sustainability

Article

The Sustainability of Rock Art: Preservation and Research

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Abstract: Rock art is a widespread cultural heritage, representing an immovable element of the material culture created on natural rocky supports. Paintings and petroglyphs can be found within caves and rock shelters or in open-air contexts and for that reason they are not isolated from the processes acting at the Earth surface. Consequently, rock art represents a sort of ecosystem because it is part of the complex and multidirectional interplay between the host rock, pigments, environmental parameters, and microbial communities. Such complexity results in several processes affecting rock art; some of them contribute to its destruction, others to its preservation. To understand the effects of such processes an interdisciplinary scientific approach is needed. In this contribution, we discuss the many processes acting at the rock interface—where rock art is present—and the multifaceted possibilities of scientific investigations—non-invasive or invasive—offered by the STEM disciplines. Finally, we suggest a sustainable approach to investigating rock art allowing to understand its production as well as its preservation and eventually suggest strategies to mitigate the risks threatening its stability.

Keywords: rock art; sustainability; ecosystem; surface processes; non-invasive sampling; scientific analyses

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1. Introduction

Rock art is widespread worldwide, from hyperarid deserts to remote islands, and represents one of humans' most fascinating cultural manifestations. Pictograms and petroglyphs are part of the archaeological record and can be found within caves and rock shelters or in open-air contexts. In all cases, rock art is directly connected to its past and present environmental settings for multiple reasons [1,2]. It is an immovable element of the material culture, created on natural rocky supports (boulders, vertical/flat rock outcrops, rock walls of caves and rock shelters) embedded in the landscape. Furthermore, rock art often depicts motifs representing past environments/ecosystems (e.g., [1,3,4]), and can serve as proxy data to reconstruct past biomes. Finally, the tight nexus between rock art, its natural support, and the surrounding landscape led paintings and engravings to suffer the same surface processes affecting rock surfaces along the Earth Critical Zone [2,5], the outer part of the planet spanning from groundwater to vegetation top that supports life on the Earth's surface [6].

Consequently, physical, chemical, and biochemical weathering and erosion menace the preservation of the world's rock art [7–9]. Surface processes include a large variety of events and dynamics that can destroy rock art or, in a limited number of cases, preserve it. Such processes act at different scales of resolution—from the macro- to the micro-scale—but the most common of them work at the micro-scale, thanks to the interaction between the lithosphere, atmosphere, hydrosphere, and biosphere. The interaction between the rock surface, pigments (in the case of pictographs), and microorganisms produces effects that are often detectable to the naked eyes in terms of degradation of the artwork (dismantling, exfoliation, change/fading in color, formation of crusts of biofilms), but in some cases, they contribute to stabilize surfaces and thus preserve rock art. However, their complete comprehension needs specific interdisciplinary laboratory investigations (Figure 1). At the same time, human activities may increase the rate of deterioration of rock art or cause its destruction. Rock art is a dynamic system at the edge between many compounds of the near-surface Earth Critical Zone. Therefore, to understand its formation and preservation, it has become mandatory to investigate the composition of rock art, the host rock, and the microbial communities (Figure 1), as well as for each type of cultural heritage [10].

Figure 1. Today, rock art research is extremely interdisciplinary and requires skills from the humanities as well as from STEM disciplines.

In this contribution, we explore the possibility offered by archaeological science to investigate rock art, going beyond the mere characterization of pigments and binder, and dating. We offer an overview on different approaches, including the description of the host rock, the role played by the local microbial community and the alteration that the rock art ecosystem suffered since its creation. Because surface and near-surface rock art contexts (rock shelters and open-air sites) are the most endangered, we focus our work on them. We discuss the sustainability of scientific analyses in terms of sampling and preservation. We suggest that a specific approach to sample pictographs and petroglyphs, while reducing the impact of sampling and maximizing information to mitigate ongoing or future threats, is mandatory.

2. The Fragility of the Rock Art Ecosystem and the Challenge of Sustainability

From the perspective of rock art fragility and its interaction with environmental processes menacing its stability and preservation, we can distinguish three major rock art sites conditions. In fact, if one considers rock art sites (i) inside a cave, (ii) in the atrial part of a cave or in rock shelters, or (iii) in completely open contexts, then a growing interaction with surface processes is evident. Such categories are merely related to topographic and geomorphological factors tuning the stability of environmental processes in correspondence of rock art sites and have no cultural, anthropological, or artistic implication.

Cave sites (Figure 2) are often isolated from the surface dynamic, and their micro-environmental conditions are generally steady up to the discovery of rock art when pristine climatic and biological conditions are perturbated by humans visiting the site for scientific and/or touristic purposes [11–16]. In such conditions, for instance, variations in humidity, light, and the colonization of microorganisms represent a potential threat to rock art [17–20], as well as for the whole cave ecosystem [21,22]. The complex ecology of communities living in natural caves has been known and explored for a long time (e.g., [22,23]), but specific investigations have also disclosed several microorganisms interacting with pigments in cave sites [18,24–26], whose metabolic processes are possibly critical for the preservation of rock art. Cave rock art sites thus appear to be substantially stable and—apart for the case of perturbation of their climatic and microbiological settings—they are substantially conservative.

Figure 2. Some examples of caves illustrating different types of deterioration of the rock walls potentially involving rock art. (**A**) Green biofilm, karst dissolution, and modern graffiti on the wall of a cave from northern Italy. (**B**) Mn-bearing coatings on the wall of a cave from the Italian

Apennines. (**C**) A cave in southern Italy with speleothems covering the rock walls and obscuring the pristine surface.

The case of rock art sites along the walls of the atrial part of cave or rock shelters is different. From the geomorphological point of view, we consider in this category all of the locations that are close to the Earth's surface, but they are, at least in part, sheltered under a rock roof (Figure 3). These include the atrial part of deep karst or solutional galleries and various types of rock shelters, formed after deterioration/erosion of rock walls or related to the collapse of rock cliffs. For the sake of brevity, we refer to this category of rock art locations as rock shelters. Due to their proximity to the surface, rock art sites in rock shelters deeply interact with physical, chemical, and biological surface processes. For the same reason, rock art galleries on bare rock walls or boulders in open-air contexts (Figure 4) are tightly related to the complex dynamic of processes acting at the interface between the lithosphere, hydrosphere, atmosphere, and biosphere. From our point of view, pictograms and petroglyphs found in rock shelters and open-air contexts share similar contexts and are affected by the same processes. Moreover, such processes oversee the preservation of rock art as well as its rocky support [5]; for that reason, we cannot distinguish between the stability and decay of the host rock and the preservation of rock art pigments.

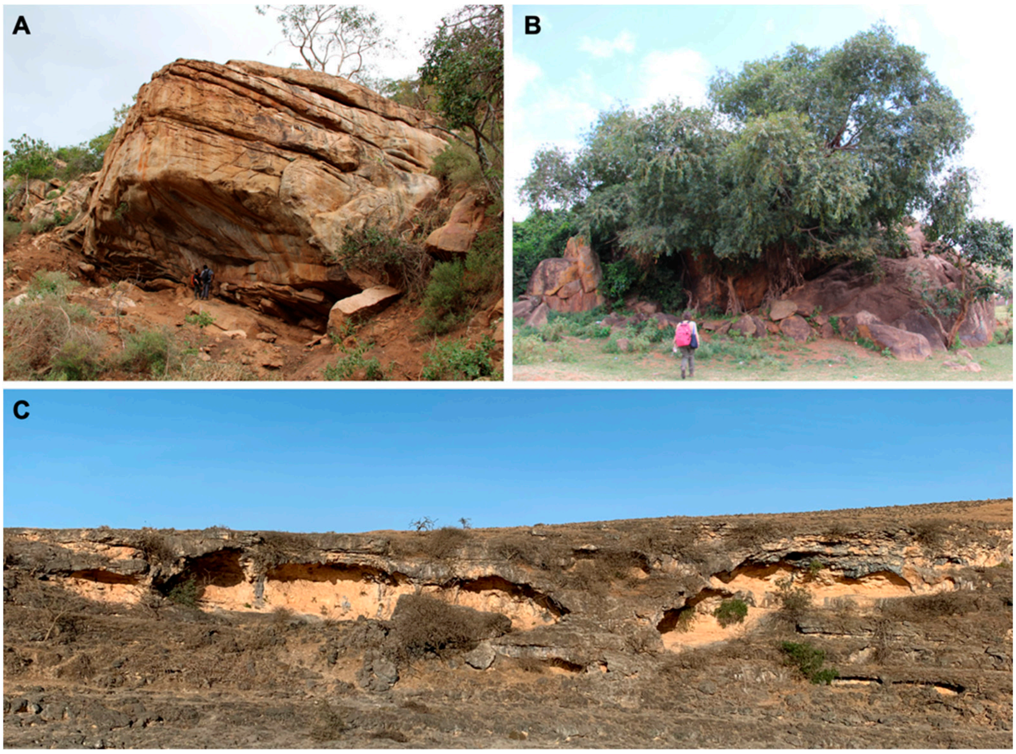

Figure 3. Some examples of rock shelters with rock art from (**A**,**B**) Ethiopia and (**C**) the Sultanate of Oman. In each case, the lithology of the bedrock and environmental processes oversees their formation and preservation along time.

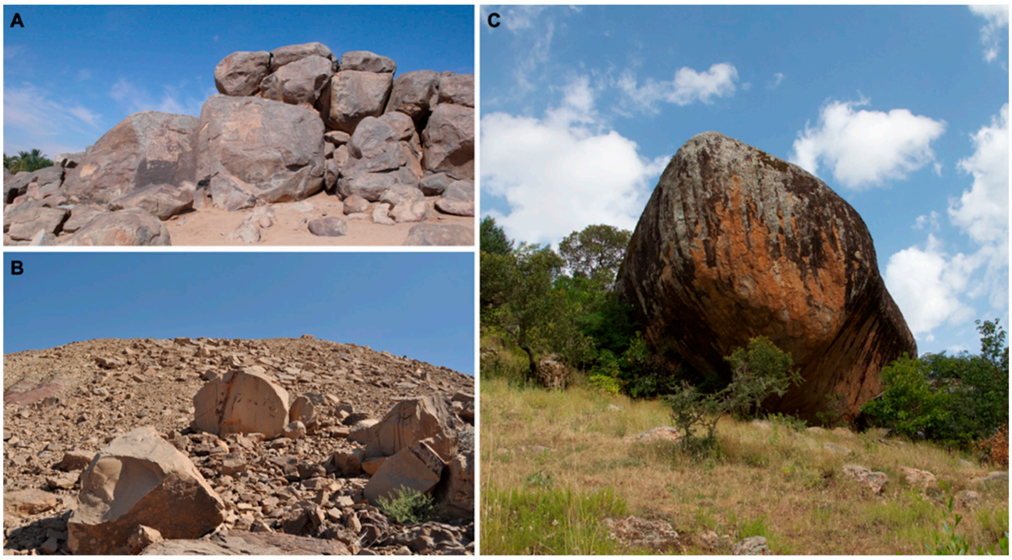

Figure 4. Some examples of open-air contexts with tock art: (**A**) rock wall with engraved hieroglyphs from Sudan, (**B**) a boulder with engravings in the Sultanate of Oman, (**C**) a granitic boulder (tor) with paintings in southern Ethiopia.

The host rock, mineral, and organic elements of pictographs and the biological community living at the interface between the two [27,28] interact in terms of biogeochemical cycles and thus belong to the same system. From this perspective, we must introduce the concept of 'rock art ecosystem' (Figure 5), meaning the complex and multidirectional interplay between the host rock, pigments, environmental parameters (humidity, light, pH, Eh, alkalinity, etc.), and the biological community that at the micro-scale tunes the preservation of rock art. Defining rock art as an ecosystem implies the existence of multiple interactions between a group of living organisms (the rock art and rock surface biome) living in a specific environment, represented by the rock–air interface and pigments.

