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Original article

HONEYCOMB WEATHERING OF SANDSTONE OUTCROPS AT AL-HIJR (MADA'IN SALIH), SAUDI ARABIA

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Abstract
In 2008 UNESCO proclaimed Mada'in Saleh as the first Saudi Arabia's world heritage site because of its rock-cut monumental tombs, with their elaborately ornamented façades, of the Nabataeans kingdom. The tombs sandstone outcrops are suffering from honeycomb weathering, which affected the rock surface. Salt weathering often results in the carving of the rock to give a honeycomb appearance. The initial spacing of the hollows may be resulted from the variations in the rock's properties, and weathering creates a roughening of the outcrops rock-cut tombs surface. The lower parts of the rock's surface are flaking of thin, multiple flakes due to salt weathering and repeat wetting and drying of the rock. To determine the mechanism of honeycomb formation at Al-Hijr archaeological site, sandstone samples have been investigated and analyzed by the following methods: field observations (visual examination), Optical Microscope (OM), Polarized Microscope (PM), Scanning Electron Microscope equipped with (SEM-EDS), and X-Ray Diffraction (XRD). The results declared that Al-Hijr sandstones samples have fine to large grained minerals (mono-crystalline and polycrystalline) that different in shape and size. The pore-filling cement is consisting mainly of clay minerals. XRD results revealed that Al-Hijr sandstones mainly composed of Quartz SiO2, Halite NaCl as a salt, Ringwoodite Mg_2SO_4 and Kaolinite $Al_2Si_2O_5$ $(OH)_4$. These results represent the correct diagnosis, which will help us to put the suitable strategy of the conservation.

Keywords: *Al-Hijr, Rock-cut tombs, Honeycomb weathering, Investigations, Diagnosis*

1. Introduction
Mada'in Salih is the largest Nabataeans site in the north of Saudi Arabia. It is situate roughly 500 km south-east of Petra, 400 km northwest of Medina and 22 km north of Al-Ula [1]. The limits of the core zone was identified by the following three points: North limit: 26° 48' 52" N – 37° 55' 51" E, East limit: 26° 47' 23" N – 37° 58' 17" E, South limit: 26° 46' 09" N – 37° 56' 12" E. It is well known among scholars and travelers for its rock-cut monumental tombs similar to those in Petra [2]. The site lies in a large plain across which the Wadi Al-Ula runs from north-east to south-west. It was marked by a number of sandstone outcrops of various sizes and heights. The most impressive among them is Jabal Ithlib, north-east of the site, rising to almost 100 m above the

surrounding plain [1]. Nabataeans settled in Al-Hijr between the second century BC and the second century AD. They left prominent antiquities in the form of magnificent rock cut tombs, praying places, settlement area, water reservoirs and irrigation system. During the early Islamic period, Al-Hijr was a main station on the pilgrimage route. A fort, water reservoir and a camp for the caravans were built for the service of the pilgrims. At the beginning of the 20th century, Hegea station built on the Hejaz railway line was laid connecting Al-Medina with Turkey via Syria. Al-Hijr site was spread on an area of 14.6 km2. Necropolis within the site, included several places and many of its tombs have local names such as; Qasr Al-Bint, Qasr Al-Fareed, Qasr Al-Sani, Al-Diwan … etc., fig. (1). Alveolar or honeycomb weathering is a weathering phenomenon found in diverse environments throughout the world. It occurs on sandstones and other rock types in natural outcrops [3]. Honeycomb weathering is a term used to describe numerous small pits or alveolae, no more than a few centimeters wide and deep, separated by the intricate network of narrow walls and resembling a honeycomb [4] [5]. The term alveolar or honeycomb weathering was also used in the description of weathering forms of building stones, explained 'alveolar weathering' on building stones generally as 'relief in the form of closely spaced cavities (alveolae)' [6]. Several authors used the term for a more or less regular system of back-weathered holes and pits in building stone surfaces [7] [8] [9]. This paper sheds the light on honeycomb weathering, its mechanism of formation and its effect on the sandstone outcrops that rock-cut tombs were carved in.

