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PRESERVATION AND RESTORATION OF THE WADI SURA CAVES IN THE FRAMEWORK OF THE "GILF KEBIR NATIONAL PARK", EGYPT

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Abstract

In 2010 the Italian-Egyptian Environmental Cooperation launched a safeguarding project for the preservation of the caves with prehistoric rock art located in the Gilf Kebir plateau in southwestern Egypt. The project was part of the cooperation program developed to establish the Egyptian Gilf Kebir National Park (GKNP) protected area. Given their bad state of preservation, the Italian conservation project focused on the Caves of Swimmers and Archers, located along the Wadi Sura. Although only very few studies of this kind have been carried out in the Saharan region, our work in the Gilf Kebir can be considered a pilot study, the results of which should be evaluated in the long term. Results obtained to date and reported in this paper provide analytical petrographic studies of the bedrock, a complete photographic and geodetic survey of the two sites, data from climate monitoring, along with a preliminary consolidation of some of the most at-risk areas of the two caves. Finally, laboratory experimentation led us to select the most suitable materials for the consolidation of the rock, shifting in the direction of nano-technology instead of ethyl silicate use because of the longer cross-linking process of the latter in hyper-arid environments; the use of the latter can in fact result in extremely long and expensive field seasons. These results will be valuable for the continuation and extension of the project, which is currently suspended due to safety concerns in the region.

Keywords: *Saharan rock art; Climatic weathering; Sandstone consolidation; Petrographic analysis; Porosimetric analysis; Laboratory experimentation on nano-silica.*

Introduction

The archaeological and conservation project in the Gilf Kebir

Developing a conservation and safeguarding program of prehistoric rock art in a desert environment is certainly a fascinating undertaking and, at the same time, a challenge entailing overcoming the difficulties inherent to the environment and to the geomorphological nature of the rock substrate itself. This paper refers to the results obtained between 2010 and 2013 by the 'Italian Archaeological and Conservation Project in the Gilf Kebir, Egypt' funded and

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sponsored by the Egyptian Italian Environmental Cooperation, and directed by B.E. Barich [1, 2]. The intervention started with an assessment season in March 2010, which was followed by two main seasons in November 2010 and April 2013. Since 2013 the project has been temporarily suspended due to the political unrest in this region, where the borders of Egypt, Libya and Sudan intersect.

The Gilf Kebir is located in a strategic position, at the center of the communication pathways between the Central Sahara and the Nile Valley (Fig. 1). Despite its extreme aridity, the plateau contains numerous faunal and botanical species, which are characteristic to the Saharan desert environment. The region is also very important for its geological and archaeological features. Driven by the extraordinary cultural and naturalistic importance of this territory, and with the aim to preserve the peculiarity of its biodiversity, the Egyptian Government established the protected area of Gilf Kebir National Park (GKNP) in 2007. Since the very beginning, protecting and enhancing the rock art sites, which are the main cultural feature of this area, has been one of the main aims of this government project.

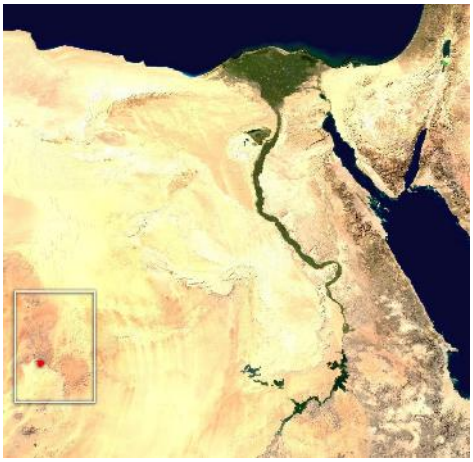

Fig. 1. Map of Egypt showing the Gilf Kebir area in the square.
The circle indicates the position of Wadi Sura.

The Gilk Kebir plateau has been known since the beginning of the 1930s thanks to the systematic excavations along the Wadi Bakht and the Wadi Ard al Akhdar in the framework of the 1938 expedition organized by Ralph A. Bagnold and the Egypt Exploration Society in the Gilf Kebir and the Jebel Uweinat [3]. The results from this expedition were only published in the 1970s by the American geologist W.P. McHugh [4]. Archaeological investigations of the region were then systematically carried out from the 1980s onwards by the University of Cologne; the German team investigated the Wadi Bakht area [5], located in the eastern section of the Kamal el-Din plateau. In recent years the interest in the region mainly focused on the Abu Ras plateau, thanks to the extraordinary rock art complexes uncovered along the Wadi Sura. This is a large valley that opens up in the Paleozoic (Silurian) sandstone of the Umm Ras formation, and which contains the three most famous rock art shelters in the entire region: the Cave of Swimmers, the Cave of Archers, and Foggini Cave (also known as the Cave of Beasts or Abu Ras shelter). While the first two were discovered and have been studied since the 1930s during the expeditions carried out in 1933 by L. Almásy, L. Frobenius, H. Rhotert and E. Pauli (DIAFE XI), and in 1935 by L. Frobenius, H. Rhotert, K. Marr and others (DIAFE XII) [6], Foggini Cave was only discovered as recently as 2002 by J. Foggini, M. Foggini and A. El Mestekawi. In recent years its rock art works were studied by a team from the University of Cologne led by R. Kuper [7].

The entire region has yielded evidence of human occupation either from the Middle Stone Age or from the Holocene, which preceded the irreversible establishment of the desert. The Holocene peopling of the Gilf is attributed to three main phases of occupation: Gilf A: 8500-6500 cal. BC; Gilf B: 6500-4400 cal. BC; and Gilf C: 4400-3500 cal. BC [8]. We can therefore say that, between 8000 and 4000 BC, the region benefited from a favorable climate, becoming a meeting point among cultures.

The conservation work described in this paper focused on the two caves we have known for the longest time, the Cave of Swimmers and Cave of Archers, which given their bad state of preservation, required the most urgent intervention. The first one opens up into a Paleozoic sandstone hill, directly at the bottom of the Wadi Sura; the entrance is large, ranging between 15 and 18 meters wide, and a c. 9-meter height. The cave's chamber is c. 8m deep, with a bedrock floor covered by a thin sand deposit. The smaller Cave of the Archers is located just 40m to the south of the Cave of Swimmers. Its entrance is 10m wide and 5m tall, with a west/southwest orientation (Fig. 2).

The pictorial complex of the Cave of Swimmers mainly shows typical features of the so-called Wadi Sura style, as defined by A. Zboray [9], which is supposedly associated with the Gilf B phase [8, 10], and some cattle figures to be associated to the Gilf C phase.

Among the paintings, human figures are undoubtedly the most numerous. The figures are of different sizes and are depicted in various postures (standing, walking, dancing, 'swimming' or 'floating') (Figs. 3c and 4a and b). Human bodies are painted using red and, less frequently, yellow ocher and often show traces of decorations made with white pigment (kaolin). The main preserved scene shows two groups of subjects. On the northern section, on a lower level, some male figures in a row present a number of damaged areas to their surfaces produced *ab antiquo*. On the southern section, instead, at a higher level, a further group of figures moving towards a headless beast can be observed. In particular, there is a larger figure with a massive body devoid of anatomical details and a small spherical head, flanked by another individual tied in bandages, while below some of the famous 'swimmers' are depicted in a floating movement (Fig. 3c).

