	FS5
(ii) Positioning limestone blocks vertically *(perpendicularly to natural bedding)*	FS6	FS4
(iii) Creating heterogeneity in masonry *(by incorporating hard stone and/or cement)*	FS3	FS2

Calculation of stone recession models

Tooling marks and hard points observed on the wall were used to reconstruct the reference surfaces («zero datum levels») used as baselines to quantitatively assess the amount of stone decay since monument building and restoration (André & Phalip, 2010). These key points were marked with stickers in the field and mapped afterward on the façade orthophoto and DEM using ArcGIS editing tools. Then, the points were interpolated with the ArcGIS 3-D analyst toolbox in order to reconstruct the zero-datum level surface in ArcGis. More precisely, a linear interpolation was performed for the reference surface reconstruction of the fine-scale windows whereas the spline interpolation method was selected at the façade scale in order to ensure a best fitting of the stone alignment. For the whole façade and each fine-scale window, the stone recession model was computed as the results of the DEM raster subtracted from the reference surface raster.

RESULTS

History of the edifice

Based on archival research on the House of Turtles, it was established that the central part of the south-facing wall had collapsed between 1839 and 1842, during Stephens and Catherwood's expeditions, possibly due to a seismic event. Catherwood reports that «*In 1839, it was trembling and tottering, and by 1842, the whole of the centre had fallen in, and the interior was blocked up with the ruins of the fallen roof*» (Catherwood, 1844, quoted by Bourbon, 1999, p. 81). The collapsed section, half-covered with vegetation, is featured on one of Catherwood's drawings, as on a digital copy of a slide preserved at the Division of Anthropology of the American Museum of Natural History of New York (http://academic.reed.edu/uxmal/galleries/Mid/Uxmal/Turtles/Uxmal-Turtles.htm). This photograph was taken by E. Segarra just before the restoration of the façade, which occurred between 1969 and 1972. Schávelzon (1990) estimates that about 70% of the limestone blocks of the House of Turtles were replaced during this massive restoration operation, including the missing central sections and much of the interior. The finding of Segarra's photo was crucial to distinguish the original from the restored parts of the investigated south-facing wall.

Weathering diagnosis at the façade scale

Stone recession models have been produced for the original and the restored sections of the south façade of the House of Turtles (fig. 4). According to these models, the restored part of the façade is spatially more affected by stone recession than the original part. Indeed, 61.64% of the restored façade have been eroded (stone recession value > 0 mm) since the 1969-1972 restoration period, whereas only 54.67% of the original façade seems to have been affected by stone recession since the early 900s, *i.e.* over more than one millennium. More precisely, taking into account the precision of the stone recession models (2 mm), 44.65% and 31.11% respectively of the restored and original façade sections have undergone a stone recession above the model uncertainty. The spatial pattern of stone recession on the original part of the façade seems to be randomly distributed. However, a singular «hotspot» of stone recession located in the middle of the right side of the original wall must be noticed (fig. 4A). On the contrary, the restored wall section shows a spatially organised distribution of stone recession values. Indeed, high values of degradation are recorded in the vicinity of cement lintels (fig. 4B): the contact zones between limestone and cement seem to be preferentially eroded.

Summary statistics of stone recession values and computed weathering rates are presented in tab. 2 and fig. 5. Raw measurements of stone recession have a similar distribution for the original and restored parts of the façade (fig. 5A) despite the higher maximum recession value recorded for the restored section (123.38 mm compared to 47.02 mm). By contrast, the calculation of weathering rates shows significant differences between the two parts. Indeed, the average weathering rate of the restored section of the façade (0.076 mm/a) is about 38 times faster than the original section rates (0.002 mm/a). Similarly, the maximum weathering rate recorded (3.084 mm/a) is 60 times faster for the restored than the original part (0.047 mm/a).

