



Fire as a geoarchaeological decay agent: reviewing methodologies for assessing physico-mechanical and chemical impacts on rock art

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ABSTRACT

Rock art, human-made artwork among the earliest expressions of human creativity, represents a crucial interface between archaeological and geological materials. However, the preservation of rock surfaces is increasingly challenged by environmental processes intensified under changing climatic conditions. This review examines the methodological approaches made to assess impacts of fire as a significant agent influencing the deterioration of rock art. Fire events can induce complex thermal and chemical alterations, including rock surface fracturing, mineral phase transformations, and soot or residue deposition, all of which compromise the stability and visibility of painted or engraved motifs. By synthesizing different methodological approaches present in current research, this review aims to evaluate the strengths and limitations of each approach in detecting and characterizing fire-related damage to rock art. Key research gaps are identified within certain rock art sites, in lithological diversity and in a lack of multi-disciplinarity for study methods, while proposing a scoring system for known fire degradation patterns in rock art. These insights aim to strengthen the geoscientific framework for assessing fire impacts on rock surfaces, thereby supporting informed approaches to the conservation of rock art within dynamic environmental settings.

1. Introduction

Rock art encompasses figurative and abstract representations created on natural rock surfaces through painting or engraving techniques. These archaeological artworks are among the earliest human symbolic expressions, with some dating back over 60,000 years (Hoffmann et al., 2018; Marquet et al., 2023). Rock art is located in diverse settings, including caves, rock shelters, and open-air environments such as cliff faces and boulders (Darvill and Fernandes, 2014; Gunn, 2011). Scholars employ various terms for these artifacts, including carvings, engravings, paintings, and petroglyphs, reflecting the different techniques and surfaces used (Allen, 1879; Bednarik, 2001; Butzer et al., 1979; Horsfield et al., 1933; Moya-Caños et al., 2021; Smith, 1972). Techniques vary from incision, carving, and engraving to painting with natural pigments, often depicting animals, humans, and geometric motifs, sometimes in complex compositions or large-scale ground drawings (Cabrerá, 2020; Sarhaddi, 2013; van Hoek, 2001).

Besides its cultural and historical significance, rock art sites are valuable economic assets, particularly in cultural tourism, attracting

visitors who engage with the heritage and history they represent (Duval et al., 2019). The influx of tourists can stimulate local economies by creating jobs and promoting infrastructure development, and preserving these sites is therefore crucial to maintain its historical, cultural, and economic importance (Deacon, 2006). However, preserving these sites poses a challenge, as they are closely linked to their natural bedrock, which is subject to deterioration due to various physical, chemical, and biological agents (ICOMOS, 2016; Pozo-Antonio et al., 2018; Vázquez et al., 2015). These deterioration patterns are influenced by environmental agents that can act independently or in tandem (Bertolin, 2019), and while some deterioration patterns could inadvertently aid preservation, most are likely to result in irreversible damage and loss of rock art (Goudie et al., 1992; Zerboni et al., 2022).

Deterioration patterns, shaped by regional environmental agents like temperature changes and precipitation, are tied to the increased threat from climate change, as it can exacerbate these agents through alterations to seasonal temperature shifts, precipitation patterns and atmospheric CO₂ levels (Sesana et al., 2021; Smith et al., 2010). It also heightens the occurrence of extreme hazardous events like floods,

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landslides and wildfires, which can severely impact archaeological sites (Howard et al., 2008; Sabbioni et al., 2010). With climate change being recognized as a pervasive threat to both the environment and society, a growing body of research has emerged to understand its effects on archaeological and cultural heritage (Daly, 2011; Sesana et al., 2021).

Commonly researched areas of study within this scope include the study of hydro-climatic events, such as sea-level rise and storm events, that place coastal, riverine and low-lying archaeological sites at significant risk (Daire et al., 2012; Murphy et al., 2009; Perez-Alvaro, 2016; Ravankhah et al., 2019; Westley et al., 2011). Notably, estimates suggest that up to 19% of UNESCO World Heritage Sites could be lost to flooding alone (Marzeion and Levermann, 2014). Studies on the impact of hydro-climatic events in heritage and archaeological sites include: direct flood risks and storm surges (Hunter, 2009; Reimann et al., 2018; García Sánchez et al., 2020), the loss of natural barriers and increased shallow-water erosion (Berenfeld, 2008; Wright, 2016), increasing moisture levels in archaeological materials and structures (Blankholm, 2009), changing river behaviours affecting buried archaeology (Howard et al., 2008), instability in underwater archaeological sites and monuments (Dunkley, 2013; Wright, 2016) and increasing salt damage due to seawater (Howard et al., 2008; Sipio and Zezza, 2011).

Other commonly researched threats to archaeological sites are tied to terrestrial and geo-climatic events, such as the increasing risk of landslides and gully erosion from extreme rainfalls (Cigna et al., 2016; Crozier, 2010; Nicu, 2017), reductions in ground stability (Cigna et al., 2016; Ravankhah et al., 2019; Sabbioni et al., 2010) and increased slope instability in cliff-carved sites (Margottini et al., 2016). Meanwhile, research on other side-effects of climate change, such as biological colonization of rock art surfaces, is still under development. Studies show that altered environmental conditions may foster the growth of microorganisms that can damage rock art through chemical interactions, potentially accelerating deterioration by degrading both the artistic pigments and the rock substrates while obscuring visual elements of rock art (Oliveira et al., 2021; Traversetti et al., 2018; Wu et al., 2022). However, some studies suggest that in certain contexts, this biological growth might inadvertently shield rock art from other deterioration processes (Zhu et al., 2025).