With the exception of two images of domestic cattle, which are still visible on the upper southern area of the shelter's wall (Fig. 4b), wild animal figures are dominant. They include giraffes, gazelles and ostriches. Several giraffes together with small human figures, both painted in red, are still visible on the northern edge of the wall, just outside the shelter. A group of small running dama gazelles is painted, in red and white, on the upper central area of the shelter. Hands stencils are also present although badly preserved. The hand prints often underlie the human and animal figures described above.

In the Cave of Archers, only a small portion of the original paintings is currently visible and covers an area longer than 2m. A number of long-limbed figures holding bows can be seen in the depicted scenes. Various bovine figures, at the opposite end of the wall, emphasize the greater presence of herder groups than that of hunters, which one would assume from the depicted bows (Fig. 5).

Fig. 2. Cave of Swimmers (center) and Cave of Archers (right).

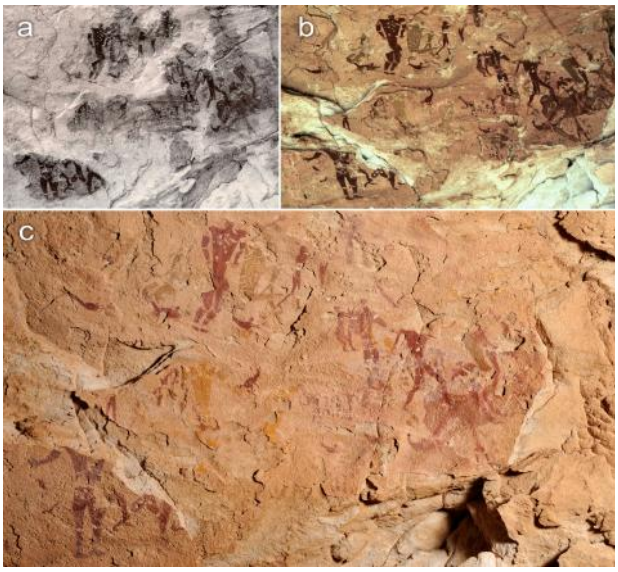

Fig. 3. Cave of Swimmers. Comparisons of the photos of the same area of painted wall showing the severe, but extremely slow degradation process which affected the cave: a. photo published in *Libysche Felsbilder* [6]; b. photo taken by G. Negro in 1983; c. photo taken by C. de la Fuente in 2010.

Fig. 4. Cave of Swimmers. Painted wall: a. the swimmers; b. two figures of domestic cattle and human figures.

Fig. 5. Cave of Archers. The painted wall of the cave showing figures of domestic cattle and archers.

Figures are always painted with compact and homogeneous drafts. They usually are monochromatic with a few exceptions painted using two colors. Several small details made in yellow or white are also present on several of the figures. Clear and elegant outlines depicting animals and humans are obtained with brushstrokes, suggesting the use of a tool that allowed precise application of color (small brushes). This refined subtlety, combined with the difficulty of painting on an uneven surface, denotes both the artists' skills and their technical competence in tool use [11]. Hand prints were produced by means of the 'negative' technique, using hands (sometimes also forearms) as stencils and blowing the color pigment directly from the mouth or with the aid of a plant or bone straw.

The pigments which were used for the paintings come from local sources and the most common colors used are: white, dark red, light red, egg yellow, bright yellow and (rarely) greenish yellow. The white color is kaolin, very widespread in the area. Red and yellow iron–oxide bearing pigments usually occur together as replacement and filling of solution holes in the bedrock. They can be collected as dark brown pebbles on the Wadi Sura ground as well on the oldest terraces.

The main aim of the study and conservation program was to develop a comprehensive plan of consolidation and preservation of these two rock art caves. Facing the difficulty of tacking action against the principal causes of degradation such as wind, sunlight, temperature oscillation, together with the petrographic characteristics of sandstone, we tried to slow down the weathering process through the consolidation of the sandstone. Our intervention has to be understood as a pilot project to evaluate the sandstone conservation state; to test the extent to which the rock responds to consolidating materials, and how these products absorb and react; and to protect the areas most at risk of collapse.

The operation sequence was carried out in consultation and with the participation of representatives from the Egyptian Ministry of Antiquities (at that time Supreme Council of Antiquities).

Materials and methods

The Caves of Swimmers and Archers are extraordinary examples of the Saharan cultural and natural heritage. In light of the information attained from the assessment season, it was decided to give priority to the work to be carried out at the Cave of Swimmers and the Cave of Archers. The sandstone was, in fact, observed to be heavily weathered and only small parts of the original painted surfaces were still visible.

The archaeological and conservation project was conceived as a multi-disciplinary undertaking and included the above-mentioned three field seasons and laboratory experimentations.

The applied methodologies are the following:

Geomorphology and petrographic analysis

This study concerned assessing the geological structure of the caves and the wider area in which they occur. The laboratory analyses (D. Poggi, freelance geologist) have been carried out on small rock samples collected in the areas around the two caves and their aim was primarily to study the composition and characteristics of the sandstone:

- X-Ray powder diffraction analysis of the fine fraction < 2 mm, and of the sandstone's crust (patina) (*Scintag X1* diffractometer);
- Determination of sandstone's specific weight; true specific weight (*Gibertini E42* scale; pycnometer); bulk density (*Gibertini E42* scale; caliper).
- Porosimetric analysis to determine the full open porosity and distribution of pore size via water absorption measurements (*ThermoQuest Pascal*

246 mercury intrusion porosimeter; mercury porosimetry according to UNI – Normal 4/80; *Gibertini E42* scale; *Termostabil K2* oven).

- Ion chromatography was used for the quantitative/qualitative detection of soluble salts – hydrosoluble anions: fluorides, chlorides, nitrates, nitrites, phosphates and sulphates (*Thermo Scientific™ Dionex™ D100* ion chromatographer).

Photographic documentation and geodetic survey

In the Caves of Swimmers and Archers a complete recording of rock art images and at-risk spots was carried out by completing data sheets for each of the rock art scenes, and through the complete photographic documentation of the sites (C. de la Fuente, freelance photographer). The photographic material produced was also compared with archive photographic collections in order to obtain information about the speed and severity of the weathering process since the time of the cave's discovery.

The aim of the geodetic survey was to reconstruct both caves in 3D. Collected data have been used to build high-resolution 3D models of both caves (A. Sonnessa, SurveyLab, Sapienza University of Rome spin-off). Surveying activities were performed using a topographical *Riegl Z210i* laser scanner. The purpose of the survey was also to collect data concerning the conservation conditions of the rock paintings. Several scans were obtained to reconstruct the exact topography of the cavities; 25 scans were produced for the Cave of Swimmers and seven for the Cave of Archers, with an average spatial resolution of about 5×5mm (c. 40,000 pts/m^2) for each scan. Purpose-built targets were used to link the scans together. A straightened section of the painted wall of the Cave of Swimmers has been processed and overlaid with a 50x50cm grid in order to facilitate the location and recording of each of the figures (Fig. 6).

An additional low-resolution scan was obtained of the façade of the domed rock within which the caves open up in order to georeference the two 3D models of the caves and thus place their reference points within the same reference system.