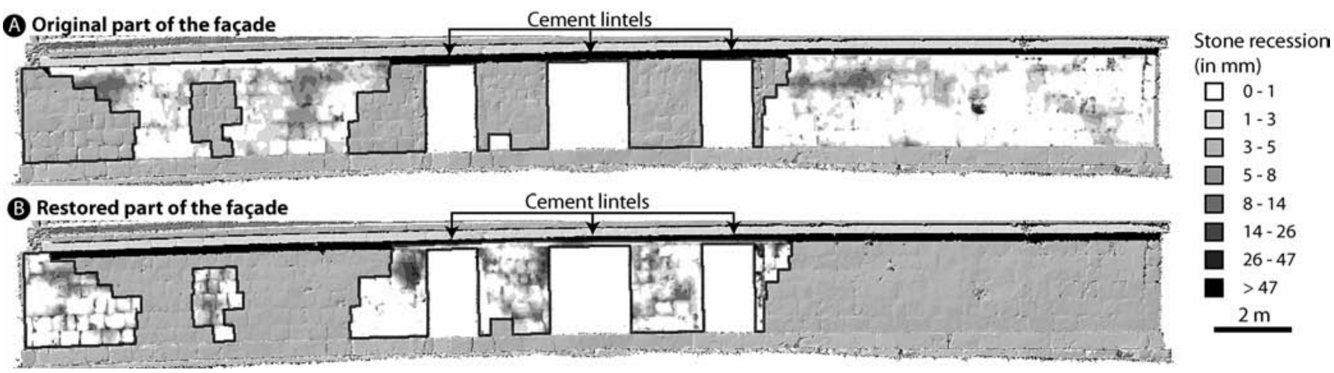

FIG. 4 - Stone recession models of the original (A) and restored (B) parts of the south façade of the House of Turtles.

TABLE 2 - Summary statistics of stone recession measurements (A) and calculated weathering rates (B) of the original and restored parts of the south façade of the House of Turtles

A — STONE RECESSION (in mm)

	N	Minimum	Maximum	Median	Mean	Standard deviations
ORIGINAL	358,930	0	47.02	0.36	1.77	2.84
RESTORED	206,045	0	123.38	1.36	3.06	4.58

B — WEATHERING RATES (in mm/a)

	N	Minimum	Maximum	Median	Mean	Standard deviations
ORIGINAL	358,930	0	0.047	0.000	0.002	0.003
RESTORED	206,045	0	3.084	0.034	0.076	0.114

Weathering diagnosis at the fine-scale

The comparison of the weathering rates of the original and restored parts of the façade was also performed based on the analysis of fine-scale windows. Summary statistics of stone recession values and weathering rates for each window are presented in tab. 3 and fig. 6. This fine-scale analysis shows similar results to the façade scale diagnosis: raw stone recession measurements of the original and restored parts of the façade have a similar distribution (fig. 6A), whereas the calculated weathering rates show highly significant differences between the restored and original parts (fig. 6B). The average weathering rates of the restored section of the façade are 5 to 37 times faster than the ones of the original section (respectively at 0.065 compared to 0.013 mm/a, and 0.113 compared to 0.003 mm/a).