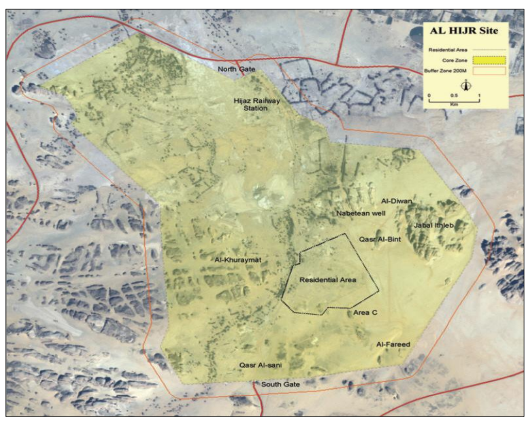

Figure (1) general view of Al-Hijr (Mada'in Salih), after Supreme Commission for Tourism Kingdom of Saudi Arabia 2007

2. Materials and Methods

Sandstone samples were collected to be examined and analyzed with the following methods: Optical Microscope (OM) Olympus BX40F-3 in order to characterize the optical features, superficial shape and the grains size [10]. Polarized Microscope (PM) ZEISS–Axioskop was used to determine the mineralogical composit-ion and the grain features by using many cross and thin sections samples [11] [12]. Scanning Electron Microscope (SEM) JEOL/EO, JSM-6380 device, equipped with an EDS link operating up to an accelerating voltage of 25 kV and a working distance of 9 mm was used to investigate the morphology of the deteriorated surface of the sandstone samples [13] and to detect the distribution of the chemical elements on the sandstone samples. X-ray diffraction method (XRD) perform-ed with an Ultima IV, multipurpose X-ray diffraction system equipped with a copper anticathode. The measuring conditions were set as follows: Cu target, 40 kV accelerating voltage, 40 mA current, the scanning range of 2θ was from 4 to 70° and the scanning speed was 2°/min. it was used to identify the chemicals compositions [14] of sandstone samples.

3. Results

3.1. *Field observations*

Through field observations of Al-Hijr (Mada'in Salih) site, it can be observed the following: The spread of the honeycomb phenomenon at Mada'in Salih sandstone outcrops differs in sizes and shapes, it is concentrating in the intermediate areas of the sandstone outcrops, fig. (2-a, b). The lower parts were suffering from severe erosion processes where the external parts of the rocky outcrop were loosed due to the multiple flaking process, fig. (3-a) and the high amount of salts in the form of solid hard crusts up to 0.7 cm thick fig. (3-b). It was also noted that the effects of rain water and its destructive effect was evident in the light yellow to white grooves at the rock surface. This resulted in dissolving and decomposing of the rock composition. This effected on the places (grooves) often surrounded by red-brown veins looking like the roots of tree, while cobbles are often observed in the red-brown sandstones fig. (3-c).

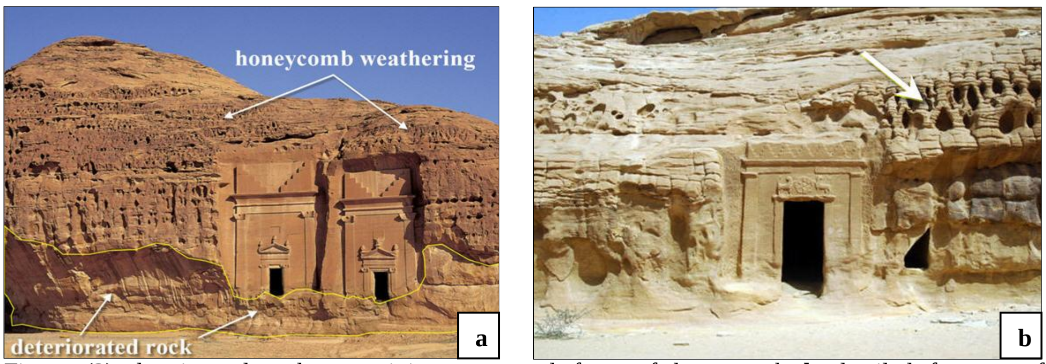

Figure (2) deteriorated rocks containing **a** general form of honeycomb **b** detailed features of honeycomb weathering in the intermediate areas of the sandstone outcrops, Al-Hijr site.