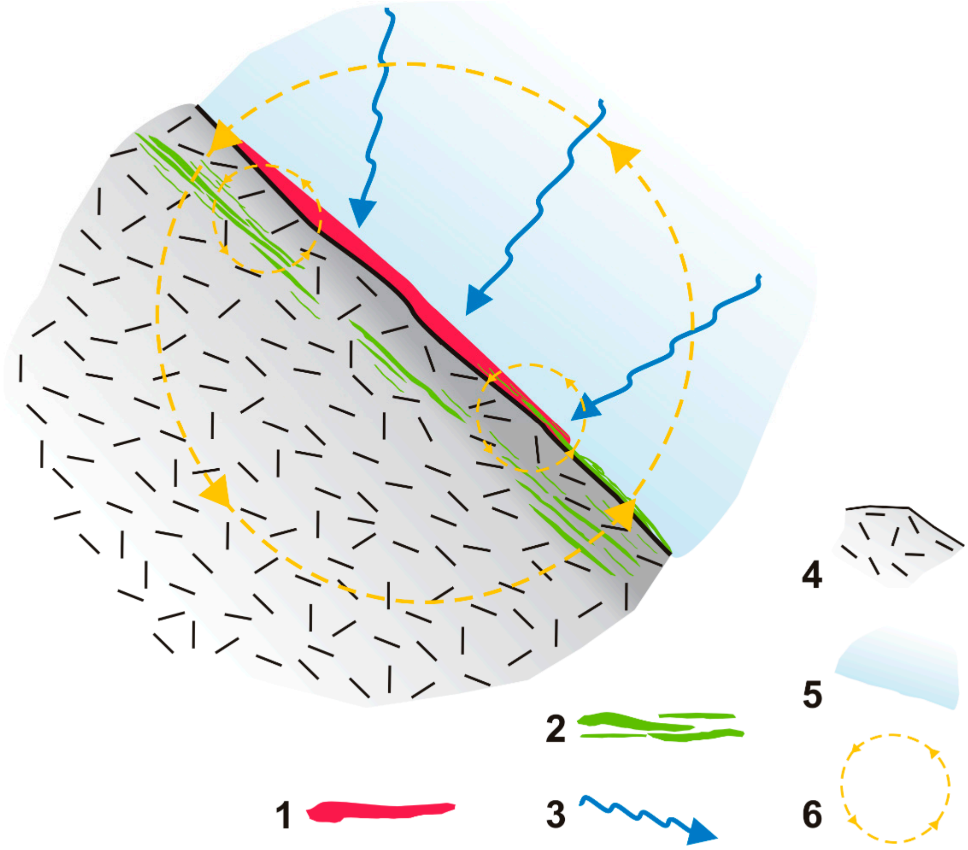

Figure 5. Theoretical sketch illustrating the concept of a 'rock art ecosystem' as the result of the interaction between the rock substrate, pigments, the biological community and external environmental the processes. Key: (1) pigment; (2) SABs (epilithic or endolithic); (3) exogenous forcings; (4) rock; (5) external environment; (6) biogeochemical exchanges between the components of the system.

To understand the processes controlling the preservation or destruction of rock art, it is therefore mandatory to investigate a complex ecosystem, including all of the mineral and biological components, postulate strategies for its preservation, and identify the way for its sustainability. Various multifaceted analyses on the rock are required to understand active and inactive processes at each site, assess the ongoing dynamics, and suggest future scenarios, including mitigation strategies for specific threats.

3. Processes Affecting Rock Art Stability

In this section, we offer a brief overview of natural and human-induced menaces threatening rock art sites in rock shelters and open-air contexts; the same processes are summarized in Table 1.

Table 1. Summary of major processes affecting rock art sites.

Process	Natural/Human	Scale	Location	Effect
Slope instability	Natural	Macro-scale	Rock shelter and open-air contexts	Destruction of rock substrate; slope deposit covers rock art sites
Cryoclastism Thermoclastism Haloclastism	Natural	Meso-scale	Rock surface along rock shelter and open-air contexts	Exfoliation; granular disaggregation; breakage; spallation; surface rejuvenation
Biological weathering	Natural	Meso-scale to macro-scale	Rock surface along rock shelter and open-air contexts	Rock surface desquamation and disruption; ecofacts (e.g., invertebrate nest) cover rock art
SABs growth	Natural	Meso-scale to micro-scale	Rock interface along rock shelter and open-air contexts	Promoting desquamation and granular disaggegation; stabiliziation of rock surface; formation of case hardening
Atmospheric agents	Natural	Micro-scale to meso-scale	Pigments	Decoloration, degradation, erosion
Continuos human occupation	Human	Macro-scale to micro-scale	Rock shelter and open-air contexts	Deterioration of rock surface; decoloration; destruction; rubbung of surfaces; alteration of chemical composition
Intensive land use	Human	Macro-scale to meso-scale	Rock shelter and open-air contexts	Destruction
Uncontrolled tourism	Human	Meso-scale to micro-scale	Rock surface along rock shelter and open-air contexts	Destruction; deterioration of surfaces; alteration of chemical composition; decoloration; vandalism
Inadequate investigation/restoration	Human	Meso-scale to micro-scale	Rock surface along rock shelter and open-air contexts	Destruction; decoloration; acceleration of the deterioration of surfaces

3.1. Natural Processes

The origin of rock art dates to the Upper Pleistocene, when parietal representations appeared at many world locations (e.g., [29]). Since that time, the locations of sites and rock art itself underwent several, major, rapid, or long-term climatic and environmental changes tuned by global climatic dynamics and local forces. For that reason, many representations depicted in rock art refer to specific environmental conditions and constitute an archive of proxy data for paleoenvironmental reconstruction complementary to the natural hydroclimatic archives commonly explored in Quaternary sciences [30–32].

A further implication of the initial statement of this section is that manifestations of rock art arose over a very long period under climatic and environmental conditions that often are no longer in balance with those of today (e.g., [2,5,33,34]). This has been primarily explored in arid lands of the Old World, where rock art representations dating to the latest Pleistocene and the Early and Middle Holocene preserve evidence of a fauna assemblage not compatible with the present-day biome of the Saharan and Arabian deserts (e.g., [1,31,35–39]), thus suggesting the occurrence of major, regional climatic shifts. Such significant climatic and environmental changes involved all of the components of the landscape. Consequently, the rock art ecosystem thermodynamically evolved towards new equilibria in terms of physical and chemical modifications of the host rock and pigments, and the evolution of the microbial communities. Moreover, a major climatic transition occurred globally since the Middle Holocene [40] and one of the main consequences was the activation of several geomorphological processes that increased the possibility to damage archaeological sites and destroy rock art galleries [34].

From the geomorphological viewpoint, surface processes acting at the micro-, meso- and macro-scale influence landscapes and ecosystems [41,42], including the rock art ecosystem (Figure 6). Among geomorphological processes, slope and fluvial processes are the most important actors in the preservation or destruction of pictographs and petroglyphs at the macro-scale. In open-air contexts, the degradation by gravity of rocky slopes may destroy or cover rock art sites. Similarly, the aggradation of sedimentary deposits along riverbeds or the lateral erosion of rivers may obscure rock art sites. Such processes are tuned by environmental changes, and ongoing climate change amplifies the dynamicity of natural systems thanks to the acceleration and increase of intensity of several geomorphic processes [43]. Extreme weather events, for instance, fuel catastrophic flooding events that are even more severe in arid lands, where the absence of vegetation cover hampers the possibility to protect the soil and reduce the times of concentration of rivers. More in general, we may refer to the concepts of biostasy and rhesistasy proposed by [44], suggesting that phases of instability push towards the obliteration or destruction of rock art and phases of biostasy may promote the rejuvenation of rock surfaces. Climatic instability oversees the increase in the intensity of slope failure and rockfall that involves rock art sites. The collapse of the roof of rock shelters, for instance, occurred at the transition towards more cold or arid conditions, and it is related to large-scaled cryoclastism or thermoclastism. In some cases, rockfalls involved rock art galleries. Along river catchments, paroxistic events of floods, including the rapid increase in fluvial load, trigger significant soil erosion, mobilization of blocks and boulders, and deposition of sediments. This is particularly severe in arid lands, where occasional and localized rainfall may result in destructive flash floods. Occasional rainfall also promotes runoff along slopes and sometimes along the walls of rock shelters, leading to the deposition of thin coatings of mud and calcite that occasionally cover paintings and engravings and promote microbial colonization.

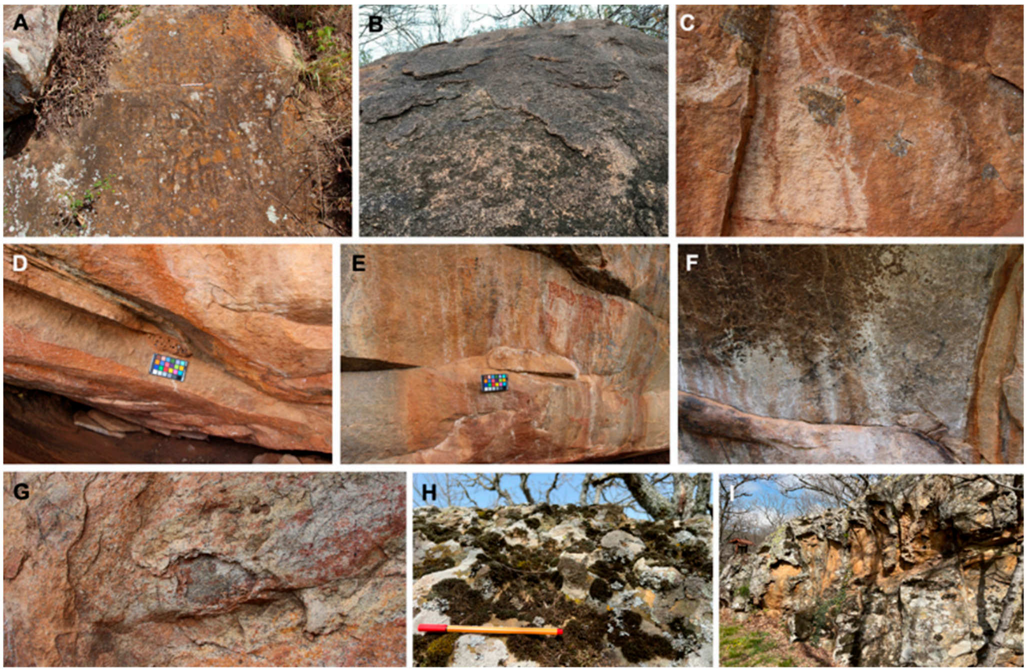

Figure 6. A variety of examples of rock surface decay from rock art sites or near them. (**A**) Lichens growing on engravings in an open-air site of Ethiopia. (**B**) Exfoliation of a granite surface; notice also the dark SAB covering most of the surface. (**C**) Exfoliation over a small area of paintings from a rock shelter in southern Ethiopia. (**D**) Hymenoptera nest in a rock shelter from southern Ethiopia. (**E**) Whitish crusts covering paintings in a rock shelter from Ethiopia. (**F**) Whitish crusts and dark SAB covering paintings in a rock shelter from Ethiopia. (**G**) Exfoliation and accumulation of reddish Fe-rich oxides on the surface of a rock shelter from Ethiopia. (**H**) Biological weathering on a limestone from southern Italy. (**I**) Effect of dissolution on a limestone from southern Italy.

At the meso-scale, thermoclastism, cryoclastism, and aloclastism induce large fractures on rocks that are evident on cliffs, walls, and single boulders, as well as—at the micro-scale—flaking, spalling, exfoliation, and granular disintegration. Such processes are critical along the walls and roofs of rock shelters, and most likely, this process oversees the loss of many rock art galleries. For instance, in arid lands, seasonal or daily temperature excursions trigger thermoclastism. Even though the true effects of this process are still debated, it appears evident that on granular and polymineral rocks, continuous expansion and contraction of grains promote the rejuvenation of surfaces through flaking [45,46]. A further process acting in arid regions is wind abrasion acting at the very rock surface; impacts of sandy particles amplify granular disaggregation and surface polishing including consequences on engravings [47]. Humidity is a further factor that can promote the rate of the dismantling of rock shelters. In fact, capillarity allows water to promote solutional weathering and weakens the outer part of rock walls. In the Sahara, it has been observed that this process was favored within rock shelters with organic deposits and in the proximity of joints between permeable and impermeable rock strata, because both factors promote the permanence of water in the proximity of the rock surface [48,49].

Various weathering processes act at the interface between the atmosphere and the rock [50], thus also involving paintings and engravings. At the micro-scale, it is hard to distinguish between physical, chemical, or biological weathering and most processes are a combination of them [51,52]. Physicochemical, biophysical, and biochemical weathering are the processes observed worldwide, and among them, biogeomorphological processes are the most evident. Insects and other invertebrates are very active on rock surfaces; for instance, wasps use the rock surface as a substrate to build up nests or excavate the rock, leading to its mechanical disruption [53]. Nevertheless, the most effective biogeomorphological processes acting at the rock–atmosphere interface are those promoted by microorganisms (bacteria, fungi, and algae) living above or inside the rock surfaces (Figure 4):

epiliths and endoliths, such as criptoendoliths, and chasmoendoliths [54]. Thus, it is not surprising to observe a thin veneer of densely packed microorganisms bound together by a secreted extracellular polymeric matrix (EPM), which forms complex communities called sub-aerial biofilms (SABs) [55]. Biofilm-dwelling cells interact intimately, influencing each other's evolutionary fitness through cooperative and collective behaviors. This social behavior confers cells substantial advantages compared to their planktonic counterpart in terms of increased resistance and resilience against external threats including desiccation and antimicrobial agents [56].