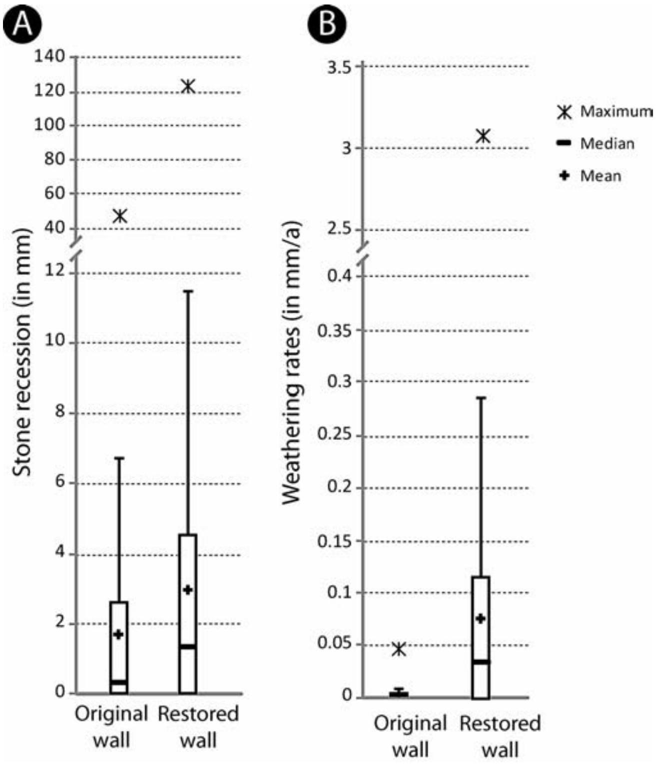

FIG. 5 - Box plots of stone recession measurements (A) and computed weathering rates (B) of the original and restored parts of the south façade of the House of Turtles.

TABLE 3 - Summary statistics of stone recession measurements (A) and calculated weathering rates (B) of the six fine-scale photogrammetric windows of the south façade of the House of Turtles

A — STONE RECESSION (in mm)

	Windows	N	Maximum	Median	Mean	Standard deviation	Skewness (Pearson)	Kurtosis (Pearson)
Original wall	FS1	71,786	53.9	6.3	12.5	14.2	1.20	0.25
	FS3	176,400	26.0	1.0	3.4	4.9	1.77	2.62
	FS6	114,866	44.9	4.0	7.2	8.4	1.96	3.87
Restored wall	FS2	369,672	53.3	1.8	4.5	6.8	2.72	9.72
	FS4	105,248	32.9	0.0	2.6	4.7	2.75	9.40
	FS5	259,554	55.9	0.3	2.9	5.4	3.30	15.11

B — WEATHERING RATES (in mm/a)

	Windows	N	Maximum	Median	Mean	Standard deviation	Skewness (Pearson)	Kurtosis (Pearson)
Original wall	FS1	71,786	0.054	0.006	0.013	0.014	1.20	0.25
	FS3	176,400	0.026	0.001	0.003	0.005	1.77	2.62
	FS6	114,866	0.045	0.004	0.007	0.008	1.96	3.87
Restored wall	FS2	369,672	1.332	0.045	0.113	0.169	2.72	9.72
	FS4	105,248	0.824	0.000	0.065	0.117	2.75	9.40
	FS5	259,554	1.397	0.007	0.072	0.134	3.30	15.11

In the same way, the maximum weathering rates recorded are between 15 to 54 times faster for the restored sections (respectively 0.824 compared to 0.054 mm/a, and 1.397 compared to 0.026 mm/a).

For each fine-scale window, a map of stone recession was produced in order to assess the spatial distribution of degradation values (fig. 7). The spatial pattern of stone recession reflects partially the construction choices. For instance, the vertical lineations observed on windows FS4 and FS6 are related to the upright positioning of limestone blocks, and the right stone of window FS2 seems to be also affected by this erosional form. However, the rest of the fine-scale windows show a similar pattern of stone recession. Severe stone degradation seems to affect preferentially the edges of ashlar blocks. From these degradation «hotspots», the recession values seem to decrease gradually toward the stone centre. In other words, the use of nodular limestone and the introduction of material heterogeneity do not induce distinctive spatial erosional patterns.

Comparison of pre and post-restoration weathering rates according to the type of construction choice

The sampling of fine-scale photogrammetric windows based on similar construction choices on both original and restored sections of the south façade allows to strictly compare pre- and post-restoration weathering rates (fig. 8). Regardless of construction choices, the mean pre-restoration weathering rates are between 5 and 40 times lower than the post-restoration rates. Similarly, the maximum pre-restoration weathering rates recorded are 18 to 50 times lower than the post-restoration rates. We can conclude that whatever the construction type, the post-restoration weathering rates are systematically higher than the pre-restoration weathering rates.