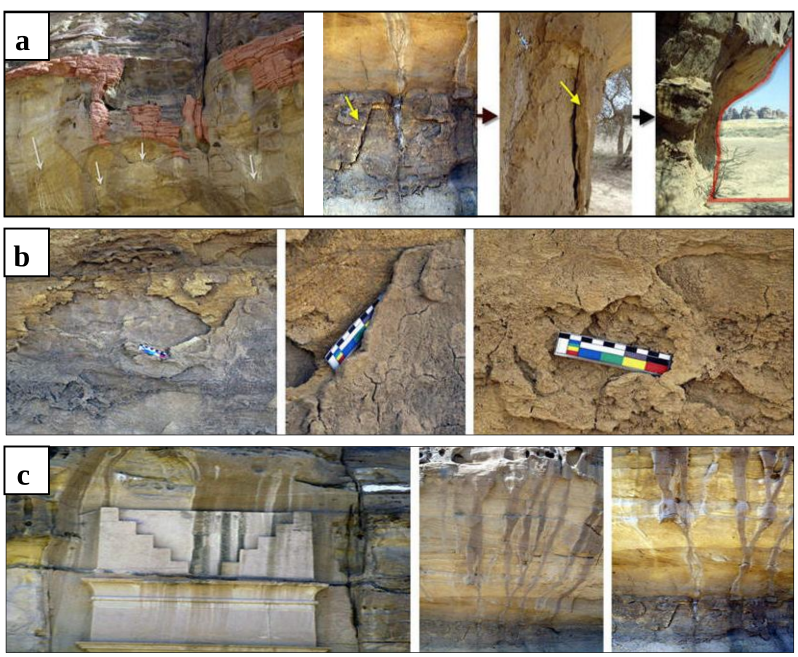

Figure (3) **a** multiple flaking process, **b** solid hard crusts of salt up to 0.7 cm thick, **c**, the dissolving and decomposing of rock by rain water

3.2. *Optical microscope results.*

The investigation of sandstone samples with the optical microscope showed that they composed of fine to large grained minerals that are different in shape and size, with pore-filling cement mainly consisting of clay minerals and feldspar in addition to lime cluster, fig (4-a, b) [15].

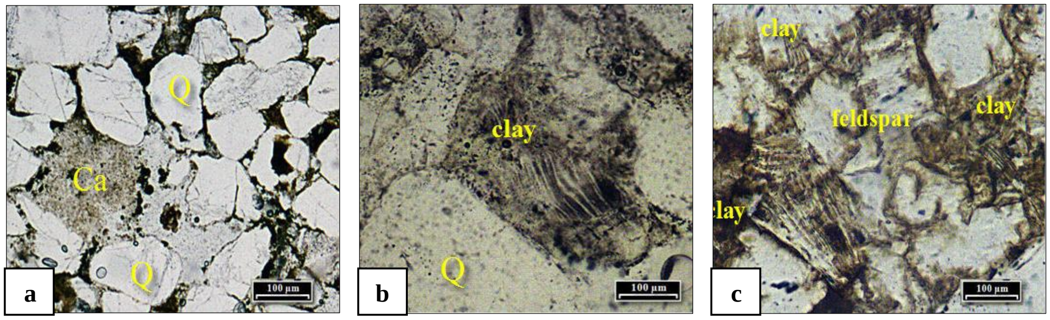

Figure (4) **a** the main components of Al-Hijr sandstone, **b** & **c** the clay mineral and feldspar between the quartz grains.

3.3. *Polarized microscope results*

Polarized microscopy "PM" is used to identify the crystal texture, grain size, shape and the type of cementing material of the sandstone rock. Its examination showed that quartz is the main component and there is variety in shape and size of quartz grains. Mono-crystalline and Polycry-stalline quartz grains were detected and feldspar, cluster of calcium and clay cement were also noticed, fig. (5-a, b) [5].

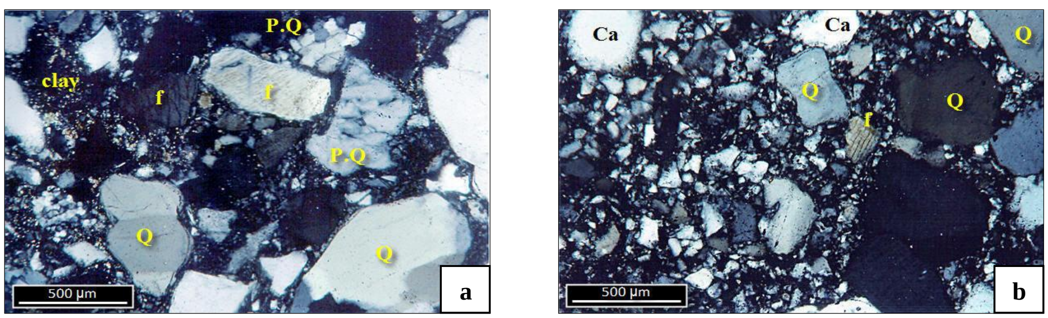

Figure (5) **a** variety in shape and size of quartz grains, Polycrystalline quartz grains (P.Q), **b** the clay mineral, feldspar and lime (Ca) between the quartz grains.