Research on high-temperature impacts in archaeological records, particularly from fires, remains in a developmental stage. While droughts and extreme heat, intensified by climate change, pose significant environmental hazards, studies typically focus on their effects on soil desiccation, structural instability, and risks of flooding in heritage (Markham et al., 2019; Sesana et al., 2021). Research on seasonal temperature shifts exacerbated by climate change also highlight increased thermoclastic stress from thermal fluctuations (Sabbioni et al., 2009; Sesana et al., 2021), but these studies primarily address long-term low-temperature changes rather than the rapid high-temperature impacts associated with fires. Current studies indicate that extreme heat and drought conditions increase fire risks, posing a particular threat to archaeological sites located near vegetation or forests, which are common in southern Europe (Gomes et al., 2025; Mallinis et al., 2016; Sabbioni et al., 2010, 2009). The European Forest Fire Information System forecasts increasing fire-conducive climate conditions across Europe, as has been highlighted in international discussions, including a 2019 seminar at the International Centre for the Study of the Preservation and Restoration of Cultural Property and an ICOMOS publication on fires in an Australian national park (Markham et al., 2019; Pearson, 2008). Fires cause significant loss and structural instability in rock art (Gunn and Whear, 2009; Pearson, 2007), as the extreme heat leads to degradation patterns in stone materials, compromising their integrity and increasing their susceptibility to further deterioration (Gunn, 2011). Fire impacts on rock surfaces can be categorized as direct or indirect. Direct impacts involve physical and chemical changes due to heat and soot deposition, while indirect impacts arise from weathering and human responses to fires (Ryan, 2010; Ryan et al., 2012). Effective fire risk management relies on robust assessments and solid evidence-based

decisions, which depend on reliable data and understanding of historical impacts (Bowman et al., 2017). Nevertheless, research into fire as a threat to rock heritage remains in its early stages, with discrepancies in the methodology for studying its impact (Lobarinhas et al., 2024).

This review paper examines the current state of knowledge in fire deterioration of rock art by analysing how existing studies address the subject: focusing on their scope, methodologies and results obtained. These studies commonly investigate scenarios such as natural wildfires, anthropogenic fires, or controlled experimental burns, and the goal is to explore which scenarios dominate the literature through documented characteristics such as rock art types, lithologies, archaeological sites contexts, as well as documented fire deterioration patterns: deposition, discolouration, cracks and scaling. Furthermore, we analysed how the current body of research is shaped by different methodological approaches, highlighting benefits and limitations of each approach for the characterization of fire degradation of rock-art. Through this analysis, we aim to redirect the underdeveloped nature of this research field towards a more standardized analysis of fire degradation in rock-art, through perspective future directions for its application and by highlighting the urgent need for more comprehensive, interdisciplinary investigations to improve understanding and inform mitigation strategies.

2. Methods

A systematic literature search was conducted in English using *Scopus* and *Web of Science* databases to not only ensure comprehensive coverage of peer-reviewed, high-quality research, but also enable reproducibility, facilitate citation tracking, and capture relevant cross-disciplinary studies. The Boolean search strategy began with the keywords “Fire”, coupled with the terms “Rock Art”, “Rock Carving”, “Rock Drawing”, “Rock Engraving”, “Rock Inscription” and “Rock Painting”, given the wide array of etymology utilized to describe rock art (Allen, 1879; Brown et al., 2011; Butzer et al., 1979; Horsfield et al., 1933; Moya-Canoles et al., 2021), as well as “Natural Stone”. The combination of these terms for each group was the result of various attempts to find the best possible pairs of terms, connected by the operator “AND,” were used in the search for relevant scientific articles written in English. The search engines of *Google* and *Google Scholar* were also used to capture relevant works that mentioned the previously listed keywords. This search also helped identify some institutional related websites that might contain relevant information for the topic of this study. The use of these eight sets of keywords led to a variety of related topics, including climate change, wildfire prevention, disaster risk reduction, historical heritage preservation, and archaeology, to name a few.

From the obtained set of articles, a screening phase was then applied, through which duplicate studies were first excluded, followed by an exclusion based on the title and keywords used (Fig. 1). Given the relatively low number of articles resulting from the screening process, the eligibility stage was conducted manually. This process was separated in two parts: (i) a first part where studies were selected based on the topics approached in the abstract, and (ii) a second part where selected studies were then screened after an integral reading. Through this eligibility phase, only references, which approached the subject of fire impact on rock art, were then included in the review process.

Regarding the identification and screening of papers, the systematic literature search began with a total of 238 articles gathered from the *Scopus* and *Web of Science* sources. Of these, 85 duplicate articles were excluded, and after analysing title and keywords for each one, another 78 were also rejected (Fig. 2). The process of identifying articles for our study continued by examining the abstract of each of the 75 articles sought for retrieval, along with 6 articles obtained earlier from sources such as *Google* and *Google Scholar*, resulting in 35 articles eligible for preliminary reading. Following a preliminary reading, only 21 of these 35 eligible studies were selected for this review. In large part, the excluded articles often met some of the mentioned criteria, but never fully realized an actual approach to the impact of fire on rock art. Some

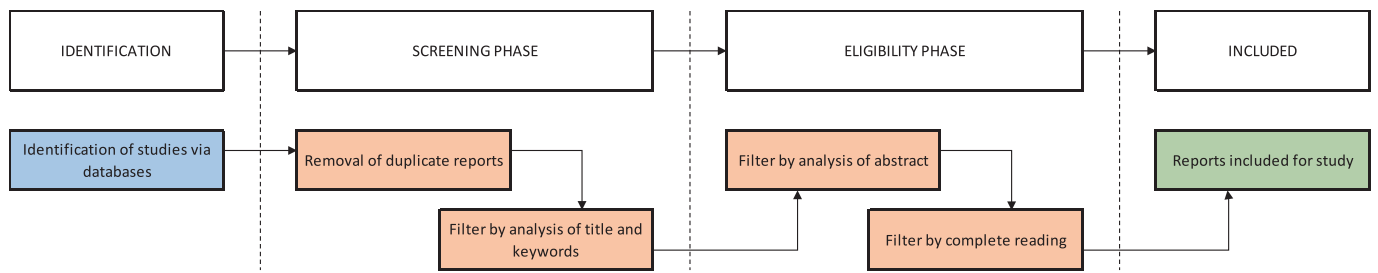


Fig. 1. Diagram of the process for screening and selecting relevant studies for review, for the bibliographic research of fire effect on rock art.