The growth of SABs on stone heritage has long been associated with a threat to conservation called biodeterioration, an undesirable change in material properties caused by the microorganisms' activity. This is not surprising given the widespread evidence of biogeomorphological (e.g., secondary mineral formation, EPM swelling, and contraction) and biogeochemical processes (e.g., production of organic and inorganic acids, metal-complexing EPM), which are vital to pedogenesis [57,58]. While SABs on stone heritage imply current or past interactions with the lithic substrates, their presence does not necessarily have a biodeteriorative role as is frequently thought [59–61]. A growing body of literature has reported SABs' neutral or even bioprotective effects on stones under certain conditions [62–66]. Such findings, combined with advances in biomineralization studies with indigenous carbonatogenic bacterial communities [67–69], have strengthened the concept of SAB-based protection as a sustainable strategy for stone heritage conservation [70,71]. SABs oversee many surface processes acting at the micro-scale on rock surfaces. Some of them are destructive and contribute to the rejuvenation of rock surfaces because they promote disaggregation and exfoliation, whereas others contribute to surface stabilization. In both cases, SABs action is relevant for rock art studies (Figure 7).

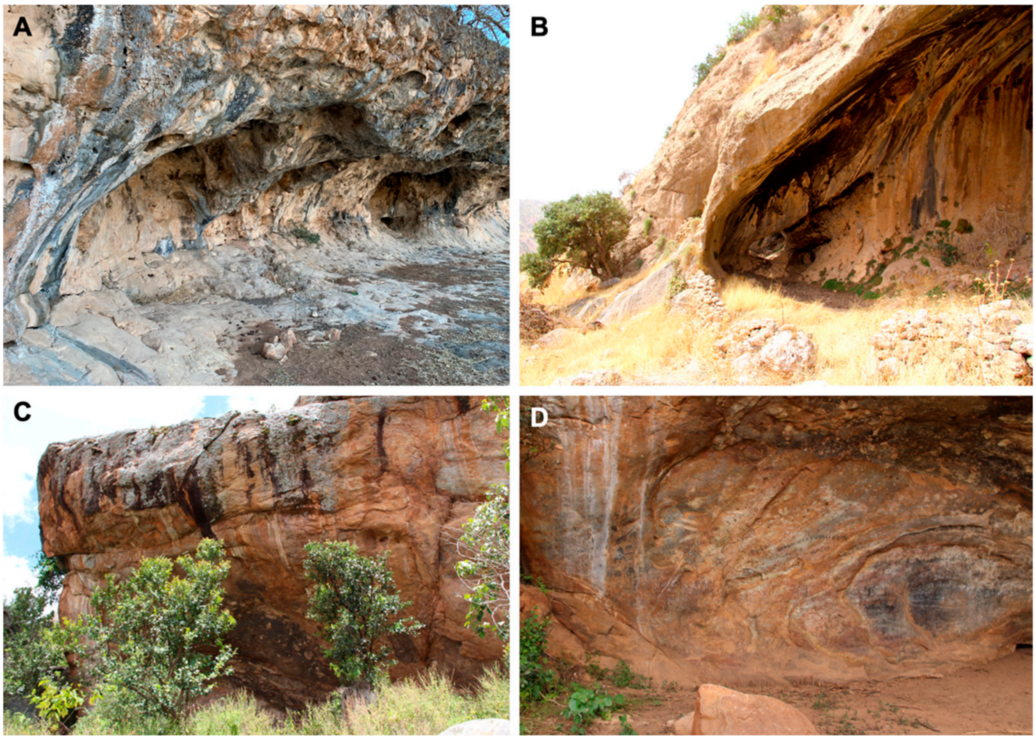

Figure 7. Examples of rock shelters displaying different types of SABs and other kinds of rock alteration from (**A**) the Sultanate of Oman, (**B**) Kurdistan Region of Iraq, and (**C**,**D**) southern Ethiopia. In each picture the difference is evident between the pristine rock surfaces and those where darkish to whitish SABs developed.

SABs flourish along the rock walls of open-air contexts and rock shelters (Figure 7), and their development is related to local environmental settings; many parameters such as environmental humidity, sunlight, and wind tune their formation and evolution. SABs forming on the rock surface may obscure pictographs and petroglyphs, and, in the case of paintings, SABs can interact with their mineral and organic constituents, leading, for instance, to their decomposition or removal. Biogeochemical cycles between rock art pigments and SABs/microorganisms (Figure 5) are poorly investigated but likely oversee the diagenesis of organic binders and prevent obtaining reliable radiocarbon dating of rock art. The case of endoliths may represent a great threat to the preservation of rock art sites. At many sites, paintings suffer severe damage due to granular disaggregation and desquamation, which can be promoted by chemical and physical stress triggered by the metabolic processes of microorganisms. The factors controlling desquamation are many and their action and interaction have never been entirely investigated. It seems that desquamation is the combined result of physical weathering and biological activity [50,72,73]. The accumulation and efflorescence of solutes (mostly gypsum, halite, oxalates), sometimes microns below the rock surface, promotes physical weathering and the detachment of the uppermost rock layers thanks to the continuous growth of crystals (haloclastism). Solutes have a twofold origin: they are accumulated from the local alkaline aerosol, or biomineralized (as a by-product) by different microorganisms living at and within the rock surface (endolithic organisms).

Microbial communities contribute to the formation of rock coatings [74], which sometimes have a sheltering effect on rock surfaces [33]. The most recurrent example of coatings formed after biogeochemical weathering and relevant to rock art research is Mn- and/or Fe-rich rock varnish. Rock varnish is the biochemical accumulation of manganese (and/or iron) oxyhydroxides thanks to the mediation of microorganisms [74–77]. The formation of rock varnish has been observed in different world environments, but it is noteworthy to notice that its preservation is favored in arid environments. Mn/Fe biomineralization likely occurs under semi-arid environmental conditions, and climatic transitions towards arid environmental conditions hamper the rejuvenation of rock surfaces; this has been reported in many deserts of the world [74]. From the geomorphological point of view, rock varnish plays a twofold role, being sometimes a canvas for engravings, and in other cases the dark veil covering and protecting surfaces (Figure 8).

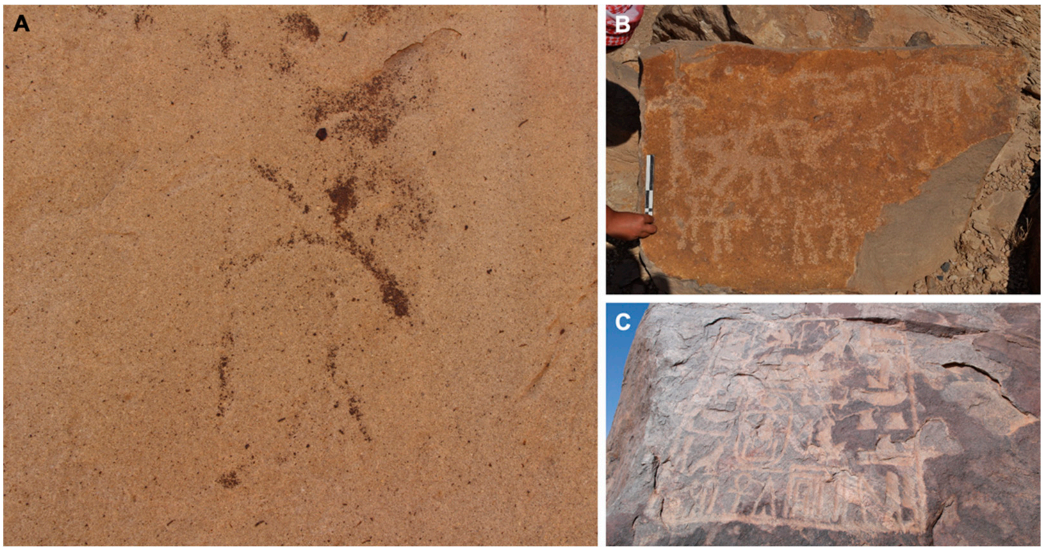

Figure 8. Mn and/or Fe rock varnish is relevant for engravings because it can preserve engravings from destruction as reported from the Sultanate of Oman (**A**). Moreover, rock varnish is also a type of natural canvas for petroglyphs, as evident from (**B**) engravings on a limestone block covered of Fe-rich varnish from the Sultanate of Oman and (**C**) engraved hieroglyphs on a rock wall of granite covered by a Mn-oxyhydroxides bearing coating found in Sudan.

When rock varnish is a relict landscape feature or the rate of varnish formation is too slow to re-cover engravings, it represents a non-renewable canvas for ancient artists and the rate of varnish [76,78]. However, the partial regrowth of rock varnish is a valid relative dating method for engravings superimposition [76,79], as well as offering the opportunity to estimate petroglyphs' age via chemical measurement of elements and areal density of Mn and Fe [80–84]. From a different point of view, the formation of continuous and some tens of microns-thick Mn-rich coating represent a case-hardened shell [61] protecting rock surfaces against wind abrasion. Where deterioration processes are particularly severe, the development of a biomineralized Mn- and Fe-rich rock varnish inside the grooves of the engravings hampers the effect of rock dismantling, sheltering petroglyphs and promoting their preservation [33].

Finally, it has been reported that biogeomorphological processes leading to the destruction of rock art are more abundant when—as in correspondence of many rock shelters—a thick archaeological deposit, rich in organics, is present [49]. Likely, this is the consequence of the micro-environmental conditions created in the rock shelter due to the accumulation of organics that increases local moisture and promotes microbial activity. However, the state of conservation of paintings is excellent if they have been buried for a long time in a sterile environment and only recently exhumed [35].

Paintings have been subjected to perhaps even more severe degradation than engravings, due to their intrinsic lower resistance to atmospheric and biological agents and surface processes. They have been preserved on the sections of shelters protected from the action of rainfall, wind, and direct sunlight, but other processes are involved in their progressive degradation (see below).

3.2. Human-Related Processes

Anthropogenic processes, ranging in intensity and severity, represent a critical threat to rock art preservation. Deliberate damages related to vandalism have the most immediate and destructive effects. Spray paint or engraved graffiti covering rock art are reported worldwide with different damage intensities [8,85–87]. The removals and thefts of portions of rock art panels have been frequently reported, as done by collectors, and sometimes in the past also by scholars [88–90]. To these deliberate damages, we should also add acts of iconoclasm that can target and destroy specific motifs [91–93].

Furthermore, it is possible to identify at least four other sets of anthropogenic processes that can (more or less) accidentally menace rock art, such as (i) the daily use of rock art shelters and caves through the millennia, (ii) unsustainable and uncontrolled economic development, (iii) the inadequate management of rock art heritage, and (iv) improper and unprofessional research study.

i. Rock art sites are often places where people live or at least spend part of their life, conducting activities that can have long-term and cumulative negative impacts on rock art. The use of fire and the continuous touch or rubbing of humans and/or animals on rock art panels result in the formation of patination that may cover the original painting or contribute to their deterioration [94,95]. Additionally, the presence of domestic animals can disturb rock art, influencing the humidity and/or chemical composition of the atmosphere in correspondence with the rock wall.
ii. Many different processes related to economic development can negatively impact rock art sites with different degrees of damage. Oil exploitation, mining, building, and infrastructures are only a few examples of the anthropogenic processes that can accelerate the degradation or even cause the destruction of rock art contexts in the open air. The effects of oil prospections can accelerate the cracking of the host rock surfaces, whereas mining, buildings, and infrastructure can cause the removal, displacement, and destruction of rock art panels [96,97].
iii. The lack of adequate management of rock art sites associated with unsustainable tourism can also dramatically impact rock art. The absence of protections distancing visitors, visitor centers, or informative panels open the way to inappropriate site visits, increasing the risk of touching, wetting, and vandalism to the rock art (e.g., [86]).

iv. Improper recording and restoring/conservation processes can significantly impact rock art. Invasive techniques of recording by direct contact and rubbing of paintings and engravings surfaces conducted by researchers contribute to the fading and vanishing of painted motifs, the alteration of carvings, and the damage of rock surfaces [98,99]. These actions can also be combined with other processes, such as enhancing the contrast between a pictograph and its rock substrate by wetting the rock surface with water or other liquids [100] or inadequate attempts to obtain casts of the petroglyphs. The former causes the fading and vanishing of paintings, whereas the latter results in the deterioration of the rock surface, the partial removal of the original rock varnish, and possibly the permanent littering of the rock. Furthermore, the use of chemical products (e.g., Paraloid B-72) to consolidate rock and painting surfaces can result in a darker tone in the color of the painting and rock surface and a crust effect, increasing the risk of surface spalling [101].

4. Methods for Investigation of Rock Art

From this brief review on processes acting in rock shelters and open-air contexts, it is clear how many varied factors represent potential threats to rock art. Some of the physical and chemical processes that cause the degradation of the rock surfaces on which there are manifestations of rock art are very evident and trigger huge losses. Climatic and environmental factors promote processes, and ongoing climate changes amplify their effects. Yet, biophysical and biogeochemical processes acting at the very rock–air interface and related to the existence of SABs are much more challenging to identify, quantify, and interpret. Likely, most of them oversee the loss of rock art, but in some cases—especially in the case of SABs—they can hamper the efficiency of specific destructive processes. In such a complicated scenario, mitigating the effects of natural processes with targeted interventions and eventually planning in situ restoration are the only possibilities for preserving rock art. To accomplish the task of threat identification, a specific diagnostic approach that includes monitoring of each site and scientific analyses of rock art and the bedrock is required. We believe that the two components (rock art and rock substrate) must be investigated together, as they represent a unique ecosystem.