3.4. *SEM investigation results*

Scanning electron microscope investigations showed that grains of quartz and feldspar (the latter showing signs of alteration) were surrounded by a clay matrix, fig. (6-a, b). Clay minerals have a flat shape like small flakes. These flaked shapes are typical of Kaolinite [16]. Different spots of sandstone samples were investigated by EDS to identify their elemental composition, tab. (1).

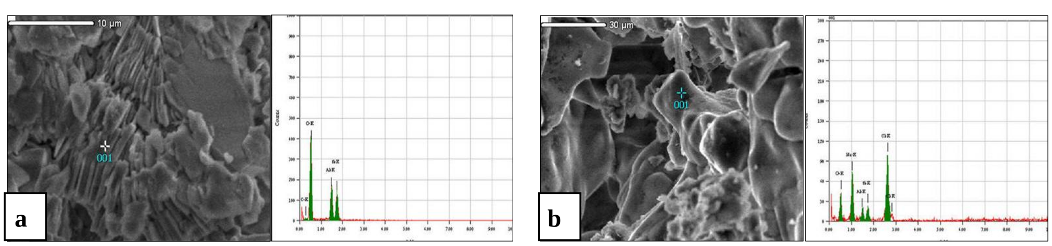

Figure (6) **a** SEM photomicrographs and EDS spectra of sandstone showing clay minerals flakes shapes, **b** halite crystal between the quartz grains.

Table (1) the elemental composition (wt. %) of the studied sandstones samples

Samples	***C***	***O***	***Na***	***Al***	***Si***	***Cl***	***Ca***
1	6.94	46.92	-	22.66	23.49	-	-
2	5.26	47.94	-	21.55	25.25	-	-
3	-	49.56	0.76	19.62	27.33	0.97	1.77
4	-	-	0.98	-	22.82	5.45	31.74
5	-	0.525	1.041	1.486	1.739	2.621	-

3.5. *XRD results*

Different sandstone samples were selected and prepared to be analyzed by the powder method [17]. The XRD analysis results were detected as listed in tab. (2) and shown in fig (7).

Table (2) the identified minerals of the stones and mortar samples by XRD analysis.

Samples	***Minerals***	***Formula***
Sandstone	Quartz	SiO_2
	Halite	$NaCl$
	Ringwoodite	Mg_2SO_4
	Kaolinite	$Al_2Si_2O_5(OH)_4$

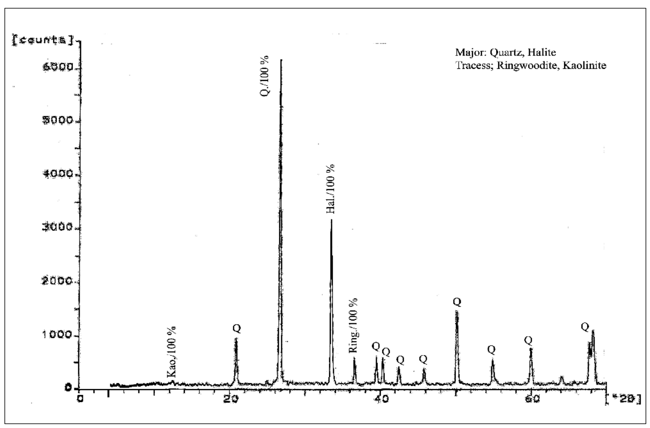

Figure (7) XRD pattern of the identified sandstone mineral phases.