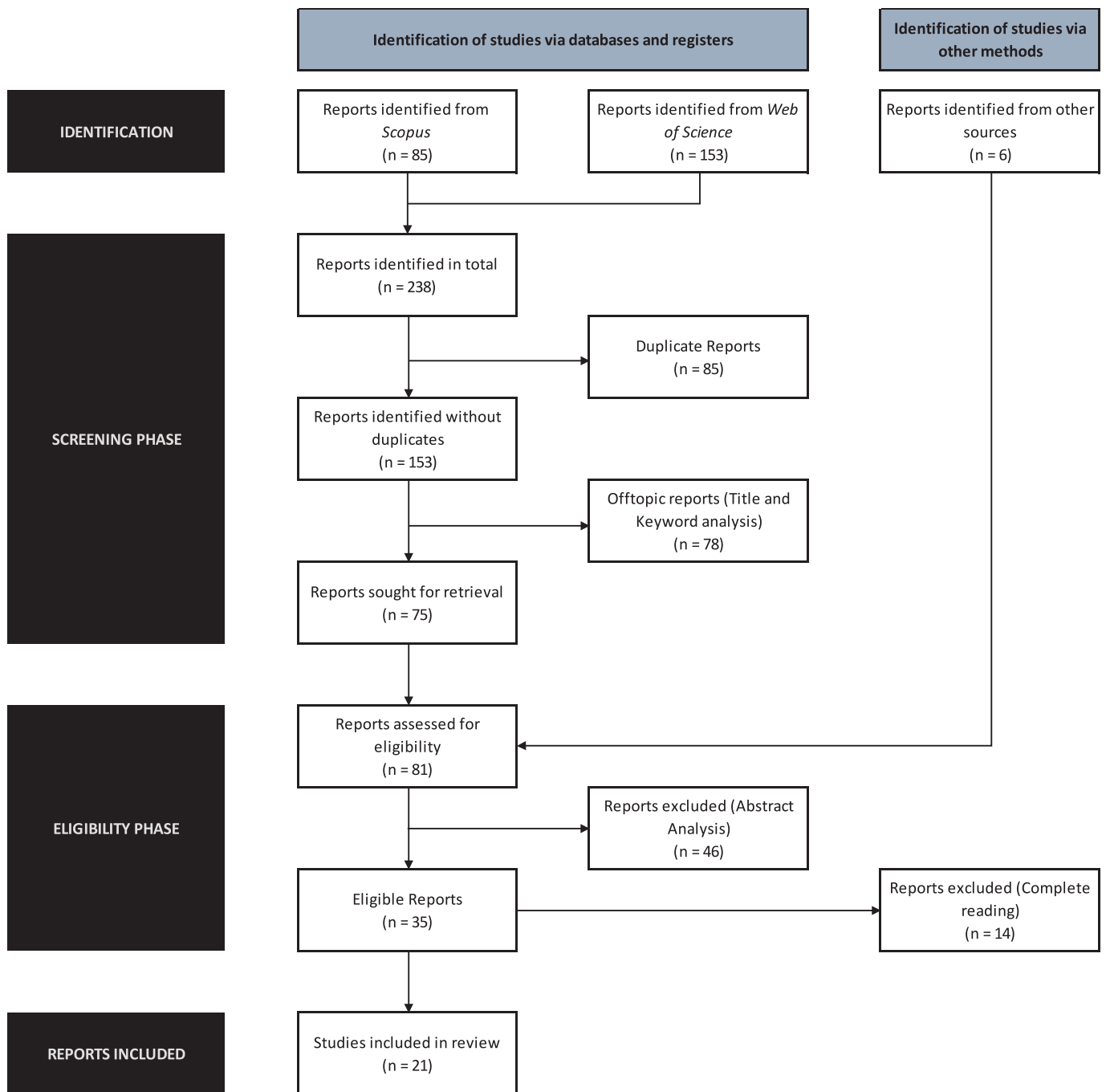


Fig. 2. Flowchart of the result of identification, screening and eligibility analysis of articles obtained from bibliographic research.

common subjects in excluded articles included: rock art depicting fire being analysed through an artistic lens; the impact of fire on artwork made in building stone, namely in churches; risk assessment of wildfires on locations containing rock art; dating of fire activity near rock art locations through vegetation development analysis.

To catalogue the results from this research, a table was then created based on the 21 articles chosen, highlighting the respective authors and date of publication, with small summaries of the main scope of each study along with the methods utilized to tackle fire impact on rock art (Table 1). Besides these summaries, key information regarding the nature of the fire events, the studied rock-art types and sites, the scale of the areas in study and the observed fire effects was also included. A bibliometric analysis was initially conducted on the resulting articles, regarding each study's year of publication, archaeological location and relevant factors regarding the rock-art in study. The main factors chosen were rock-art types, rock-art sites, rock lithologies, the nature of the fire event(s) and the observed fire degradation patterns. Given the context of the topic of fire degradation in rock-art, these factors were then identified and classified, followed by an analysis of their distribution within the framework of the reviewed articles. This process allowed us to further understand which factors were more often encountered, which may lack relevant research documentation, and under which contexts they tend to most commonly occur. To proceed with the distribution analysis, each of these datapoints was classified based on known nomenclature: Rock-art types were identified as either paintings, engravings or sculptures; while rock-art sites were identified as being open-air sites, shelters, caves or others (for scenarios where they did not fit the previous classifiers). The analysis of lithologies utilized the bedrock classification present in each study, while the known nature of the fire events was classified as either a natural fire (for wildfires and bushfires of natural or unknown origins), an anthropogenic fire (for man-made fires outside of controlled studies), or as an experimental fire (for controlled burns). For the macroscopic observation of fire deterioration on rock art, the ICOMOS glossary on stone deterioration patterns (ICOMOS, 2016) was used as a reference. Although it was not specifically developed for fire-induced damage, it encompasses all types of fire-related deterioration reported in the reviewed articles. We initially applied the major classification families for the macroscopic deterioration patterns observed, namely "Crack & Deformation", "Detachment" and "Discolouration and Deposit" and then considered the more specific terms within each family, i.e. "Cracks", "Scaling", "Deposit" and "Discolouration", as these more accurately represent the phenomena observed across the studies.