Starting from this consideration, we suggest a biogeomorphological approach to weathering processes based on in situ and laboratory analyses of rocks and pigments, and the multidisciplinary investigation of SABs [5,27,33,102]. As most of the rock decay processes act at the micro-scale—thus representing a sort of ‘phantom menace’—it is almost unrealistic to identify and describe threatening processes without sampling SABs, pigments, and the rock surface. An in situ characterization of the components of the rock art ecosystem is not entirely informative, as it is impossible to fully understand the proper dimension of the biological community and ongoing biogeochemical cycles. Physical, chemical, mineralogical, and biological analyses on rock surfaces and rock art have different degrees of disturbance, from non-invasive to considerably invasive, depending on the applied sampling strategy and the amount of material sampled for analyses. The scientific community is aware that rock art sampling is controversial, because, in many cases, it leads to great damage (e.g., Dayet et al., 2022 [103]), but recent approaches demonstrate that strategies of limited destruction and almost non-invasive sampling are possible [5]. Besides that, we are also aware that scientific investigation is mandatory to understand many cultural traits of rock art [104], including ancient technologies and the choice of ingredients for pigments [105–108], and for dating [109–111]. Scientific analyses in the recent two decades revealed diverse mineral colorants in pigments, and in rare cases investigated organic binding agents that are more prone to deterioration.

We briefly review the major possibility offered by scientific investigations on rock art, which are reported in Table 2. Non-invasive methods are currently applied to record rock walls hosting rock art [112–114] and to assess their state of preservation, including to identify ongoing processes of rock decay [115]. Different instruments (including low-cost instruments) and methodologies have been applied to perform structure-from-motion photogrammetry on rock art panels. Moreover, several indexes exist to scientifically estimate the stability of rock art and they are based mostly on biogeomorphology observations and in situ measurements [34,116]. Stability indexes offer the first effective tool to plan investigation and preservation strategies, as in the case of the Rock Art Stability Index [117,118].

Table 2. Summary of scientific analyses carried out on rock art illustrating their aims, limitations, and invasiveness of sampling.

Analytical Method	Sample Requirements	Research Question	Information Provided	Limits
Structure-from-motion photogrammetry	Non-invasive	Rock art recording	3D models or rock art sites	
Stability indexes	Non-invasive	Define the preservation of rock art	Quantitative data on rock surface stability	
Optical microscopy	Enough sample to manufacture thin section	Mineral composition and texture	Identify minerals and their interaction	Difficult to identify organic constituents
XRF	Portable: in situ, no sampling; benchtop: sampling required	Inorganic pigment, bed rock, crust, accretions	Qualitative elemental analysis	Detect elements heavier than Al or Si; only surface analyses
Raman	Portable: in situ, no sampling; benchtop: sampling required	Organic and inorganic pigments, bed rock, crust, accretions	Identify minerals, organic and inorganic molecules	Background noise and fluorescence affect results in situ; only surface analyses
XRD	Small sample to produce powder	Crystalline structure	Quantitative mineral analysis	Difficult to identify pristine and newly formed minerals
FTIR	Small sample to produce KBr powder pellet or micro-sample	Mineral and organic residues	Identify minerals and organic molecules	More proficient with amorphous and organic materials
SEM-EDX	Non-destructive to sample but requires carbon coating and sometimes polished surface; alternatively very small samples	Surface morphology, stratigraphy and composition of pigments	High resolution images and semi-quantitative elemental analysis	Analyses are semi-quantitative
Confocal laser scanning microscopy	Non-invasive sampling procedure through adhesive tapes	SAB architecture and interaction with the mineral substrate	3D images and semi-quantitative analyses of the SAB components	Analyses are semi-quantitative
Molecular investigations	Small samples, destructive	Structure and function of the SAB community	Qualitative and quantitative data about the identified microorganisms and their activity.	Difficult to recover genetic materials from SABs on rock art.
ICP-AES	Small samples, destructive	Concentration of elements	Quantitative analysis of major elements	
NAA	Small samples, destructive	Concentration of elements, provenance studies	Quantitative analysis from major to trace elements	

LA-ICP-MS	Small samples, micro-sample	Concentration of elements, provenance studies	Quantitative analysis from major to trace elements	
GCMS	Small samples, destructive	Organic binder	Identify organic molecules	
LC–MS/MS	Small samples, destructive	Organic binder	Identify proteins	
AMS 14C	Small samples, destructive	Chronology	Age of painting	Require a preliminary assessment of organic content
Uranium-series dating	Drilling microcores	Chronology	Relative age of painting (limit ante or post quem)	Possible gaps between carbonate deposition and rock art production

A wide range of geochemical techniques have been used to characterize the composition of rock art and ochre materials ([107,119] and references therein), in which the mineral composition could be identified by thin section petrography, X-ray diffraction (XRD), Raman spectroscopy and Fourier transformed infrared spectrometry (FTIR). Elemental analysis could be carried out by semi-quantitative methods such as scanning electron microscopy coupled with dispersive X-ray spectroscopy (SEM-EDX) and X-ray fluorescence (XRF), or the concentration of elements could be determined by inductively coupled plasma and atomic emission spectroscopy (ICP-AES), neutron activation analysis (NAA), and laser ablation inductively coupled mass spectroscopy (LA-ICP-MS), in which NAA and LA-ICP-MS are considered the most sensitive to trace elements [120]. Among these, the portable version of XRF and Raman are non-invasive methods that could be executed without sample removal and preparation, while the attenuated total reflectance (ATR) mode of FTIR and LA-ICP-MS require tiny volumes or micro-samples. It is important to highlight that portable instruments can be easily employed in the field but with the limitation of use only on external surfaces. To preserve the integrity of the rock art, non-invasive spectroscopic analyses are recommended for a preliminary inspection to thoroughly understand the current situation in situ. Based on preliminary analyses, plans could then be laid out for sampling that is crucial to answering research questions, thus minimizing the risk of damages. This strategy requires the use of portable instruments that could be transferred to the site [107], but not in remote rock art contexts. The most applied devices are portable XRF (pXRF) and Raman. Portable XRF can read elements heavier than Al or Si; it is, therefore, possible to identify pigments in rock art palettes such as Fe from red hematite ochre and Mn in black manganese oxides [103]. Raman identifies both minerals and organic substances but encounters difficulties when identifying organic binders in situ due to fluorescent background materials; moreover, the possible diagenesis of organics may hamper the possibility to distinguish between primary constituents and neoformations. FTIR can act as a complementary vibrational spectroscopy method in some cases for characterizing organic binder residues. However, sampling is usually required for further details, and such is the case when using gas chromatography-mass spectrometry (GCMS) that effectively identifies organic molecules in works related to cultural heritage [107,121]. Non-invasive spectrophotometric and colorimetric methods have been occasionally applied to rock art research to characterize paintings and engraved rock surfaces based on color gradations; spectroradiometers, colorimeters, and mobile platform apps for recording of color have been tested [122,123]. Such methods have been developed to improve the characterization of colors for recording of rock art sites [124] and sometimes include the development of low-cost software allowing the colorimetric recording from complete image scenes with commercial cameras [123]. In situ microfading spectrometry has been tested for mapping color degradation of rock art paintings [125], and colorimetric analysis testing the possibility that color gradations might be quantifiable for purposes of dating has been experimented on petroglyphs [126].

In recent decades, archaeological dating methods improved precision and minimized the amount of sample needed [110,111]. These developments also benefit the dating of rock art, which is more challenging than other archaeological issues due to the limited material available for dating. Radiocarbon dating remains the most exploited methodology because colors are generally obtained by mixing mineral pigments and organic binder (milk, egg, honey, resin). Unfortunately, the organic remains of microorganisms are also present within pigments; their occurrence suggests that the organic binder may offer a good substrate for bacteria, fungi, and algae, but also implies that the organic fraction of paintings underwent degradation and diagenesis across time [5,30]. This is one of the reasons why radiocarbon dating on paintings is very difficult and requires accurate identification and characterization of the organic compound submitted to measurements [127,128]. The main component of rock art—namely the organic pigment, charcoal, carbon black or soot—is scarce and available to limited sampling due to its value and conservation issues. Moreover, what will be analyzed for each individual sample must be understood to interpret the dating result correctly. With accelerator mass spectroscopy (AMS) 14C dating, only a few milligrams of sample are required. Bonneau et al. (2017) [127] employed an extensive protocol on south African rock art using SEM-EDX, Raman spectroscopy and FTIR analysis to determine organic carbon in the samples before treating them with a modified acid-base-acid (ABA) treatment. These investigations helped ensure enough organic carbon from the paint source while ABA pre-treatment removed contaminating calcium oxalates before combustion and graphitization for radiocarbon dating. Steelman et al. (2021) [129] used a different approach at Eagle Cave in Langtry, Texas, with plasma oxidation to isolate organic carbon directly from the paint layer, and avoided loss of dating material during an acid pre-treatment. An alternative to dating pigments is to date oxalate accretions over and beneath the painting. Calcium oxalates are often associated with microbial activities that precipitate minerals over the rock art, obscuring the art while preventing further deterioration. Oxalates formed under the painting provide the maximum age while accretions formed over the painting give a minimum age, suggesting a possible chronology for the painting. In this case, carbonate and organic carbon were removed with plasma oxidation, and pure oxalate samples were dated. Caution is required in dating oxalates as they are highly soluble and they can suffer multiple recrystallizations [5] and consequent re-opening of the carbon system. The same stratigraphic concept described for oxalates could be employed for coralloid speleothems formed from thin water running over the surface [130]. In this case, micro-drilling or scratching of calcium carbonate developed above/beneath rock art can be dated, thus offering not a direct age for rock art manufacture (as in the case of radiocarbon dating) but a limit ante quem (speleothem covering rock art) or post quem (rock are above speleothem) for its production. Samples of speleothems with paint in between were taken from caves for uranium-series dating on rock art from Europe [131–133] and Asia [111,134,135]. Carbonates are more stable than oxalates and U-series dating results are more reliable than other dating systems. Attempts have been made to determine the age of petroglyphs and weathering crusts and varnishes efficiently support the substrate for radiocarbon [30,33] and chemical measurement of elements [80–84]. In this case, the required sample is small, and it can be collected, after a careful geomorphological assessment of surfaces, on the rock substrate of engravings but not directly on them. Luminescence methods have been attempted in some cases; in fact, surface luminescence dating of rock surfaces and Optical Stimulated Luminescence (OSL) have made some considerable progress and can be applied to engraved rock surfaces [136,137]. In this case, sampling can be made not directly on engraved surfaces, but such studies must also carefully consider the degree of deterioration of the host rock surface [137].

The analysis of organic residues and SABs is a new development of heritage science and offers perspectives on how microorganisms are changing the art and its surrounding lithic environment. Early research was conducted in Atlanterra shelter (south Spain) using cultured methods [138], whereas in recent years, next-generation sequencing allowed the identification of non-culturable bacteria, which are the majority in environmental samples. This includes research from Ethiopia that identified bacterial communities from rock art panels by 16S rRNA gene sequencing, which found bacteria with mineralization potentials that could form patinas, and animal microbiomes possibly resulting from herding activities at the site [27]. The researchers used confocal laser scanning microscopy (CLSM) to reconstruct 3D images of the SABs colonizing the colored outer coatings from the Ethiopian rock art gallery. The samples were collected using the adhesive tape strip technique, which allows obtaining a mirrored image of the SABs. This technique is easy to apply, inexpensive, reproducible, and safe for the rock surface. In addition, it is possible to obtain information on the morphology and taxonomy of microorganisms and their relationships with the colonized material surfaces. The 3D SAB images showed the organization of the microbial communities, highlighting the differences between the two samples investigated. The sample close to the bottom of the rock art panel with a whitish patina presented a more diverse SAB with higher phototrophs, chemotrophs, and EPM than the sample taken from the lower right with a red patina on the surface. Another study used shotgun metagenomics combined with microscopic investigations to reveal the structure and function of the SABs colonizing petroglyphs in the Negev desert (Israel) [28]. A total of 96% of the identified sequences were phylogenetically assigned to the Bacteria, suggesting the predominance of this domain in the SAB community of petroglyphs. The SABs showed metabolic pathways involved in elements cycles and uptake processes, providing evidence of their potential role in the solubilization and mineralization of the mineral substrates. Interestingly, Roldán et al. (2018) [139] applied both 16S rRNA sequencing and proteomics (protein analysis with liquid chromatography and tandem mass spectrometry (LC–MS/MS)) on Levantine rock art to reveal bacterial communities and possible protein binders. Moreover, metagenomics is often applied to the investigation of the decay of building materials [55,140,141]. Traditionally, to know genera and species of lichens, symbiotic organisms formed by fungi, and algae or cyanobacteria, identification tools were paper-published as dichotomous keys [142–144]. More recently, digital keys are also available [145]. However, we should keep in mind that either cultural or molecular techniques only provide a current snapshot of the colonization. Thus, previous rock art phenomena (e.g., mineral precipitation or dissolution) cannot be associated with the current biological activity with high fidelity, especially if the time gap is significantly large.