However, the amount of contemporary increase of stone deterioration varies according to the construction choices. Whereas average post-restoration weathering rates are 5 to 10 times faster than pre-restoration rates for both nodular and vertical limestone ashlars, they are almost 38 times faster for heterogeneised materials. Similarly, the maximum rates are 18 to 26 times faster for nodular and vertical blocks, compared to 51 times faster for heterogeneised materials.

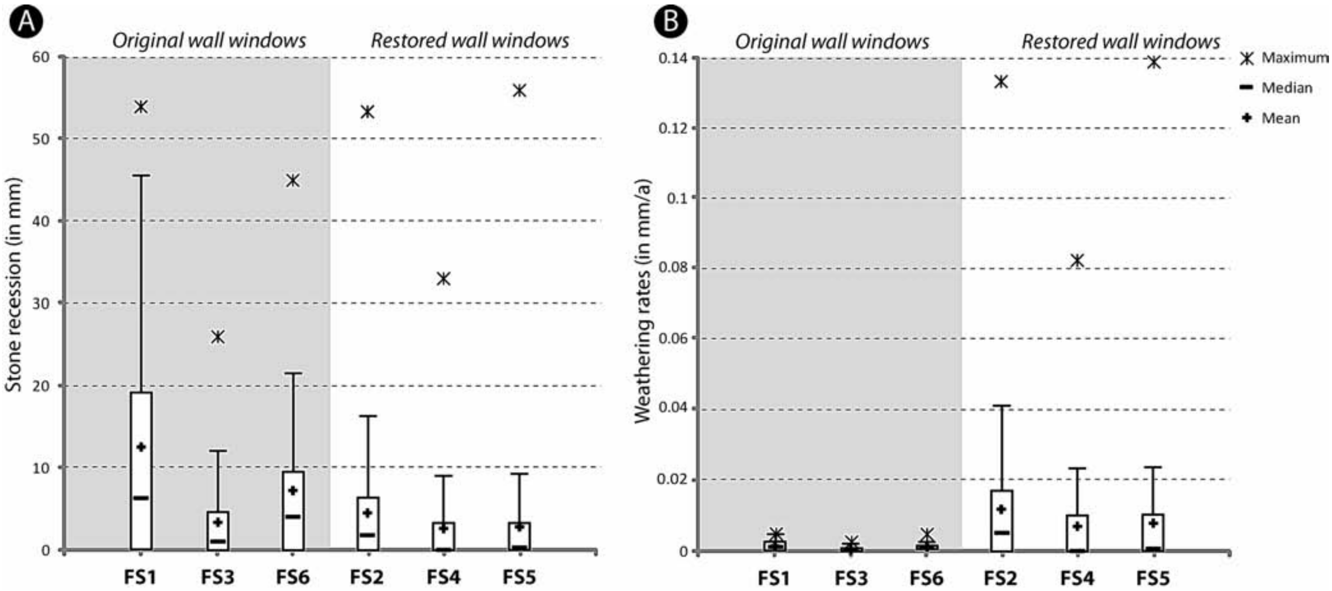

FIG. 6 - Box plots of stone recession measurements (A) and computed weathering rates (B) of the six fine-scale photogrammetric windows of the south façade of the House of Turtles.

INTERPRETATION AND DISCUSSION

The first significant result of the present study concerns the contemporary acceleration of stone deterioration. Whatever the study scale and the construction choice, the weathering rates over the last 50 years (post-restoration period) have been systematically faster (5 to 38 times) than the weathering rates over one millennium, *i.e.* since the Maya building period. Based on the universality of this trend, we ascribe it to the protective effect of Mayan stucco coatings that has delayed limestone deterioration. This protective layer was removed by restorers in the early 1970s and no stucco was applied on the new limestone blocks, exposing them directly to weathering processes.