We then synthesised the methodologies employed in each of the reviewed articles, by dividing them into seven groups based on their content: (i) microscopic and mineral analysis of rock surfaces, (ii) chronometric dating of soot, (iii) stratigraphic and contextual approaches, (iv) simulations of fire behaviour, (v) landscape scale fire studies, (vi) historical, archival and qualitative approaches, and (vii) synthesis/review studies of fire deterioration. Each group is based on studies with similar or overlapping methodologies, with some studies naturally being present in multiples groups. For each group we then highlight the methods employed (techniques and data sources) and discuss not only the main strengths of that methodological group, but also the limitations within the overall context of assessing fire degradation in rock-art, particularly through the lens of conservation. All the articles and subsequent synthesis were exported to the Zotero reference manager software (Dan Stillman et al., 2025), allowing cited references and research data storing and organising.

3. Results

An analysis of the publication dates of the studies presented in Table 1 shows that research on the effects of fire on rock art has been occurring since at least 1998, when Hedges et al. (1998) examined the influence of soot on the dating of Common Era cave paintings. However,

a more systematic approach to fire degradation of rock-art only began to emerge consistently from 2017 onwards, with research activity peaking in 2020 and 2021 (Fig. 3). Of the 21 studies considered, only six were published prior to 2017.

Studies conducted prior to 2017 were primarily carried out in countries that have remained central to research on fire degradation of rock art, namely Argentina, Australia and United States of America. Based on the 21 studies analysed, these countries, along with Spain, emerge as the most frequently represented, each contributing three articles focused on specific national archaeological sites (Fig. 4). However, this does not imply that studies within a given country are geographically concentrated. In Spain, for example, all three studies are located in the north-western part of the Iberian Peninsula, whereas countries such as Australia display a wider array of geographical regions under study. Australian case studies range from the Arnhem Land in the northern area of the Australian country (Gunn & Whear 2009), to Woronoa Plateau in the southern area of New South Wales (Sefton 2011) and to Murujuga in the western region of Australia (Pillans & Fifield, 2013), and all these areas present different scenarios under which rock art is integrated. Besides these four major countries, there are also articles presented here on locations such as Portugal, Indonesia, Zimbabwe and Chile.

3.1. Rock-art types and rock-art sites

The most commonly found archetype of rock-art were paintings, comprising more than 66% of the rock art reviewed, followed by engravings with less than 39%. Only a single article mentioned fire degradation on sculpture-like archaeological artwork (Fig. 5a). The distribution of rock art site categories is relatively balanced: among the 21 articles reviewed, cave sites and rock-art shelters are each referenced in nine studies, while open-air sites appear in eight references (Fig. 5b). Examining the relationship between site type and rock art technique, engraved rock art is found predominantly in open-air contexts, with only one exception reported in a cave site, where engravings were later painted over (Steelman et al., 2017). All open-air sites analysed included engravings, along with a single instance of sculpture, and no paintings were recorded in these contexts. In contrast, paintings are evenly distributed between shelters and cave sites, each represented in nine studies. Although some overlap exists, since certain articles address multiple sites, the only occurrence of engravings in sheltered or cave contexts corresponds to the aforementioned case of superimposed paintings over engravings.

Although the number of articles is too small to acknowledge any statistical conclusions, it is possible to understand from these observations that rock-art sites and rock-art types share an important connection in the body of reviewed articles: these studies predominantly featured scenarios of (i) open-air sites featuring engravings or sculptures, (ii) caves and rock shelters featuring paintings (iii) combinations of the above. The reason for the clear divide between open-air/engravings/sculptures and caves/shelters/paintings is likely due to the nature of caves and shelters offering better natural protection against weathering agents, which can gradually erode surfaces or cause pigments to fade over time. This means that these locations are better suited for preserving archaeological paintings, as these are surface-based artworks. In contrast, engravings and sculptures, being more deeply carved into the bedrock, tend to be more resilient to weathering agents, and are more likely to be found and studied in open-air spaces.

3.2. Lithology, fire nature and fire degradation patterns

The lithology of the studied rock art varied significantly compared to other factors, as expected. The most common lithologies were granite, limestone and sandstone, collectively accounting for nearly 70% of the reviewed records. Other lithologies included slate (or schist/phyllite), evaporite gypsum, gabbro, tuff, granophyre, basalt. Richard et al. (2024) also reported calcite, where soot layers on stalagmites adjacent to cave

Table 1

Summary of reviewed articles in which the study of fire degradation of rock-art was present, highlighting each article's scope and methodology, as well as relevant contextual factors.