5. Non-Invasive or Micro-Invasive Methods?

The delicate equilibrium between sampling and quality of collected data is crucial in understanding rock art in terms of dating, composition, and assessment of its preservation. In the case of rock art dating, sampling is mandatory apart from the very few relative dating cases, such as luminescence dating applied to sediments covering rock art sites (see, for instance, [35]). State-of-the-art radiocarbon and U-series dating methods require few milligrams of organics or carbonate, respectively, thus resulting in minimum invasive sampling. In any case, sampling points fall on representations; only for U/Th dating, the sampling can be done besides rock art representations, after an accurate assessment of the lateral continuity of speleothem related to rock art. The same minimal invasive approach is rarely applicable for radiocarbon dating, except in the case of engravings covered by rock varnish or other kinds of crusts/coatings [33,76,146].

Non-invasive methods such as photogrammetry and the definition of stability indexes are mandatory to assess the preservation of rock art sites. Moreover, non-invasive analytical methods can help trace a preliminary assessment of the characteristics of rock art and its support, but their application is limited to the surface. Yet, the major biogeomorphological processes occur within pigments and/or below the rock surface; this suggest that sampling is required to fully understand the relationships between the many components of the rock art ecosystem and assess the threats to rock art preservation.

Microsamples also offer the opportunity to conduct laboratory experiments on rock substrate stability after artificial aging [147]. In a recent experiment with pXRF, Dayet et al. (2022) [103] observed that the heterogeneity of paintings systems and the variability in primary and secondary minerals hamper the possibility of investigating rock art only following a non-invasive approach and concluded that the best solution for rock art research is a combination of in situ and laboratory analyses. From this perspective, a micro-invasive approach that guarantees rock art preservation and makes available a small quantity of pigments and/or rock substrate is mandatory.

In our recent experience in rock art research in a variety of remote locations, we tried to establish a procedure to reduce sampling and, at the same time, increase the possibility of mining information using different methodological approaches [5,27,33,148]. In remote locations, it is hard to transport (or export) portable instrumentation; thus, we decided to proceed with several steps: (1) biogeomorphological survey of the rock substrate to assess the potentially many and diversified types of surface rock decay and SABs formation at the rock surface and/or below it; (2) micro-sampling (using small sterile chisels) of each type of deterioration evidence on the rock surface, far from rock art representations; (3) very micro-invasive sampling of painting (pigments) or rock decay evidence related to representations. The latter point is the most critical of the procedure, and to guarantee the sustainability of a micro-invasive sampling we decided to use sterile tape for sampling. The sterile tape removes a minimal part of pigments, SABs, and weathering surfaces from a rock art gallery, allowing a quantity of sample sufficient for microbiological investigation and chemical and mineralogical characterization. Tape samples are divided into subsamples and sent to the different analytical lines, starting with observation under optical and scanning electronic microscopes. SEM imaging and semiquantitative analyses guarantee the first assessment of the composition of rock art and intensity of rock decay, highlighting the occurrence of organics and the interaction between the components of the rock art ecosystem. Such a procedure is, in our opinion, the best compromise between sampling and preservation and it allows us to understand the major surface processes affecting rock art.

6. Rock Art between Sustainability of Research and Responsible Tourism

World rock art constitutes a significant archive on the past that can help understand tangible and intangible aspects of ancient societies. It represents an extraordinary tool to fill the gap between the past and present, raising the awareness of civil society about the outstanding value of this heritage. Furthermore, rock art can represent a significant source of economic development (e.g., to promote tourism), particularly in remote areas of the world. However, rock art is one of the most fragile elements of the cultural heritage, a non-renewable resource that needs to be properly investigated, managed, and preserved. As evident from this contribution, rock art is a complicate ecosystem, and the understanding of its many interactions requires an interdisciplinary approach. Many natural and anthropogenic factors largely damage paintings and petroglyphs as well their rocky support. In many cases, there is little to do, and prevention is the most effective mitigation strategy, through education and training of local people, especially in areas where continuous monitoring is not possible. Yet, recent developments in the research allow to minimize the impact of recording and sampling techniques, highly reducing the damages related to the research.

At the same time, physicochemical and microbiological analyses are opening new perspective for the preservation of rock art, that, if combined with efficient development and management plans, can favor and support programs of sustainable tourism. Rock art has an extraordinary potential for the development of local communities, being highly appreciated by tourists [149,150]. Today, rock art tourism ranges from well-designed and controlled visitor centers and full fee-paying tourism ventures run by commercial operators to unrestricted visitation of archaeological areas promoted by amateur local guided tours [150]. The different approaches have consequently different results in terms of economic growth of local communities and in the standards of rock art site preservation and maintenance. As suggested by Deacon (2006) [149], the promotion of rock art as a touristic resource requires shared strategies aimed at understanding the interaction of key elements that affect the long-term conservation of frequently visited rock art sites as well as their original environmental and cultural (e.g., ethnoarchaeological) settings. In fact, specific tourism practices need to be adequate to local circumstances and local stakeholders [150–152] and the successful touristic development of rock art sites must include the development of the local economy and the promotion the local cultural landscape [153–155]. In such contexts of potential human-triggered threats to rock art sites, several successful examples of touristic accessibility exist, combining preservation and cultural and economic promotion. In some places there are on-site visitor centers; elsewhere tourist can freely visit a site without any form of supervision. In the case of caves [150], successful strategies include the complete closure of the original site, the allocation of a limited number of visitors, and the definition of restrictions. Occasionally, impressive on-site three-dimensional replicas of cave sites have been built (e.g., at Lascaux, Altamira, Pont d'Arc) or replicas are located within archaeological museums. Controlling the access to rock shelter and open-air sites is more difficult [86,150] and requires infrastructure, including physical barriers, walkways, and information panels. For remote areas where it is difficult to control the access to rock art sites, a common strategy is to not divulge the exact location of the sites to allow the access to such sites only through the services of local guides [150]. Finally, new technologies (e.g., immersive virtual reality) can provide powerful tool to increase the potentiality of virtual visits to rock art sites.

In conclusion, rigid (and standardized) protocols for sampling and analyses are required [156] to obtain comparable results, and a general more ethical approach to the sustainable study of rock art can no longer be postponed. Sustainability of rock art in terms of scientific investigation and its exploitation as a touristic attraction is the challenge for the future.

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References

1. Cremaschi, M.; Pizzi, C.; Zerboni, A. L'arte rupestre del Tadrart Acacus: Testimone e vittima dei cambiamenti climatici. In *La Memoria dell'Arte. Le Pitture Rupestri Dell'Acacus Tra Passato e Futuro*; di Lernia, S., Zampetti, D., Eds.; Edizioni All'Insegna del Giglio: Firenze, Italy, 2008; pp. 361–369.
2. Zerboni, A.; Cremaschi, M. The role of climate and bio-geomorphology in the degradation and conservation of Saharan rock art. In *Atlas of Rock Art of the Tadrart Acacus*; di Lernia, S., Gallinaro, M., Eds.; Edizioni All'Insegna del Giglio: Firenze, Italy, 2022.
3. Guagnin, M.; Jennings, R.; Eager, H.; Parton, A.; Stimpson, C.; Stepanek, C.; Pfeiffer, M.; Groucutt, H.S.; Drake, N.A.; Alsharekh, A.; et al. Rock art imagery as a proxy for Holocene environmental change: A view from Shuwaymis, NW Saudi Arabia. *Holocene* **2016**, *26*, 1822–1834. https://doi.org/10.1177/0959683616645949.
4. David, B.; Geneste, J.M.; Petchey, F.; Delannoy, J.J.; Barker, B.; Eccleston, M. How old are Australia's pictographs? A review of rock art dating. *J. Archaeol. Sci.* **2013**, *40*, 3–10. https://doi.org/10.1016/j.jas.2012.08.019.
5. Gallinaro, M.; Zerboni, A. Rock, pigments, and weathering. A preliminary assessment of the challenges and potential of physical and biochemical studies on rock art from southern Ethiopia. *Quat. Int.* **2021**, *572*, 41–51. https://doi.org/10.1016/j.quaint.2020.05.056.
6. Richter, D.D.; Mobley, M.L. Monitoring Earth's Critical Zone. *Science* **2009**, *326*, 1067–1068. https://doi.org/10.1126/science.1179117.
7. Clottes, J. Rock art: An endangered heritage worldwide. *J. Anthropol. Res.* **2008**, *64*, 1–18. https://doi.org/10.3998/jar.0521004.0064.101.
8. Agnew, N.; Deacon, J.; Hall, N.; Little, T.; Sullivan, S.; Taçon, P. *A Cultural Treasure at risk*; Getty Conservation Institute: Los Angeles, CA, USA, 2015.
9. Darvill, T.; Batarda Fernandes, A.P. *Open-Air Rock-Art Preservation and Conservation: A Current State of Affairs*; Routledge: New York, NY, USA, 2014.
10. Liritzis, I. STEMAC (science, technology, engineering, mathematics for arts & culture): The emergence of a new pedagogical discipline. *Sci. Cult.* **2018**, *4*, 73–76. https://doi.org/10.5281/zenodo.1214567.
11. Albertano, P.; Bruno, L. The importance of light in the conservation of hypogean monuments. In *Molecular biology and Cultural Heritage*; Saiz-Jimenez, C., Ed.; Balkema: Lisse, The Netherlands, 2003; pp. 171–177.
12. Bastian, F.; Alabouvette, C. Lights and shadows on the conservation of a rock art cave: The case of Lascaux Cave. *Int. J. Speleol.* **2009**, *38*, 55–60. https://doi.org/10.5038/1827-806X.38.1.6.
13. Hoyos, M.; Cañaveras, J.C.; Sánchez-Moral, S.; Sanz-Rubio, E.; Soler, V. Microclimatic characterization of a karstic cave: Human impact on microenvironmental parameters of a prehistoric rock art cave (Candamo Cave, northern Spain). *Environ. Geol.* **1998**, *33*, 231–242. https://doi.org/10.1007/s002540050242.
14. Mangin, A.; Bourges, F.; d'Hulst, D. La conservation des grottes ornées: Un problème de stabilité d'un système naturel (l'exemple de la grotte préhistorique de Gargas, Pyrénées françaises). *Comptes Rendus l'Académie des Sci.-Ser. IIA-Earth Planet. Sci.* **1999**, *328*, 295–301. https://doi.org/10.1016/S1251-8050(99)80120-7.
15. Denis, A.; Lastennet, R.; Huneau, F.; Malaurent, P. Identification of functional relationships between atmospheric pressure and CO2 in the cave of Lascaux using the concept of entropy of curves. *Geophys. Res. Lett.* **2005**, *32*, 1–4. https://doi.org/10.1029/2004GL022226.
16. Saiz-Jimenez, C.; Cuezva, S.; Jurado, V.; Fernandez-Cortes, A.; Porca, E.; Benavente, D.; Cañaveras, J.C.; Sanchez-Moral, S. Paleolithic art in peril: Policy and science collide at altamira cave. *Science* **2011**, *334*, 42–43. https://doi.org/10.1126/science.1206788.
17. Van Grieken, R.; Delalieux, F.; Gysels, K. Cultural heritage and the environment. *Pure Appl. Chem.* **1998**, *70*, 2327–2331. https://doi.org/10.1351/pac199870122327.
18. Dupont, J.; Jacquet, C.; Dennetière, B.; Lacoste, S.; Bousta, F.; Orial, G.; Cruaud, C.; Couloux, A.; Roquebert, M.-F. Invasion of the French Paleolithic painted cave of Lascaux by members of the Fusarium solani species complex. *Mycologia* **2007**, *99*, 526–533. https://doi.org/10.1080/15572536.2007.11832546.
19. Lacanette, D.; Large, D.; Ferrier, C.; Aujoulat, N.; Bastian, F.; Denis, A.; Jurado, V.; Kervazo, B.; Konik, S.; Lastennet, R.; et al. A laboratory cave for the study of wall degradation in rock art caves: An implementation in the Vézère area. *J. Archaeol. Sci.* **2013**, *40*, 894–903. https://doi.org/10.1016/j.jas.2012.10.012.
20. Malaurent, P.; Brunet, J.; Lacanette, D.; Caltagirone, J.-P. Contribution of numerical modelling of environmental parameters to the conservation of prehistoric cave paintings: The example of Lascaux Cave. *Conserv. Manag. Archaeol. Sites* **2006**, *8*, 59–76. https://doi.org/10.1179/175355206x202976.
21. Hong, C.-R. Study on Cave Environment Features and Preservation Methodologies. *J. Korean Speleol. Soc.* **2006**, *71*, 31–34.
22. Moldovan, O.T.; Kováč, Ľ.; Stuart, H. (Eds.) *Cave Ecology*; Springer: Berlin/Heidelberg, Germany, 2018.
23. Hershey, O.S.; Barton, H.A. T*he Microbial Diversity of Caves*; Moldovan, O.T., Kováč, Ľ., Stuart, H., Eds.; Springer: Berlin/Heidelberg, Germany, 2018; pp. 69–90.