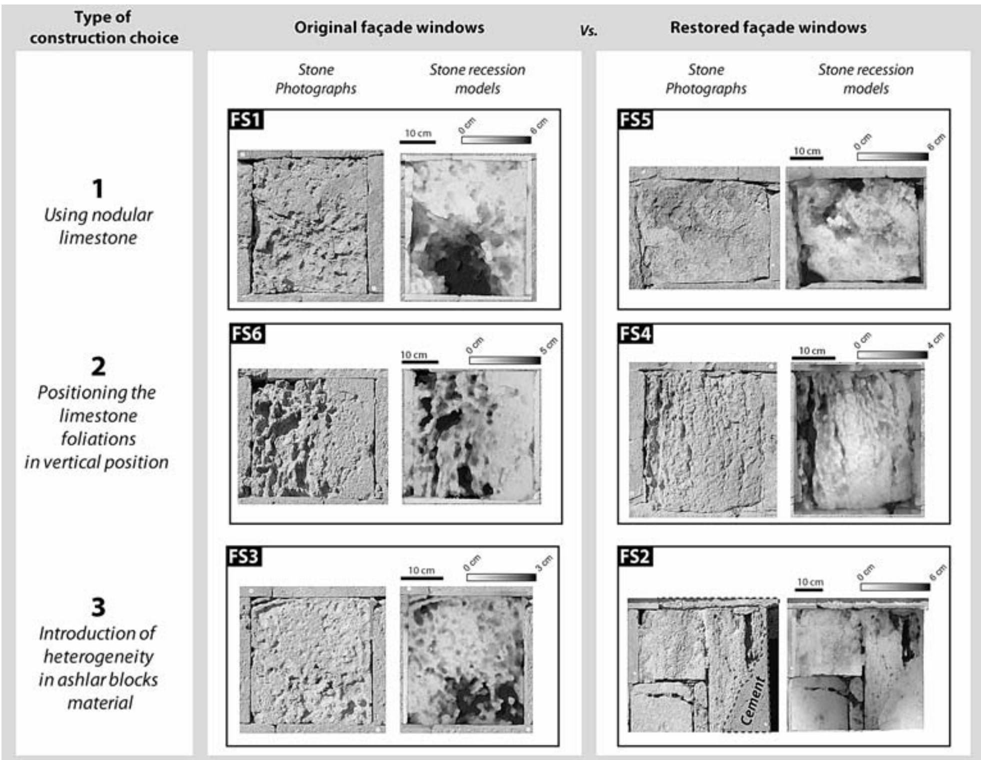

FIG. 7 - Stone recession models of the original and restored fine-scale photogrammetric windows of the south façade of the House of Turtles according to the type of construction choice.