Author(s)	Methodology	Scope/Aim	Fire Type	Rock Art Type and Site	Scale of Observation	Observed Fire Effects
Dorn & Whitley 2021	VML dating ^a , sampling, SEM-EDS ^b , pre/postfire comparison	Mechanisms of exfoliation and varnish loss under fire	Wildfire (repeated events)	Open-air engravings	Panel	Detachment
Figueiredo et al. 2020	Database recording, X-ray spectroscopy, SEM-EDS ^b and XRD ^c	Technological and social interpretation of portable art	Possible surface treatment by fire (heat/pigment)	Portable engraved plaques	Sample	Discolouration
Friggens et al. 2021	Software based spatial analysis via postfire archaeological assessments and environmental predictors	Predicting likelihood of fire effects and site burn severity as a function of environment	Wildfires (five events, 2000–2011)	Sculptures	Site and Landscape (858 sites)	Deposits; Discolouration; Crack & Deformation, Detachment
Gagan et al. 2022	Field recording, time-lapse photography and comparison with sulphur emission data	Mechanisms of exfoliation and salt crusts; link to pollution and soot	Contemporary domestic/traffic fires, industrial sulphur; not wildfires	Cave and shelter paintings	Panel and Regional	Detachment
Gheco et al., 2017	Stratigraphic excavation, Harris matrix, photography, microscopy, SEM-EDS ^b , Raman spectroscopy	Historical reconstruction of painting and occupation sequences	Repeated hearths inside cave (prehistoric domestic/ritual fires)	Cave paintings	Panel to Site	Deposits
Gheco, 2020	Spatial data analysis, overlapping image data, stylistic analysis, and stratigraphic excavation	Long-term history of panel construction and modification	Fires in caves (domestic/ritual)	Cave and shelter paintings/ engravings	Panel, Site and Regional	Deposits
Gunn & Whear 2009	Controlled burn, temperature and smoke observations	Empirical assessment of bushfire impact	Bushfire (natural/managed)	Rock shelter paintings	Site	Deposits
Harde, 2023	Archival study, repeat photography	Assessment of long-term soot accumulation and peeling, to understand social use of fire	Contemporary religious/domestic fires	Rock shelter paintings	Panel to site	Deposits; Detachment
Hedges et al. 1998	Infrared spectrometry, Raman spectroscopy, radiocarbon dating	Methodological critique and strategy for dating in soot affected cave paintings	Fire derived carbon in grounds and cave deposits	Cave and shelter paintings	Sample and Panel	Deposits
Huntley and Webster, 2023	Literature review of fire affected sites, comparative synthesis	General framework for fire impacts and management	Wildfire, hearth, industrial and domestic fires	Cave and shelter paintings; Open-air engravings	Site to Regional (multiple case studies)	Deposits; Discolouration; Crack & Deformation; Detachment
Lambert and Welsh, 2011	Case descriptions, qualitative assessment fire affected sites	Conservation/management of sites affected by intense fires, management proposals	Bushfires with varying regimes	Rock shelter paintings	Site to Regional (multiple case studies)	Deposits; Crack & Deformation
Moya-Cañoles et al., 2021	Photography, micro-stratigraphy, excavation, Raman spectroscopy, SEM-EDS ^b , radiocarbon dating	Long-term interplay of fire, soot, repainting, and social practice	Prehistoric hearths in shelter	Rock shelter paintings	Panel to Site	Deposits
Pillans & Fifield 2013	Sample collection, geomorphology, AMS ^d and ¹⁰ Be cosmogenic nuclide measurements	Long-term erosion, weathering rates and longevity, including fire affected sites	Wildfire	Open-air engravings	Site and Landscape	Crack & Deformation
Pozo-Antonio et al., 2018	Geotechnical characterization, microscopy, XRD ^c , FTIR ^e , SEM-EDS ^b	Diagnose deterioration of granite petroglyphs	Wildfire	Open-air engravings	Panel to Site	Discolouration
Pozo-Antonio et al., 2020	Field sampling across vegetation types, microscopy, XRD ^c , FTIR ^e , CIELab colorimetry and thermoluminescence	Fire impact on granite outcrops under different vegetation types	Wildfire	Open-air engravings	Site and Landscape	Crack & Deformation
Richard et al. 2024	Excavations, micro-stratigraphy, microscopy, SEM-EDS ^b , FTIR ^e , Raman spectroscopy, radiocarbon and U-series dating	Chronology of human presence via soot events	Prehistoric hearths in cave entrance (Upper Palaeolithic)	Cave paintings	Site	Deposits
Salmon et al. 2019	Fire simulation software, numerical modelling	Model and validation for anthropogenic fires in natural gallery	Localized experimental wood fire	Cave paintings	Site	Deposit; Discolouration; Detachment
Salmon et al. 2021	Fire simulation software, numerical modelling	Reconstruction of Palaeolithic fires, hearth size/ placement	Intentional wood fires in decorated cave (prehistoric)	Cave paintings	Site	Deposits
Sefton 2011	Comparative field observation of panels under different fire regimes	Relation between fire frequency and exfoliation	Bushfires with varying regimes	Rock shelter paintings; Open-air engravings	Panel to site	Crack & Deformation
Steelman et al. 2017	SEM-EDS ^b , FTIR ^e , Raman spectroscopy, plasma oxidation, radiocarbon dating	Dating charcoal paintings and constraining engraving age	Medieval fires contaminating pigments; Palaeolithic hearths	Cave paintings over engravings	Panel to site	Deposits
Tratebas et al. 2004	Pre/postfire field recording, ICP spectroscopy, microscopy, SEM	Documenting wildfire damage modes to rock art	Wildfire	Open-air engravings	Panel to site	Deposits; Crack & Deformation

^a Varnish Microlamination Dating (VML Dating).

- ^b Scanning Electron Microscopy (SEM) coupled with Energy Dispersive Spectroscopy (EDS).
- ^c X-ray Diffraction (XRD).
- ^d Accelerator Mass Spectrometry (AMS).
- ^e Fourier Transform Infrared (FTIR).

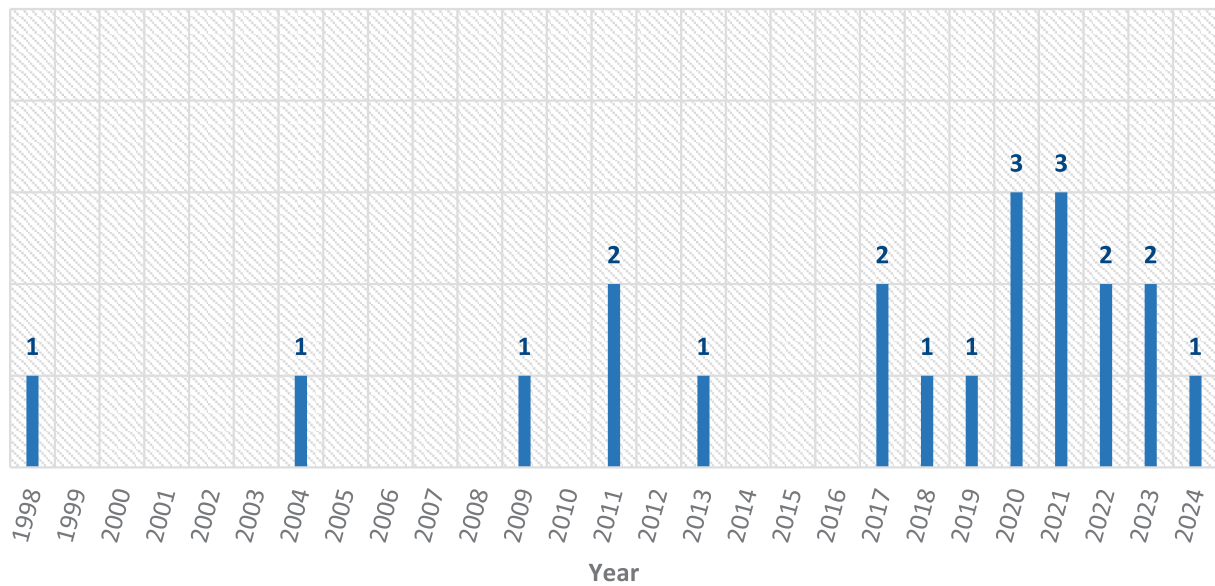


Fig. 3. Yearly distribution of publications among the selected studies (total = 21).