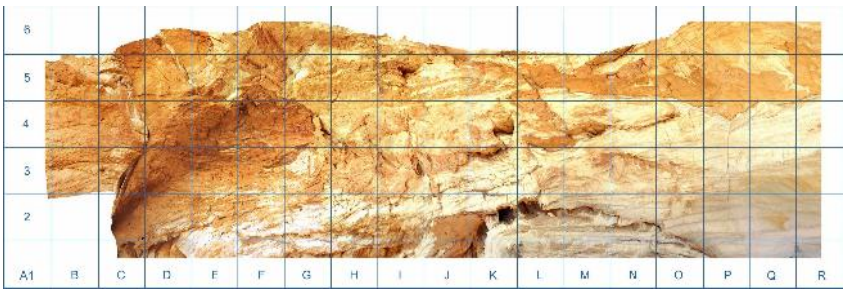

Fig. 6. Cave of Swimmers. Straightened section of the painted wall of the cave, with a 50×50cm grid.

Archaeology

Archaeological work (B.E. Barich, G. Lucarini, G. Mutri, at the time of the Sapienza University of Rome) primarily dealt with the inventory and documentation of the artistic repertoire and with the excavation of the deposit inside the Cave of Swimmers. The Cave of Swimmers shows a limestone floor covered by a medium-to-thin aeolian sandy sediment c. 20 cm deep. Removal of this deposit was carried out on the northern edge of the cave in order to detect the possible presence of blocks collapsed from the shelter's ceiling and walls, which could be consolidated and reintegrated. Sand was only removed in this area of the cave where the sandstone bedrock emerges very close to the surface, while on the southern half, the thicker deposit was left untouched. The excavation yielded archaeological materials, which will be discussed in a separate paper.

Climatic and environmental monitoring

The restoration work in the caves was preceded and followed by a climate monitoring program to record and process climatic data of both the cave and the general area. Data collected on air temperature, temperature of the sandstone surface, relative humidity, wind and sun radiation are indispensable to our understanding of weathering development and when selecting the most suitable restoration materials.

A *Davis Vantage VUE* meteorological station was positioned in the Cave of Swimmers to record data on air temperature and relative humidity as well as wind direction and intensity inside and outside the site. The station recorded data 24h a day for the whole duration of the fieldwork. Moreover an *EL-USB series* data logger was positioned inside the Cave of Archers in order to record data on air temperature and relative humidity.

The temperature of the sandstone wall surface was also recorded at 10 different points (six in the Cave of Swimmers and four in the Cave of Archers) by means of a *Trotec TSEC 60V* infrared thermal camera. The data were recorded each hour between 8am and 5pm.

Information on sun radiation was also collected by means of a *Delta OHM – HD2302.0* photo radiometer. Data were recorded in both the Swimmers and Archers caves - on the same 10 points where surface temperature was also recorded - through continuous monitoring between 2pm and 5pm (recording maximum, minimum and average radiation) when the caves' walls were directly exposed to sunlight.

The sandstone surface temperature and relative humidity referred data have led to an initial selection of the materials to be tested, both for the consolidation of stone and to fix the detached laminae: especially the ultra-low relative humidity values led us to exclude certain products, as will be later discussed, and has emphasized the important role played by laboratory experimentation in selecting the most suitable restoration materials.

Restoration

Restoration activities were carried out by the Italian restoration team (M.C. Tomassetti, C. Caldi, F. Ratti, freelance restorers), in collaboration with Egyptian restorers (Behe G.A., Saned S.H., Ministry of Antiquities, New Valley Inspectorate). This restoration work comprised several phases, ranging from sandstone consolidation, stabilization and fixing of partially detached areas, sealing of loss edges, and assessment and restoration of damage due to vandalism.

This intervention was a pilot project to test the extent to which the rock responds, how consolidating materials absorb and react, and to protect the areas most at risk of collapse. It was conducted with great care on a limited portion of the walls respecting the original conditions as much as possible, with no alteration of the rock color nor of its texture. The operation sequence was carried out in consultation and with the participation of representatives from the Egyptian Ministry of Antiquities (at that time Supreme Council of Antiquities).

Three c. 50cm^2 areas from inside the Cave of Swimmers have been chosen to be restored. They show different conservation problems:

- Area 1 is characterized by deep cracks and thin and superficial fractures, lacunae in the iron crust, detached stone layers and wide gaps underneath the crust. There are also figures painted in red ocher (Fig. 7a);
- Area 2 is characterized by a deep and extended hollow below the surface crust. It is extremely thin and only anchored in a few points. There are no painted figures (Fig. 7c);
- Area 3 is located at the top center of the northern half. It has lost its crust, and for this reason, the area is characterized by strong decohesion. A severe phenomenon of sandstone layer detachment is present (Fig. 7e).

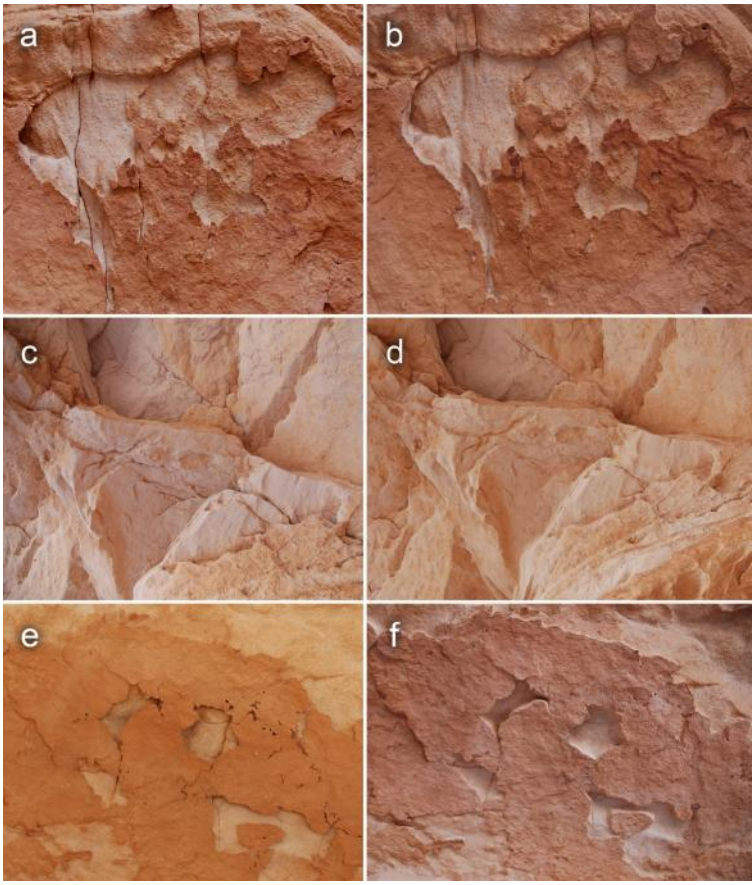

Fig. 7. Cave of Swimmers. The three intervention areas: a. Area 1 prior to restoration; b. Area 1 after restoration; c. Area 2 prior to restoration; d. Area 2 after restoration; e. Area 3 prior to restoration; f. Area 3 after restoration.

Sandstone consolidation: Ethyl silicate is generally considered the most suitable product for sandstone consolidation. It is a silicic acid ester: from the well-known reaction of slow hydrolysis and tetralkylic esters condensation of the orthosilicic acid, amorphous silica formed inside the bedrock, at the beginning as a gel and later, through quite a long evolution, towards an inorganic mineral phase.

This consolidating product was applied for the first time during the March 2010 intervention. In the field we tested the application of ethyl silicate, both in white spirit (Rhodorsil RC 70, Phase - Proind Ltd.) and in ethyl alcohol forms (Silester AR, Kremer Pigmente GmbH & Co.). The treatment was performed on sanding bedrock underlying the crust by applying ethyl silicate in increasing concentrations (10%, 30%, 60%) after imbibition of the surface with ethyl alcohol. The imbibition was made by brush and syringes equipped with a drip rubber tube.