24. Bastian, F.; Jurado, V.; Nováková, A.; Alabouvette, C.; Saiz-Jimenez, C. The microbiology of Lascaux Cave. *Microbiology* **2010**, *156*, 644–652. https://doi.org/10.1099/mic.0.036160-0.
25. Schabereiter-Gurtner, C.; Saiz-Jimenez, C.; PiÃ±ar, G.; Lubitz, W.; Rölleke, S. Altamira cave Paleolithic paintings harbor partly unknown bacterial communities. *FEMS Microbiol. Lett.* **2002**, *211*, 7–11. https://doi.org/10.1111/j.1574-6968.2002.tb11195.x.
26. Schabereiter-Gurtner, C.; Saiz-Jimenez, C.; Piñar, G.; Lubitz, W.; Rölleke, S. Phylogenetic diversity of bacteria associated with Paleolithic paintings and surrounding rock walls in two Spanish caves (Llonín and La Garma). *FEMS Microbiol. Ecol.* **2004**, *47*, 235–247. https://doi.org/10.1016/S0168-6496(03)00280-0.
27. Wu, Y.-L.; Villa, F.; Mugnai, G.; Gallinaro, M.; Spinapolice, E.E.; Zerboni, A. Geomicrobial Investigations of Colored Outer Coatings from an Ethiopian Rock Art Gallery. *Coatings* **2020**, *10*, 536. https://doi.org/10.3390/coatings10060536.
28. Nir, I.; Barak, H.; Kramarsky-Winter, E.; Kushmaro, A.; de los Ríos, A. Microscopic and biomolecular complementary approaches to characterize bioweathering processes at petroglyph sites from the Negev Desert, Israel. *Environ. Microbiol.* **2021**, *24*, 967–980. https://doi.org/10.1111/1462-2920.15635.
29. Aubert, M.; Brumm, A.; Taçon, P.S.C. The timing and nature of human colonization of southeast asia in the late pleistocene a rock art perspective. *Curr. Anthropol.* **2017**, *58*, S553–S566. https://doi.org/10.1086/694414.
30. Zerboni, A. Rock art from the central Sahara (Libya): A geoarchaeological and palaeoenvironmental perspective. In *The Signs of Which Times? Chronological and Palaeoenvironmental Issues in the Rock Art of Northern Africa*; Huyge, D., van Noten, F., Swinne, D., Eds.; Royal Academy for Overseas Sciences: Brussels, Belgium, 2012; pp. 175–195.
31. Guagnin, M. Animal engravings in the central Sahara: A proxy of a proxy. *Environ. Archaeol.* **2015**, *20*, 52–65. https://doi.org/10.1179/1749631414Y.0000000026.
32. McDonald, J. I must go down to the seas again: Or, what happens when the sea comes to you? Murujuga rock art as an environmental indicator for Australia's north-west. *Quat. Int.* **2015**, *385*, 124–135. https://doi.org/10.1016/j.quaint.2014.10.056.
33. Zerboni, A.; Esposti, M.D.; Wu, Y.-L.; Brandolini, F.; Mariani, G.S.; Villa, F.; Lotti, P.; Cappitelli, F.; Sasso, M.; Rizzi, A.; et al. Age, palaeoenvironment, and preservation of prehistoric petroglyphs on a boulder in the oasis of Salut (northern Sultanate of Oman). *Quat. Int.* **2021**, *572*, 106–119. https://doi.org/10.1016/j.quaint.2019.06.040.
34. Dorn, R.I.; Whitley, D.S.; Cerveny, N.V.; Gordon, S.J.; Allen, C.D.; Gutbrod, E. The Rock Art Stability Index. *Herit. Manag.* **2008**, *1*, 37–70. https://doi.org/10.1179/hma.2008.1.1.37.
35. Huyge, D.; Vandenberghe, D.A.G.; De Dapper, M.; Mees, F.; Claes, W.; Darnell, J.C. First evidence of Pleistocene rock art in North Africa: Securing the age of the Qurta petroglyphs (Egypt) through OSL dating. *Antiquity* **2011**, *85*, 1184–1193. https://doi.org/10.1017/S0003598X00061998.
36. Jennings, R.P.; Shipton, C.; Al-Omari, A.; Alsharekh, A.M.; Crassard, R.; Groucutt, H.; Petraglia, M.D. Rock art landscapes beside the Jubbah palaeolake, Saudi Arabia. *Antiquity* **2013**, *87*, 666–683. https://doi.org/10.1017/S0003598X00049383.
37. Guagnin, M.; Jennings, R.P.; Clark-Balzan, L.; Groucutt, H.S.; Parton, A.; Petraglia, M.D. Hunters and herders: Exploring the Neolithic transition in the rock art of Shuwaymis, Saudi Arabia. *Archaeol. Res. Asia* **2015**, *4*, 3–16. https://doi.org/10.1016/j.ara.2015.08.001.
38. Guagnin, M.; Shipton, C.; Al-Rashid, M.; Moussa, F.; El-Dossary, S.; Sleimah, M.B.; Alsharekh, A.; Petraglia, M. An illustrated prehistory of the Jubbah oasis: Reconstructing Holocene occupation patterns in north-western Saudi Arabia from rock art and inscriptions. *Arab. Archaeol. Epigr.* **2017**, *28*, 138–152. https://doi.org/10.1111/aae.12089.
39. Guagnin, M.; Shipton, C.; el-Dossary, S.; al-Rashid, M.; Moussa, F.; Stewart, M.; Ott, F.; Alsharekh, A.; Petraglia, M.D. Rock art provides new evidence on the biogeography of kudu (*Tragelaphus imberbis*), wild dromedary, aurochs (*Bos primigenius*) and African wild ass (*Equus africanus*) in the early and middle Holocene of north-western Arabia. *J. Biogeogr.* **2018**, *45*, 727–740. https://doi.org/10.1111/jbi.13165.
40. Mayewski, P.A.; Rohling, E.E.; Stager, J.C.; Karlén, W.; Maasch, K.A.; Meeker, L.D.; Meyerson, E.A.; Gasse, F.; van Kreveld, S.; Holmgren, K.; et al. Holocene climate variability. *Quat. Res.* **2004**, *62*, 243–255. https://doi.org/10.1016/j.yqres.2004.07.001.
41. Slaymaker, O.; Spencer, T.; Embleton-Hamann, C. (Eds.) *Geomorphology and Global Environmental Change*; Cambridge University Press: Cambridge, UK, 2009.
42. Dorn, R.I.; Gordon, S.J.; Allen, C.D.; Cerveny, N.; Dixon, J.C.; Groom, K.M.; Hall, K.; Harrison, E.; Mol, L.; Paradise, T.R.; et al. The role of fieldwork in rock decay research: Case studies from the fringe. *Geomorphology* **2013**, *200*, 59–74. https://doi.org/10.1016/j.geomorph.2012.12.012.
43. Allen, P.A. *Earth Surface Processes*; John Wiley & Sons: Hoboken, NJ, USA, 1997.
44. Erhart, H. *Lagenèsedessolsentant quephénomènegéologique. Esquissed'unethéoriegéologique etgéochimique BiostasieetRhexistasie. ColLEvolution desSciences*; MassonetCie: Paris, France, 1956.
45. Peña-Monné, J.L.; Sampietro-Vattuone, M.M.; Báez, W.A.; García-Giménez, R.; Stábile, F.M.; Martínez Stagnaro, S.Y.; Tissera, L.E. Sandstone weathering processes in the painted rock shelters of Cerro Colorado (Córdoba, Argentina). *Geoarchaeology* **2022**, *37*, 332–349. https://doi.org/10.1002/gea.21890.
46. Vincente, M.A.; Garcia-Talegon, J.; Inigo, A.C.; Molina, E.; Rives, V. Weathering mechanisms of silicated rocks in continental environments. In *Proceedings of the Conservation of Stone and Other Materials: Proceedings of the International RILEM/UNESCO, UNESCO Headquarters, Paris, France, 29 June–1 July 1993*; E. & F.N. Spon Ltd: London, UK, 1993.
47. Zerboni, A.; Perego, A.; Cremaschi, M. Geomorphological Map of the Tadrart Acacus Massif and the Erg Uan Kasa (Libyan Central Sahara). *J. Maps* **2015**, *11*, 772–787. https://doi.org/10.1080/17445647.2014.955891.

48. di Lernia, S.; Bruni, S.; Cislaghi, I.; Cremaschi, M.; Gallinaro, M.; Gugliemi, V.; Mercuri, A.M.; Poggi, G.; Zerboni, A. Colour in context. Pigments and other coloured residues from the Early-Middle Holocene site of Takarkori (SW Libya). *Archaeol. Anthropol. Sci.* **2016**, *8*, 381–402. https://doi.org/10.1007/s12520-015-0229-4.
49. Cremaschi, M.; Zerboni, A.; Mercuri, A.M.; Olmi, L.; Biagetti, S.; di Lernia, S. Takarkori rock shelter (SW Libya): An archive of holocene climate and environmental changes in the central sahara. *Quat. Sci. Rev.* **2014**, *101*, 36–60. https://doi.org/10.1016/j.quascirev.2014.07.004.
50. Hall, K.; Thorn, C.; Sumner, P. On the persistence of “weathering”. *Geomorphology* **2012**, *149–150*, 1–10. https://doi.org/10.1016/j.geomorph.2011.12.024.
51. Carroll, D. *Rock Weathering*; Plenum Press: New York, NY, USA; London, UK, 1970.
52. Bland, W.J.; Rolls, D. *Weathering: An Introduction to the Scientific Principles*; Routledge: London, UK, 1998.
53. Zerboni, A.; Nicoll, K. Enhanced zoogeomorphological processes in North Africa in thehuman-impacted landscapes of the Anthropocene. *Geomorphology* **2019**, *331*, 22–35. https://doi.org/10.1016/j.geomorph.2018.10.011.
54. Golubic, S.; Friedmann, E.I.; Schneider, J. The lithobiontic ecological niche, with special reference to microorganisms. *J. Sediment. Res.* **1981**, *51*, 475–478. https://doi.org/10.1306/212F7CB6-2B24-11D7-8648000102C1865D.
55. Villa, F.; Stewart, P.S.; Klapper, I.; Jacob, J.M.; Cappitelli, F. Subaerial Biofilms on Outdoor Stone Monuments: Changing the Perspective Toward an Ecological Framework. *Bioscience* **2016**, *66*, 285–294. https://doi.org/10.1093/biosci/biw006.
56. Villa, F.; Cappitelli, F. The ecology of subaerial biofilms in dry and inhospitable terrestrial environments. *Microorganisms* **2019**, *7*, 380. https://doi.org/10.3390/microorganisms7100380.
57. Negi, A.; Sarethy, I.P. Microbial Biodeterioration of Cultural Heritage: Events, Colonization, and Analyses. *Microb. Ecol.* **2019**, *78*, 1014–1029. https://doi.org/10.1007/s00248-019-01366-y.
58. Liu, X.; Koestler, R.J.; Warscheid, T.; Katayama, Y.; Gu, J.-D. Microbial deterioration and sustainable conservation of stone monuments and buildings. *Nat. Sustain.* **2020**, *3*, 991–1004. https://doi.org/10.1038/s41893-020-00602-5.
59. Pinna, D. Biofilms and lichens on stone monuments: Do they damage or protect? *Front. Microbiol.* **2014**, *5*, 133. https://doi.org/10.3389/fmicb.2014.00133.
60. Gadd, G.M.; Dyer, T.D. Bioprotection of the built environment and cultural heritage. *Microb. Biotechnol.* **2017**, *10*, 1152–1156. https://doi.org/10.1111/1751-7915.12750.
61. Dorn, R.I.; Dorn, J.; Harrison, E.; Gutbrod, E.; Gibson, S.; Larson, P.; Cerveny, N.; Lopat, N.; Groom, K.M.; Allen, C.D. Case Hardening Vignettes from the Western USA: Convergence of Form as a Result of Divergent Hardening Processes. *Yearb. Assoc. Pacific Coast Geogr.* **2012**, *74*, 53–75. https://doi.org/10.1353/pcg.2012.0003.
62. Viles, H.A.; Goudie, A.S. Biofilms and case hardening on sandstones from Al-Quwayra, Jordan. *Earth Surf. Process. Landforms* **2004**, *29*, 1473–1485. https://doi.org/10.1002/esp.1134.
63. Viles, H.A.; Cutler, N.A. Global environmental change and the biology of heritage structures. *Glob. Chang. Biol.* **2012**, *18*, 2406–2418. https://doi.org/10.1111/j.1365-2486.2012.02713.x.
64. Coombes, M.A.; Viles, H.A.; Zhang, H. Thermal blanketing by ivy (*Hedera helix* L.) can protect building stone from damaging frosts. *Sci. Rep.* **2018**, *8*, 1–11. https://doi.org/10.1038/s41598-018-28276-2.
65. Gulotta, D.; Villa, F.; Cappitelli, F.; Toniolo, L. Biofilm colonization of metamorphic lithotypes of a renaissance cathedral exposed to urban atmosphere. *Sci. Total Environ.* **2018**, *639*, 1480–1490. https://doi.org/10.1016/j.scitotenv.2018.05.277.
66. Sanmartín, P.; Villa, F.; Cappitelli, F.; Balboa, S.; Carballeira, R. Characterization of a biofilm and the pattern outlined by its growth on a granite-built cloister in the Monastery of San Martiño Pinario (Santiago de Compostela, NW Spain). *Int. Biodeterior. Biodegrad.* **2020**, *147*, 104871. https://doi.org/10.1016/j.ibiod.2019.104871.
67. Rodriguez-Navarro, C.; Jroundi, F.; Gonzalez-Muñoz, M.T. Stone Consolidation by Bacterial Carbonatogenesis: Evaluation of in situ Applications. *Restor. Build. Monum.* **2015**, *21*, 9–20. https://doi.org/10.1515/rbm-2015-0002.
68. Jroundi, F.; Schiro, M.; Ruiz-Agudo, E.; Elert, K.; Martín-Sánchez, I.; González-Muñoz, M.T.; Rodriguez-Navarro, C. Protection and consolidation of stone heritage by self-inoculation with indigenous carbonatogenic bacterial communities. *Nat. Commun.* **2017**, *8*, 279. https://doi.org/10.1038/s41467-017-00372-3.
69. Jroundi, F.; Elert, K.; Ruiz-Agudo, E.; Gonzalez-Muñoz, M.T.; Rodriguez-Navarro, C. Bacterial Diversity Evolution in Maya Plaster and Stone Following a Bio-Conservation Treatment. *Front. Microbiol.* **2020**, *11*, 2824. https://doi.org/10.3389/fmicb.2020.599144.
70. Favero-Longo, S.E.; Viles, H.A. A review of the nature, role and control of lithobionts on stone cultural heritage: Weighing-up and managing biodeterioration and bioprotection. *World J. Microbiol. Biotechnol.* **2020**, *36*, 100. https://doi.org/10.1007/s11274-020-02878-3.
71. Ortega-Morales, B.O.; Gaylarde, C.C. Bioconservation of historic stone buildings—An updated review. *Appl. Sci.* **2021**, *11*, 5695. https://doi.org/10.3390/app11125695.
72. Chen, J.; Blume, H.-P.; Beyer, L. Weathering of rocks induced by lichen colonization—A review. *Catena* **2000**, *39*, 121–146.
73. Mergelov, N.S.; Goryachkin, S.V.; Shorkunov, I.G.; Zazovskaya, E.P.; Cherkinsky, A.E. Endolithic pedogenesis and rock varnish on massive crystalline rocks in East Antarctica. *Eurasian Soil Sci.* **2012**, *45*, 901–917. https://doi.org/10.1134/S1064229312100067.
74. Dorn, R.I. *Rock Coatings*; Elsevier Science B.V.: Amsterdam, The Netherlands, 1998.
75. Zerboni, A. Holocene rock varnish on the Messak plateau (Libyan Sahara): Chronology of weathering processes. *Geomorphology* **2008**, *102*, 640–651. https://doi.org/10.1016/j.geomorph.2008.06.010.