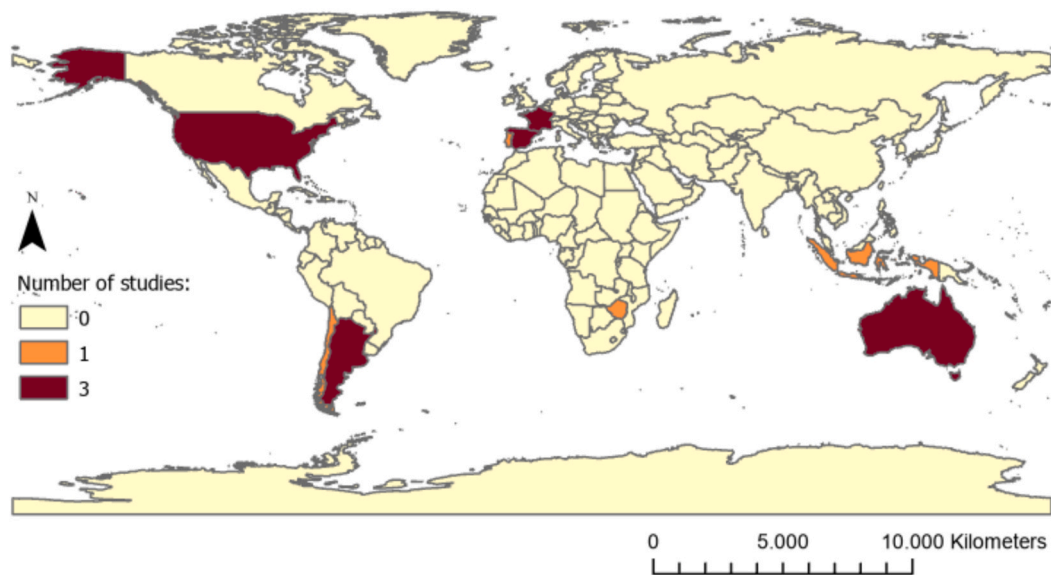


Fig. 4. Map highlighting the countries most frequently represented the selected articles studies.

paintings were dated, rather than representing the actual bedrock in which the paintings were made. Another factor considered was the nature of the fires responsible for rock-art degradation, which was identified in all reviewed articles. Of the 21 articles analysed, more than 85% examined fire degradation in rock-art in post-fire scenarios. Among these, twelve studies attributed the damage to anthropogenic fires, while eight associated it with natural fires. The remaining three studies were experimental, involving sample collection and controlled fire simulations. Regarding the relationship between fire origin and site type, a clear pattern emerges. In cave contexts, all reported degradation patterns were linked to anthropogenic fires. Even in the exceptional case of Salmon et al. (2019, 2021), where the methodology involved

simulating fire conditions inside a cave, the assumed nature of the fire event was anthropogenic. In contrast, natural fires were almost always reported as the cause of fire degradation in contexts where rock-art was located in an open-air site, with a notable exception being the case where portable rock-art with engravings was suspected to have received heat treatment (anthropogenic nature). For rock shelter contexts, anthropogenic fires account for approximately two-thirds of the cases, while two studies attribute damage to natural fires. One additional study (Gunn and Whear, 2009) employed an experimental approach simulating, although this approach was meant to simulate natural fire conditions.