Stabilization by hydraulic mortar injections: in order to re-establish the wall continuity and to re-adhere both small raised wall flakes and detached thicker layers, infiltration tests with hydraulic mortars were performed. Mortars LEDAN® (TecnoEdileToscana), TB1, ITAL B2, TA1 and CIE, selected for their technical characteristics and behavior, have been tested.

Fixing partially detached laminae: To fix both thin crustal plates, sometimes almost completely detached, and layers of thicker and cracked sandstone, nails of different sizes were made. A mixture of sand, kaolin and *Paraloid B 44* (The Dow Chemical Company - Rohm And

Haas) 10% in acetone (1:1:1) was used. We preferred *Paraloid B 44* (copolymer of MMA) instead of the more common *B 72* (copolymer of EMA/MMA) for its higher Tg point (60°C). The glass transition temperature is a fundamental parameter in the selection of the resin/adhesive, as it represents the temperature value below which an amorphous material behaves as a glassy solid and it is therefore necessary that the selected polymer is elastic enough to undergo plastic deformations without fracturing.

Nails were made with small spatulas and dental explorers/sickle probes. To intervene behind the crust of the detached portions, the bridges were built with a syringe fitted with a rubber tube. The mixture is liquid enough to be injected, but it has a very fast drying time due to the volatility of acetone.

In Area 3, characterized by very deep gaps between the crust and the substrate, it was necessary to reinforce the nails with polypropylene fibers. We also applied fiberglass sticks to anchor a large and heavy detached crust fragment found in the Cave of Archers (Fig. 12b).

Sealing of loss edges: In the three areas chosen for the intervention, interruptions of surface continuity, such as lacunae edges and cracks, were sealed to make the sandstone more resistant to external aggressions and degradation. Sealing of crust contours is considered very effective to prevent the wind from continuing its erosive action below it. Moreover this operation also strengthens the holding nails. For this purpose different colored sands collected in the area surrounding the cave or obtained by grinding sandstones were selected. At the beginning a traditional lime and sand (1:4) based mortar was tested in Area 2, but several reasons led us to choose a colloidal dispersion of silicic acid in water (*Syton® X 30* - Kremer Pigmente GmbH & Co.) as a binder for the mortar. The inert was thus sifted and added to a small percentage of kaolin, and then mixed with *Syton® X 30*. Its affinity with the siliceous matrix of the rock and its quick drying time make it the most suitable material, both aesthetically and in relation to its chemical- physical characteristics.

Laboratory experimentation

Laboratory experimentation on sandstone consolidation was aimed at verifying the capacity of the products commonly used for sandstone to develop their consolidating power in arid environments like that of the Egyptian desert. Experimentation methods reported in the literature restrict the experimentation in a range of medium temperatures and relative humidity - 25°C and 75% RH - and monitor any variation simulating artificial ageing in a climatic chamber [12]. These conditions do not reflect the extreme climatic situation of the Gilf Kebir; during November 2010, the air temperatures recorded reached quite high values (maximum 41.5°C on November 7) and relative humidity was never above 32.5%, remaining very low for several days (minimum 4% on November 11) (Fig. 8). The hydrolysis process necessary to crosslink the ethyl silicate, even in normal environmental conditions (20-25°C / UR 70%) usually requires at least 3-4 weeks. In our case, due to the low humidity of the region, the time necessary could also be longer. Considering the limited extension of the areas that we selected for the intervention, this aspect did not create particular difficulties during the field season we had in November 2010, but it may be a problem during the completion of the work, because it would require the organization of extremely long and expensive field seasons. For this reason we decided to look for and test the potential of alternative products.

For the reasons above, our experimentation was conducted to note the effectiveness of some innovative solutions [13], such as geo-polymerization by using soluble salts [14] and nano-particle-based materials (Table 1).

Laboratory samples were prepared by mixing fine sand and kaolinite in a 5:1 ratio. This mix ratio was chosen after several attempts in order to achieve a sample with the most similar chemical-physical characteristics to the original stone. The aggregate, 5cm in thickness, was left drying for 48 hours and then calcined at 300°C. To simulate the microclimate of the site, treated

samples were stored in a climatic chamber (Angelo Antoni) for 30 days using a 24-hour cycle: T = 40°C / RH = 10% (12h) and T = 15°C / RH = 45% (12h).

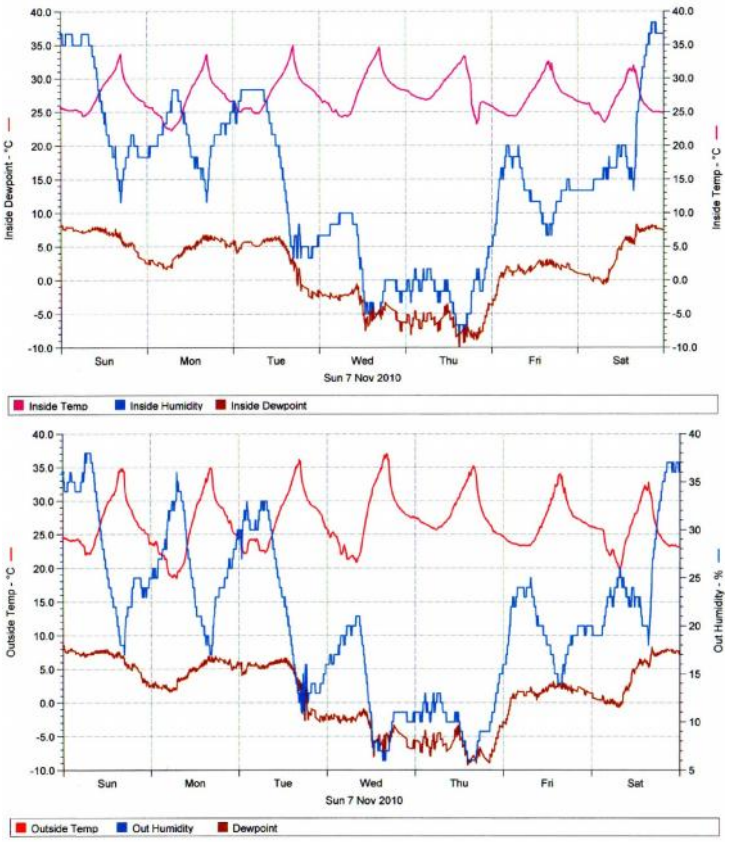

Fig. 8. Cave of Swimmers. Climatic monitoring inside and outside the cave (temperature; humidity; dew point; atmospheric pressure) recorded with a *Davis Vantage VUE* meteorological station.

Table 1. Chemical products tested during laboratory experimentation.