76. Cremaschi, M. The rock varnish in the Messak Settafet (Fezzan, Libyan Sahara), age, archaeological context, and palaeoenvironmental implication. *Geoarchaeology* **1996**, *11*, 393–421.
77. Potter, R.M.; Rossman, G.R. Desert varnish: The importance of clay minerals. *Science* **1979**, *196*, 1446–1448.
78. Martínez-Pabello, P.U.; Villalobos, C.; Sedov, S.; Solleiro-Rebolledo, E.; Solé, J.; Pi-Puig, T.; Chávez-Vergara, B.; Díaz-Ortega, J.; Gubin, A. Rock varnish as a natural canvas for rock art in La Proveedora, northwestern Sonoran Desert (Mexico): Integrating archaeological and geological evidences. *Quat. Int.* **2021**, *572*, 74–87. https://doi.org/10.1016/j.quaint.2020.10.028.
79. Eisenberg-Degen, D.; Rosen, S. Chronological Trends in Negev Rock Art: The Har Michia Petroglyphs as a Test Case. *Arts* **2013**, *2*, 225–252. https://doi.org/10.3390/arts2040225.
80. Macholdt, D.S.; Jochum, K.P.; Al-Amri, A.; Andreae, M.O. Rock varnish on petroglyphs from the Hima region, southwestern Saudi Arabia: Chemical composition, growth rates, and tentative ages. *Holocene* **2019**, *29*, 1377–1395. https://doi.org/10.1177/0959683619846979.
81. Andreae, M.O.; Al-Amri, A.; Andreae, T.W.; Garfinkel, A.; Haug, G.; Jochum, K.P.; Stoll, B.; Weis, U. Geochemical Studies on Rock Varnish and Petroglyphs in the Owens and Rose Valleys, California. *PLoS ONE* **2020**, *15*, e0235421. https://doi.org/10.1371/journal.pone.0235421
82. Andreae, M.O.; Al-Amri, A.; Al-Jibrin, F.H.; Alsharekh, A.M. Iconographic and archaeometric studies on the rock art at Musayqira, Al-Quwaiyah Governorate, central Saudi Arabia. *Arab. Archaeol. Epigr.* **2021**, *32*, 153–182. https://doi.org/10.1111/aae.12191.
83. Guagnin, M.; Charloux, G.; AlSharekh, A.M.; Crassard, R.; Hilbert, Y.H.; Andreae, M.O.; AlAmri, A.; Preusser, F.; Dubois, F.; Burgos, F.; et al. Life-sized Neolithic camel sculptures in Arabia: A scientific assessment of the craftsmanship and age of the Camel Site reliefs. *J. Archaeol. Sci. Reports* **2022**, *42*, 103165. https://doi.org/10.1016/j.jasrep.2021.103165.
84. Andreae, M.O.; Andreae, T.W. Archaeometric studies on rock art at four sites in the northeastern Great Basin of North America. *PLoS ONE* **2022**, *17*, e0263189. https://doi.org/10.1371/journal.pone.0263189.
85. Higgins, H.C. Rock art vandalism: Causes and prevention. *Vandal. Res. Prev. Soc. Policy* **1992**, 293, 221–232.
86. Di Lernia, S.; Gallinaro, M.; Zerboni, A. UNESCO World Heritage Site vandalised : Report on damages to Acacus rock art (SW Libya). *Sahara. Preist. Stor. Sahara* **2010**, *21*, 59–76.
87. Taruvinga, P.; Ndoro, W. The vandalism of the Domboshava rock painting site, Zimbabwe: Some reflections on approaches to heritage management. *Conserv. Manag. Archaeol. Sites* **2003**, *6*, 3–10. https://doi.org/10.1179/135050303793137983.
88. Hachid, M. Rock art in danger: The case of the Saharan Atlas. *Museum Int.* **1985**, *37*, 32–37.
89. Bednarik, R.G. More on Rock Art Removal. *South African Archaeol. Bull.* **2008**, *63*, 82–84. https://doi.org/10.2307/20474997.
90. Yates, D.; Bērziņa, D.; Wright, A. Protecting a Broken Window: Vandalism and Security at Rural Rock Art Sites. *Prof. Geogr.* **2022**, *74*, 384–390. https://doi.org/10.1080/00330124.2021.1957690.
91. Červíček, P.; Kortler, F. Rock art discoveries in the northern Yemen. *Paideuma* **1979**, 25, 225–250.
92. Holtorf, C. Can less be more? Heritage in the age of terrorism. *Public Archaeol.* **2006**, *5*, 101–109. https://doi.org/10.1179/pua.2006.5.2.101.
93. Suková, L. Pictures in place : A case study from Korosko (Lower Nubia). In *Hunter-Gatherer and Early Food Producing Societies in Northeastern Africa (Studies in African Archaeology)*; Poznán Archaeological Museum: Poznán, Poland, 2015; pp. 120–143.
94. Smith, D.C.; Bouchard, M.; Lorblanchet, M. An initial Raman microscopic investigation of prehistoric rock art in caves of the Quercy District, S.W. France. *J. Raman Spectrosc.* **1999**, *30*, 347–354.
95. Gunn, R.G. The impact of bushfires and fuel reduction burning on the preservation of shelter rock art. *Rock Art Res.* **2011**, *28*, 53–69.
96. Anag, G.; Cremaschi, M.; di Lernia, S.; Liverani, M. Environment, Archaeology, and Oil: The Messak Settafet Rescue Operation (Libyan Sahara). *African Archaeol. Rev.* **2002**, *19*, 67–73.
97. Klemm, R.; Klemm, D. *Gold and Gold Mining in Ancient Egypt and Nubia: Geoarchaeology of the Ancient Gold Mining Sites in the Egyptian and Sudanese Eastern Deserts*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012.
98. Loendorf, L. Rock art recording. In *Handbook of Rock Art Research*; Whitley, D.S., Ed.; Altamira Press: Lanham, MD, USA, 2001; pp. 55–79.
99. Di Lernia, S.; Gallinaro, M. The Rock Art of the Acacus Mountains (SW Libya), between originals and copies. *Sahara. Preist. Stor. Sahara* **2009**, *20*, 13–30.
100. Chaffee, S.D.; Hyman, M.; Rowe, M.W. Vandalism of rock art for enhanced photography. *Stud. Conserv.* **1994**, *39*, 161–168. https://doi.org/10.1179/sic.1994.39.3.161.
101. MacLeod, I. Rock art conservation and management: The past, present and future options. *Stud. Conserv.* **2000**, *45*, 32–45. https://doi.org/10.1179/sic.2000.45.s3.005.
102. Liritzis, I.; Korka, E. Archaeometry's role in cultural heritage sustainability and development. *Sustainability* **2019**, *11*, 1972. https://doi.org/10.3390/su11071972.
103. Dayet, L.; dErrico, F.; Diez, M.G.; Zilhão, J. Critical evaluation of in situ analyses for the characterisation of red pigments in rock paintings: A case study from El Castillo, Spain. *PLoS ONE* **2022**, *17*, e0262143. https://doi.org/10.1371/journal.pone.0262143.
104. Domingo, I.; Gallinaro, M. Impacts of scientific approaches on rock art research: Global perspectives. *Quat. Int.* **2021**, *572*, 1–4. https://doi.org/10.1016/j.quaint.2020.10.033.