The last major factor we examined was the observed fire degradation

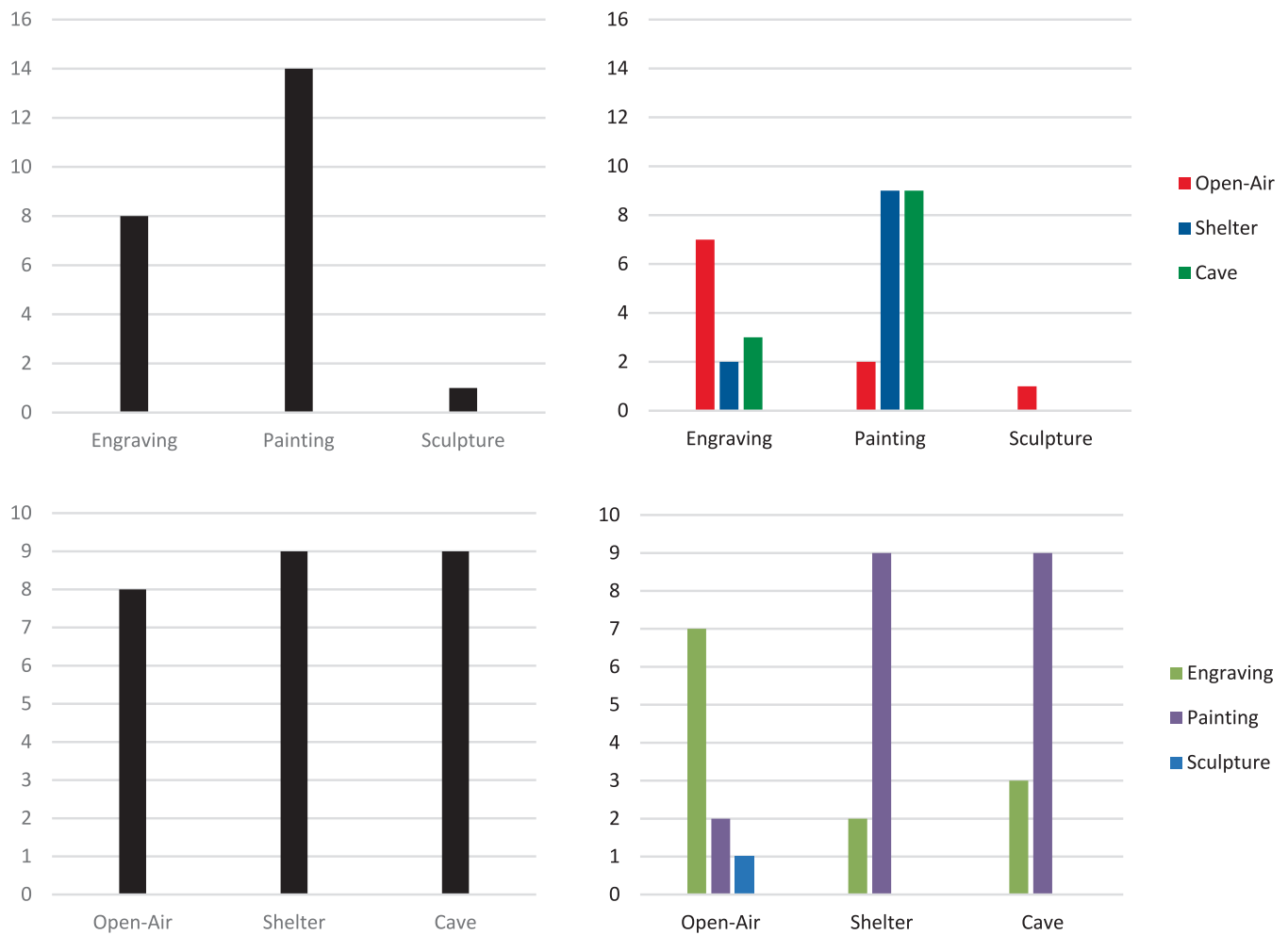


Fig. 5. Distribution of the a) studied rock art sites (left) and b) rock art types (right).

patterns reported in each study. Despite the varying descriptions of these effects, they accurately matched four terms of rock deterioration patterns mentioned in the ICOMOS glossary (ICOMOS 2016) (Fig. 6). These terms were part of three major families of stone macroscopic deterioration patterns: “Crack & Deformation”, “Detachment” and “Discolouration and Deposit”, as previously mentioned. The first term is “Deposit”, which tackles soot, the dark residue produced by fires that

can form a layer obscuring underlying rock art. Soot was the most reported effect (Fig. 7), appearing in 14 of the 21 reviewed studies.

A strong relationship between the rock-art site type and the presence of soot was noted, as all but cave sites present in the reviewed articles highlighted the presence of soot deposits, typically on ceilings and walls, with only the exception of one study. Similar observations of soot presence we also made in almost all shelter sites studied, bar from 2

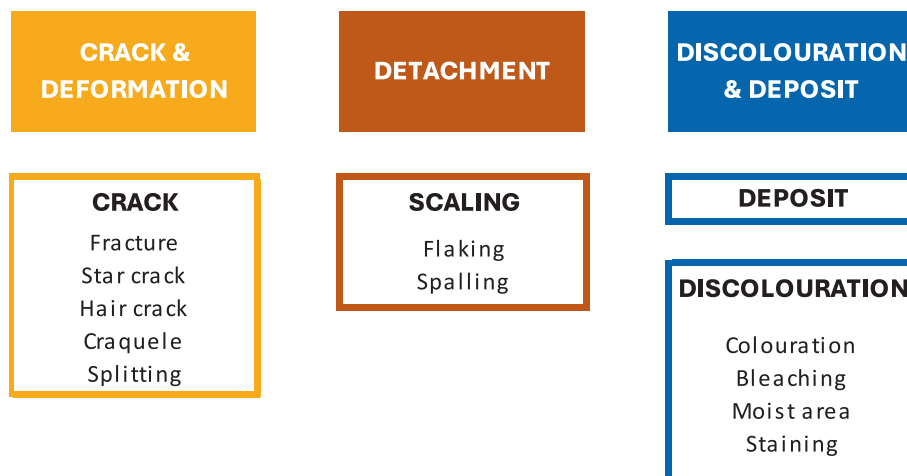


Fig. 6. Major terms of macroscopic rock deterioration patterns registered in the selected studies, according to ICOMOS glossary (ICOMOS, 2016): Crack, Scaling, Deposit and Discolouration.