PRODUCTS	COMPOSITION	DISPERSION/CONCENTRATION – MODE OF APPLICATION
Nanorestore (CSGI – Università degli Studi di Firenze)	Monophasic calcium hydroxide in isopropyl alcohol (5%)	Ratio isopropyl alcohol : $Ca(OH)_2$ = 8:1. The dispersion was applied 3 times with an intermission of 10 minutes
Consolida Nano (CIR - Chimica Italiana Restauri)	Nano dispersion in water of colloidal silanized silica	The product was applied 3 times up to complete rejection
Alkaline Solutions	KOH and NaOH	5M KOH+NaOH solution was applied 3 times with an intermission of 30 minutes
BIO R-IPC 30 (CIR)	Ethyl silicate mixed with siloxanes and additives	The same as Consolida Nano
Nano Estel (CTS)	Nano dispersion in water of colloidal silica	The same as Consolida Nano
TEOS (Estel 1000 - CTS) + Alkaline solutions	Alkaline solution + Estel 1000	First the alkaline solution was applied and 3 hours later Estel 1000 was applied up to complete rejection
TEOS (Estel 1000 - CTS)	Ethyl silicate	The same as Consolida Nano

To evaluate the effectiveness and the penetration capacity of the tested products analyses on both treated and untreated samples were performed by using the following methodologies:

a) Water absorption by capillarity: performed according to EN 1925:1999 standard; this was carried out to investigate any change in absorption rate due to the action of the consolidant, which determines a variation of the porosity (also related to stronger or weaker cohesion effects due to treatment).
b) Drilling resistance (DRMS): carried out according to the operating conditions suggested by Tiano *et al.* [15] for some lithotypes (sandstone and limestone): measuring depth: 0–10mm, rotation speed: 600rpm, penetration rate: 20mm/min. The measurements were also collected on the opposite untreated surface to obtain information on the entire thickness of the sample.
c) Analysis by scanning electron microscope combined with dispersion energy X-ray microanalysis (EDS - SEM, LEO 1450 VP – INCA 300): carried out on polished cross sections of samples, after their incorporation into epoxy resin, to verify the penetration of consolidating products and evaluate possible changes caused by treatments (morphological, structural and compositional changes). Using a nano titanium dioxide particle (Mknano, 3wt%, 50nm) as a marker, it was possible to evaluate the depth of penetration and the distribution of products (from the treated surface three intervals in the section have been studied by analysing the percentage of titanium: 0-4mm, 4-8mm, 8-12mm).
d) Spectrophotometric analysis was performed with a Minolta spectrophotometer to measure any changes in the color of the samples before and after the consolidation treatment, after cycles in the climatic chamber, to exposure to artificial ageing by means of a QUV testing veterometer and to exposure of the sample surfaces to three weeks of UV radiation.

Results and discussion

The two caves were observed to be heavily weathered; natural fractures and the parallel exfoliation process had triggered the loss of large parts of the painted surfaces and sandstone blocks. The crust on which the paint layer stands was observed to be fractured and detached along the edges and from the openings it was possible to estimate the erosion of the underlying sandstone.

Weathering processes of the sandstone have been the object of extensive research: starting from the more specialized studies, mainly focusing on the physical/chemical or biological causes, a more holistic approach has been developed over time, which has allowed evaluating the causes and the consequent effects of this phenomenon [16-20].

As regards the two above-mentioned caves, the natural fractures and the parallel layer exfoliation process caused a loss of large parts of the painted surfaces and sandstone blocks. The majority of the images have unfortunately disappeared, and some parts are clearly endangered due to likely further collapse with the consequent high risk for the painted areas in their vicinity. Albeit the weathering process is very significant, it has been extremely slow and has spread over millennia; it does not seem to have accelerated much since the cave was discovered. This is clear from a comparison of the photos and sketches from the DIAFE XI (1933) and XII (1935) expeditions [6], with the photos taken by Giancarlo Negro 50 years later in 1983, and with our 2010 and 2013 photographic documentation (Fig. 3). All these materials did not reveal any substantial differences, both in terms of possible portions of collapsed sandstone and color brightness. The only pieces missing from the wall seem to have been damaged by deliberate acts of vandalism. Unintentional damage due to increasing numbers of visitors and the consequent rise in humidity can also be ruled out considering the great openness of the sites.

Causes of bedrock deterioration

Our analysis showed the bad state of preservation of the two caves can be attributed to two main factors: endogenous (or intrinsic) causes, related to the characteristics of the rock itself (e.g., mineralogical composition, stratification, joints, etc.), and exogenous (or extrinsic) causes, due to external factors (e.g., climate, anthropogenic damage, etc.). While it is true that the latter initiated the weathering process on the rocks, the development and increase of such a process was due to a lack of cohesion in the sandstone cement. As a matter of fact the very poor state of conservation of the internal walls in the Cave of Swimmers is due to several endogenous factors which, currently as in the past, are strictly interrelated.

The geomorphological study showed that the main deterioration factor in the Wadi Sura rock art caves is the bedrock structure of the area itself. Here, one of the main geological units is the Umm Ras Formation; this is made of Silurian, fine-to-medium grained and partly coarse-grained, white sandstone of deltaic origin, interbedded with nearshore marine sandstone and beach silty shale and siltstone. This unit makes up the lower part of both the Kamal el-Din and Abu Ras plateaus, and on the latter's foot slope is exposed at an elevation of up to 700m asl.

In the rock art caves two main geological phenomena are recognized: sedimentary structures (cross bedding and graded bedding) and the erosion of the surfaces, all of which represent weakness plains in the bedrock. Joints and fractures represent other elements of weakness, the length, width and direction of which have been analyzed. The Cave of Swimmers is greatly affected by cross bedding to a greater extent than Foggini Cave is (the rocks of the latter are mainly large meaning the deterioration effect is minimized). Most of the joints are wide and vertical, generally filled with iron oxide patina. 'Curved joints' can also be found in the caves, probably due to the brittle nature of the rocks. Weathering of the joints' footwall led to the formation of rock shelters of different dimensions. In the Cave of Swimmers a network of square, hexagonal and polygonal fractures have been observed. They are responsible (together with the vertical joints) for the formation of cubic-shaped slumped sandstone blocks [21].

Through laboratory analyses [22] the main petrographic characteristics and composition of the rocks have been identified. Sandstone from the Cave of Swimmers consists almost exclusively of medium-sized quartz grains, with very scant cement and, therefore, is characterized by a very low degree of cohesion becoming easily perishable even with wind erosion.

Furthermore, the mineralogical analysis of the fine-sized fraction (less than 2 micrometres), followed by X-Ray diffraction (XRD), detected a small percentage of dickite [$Al_2Si_2O_5(OH)_4$], a mineral belonging to the kaolinite group, as a main constituent of the stone binder [22].

The following physical parameters point to a sandstone characterized by poor cohesion due to the presence of micro cracks, or pores, of secondary origin produced by weathering, mainly thermoclastic (Table 2).

Table 2. Cave of Swimmers. Physical parameters of the sandstone

Specific weight	2.631g/cm^3
Bulk density	about 1.96g/cm^3
Total porosity	about al 25%
Water accessible porosity	about al 12-13%

On the other hand, the exogenous causes, linked to environmental factors - sharp daily and seasonal thermic variations, solar radiation, direction and intensity of wind - act in synergy with the endogenous causes of sandstone deterioration.

Inside the cave, artwork was produced on a coating crust (Figs. 4-6), which covers all the walls' surfaces. The crust, whose formation started during the wet phases of the Holocene since this process is known to take place in the presence of humidity [23, 24], is harder and darker than the underlying substrate because of the presence of iron oxides. Three types of surfaces can be recorded: one with a heavy dark patina, another, light very yellowish tan, showing some traces of iron oxide filling the spaces between the grains and, finally, newly-exposed surfaces due to loss of crust and surface ablation.