4. Discussion

It should be noticed that the sandstones are not uniformly resistant and many layers are more subjected to erosion. The region of Mada'in Salih is arid with average rainfall below 50 mm per year (40 to 50 % of the rain falls in winter and 30 % in spring). The average annual temperature is 22°C, 12°C in winter and 30°C in summer [1]. Wind is one of the main agents of erosion in the area. Wind blowing mainly from the northwest is stronger in spring and at the beginning of the summer. Two main aspects should be considered regarding to honeycomb weathering of sandstones rocks; first is the influence of external factors such as climate, moisture, and salt availability, secondly is the intrinsic factors of the rock texture (homogeneity/heterogeneity) and the minerals composition of the sandstone rock. The investigations of the sandstones samples by OM, PM and SEM-EDS revealed that they have fine to large quartz grains (Mono-crystalline and Polycrystalline) different in shape and size. The polycrystalline quartz grains have sutured boundaries between the crystals. This is characteristic of quartz from a metamorphic source. Composite quartz from igneous sources usually has straighter crystal boundaries. The much finer sediment surrounds the composite quartz grains of mono-crystalline quartz. The pore-filling cement consists mainly of clay mineral and feldspar. The chemical weathering of feldspars may be rapid, producing micas and clay minerals. Therefore feldspars are most abundant and best preserved in rocks derived from mechanical weathering [18] [19]. SEM-EDS investigations showed that the grains of quartz surrounded by a clay matrix. Clay minerals are appearing flat in shape that is typical of Kaolinite [20]. The EDS investigation results of the sandstone samples identify the elemental composition where, Al, Si and O are representing clay minerals, Na and Cl representing halite salt, and Ca and C representing calcite (lime cluster). XRD results revealed that Al-Hijr sandstones mainly composed of Quartz SiO_2 the main component of the rock, and Halite NaCl as a salt. Ringwoodite Mg_2SO_4 and Kaolinite $Al_2Si_2O_5(OH)_4$ that considered as cementing matrix were detected as traces compounds. Deterioration caused by salt can occur from a variety of sources [21]. The soluble salt in porous stone can be spread into the stone by rain or ground water. As the water evaporates, salt re-crystallizes inside the rock. The salt crystals outgrowing the available space in the rock's pores exert pressure. This leads to a breakdown of the rock surface that often results in a loose powdery surface with a white appearance. The salty water in the weathering process seems to be the most important factor for honeycomb weathering. The wind might play a role in the initial formation of alveoli in salt-loaded rocks; honeycomb formation is necessarily related to heterogeneities in rock texture. Alveole can be evolution from a small pit in the rock surface and solely by salt crystallization during wetting / drying cycles [5] [22] [23]. The main deterioration mechanism of the rock-cut monumental tombs at Al-Hijr is swelling and shrinking of the clay minerals that form the cement or the matrix of the sandstone. In the presence of humidity, all clay minerals that Kaolinite includes, may be subjected to osmotic-type swelling processes if the pores in the rock contain an electrolyte in solution [16] [24]. Halite salt NaCl is one of the most effective electrolytes in osmotic swelling of clays. Figure (8) shows the processes of intra-crystalline and osmotic swelling in clays. Sandstone can absorb water to depths 1-2 cm inside the rock. This means that when rain falls directly on the rocks surface (wind-driven rain), the first few centimeters of the rock may experience a volume increase as a result of the clays expansion. This creates an area of tension that results in development of fractures between the wet zone of the rock and the dry zone behind it. Swelling stresses lead to the development of scaling and flaking as well as contour-scaling [16]. Once the external wet layer has dried as a result of evaporation due to the action of the sun, temperature increase during the day, and evaporation accelerated by the effects of the wind, the clays contract causing the appearance of drying or retraction fractures perpendicular to the surface as observed all over the Al-Hijr rocks. Water, swelling clays, and halite salt NaCl, together with the high degree of anisotropy of Al-Hijr rocks, all of them caused severe deterioration problems to the rock-cut monumental tombs. Once the rock starts to weather, it creates a hollow that in turn encourages further salt retention. This means that the salt weathering often results in the hollowing out of the rock to give a honeycomb appearance. The initial spacing of the hollows may be related to variations in rock properties and weathering creates a roughening of the rock surface. As weathering continues, small depressions either merge or become overwhelmed by adjacent hollows. Through this process of self-selection, collections of what appear to be optimally-sized honeycombs develop and can replace the majority surface of the rock. The hydration/dehydration behavior of magnesium sulphate is an additional factor that leads to damage and material loss in the developing alveolar holes. In addition to crystallization pressure, volume changes of this salt cause expansion and shrinking of the sandstone in the affected zone [5] [25], and accelerate the damage of the surface grain layers in the alveole. Since these processes are only dependent on the changing relative humidity of the air in the alveole and not on contact with liquid water, they can work even in dry periods without rain events. Weathering is limited to the outermost grain layers at the bottom and on the walls of the alveole with extremely high salt concentrations, gradually moving deeper each time after loss of the surface material. Detached sand grains mixed with salts can be frequently detected at the bottom of alveole. Larger holes can finally coalesce, fig. (9) [26].