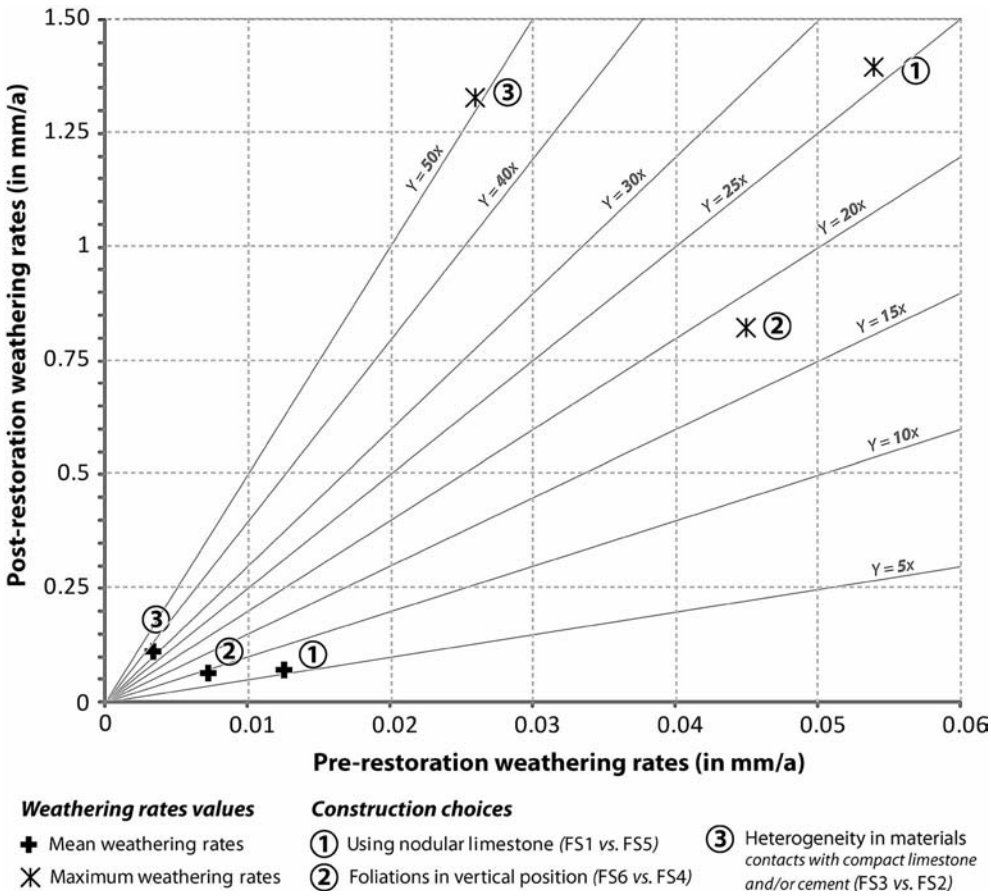

FIG. 8 - Comparison of pre- and post-restoration weathering rates according to the type of construction choice.

The fact that no stucco remnant was observed on the exterior wall of the House of Turtles is due to the completeness of restoration operations at the Uxmal site (Atwood, 2006). This is confirmed by additional observations carried out at Chunhuhub, a nearby Late Classic site, which displays a sharp contrast between restored and non-restored walls: whereas the main palace has been subject to intensive restoration and does not show any stucco remnant, the non-restored secondary palace displays widespread stucco remains (fig. 9 A, B). As demonstrated by Kowalski (1985)'s inventory of painted stucco remnants in North and Central Yucatan, all Mayan buildings were originally covered with stucco, a mixture of burnt limestone, fine sand and bark extracts, often painted in blood red (Littmann, 1959).

The protective effect of stucco and other lime wash and lime renders has been extensively described in the literature (*e.g.*, Ashurst & Ashurst, 1989; Koller, 1989, 1994; Ashurst & Dimes, 2011). These lime coatings act as a «sacrificial layer» or protective skin for stone, that keeps the stone dry, buffers it against the atmospheric attacks and allows the walls to breathe. At Xcalumkin, a Puuc site which has been recently and only partly cleared from tropical vegetation (fig. 9C), the protective effect of stucco is obvious: tooling marks dating back to AD 800 appear from below the stucco coating as fresh as if they had been made yesterday by the Mayan stonemason (fig. 9D).

The second main finding deals with the acceleration of limestone deterioration due to the replacement of wooden lintels by cement lintels above the façade doors. Hotspots of limestone deterioration that appear on the façade (in black in fig. 4, see above) are systematically located below these cement lintels incorporated in the ashlar masonry in the early 1970s. The deleterious effects of cement are confirmed by the very fast post-restoration weathering rates recorded in ashlar blocks located next to the cement (window FS2): these rates are on average 38 times faster than the corresponding pre-restoration weathering rates (window FS3). In the governor's palace next to the House of Turtles, additional damage including limestone cracking is induced by iron fixings incorporated in reinforced concrete lintels (fig. 10). Such effects have been widely observed in other sites worldwide, such as the Acropolis in Athens where iron fixings have been removed and replaced with titanium substitutes (Ashurst, 2007).