The most visible and widespread phenomenon is exfoliation (or sheeting), identified both on the surface, in the form of thin raised flakes, and in deeper portions, with the detachment of thick layers of rock (Fig. 9a). The sheeting is connected to changes in temperature that cause cycles of expansion and contraction of the material, resulting in a strong mechanic stress [25]. The sandstone surface subjected to solar radiation reached high temperatures (up to 52.5°C in the Cave of the Archers, with an air temperature of 30°C). Information on sun radiation collected by means of the photo radiometer yielded values reaching up to 1,076.2W/m^2. In particular, the expansion of outer layers during the day because of the heat and solar radiation, and their sudden contraction due to the drop in the external temperature during the night, cause traction forces leading to the detachment of layers. The quicker the changes, the easier the exfoliation phenomenon takes place [26, 27]. The whole process is further accelerated on the surface layer by the presence of the crust, which, being darker in color and iron-enriched, warms faster than the underlying rock. Other exogenous causes of sandstone degradation include the dry thermoclastic phenomena which, acting very slowly, occur over an extended period of time. We can say that some exfoliation was already present on the rock surface when pigments were applied to the surface. Finally, we must also consider the sandstone decohesion, which affects the entire bedrock but is more accentuated towards the outside, except in some portions where the crust is preserved.

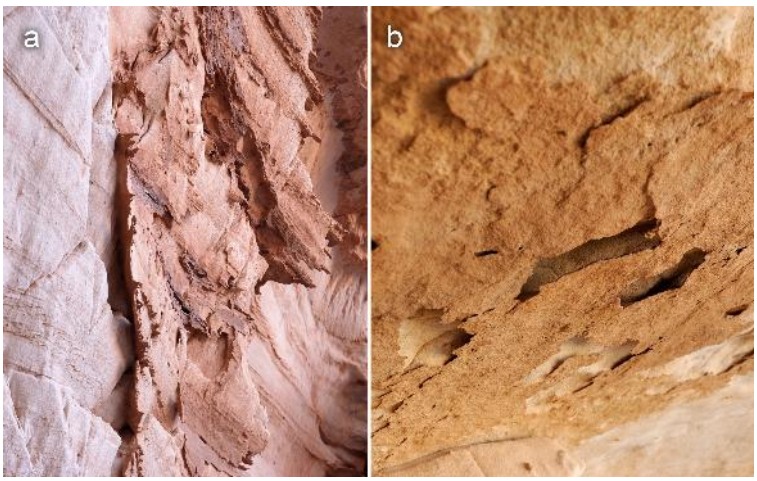

Fig. 9. Cave of Swimmers. Mechanisms of sandstone degradation: a. fractures and detachments of the surficial crust which expose the sandstone underneath to wind erosion and ablation; b. deeper erosion creating large gaps; the surficial crust is almost completely detached from the sandstone underneath.

All these phenomena are integrated and accentuated by wind erosion. The Cave of Swimmers opens up facing W/N-W. The Sahara's prevailing winds blow from the south, so they mainly hit the northern and central section of the cave. These are the areas where the crust

is better preserved, but also where the strong wind-borne sand meets the crust openings and continues its ablation action below the crust, thus increasing the effects of the degradation already in progress. Deeper erosion occurs, causing large gaps. In many areas only a few 'anchor' points secure the crust, which seem to be 'floating' (Fig. 9b). The southern section of the cave's wall is characterized by the almost total loss of the crust as well as of the paintings that presumably also decorated that section of the cave. A further type of degradation biological in origin can be recognized in the less exposed northern half of the cave where numerous wasp nests confirm the presence of humid phases in the past.

Information on the insolation intensity and duration, and on temperature changes to the rock surface will be fully addressed in future seasons, but the data gathered so far seem to confirm that the most exposed areas are not the most deteriorated and the weathering visible today, given its location inside the cave, is probably due to the humidity oscillations that took place in the past. Wind ablation seems to intensify the existing degradation, aggravating the sandstone erosion together with the action of the dry thermoclasty which keeps separating quartzite clasts from the sandstone matrix and causing surface exfoliation.

As a final comment and concern for the preservation of the Wadi Sura rock art repertoire, the impact of visiting tourists should also be considered [28]. Although at present tourism in Egypt and Libya has declined, due to political unrest, overall tourism in Gilf Kebir has grown in recent years, with the consequent intensification of vandalism. The lower southern area of the Cave of Swimmers has been extensively vandalized by modern graffiti and engravings (Fig. 10).

Fig. 10. Cave of Swimmers. Area of the cave's wall recently vandalized by visitors (between March and November 2010).

Restoration

Sandstone consolidation: The application test of ethyl silicate, both in white spirit (Rhodorsil RC 70, Phase - Proind Ltd.) and in ethyl alcohol (Silester AR, Kremer Pigmente GmbH & Co.), showed the latter to be more suitable because of the higher penetration capacity of its solvent, empirically tested on some rock samples (Fig. 11).

Stabilization by hydraulic mortar injections: Through hydraulic mortars infiltrations, it was possible to re-establish the wall continuity, and to re-adhere both small raised wall flakes and detached thicker layers. Mechanical characteristics of premixed mortars make them sufficiently adhesive, light and easily injectable, and avoid them interfering chromatically with the substrate. Among the different products tested, and taking the empirically-obtained results into account, we consider TB1 and ITAL B2 to be the two products with the most suitable mechanical characteristics, lighter than the rest, but with the same adhesive power.

Fig. 11. Area around the Cave of Swimmers. Application of ethyl silicate tested on a sandstone sample.

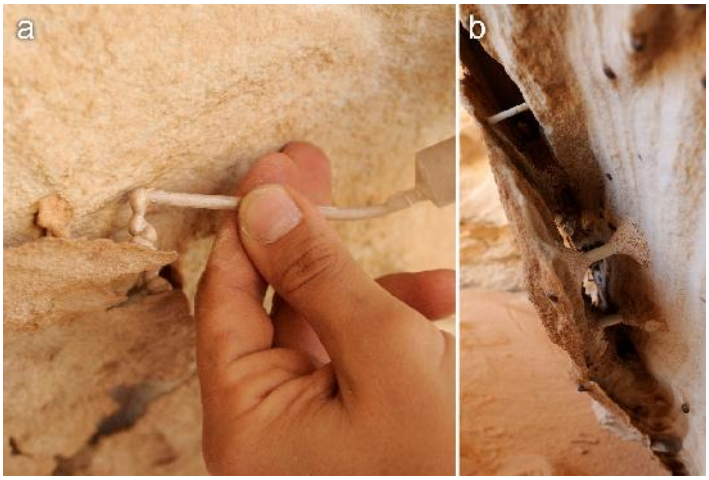

Fig. 12. Caves of Swimmers and Archers. Anchoring the detached sections of the wall: a. Cave of Swimmers; *Paraloid B 44* nails produced using a syringe fitted with a rubber tube; b. Cave of Archers; fiberglass stick nails used to anchor a large detached crust fragment.

Fig. 13. Cave of Swimmers. Sealing of openings and cracks

Other products that could be tested are the hydraulic mortars RI.STAT EXTRA (TecnoEdileToscana) to fill wider gaps, and ALBARIA™ STRUTTURA (BASF Construction Chemicals Italia Spa) for its greater compositional affinity with the original substrate. RI.STAT EXTRA is a premixed hydraulic mortar consisting of natural lime and special hydraulic binders (C30), pozzolan, ventilated perlite and a special blend of water-retention additives, aerating and foaming agents. Its low specific weight and mechanical strength make it suitable for the re-joining of items with no static functions, which have not to be loaded. ALBARIA™ STRUTTURA is a premixed hydraulic mortar consisting of pozzolanic-hydraulic lime obtained by mixing hydrated lime cooked at a low temperature (<1000°C) and fully hydrated, with metakaolin (calcined kaolin with high pozzolanic reactivity) cooked at a low temperature (500–900°C), mixed with natural siliceous aggregates of river and non-toxic inorganic mineral fibers.