105. Martinon-Torres, M.; Killick, D. Archaeological Theories and Archaeological Sciences. In *The Oxford Handbook of Archaeological Theory*; Gardner, A., Lake, M., Sommer, U., Eds.; Oxford University Press: Oxford, UK, 2015. https://doi.org/10.1093/oxfordhb/9780199567942.013.004.
106. Sillar, B.; Tite, M.S. The challenge of 'technological choices' for materials science approaches in archaeology*. *Archaeometry* **2000**, *42*, 2–20. https://doi.org/10.1111/j.1475-4754.2000.tb00863.x.
107. Domingo, I.; Chieli, A. Characterizing the pigments and paints of prehistoric artists. *Archaeol. Anthropol. Sci.* **2021**, *13*, 196. https://doi.org/10.1007/s12520-021-01397-y.
108. Dorn, R.I. Petroglyphs in Petrified Forest National Park: Role of rock coatings as agents of sustainability and as indicators of antiquity. *Bull. Museum North. Arizona* **2006**, *63*, 52–63.
109. Watchman, A. Perspectives and potentials for absolute dating prehistoric rock paintings. *Antiquity* **1993**, *67*, 58–65. https://doi.org/10.1017/S0003598X00045051.
110. Bednarik, R.G. The dating of rock art: A critique. *J. Archaeol. Sci.* **2002**, *29*, 1213–1233. https://doi.org/10.1006/jasc.2001.0711.
111. Bednarik, R.G. Direct dating of chinese immovable cultural heritage. *Quaternary* **2021**, *4*, 42. https://doi.org/10.3390/quat4040042.
112. Jalandoni, A.; Domingo, I.; Taçon, P.S.C. Testing the value of low-cost Structure-from-Motion (SfM) photogrammetry for metric and visual analysis of rock art. *J. Archaeol. Sci. Reports* **2018**, *17*, 605–616. https://doi.org/10.1016/j.jasrep.2017.12.020.
113. Peña-Villasenín, S.; Gil-Docampo, M.; Ortiz-Sanz, J. Professional SfM and TLS vs. a simple SfM photogrammetry for 3D modelling of rock art and radiance scaling shading in engraving detection. *J. Cult. Herit.* **2019**, *37*, 238–246. https://doi.org/10.1016/j.culher.2018.10.009.
114. Degli Esposti, M.; Brandolini, F.; Zerboni, A. 3D Digital Documentation of Archaeological Features, A Powerful Tool for Research and Dissemination. Case Studies from the Oasis of Salūt (Sultanate of Oman). *J. Oman Stud.* **2021**, *22*, 214–227.
115. Mol, L.; Clarke, L. Integrating structure-from-motion photogrammetry into rock weathering field methodologies. *Earth Surf. Process. Landforms* **2019**, *44*, 2671–2684. https://doi.org/10.1002/esp.4693.
116. Groom, K.M.; Cerveny, N.V.; Allen, C.D.; Dorn, R.I.; Theuer, J. Protecting stone heritage in the painted desert: Employing the rock art stability index in the petrified forest national park, Arizona. *Heritage* **2019**, *2*, 2111–2123. https://doi.org/10.3390/heritage2030127.
117. Cerveny, N.V.; Dorn, R.I.; Allen, C.D.; Whitley, D.S. Advances in rapid condition assessments of rock art sites: Rock Art Stability Index (RASI). *J. Archaeol. Sci. Reports* **2016**, *10*, 871–877. https://doi.org/10.1016/j.jasrep.2016.06.032.
118. Cerveny, N. *A Weathering-Based Perspective on Rock Art Conservation*; Arizona State University: Tempe, AZ, USA, 2005.
119. Popelka-Filcoff, R.S.; Zipkin, A.M. The archaeometry of ochre sensu lato: A review. *J. Archaeol. Sci.* **2022**, *137*, 105530. https://doi.org/10.1016/j.jas.2021.105530.
120. Dayet, L. Invasive and Non-Invasive Analyses of Ochre and Iron-Based Pigment Raw Materials: A Methodological Perspective. *Minerals* **2021**, *11*, 210. https://doi.org/10.3390/min11020210.
121. Domingo Sanz, I.; Vendrell, M.; Chieli, A. A critical assessment of the potential and limitations of physicochemical analysis to advance knowledge on Levantine rock art. *Quat. Int.* **2021**, *572*, 24–40. https://doi.org/10.1016/j.quaint.2020.09.020.
122. Ruiz, J.F.; Pereira, J. The colours of rock art. Analysis of colour recording and communication systems in rock art research. *J. Archaeol. Sci.* **2014**, *50*, 338–349. https://doi.org/10.1016/j.jas.2014.06.023.
123. Molada Tebar, A. *Colorimetric and Spectral Analysis of Rock Art by Means of the Characterization of Digital Sensors*; Universitat Politècnica de València: Valencia, Spain, 2020.
124. Molada-Tebar, A.; Marqués-Mateu, Á.; Lerma, J. Camera Characterisation Based on Skin-Tone Colours for Rock Art Recording. **2019**, *19*, 12. https://doi.org/10.3390/proceedings2019019012.
125. Carrión-Ruiz, B.; Riutort-Mayol, G.; Molada-Tebar, A.; Lerma, J.L.; Villaverde, V. Color degradation mapping of rock art paintings using microfading spectrometry. *J. Cult. Herit.* **2021**, *47*, 100–108. https://doi.org/10.1016/j.culher.2020.10.002.
126. Bednarik, R.G. Experimental Colorimetric Analysis of Petroglyphs. *Rock Art Res.* **2009**, *26*, 55–64.
127. Bonneau, A.; Staff, R.A.; Higham, T.; Brock, F.; Pearce, D.G.; Mitchell, P.J. Successfully Dating Rock Art in Southern Africa Using Improved Sampling Methods and New Characterization and Pretreatment Protocols. *Radiocarbon* **2017**, *59*, 659–677. https://doi.org/10.1017/RDC.2016.69.
128. Bonneau, A.; Pearce, D.; Mitchell, P.; Staff, R.; Arthur, C.; Mallen, L.; Brock, F.; Higham, T. The earliest directly dated rock paintings from southern Africa: New AMS radiocarbon dates. *Antiquity* **2017**, *91*, 322–333. https://doi.org/10.15184/aqy.2016.271.
129. Steelman, K.L.; Boyd, C.E.; Allen, T. Two independent methods for dating rock art: Age determination of paint and oxalate layers at Eagle Cave, TX. *J. Archaeol. Sci.* **2021**, *126*, 105315. https://doi.org/10.1016/j.jas.2020.105315.
130. Hoffmann, D.L.; Pike, A.W.G.; García-Diez, M.; Pettitt, P.B.; Zilhão, J. Methods for U-series dating of $CaCO_3$ crusts associated with Palaeolithic cave art and application to Iberian sites. *Quat. Geochronol.* **2016**, *36*, 104–119. https://doi.org/10.1016/j.quageo.2016.07.004.
131. Pike, A.W.G.; Hoffmann, D.L.; García-Diez, M.; Pettitt, P.B.; Alcolea, J.; De Balbín, R.; González-Sainz, C.; de las Heras, C.; Lasheras, J.A.; Montes, R.; et al. U-Series Dating of Paleolithic Art in 11 Caves in Spain. *Science* **2012**, *336*, 1409–1413. https://doi.org/10.1126/science.1219957.
132. Hoffmann, D.L.; Standish, C.D.; Pike, A.W.G.; García-Diez, M.; Pettitt, P.B.; Angelucci, D.E.; Villaverde, V.; Zapata, J.; Milton, J.A.; Alcolea-González, J.; et al. Dates for Neanderthal art and symbolic behaviour are reliable. *Nat. Ecol. Evol.* **2018**, *2*, 1044–1045. https://doi.org/10.1038/s41559-018-0598-z.

133. Hoffmann, D.L.; Standish, C.D.; García-Diez, M.; Pettitt, P.B.; Milton, J.A.; Zilhão, J.; Alcolea-González, J.J.; Cantalejo-Duarte, P.; Collado, H.; de Balbín, R.; et al. U-Th dating of carbonate crusts reveals Neandertal origin of Iberian cave art. *Science* **2018**, *359*, 912–915. https://doi.org/10.1126/science.aap7778.
134. Aubert, M.; Setiawan, P.; Oktaviana, A.A.; Brumm, A.; Sulistyarto, P.H.; Saptomo, E.W.; Istiawan, B.; Ma'rifat, T.A.; Wahyuono, V.N.; Atmoko, F.T.; et al. Palaeolithic cave art in Borneo. *Nature* **2018**, *564*, 254–257. https://doi.org/10.1038/s41586-018-0679-9.
135. Wu, Y.; Jiao, Y.; Ji, X.; Taçon, P.S.C.; Yang, Z.; He, S.; Jin, M.; Li, Y.; Shao, Q. High-precision U-series dating of the late Pleistocene—Early Holocene rock paintings at Tiger Leaping Gorge, Jinsha River valley, southwestern China. *J. Archaeol. Sci.* **2022**, *138*, 105535. https://doi.org/10.1016/j.jas.2021.105535.
136. Liritzis, I.; Evangelia, P.; Mihalis, E. Novel approaches in surface luminescence dating of rock art: A brief review. *Mediterr. Archaeol. Archaeom.* **2017**, *17*, 89–102. https://doi.org/10.5281/zenodo.893194.
137. Liritzis, I.; Bednarik, R.G.; Kumar, G.; Polymeris, G.; Iliopoulos, I.; Xanthopoulou, V.; Zacharias, N.; Vafiadou, A.; Bratitsi, M. Daraki-Chattan Rock Art Constrained Osl Chronology and Multianalytical Techniques: A First Pilot Investigation. *J. Cult. Herit.* **2019**, *37*, 29–43. https://doi.org/10.1016/j.culher.2018.09.018.
138. Gonzalez, I.; Laiz, L.; Hermosin, B.; Caballero, B.; Incerti, C.; Saiz-Jimenez, C. Bacteria isolated from rock art paintings: The case of Atlanterra shelter (south Spain). *J. Microbiol. Methods* **1999**, *36*, 123–127. https://doi.org/10.1016/S0167-7012(99)00017-2.
139. Roldán, C.; Murcia-Mascarós, S.; López-Montalvo, E.; Vilanova, C.; Porcar, M. Proteomic and metagenomic insights into prehistoric Spanish Levantine Rock Art. *Sci. Rep.* **2018**, *8*, 10011. https://doi.org/10.1038/s41598-018-28121-6.
140. Cappitelli, F.; Cattò, C.; Villa, F. The Control of Cultural Heritage Microbial Deterioration. *Microorganisms* **2020**, *8*, 1542. https://doi.org/10.3390/microorganisms8101542.
141. Delegou, E.T.; Karapiperis, C. Metagenomics of the built cultural heritage: Microbiota characterization of the building materials of the holy aedicule of the holy sepulchre in Jerusalem. *Sci. Cult.* **2022**, *8*, 59–83. https://doi.org/10.5281/zenodo.5772545.
142. Clauzade, G.; Roux, C.; Houmeau, J.; Raimbault, P. *Likenoj de Okcidenta Europo: Ilustrita Determinlibro. Bulletin de la Société Botanique du Centre-Ouest, Nouvelle Série. Numéro Spécial, 7-1985*; Société Botanique du Centre Ouest: Saint-Sulpice-de-Royan, France, 1985.
143. Wirth, V. *Die Flechten Baden-Württembergs. Verbreitungsatlas*; E. Ulmer Verlag: Stuttgart, Germany, 1987.
144. Smith, C.W.; Aptroot, A.; Coppins, B.J.; Fletcher, A.; Gilbert, O.L.; James, P.W.; Wolseley, P.A. (Eds.) *The Lichens of Great Britain and Ireland*; The British Lichen Society, Department of Botany, The Natural History Museum, Cromwell R: London, UK, 2009.
145. Nimis, P.L.; Martellos, S. Towards a digital key to the lichens of Italy. *Symbiosis* **2020**, *82*, 149–155. https://doi.org/10.1007/s13199-020-00714-8.
146. Huyge, D.; Watchman, A.; De Dapper, M.; Marchi, E. Dating Egypt's oldest 'art': AMS 14C age determinations of rock varnishes covering petroglyphs at El-Hosh (Upper Egypt). *Antiquity* **2001**, *75*, 68–72. https://doi.org/10.1017/S0003598X0005273X.
147. Abd El-Hakim, A. El-Badry Mona, F.A.; Badawi, M.I. Assessment of the Aging Treatments of Sandstone Greywacke Rock Art (Wadi Hammamat) By Petrography, SEM, XRD, EDX. *Sci. Cult.* **2019**, *5*, 37–48. https://doi.org/0.5281/zenodo.2649505.
148. Villa, F.; Wu, Y.-L.; Zerboni, A.; Cappitelli, F. In living color: Pigments-based microbial ecology at the mineral/air interface. *Bioscience* in press.
149. Deacon, J. Rock art conservation and tourism. *J. Archaeol. Method Theory* **2006**, *13*, 376–396. https://doi.org/10.1007/s10816-006-9024-y.
150. Duval, M.; Gauchon, C.; Smith, B. Rock Art Tourism. In *The Oxford Handbook of the Archaeology and Anthropology of Rock Art*; Bruno, D., McNiven, I.J., Eds.; Oxford University Press: Oxford, UK, 2019.
151. Little, T.; Borona, G. Can Rock Art in Africa Reduce Poverty? *Public Archaeol.* **2014**, *13*, 178–186. https://doi.org/10.1179/1465518714Z.00000000067.
152. El Menshawy, S. Qatar rock arts: Re-consideration and prospectives of Qatar cultural heritage tourism map. *Mediterr. Archaeol. Archaeom.* **2017**, *17*, 33–42. https://doi.org/10.5281/zenodo.893190.
153. Bollati, I.; Reynard, E.; Cagnin, D.; Pelfini, M. The enhancement of cultural landscapes in mountain environments: An artificial channel history (Torrent-Neuf, Canton Valais, Switzerland) and the role of trees as natural archives of water flow changes. *Acta Geogr. Slov.* **2018**, *58*, 87–100. https://doi.org/10.3986/AGS.4137.
154. Gallinaro, M.; Zerboni, A.; Solomon, T.; Spinapolice, E.E. Rock Art Between Preservation, Research and Sustainable Development—a Perspective from Southern Ethiopia. *African Archaeol. Rev.* **2018**, *35*, 211–223. https://doi.org/10.1007/s10437-018-9289-z.
155. Filippo, B.; Cremaschi, M.; Manuela, P. Estimating the Potential of Archaeo-historical Data in the Definition of Geomorphosites and Geo-educational Itineraries in the Central Po Plain (N Italy). *Geoheritage* **2019**, *11*, 1371–1396. https://doi.org/10.1007/s12371-019-00370-5.
156. Hadda, N.A.; Fakhoury, L.A.; Sakr, Y.M. critical anthology of international charters, conventions & principles on documentation of cultural heritage for conservation, monitoring & management. *Mediterr. Archaeol. Archaeom.* **2021**, *21*, 291–310. https://doi.org/10.5281/zenodo.4575718.