Although providing promising results, the present study suffers limitations and opens new questions. First, the temporality of stucco removal must be specified. Stucco deterioration may have started around *ca*. 1050, following the decline of the Uxmal Maya centre, but it is highly probable that it operated slowly in forested environments, before accelerating in the 1920s when the site was cleared from vegetation. As indicated by Taylor (1995), «*Once unearthed and exposed, stucco monuments deteriorate in a*

FIG. 9 - 1200-year old stucco coatings. A-B: Chunhubub site (AD 800-970): stucco-free restored façade of the main palace (A) and well-preserved stucco remains on the unrestored façade of the secondary palace (B). C-D: Xcalumkin site (AD 680-800): stucco preserved below vegetation (C) and periphery of stucco displaying fresh tooling marks dating back to the Terminal Classic Maya period (D).

matter of years. The fragile, powdery remnants of […] stucco quickly crumble and fall from façades leaving only the rough-hewn blocks of limestone armature». At Uxmal, the 1970s restoration operations obviously rang the knell of the remaining stucco patches, but it would be of interest to estimate from old photographs the percentage of the wall still bearing stucco before restoration. The second open question concerns the discrepancy between the results obtained at the large and fine scales. Whereas at the scale of the whole façade, post-restoration weathering rates have been 38 times faster than pre-restoration rates, such a tremendous acceleration is only reached in one case at the fine scale (window FS2); in the other cases, fine-scale windows provide post-restoration weathering rates that are only 5 to 10 times faster than the pre-restoration rates. An explanation might be the fact that hotspots of severe deterioration at the façade scale (*i.e.*, next to cement lintels, as FS2) significantly influence the average rates, but a larger number of fine-scale windows would be required to test this working hypothesis.

FIG. 10 - Limestone cracking provoked by the replacement of a wood lintel by a reinforced concrete lintel in the Governor's Palace, next to the House of Turtles (Uxmal).

PERSPECTIVES

The present study demonstrates the deleterious effects of stucco removal and cement incorporation during restoration operations carried out in Uxmal until the early 1970s. Such interventions have induced a 5-fold to 38-fold acceleration of deterioration of limestone ashlar masonry in terms of stone recession. This quantitative assessment leads to emphasise the need for softer, less intrusive restoration practices, as already promoted by a number of Mexican restorers. In particular, stucco should be definitively considered as an architectural protective skin worth being preserved (Cedillo, 1987). By contrast, the use of cement should be restricted because «*there is an inherent and fatal incompatibility between cement and lime-mortared construction*» (Ashurst, 2007, p. 129); this is due to the cement salt content, impermeable character and high mechanical strength (Ashurst & Dimes, 2011; Phalip & *alii*, 2012).

At sites where stucco has been already eliminated, new applications might be a solution to preserve the limestone skin of the monuments. The discovery by archaeologists of superimposed layers of stucco indicates that stucco maintenance was ensured by the Mayas, and this practice should be more systematically promoted as a preventive conservation strategy. In some cases, an alternative might be to favour the formation of natural bio-patinas containing calcium oxalates, which appear to have a protective effect due to their low solubility and porosity compared to the ones of the underlying limestone blocks (Hansen & *alii*, 2003; Pavía & Caro, 2006; Concha-Lozano, 2012). However, multidisciplinary studies associating biologists and physical geographers are a prerequisite to define the environmental conditions and the type of vegetation cover favouring the formation of protective bio-patinas without impeding the tourists' access to archaeological sites. In this context, recent studies about bio-deterioration *versus* bio-stabilisation are of special interest (Ortega-Morales & *alii*, 2000 and 2012), especially when conducted jointly with geomorphologists involved in microclimate monitoring and quantitative assessment of weathering damage.

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