Fixing partially detached laminae: Different dimensions nails allowed us to fix both thin crustal plates and layers of thicker and cracked sandstone (Fig. 12a). The decision to use *Paraloid B 44* for its higher Tg point (60°C) in place of the more common *B 72* was successful. As already mentioned, the glass transition temperature is a fundamental parameter in the selection of the resin/adhesive. Although it was late fall, the surface had in fact reached a temperature of 52.5°C when it was exposed to direct sunlight, with an air temperature of 32°C. The addition of kaolin as filler improved the thermal resistance of nails (the glass transition temperature of *Paraloid B 44* is normally about 60°C), their dimensional stability, toughness, tensile strength and resistance to abrasion, making the mixture compatible with high temperatures reached by surfaces exposed to sunlight.

During the inspection carried out in April 2013, after almost three years from the intervention, we noticed that even the heaviest pieces that we re-adhered using polypropylene fibers nails showed no signs of subsidence.

Sealing of loss edges: Syton® X 30, which was preferred to the traditional lime and sand based mortar, ended up being the most suitable material. The fillings we realized are in fact very similar to sandstone in composition and grain size, but with slightly lower mechanical properties in terms of hardness (Fig. 13).

Figures 20 a-f show Areas 1, 3 and 2, respectively before and after the conservation work. This has not affected surface cleaning nor any pictorial reintegration. Only a small amount of dusting was carried out to remove dust and sand. It was decided that the tone of the recent fracture surfaces should not be darkened even though doing so would have been more visually-appealing to visitors as these fractures are useful indicators of weathering development and thus provide important information to our conservation efforts.

Laboratory experimentation

The results of the experimentation on the sandstone consolidation showed that nano-silica may represent the best solution considering also the short time span (3-4 days) necessary for the process to take place, which is less complex than that of ethyl silicate: following on from water evaporation, the particles bind together forming a silica gel and creating bridges between quartz granules. Furthermore, nano-particles render the stone more permeable to water evaporation than does ethyl silicate. Not least, the safety factor should also be considered: being an aqueous dispersion, nano-silica are not flammable and do not exhibit toxicity symbols, with the consequent risk reduction during transportation and storage.

All tested materials have shown only a consolidating power of the most surficial layer, but collected data enable us to establish that nano-silica particle dispersions (Consolida Nano and Nano Estel) are better products. They enhance, in fact, the cohesion improving the mechanical strength with the minimum hardening of the sandstone, without altering its original physical characteristics greatly and avoiding the occlusion of porosity. TEOS and nano lime produce a consolidating effect characterized by high resistance to drilling, but only on the

surficial layer. Basic solutions are valid alternatives but they require additional experimentation to better understand some of the results that can be achieved when they are used.

Water absorption: In the water absorption curves (Fig. 14a-g), non-treated specimens reached their plafond values fast (30 minutes). The treated samples absorbed less water than the untreated ones, but with a similar trend (expect for the basic solutions). Each of the consolidation treatments reduced the size of large pores, but did not completely close them. The three graphs (untreated - treated surface - opposite treated surface) showed that a different behavior takes place with the use of different consolidants. In particular, the strong reduction of water capillary absorption, for Nanorestore and TEOS, missing in the opposite treated surface group, allowed us to suppose the low penetration of these products in the stone and the production of a film which prevented the passage of additional water.

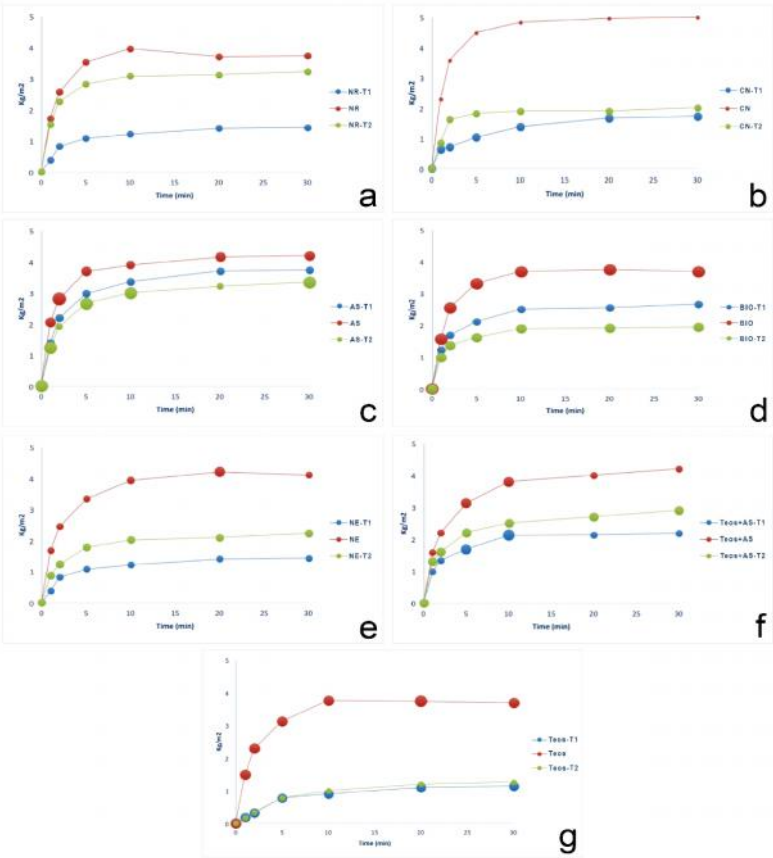

Fig. 14. Absorption curves of the laboratory samples. The sizes of the circles show the standard deviation of measures; Key:
a. Nanorestore (NR); NR: untreated; NR-T1: treated surface; NR-T2: opposite treated surface;
b. Consolida Nano (CN); CN: untreated; CN-T1: treated surface; CN-T2: opposite treated surface;
c, Alkaline Solutions (AS); AS: untreated; AS-T1: treated surface; AS-T2: opposite treated surface;
d. BIO R-IPC 30 (BIO); BIO: untreated; BIO-T1: treated surface; BIO-T2: opposite treated surface;
e. Nano Estel (NE); NE: untreated; NE-T1: treated surface; NE-T2: opposite treated surface;
f. TEOS + Alkaline solutions (Teos+AS); Teos+AS: untreated; Teos+AS-T1: treated surface; Teos+AS-T2: opposite treated surface; g: TEOS; Teos: untreated; Teos-T1: treated surface; Teos-T2: opposite treated surface

Drilling resistance: The drilling resistance test allowed the evaluation of the effects in these materials (Fig. 15). In terms of the Nanorestore, Estel 1000 and Nano Estel, the consolidation effect is visible only near the surface, and it decreases with increasing sample

thickness. The results obtained from the alkaline solutions are heterogeneous and the drilling plot showed two zones characterized by an increase of resistance (0–2mm and 5.9nm). BIO R-IPC 30 and Estel 1000 + alkaline solution values showed that the consolidant was able to increase the resistance on the total thickness of the sample. The best results were obtained using Consolida Nano.