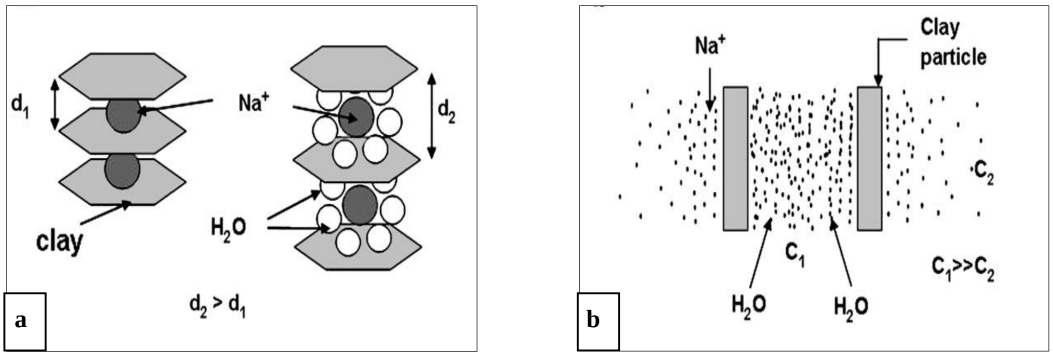

Figure (8) diagram of the processes of intracrystalline swelling **a** osmotic swelling of the clays **b** (basal spacing of the clays and concentration of Na ions (*after Sebastian and others 2007*)

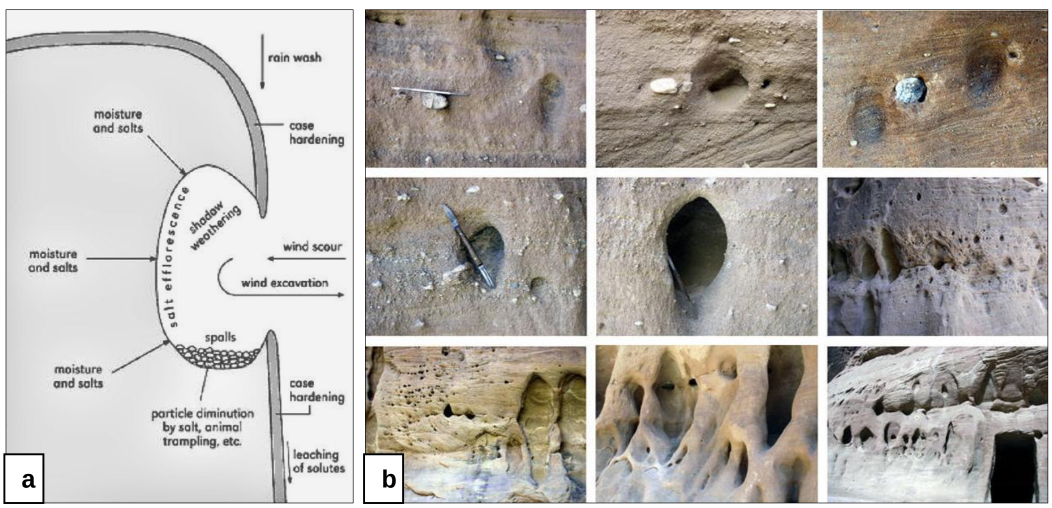

Figure (9) **a** the mechanism formation of honeycomb (*after Angel Ginés and others 2009*), **b** different stages of honeycomb weathering at Al-Hijr archaeological site.

5. Conclusions

The interaction of the following variables, i.e. water, swelling clays and NaCl, together with the high degree of anisotropy of these rock-cut monumental tombs, causes severe decay deterioration problems to the rock-cut monumental tombs. The most effective strategy for the conservation of this material would therefore be controlling these variables to minimize or prevent future damage to the rocks. This conservation strategy should include preventing the water from penetrating into the pores in the rock by implementing barriers (e.g. hydrophobic coatings), reducing the amount of NaCl in the pores for example by poulticing and increasing the mechanical resistance of the sandstone in areas of severe damage using suitable consolidants. The obtained results can be an important contribution to the study of sandstone's deterioration in historic buildings, and may facilitate the choice of the most suitable restoration method for the rock-cut monumental tombs.

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