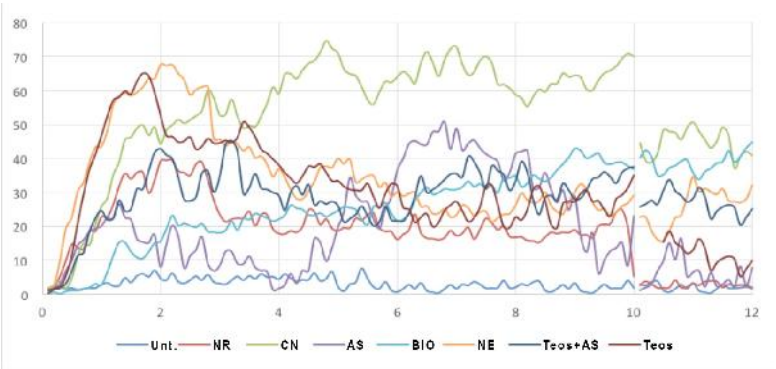

Fig. 15. Drilling test on laboratory samples: samples treated with different solutions compared to the untreated sample. Key: Unt.: untreated; NR: Nanorestore; CN: Consolida Nano; AS: Alkaline Solutions; BIO: BIO R-IPC 30; NE: Nano Estel; Teos+AS: TEOS + Alkaline solutions; Teos: TEOS.

Scanning Electronic Microscopy: SEM observations confirmed that the consolidation products are present in the specimens and showed that the penetration of the TiO_2 marker into the stone occurred to different extents depending on the type of consolidant (Fig. 16). In the present research, the total lack of Ti in all the treated specimens allowed to use this element as a marker to analyze the degree of penetration, although possible particle aggregation phenomena could have taken place. The plot showed the presence of Ti in every zone of the analyzed specimens except for TEOS, where the Ti was missing in the 8–12mm zone. In general, Ti concentration decreased in relation to the depth, while for Consolida Nano Ti was homogeneously distributed in all thicknesses. Alkaline solutions (with and without TEOS) showed a sharp Ti % decrease from 4.8mm to 8–12mm.

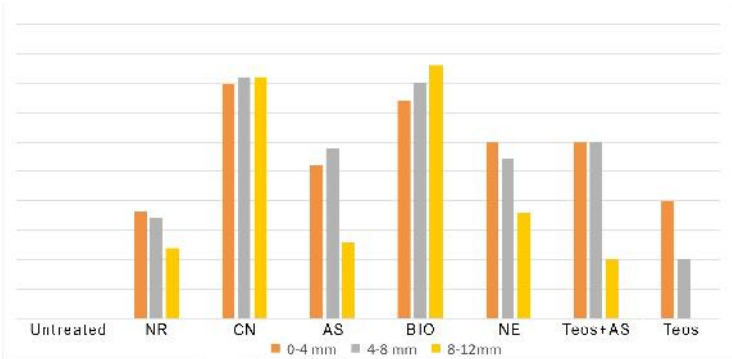

Fig. 16. Laboratory samples. SEM/EDS analysis on different sample depths; a: 0–4 mm; b: 4–8 mm; c: 8–12 mm. Key: NR: Nanorestore; CN: Consolida Nano; AS: Alkaline Solutions; BIO: BIO R-IPC 30; NE: Nano Estel; Teos+AS: TEOS + Alkaline solutions; Teos: TEOS.

Titanium was found in all treated samples, except for the TEOS treatment, in which it was missing in the 8–12mm thickness layer. In all treatments, the percentage of titanium

decreases in relation to the depth of the sample, while for Consolida Nano the distribution of titanium is homogenous for the entire thickness. The alkaline solutions (with and without TEOS) showed a strong decrease of the amount of titanium in 8–12mm.

Spectrophotometric analysis: Colorimetric changes (DE) of the treated samples were calculated with respect to the values of the colorimetric coordinates of the respective untreated stones and before ageing. In each of the treatments undertaken, the DE was always <5 and no noticeable effects were produced.

Conclusion

The conservation project of the Wadi Sura rock art in the Egyptian Gilf Kebir aimed to find the most suitable methodologies and materials for the restoration of the paintings, especially considering the small number of studies and interventions in extreme climatic conditions such as those characterizing this region.

The study of environmental parameters, even if limited to a short period, has already led to a first evaluation of the weathering causes. Some of them lie in the past, when humidity acted in synergy with other factors, increasing their action. Among the main causes of weathering which affect the shelters today, the strong wind-borne sand ablation should certainly be taken into consideration together with the slower dry thermoclastic phenomenon. It is not possible to halt the effects produced by these factors, but we can mitigate them, increasing the mechanical strength of the sandstone and closing broken openings on the surface crust through precise sealing operations.

The preliminary and indispensable study of the causes and phenomena for sandstone decay, the petrographic and mineralogical analyses for the characterization of the sandstone and subsequent laboratory experiments led to the selection of the most suitable materials for the rock consolidation.

The required time for the crosslinking of ethyl silicate in hyper arid environments has resulted in the exclusion of that product, considering the limited duration of the conservation field-campaigns. The laboratory research then evaluated the applicability of a range of nano-silica, considering their consolidating power rating and the ability to penetrate the sandstone. These products, already in use in the field of stone restoration, pure or in combined used, should allow the performing of operations following the consolidation of the stone within the same season.

At the same time materials and techniques for fixing portions of sandstone at risk of falling and for filling gaps were tested and improved *in situ*.

The intervention carried out in the caves and the results from the laboratory experiments will be the starting point for the restoration work of the entire surfaces of the Cave of Swimmers and Cave of Archers; this final phase will take place when the region is declared safe and is again accessible.

Considering the current unstable situation, the Gilf Kebir region, like many other areas of the Egyptian Western Desert, became recently inaccessible both for archaeological research and tourism. We hope the situation will return back to normal in the next few years and, when this happens, the region will return to face the ‘ordinary’ threats mainly triggered by uncontrolled tourism activities. Prior to the decline in safety, which led the Egyptian Western Desert to become almost completely inaccessible since 2015, the establishment of a Gilf Kebir National Park, in January 2007, represented a much-needed step for the better management and protection of the region. The real challenge for the future will be to reconcile the value of tourism as a factor for the development of local communities and the need for protection of archaeological sites. One of the priorities should be the continuous control of cars accessing the area and, at the same time, the training programs for local guides and drivers should be improved. It is necessary to promote a code of conduct among foreign visitors and tour

operators, together with an awareness of the deep cultural significance that local rock art and prehistoric evidence hold. Our challenge will be to promote awareness of the cultural significance of these irreproducible places through ever-improving training programs for local people and research dissemination efforts.

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The multidisciplinary *Italian Archaeological and Conservation Project in the Gilf Kebir, Egypt* directed by Barbara E. Barich, at that time of the Sapienza University of Rome, was launched in 2010 by the 'Egyptian Italian Environmental Cooperation - Enhancement of the Egyptian Protected Areas- Gilf Kebir component' Program, which fully financed the activities. The following members were part of the scientific team: Giulio Lucarini (Deputy Director), Cristina Caldi, Carlos de la Fuente, Mona Fouad, Behe G. Ahmed, Mohamed A. Hamdan, Giuseppina Mutri, Federico Ratti, Alberico Sonnessa, and Maria Cristina Tomassetti. Massimo Foggini, who discovered Foggini Cave, also took part in the first two field seasons.

The participation of Cristina Caldi in the restoration of the Caves of Swimmers and Archers has been particularly important for the continuous exchange of ideas relating to the choice of methods and restoration materials.

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This paper is dedicated to the loving memory of Abdelmonein 'Laulau' Mabrouk

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