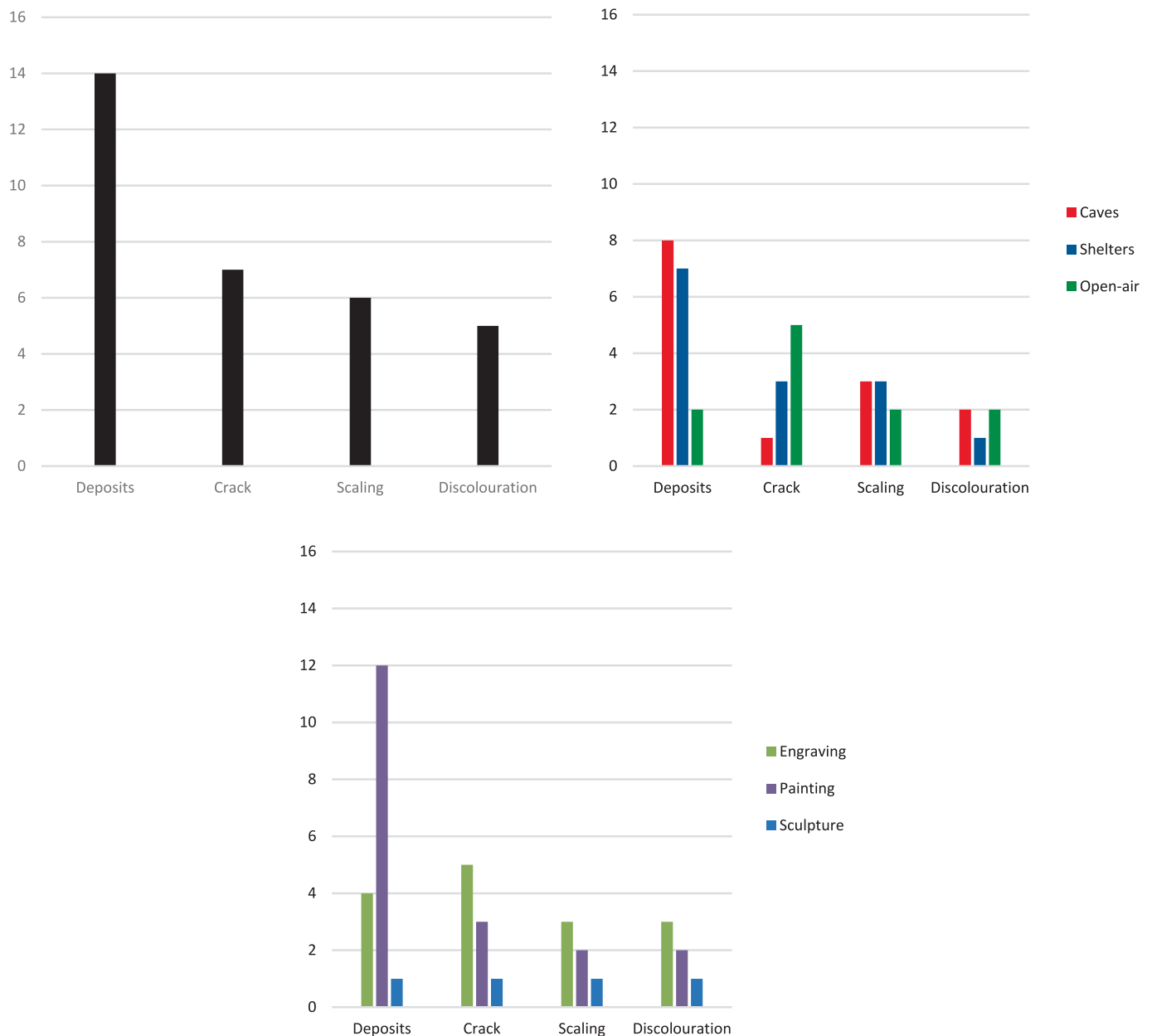


Fig. 7. Frequency of effects observed on fire-affected rock art, from the selected articles for review.

exceptions. In contrast, soot deposition was observed in only two cases involving open-air sites. Meanwhile, when compared to the type of rock-art, soot deposition was almost always identified in cases where the article approaches rock paintings, with only four cases identifying soot in rock engravings. These observations are well correlated with the previously analysed relationship between rock-art types and sites: as paintings were almost always analysed in cave or shelter sites, which in turn were heavily tied to soot deposition, it's logical that paintings would also be mostly affected by the same degradation pattern. For open-air sites, since we know that the presence of air-flow aids in the lack of soot deposition (Gunn and Whear, 2009) and that these are closely tied with engraved rock-art, we can also understand why both these features present soot deposition to a much lesser extent.

Other degradation patterns, such as material detachment on rock art bedrock was classified as either “Scaling”, to describe phenomena of flaking or the spalling of weathering rinds from the surfaces of rock, or “Crack”, to describe fractures, micro-fractures and block separation as a product of thermal stress. Together, both phenomena of appear in

similar measure across ten different studies, but while cracks in rock-art bedrock were more commonly observed in open-air sites, scaling degradation patterns were more commonly found in caves and rock shelters. Similarly, crack and scaling were more commonly documented in engraved rock-art, rather than in paintings. These behaviours are likely to resonate with the nature of the fires that each type of rock-art site (and therefore rock-art type) are likely to encounter. As mentioned above, we know that anthropogenic fires (typically lower intensity) were more likely to be mentioned as the origin for fire degradation patterns in cave paintings, and that natural fires (typically higher intensity) were the events tied to open-air engraving degradation. As such, we can surmise that the degradation patterns of cracks and scaling are likely to be correlated with more intense fire events, such as bushfires or wildfires, rather than with pre-historic hearths or campfires, lower intensity events that are more correlated with soot deposition.

Finally, the last described degradation pattern was “Discolouration”, a term from the ICOMOS glossary that describes deterioration patterns of colouration, bleaching, moisture areas and staining. Nevertheless, in



Fig. 8. Close-up photograph capturing the discolouration patterns on a rock art outcrop in Foz Côa, Portugal, likely resulting from anthropogenic fires.

the reviewed articles fire exposure led only to bleaching of paintings or reddening of rock surfaces (Fig. 8) (this classification does not include the black layers caused by soot, as those belong in the “Deposit” subclass). This degradation pattern was the least frequently noted in the reviewed studies as just five articles noted colour changes. Surprisingly, although colour and pigment are critical elements in cave paintings, and at least more so than in engraved or sculpted rock-art, colour changes were predominantly identified in engravings, which often described as the reddening of the bedrock. Again, this could be tied to the previously made observation regarding the fire intensities which different rock-art sites and rock-art types are more likely to have been exposed to. Since the reddening (or bleaching) of bedrock is known to be caused by higher temperature thresholds, from at least 300°C (Lobarinhas et al., 2025), rock-art exposed to higher intensity wildfires would be more likely to present this degradation pattern, as is the case for open-air engravings.

4. Discussion

The results show that, within the reviewed studies, rock-art types, sites, fire origins and degradation patterns are tightly connected rather than randomly distributed. Studies on open-air contexts focus almost exclusively on engravings, whereas paintings are predominantly confined to caves and rock shelters. This pattern supports the idea that caves and shelters, by buffering surfaces from direct weathering, selectively preserve surface-based artworks such as paintings, while engravings and sculptures are more resilient and therefore more frequently documented in exposed, open-air settings. A similar structuring is observed in the nature of the fires affecting rock-art, as degradation of cave paintings is consistently attributed to anthropogenic fires (prehistoric hearths, domestic or ritual fires), while natural fires (bushfires or wildfires) overwhelmingly account for damage on open-air engraved

panels and rock-shelter cases occupying an intermediate position in which both anthropogenic and natural fires are represented, alongside a small experimental subset.

These contextual contrasts are mirrored in the observed deterioration patterns: soot deposits are strongly associated with caves and shelters and with painted rock art, occurring on ceilings and walls in almost every such case, but are rare in open-air engraving contexts, where airflow tends to disperse combustion products more effectively. Conversely, cracks and scaling are more commonly reported on engraved bedrock in open-air sites and less so on sheltered paintings, suggesting that higher-intensity natural fires are more likely to generate mechanical stress and detachment, while lower-intensity anthropogenic fires primarily produce surface deposits. Meanwhile, discolouration appears predominantly on engraved outcrops rather than painted cave walls, despite the central importance of colour in paintings, again pointing toward exposure to higher-temperature events in open-air settings. When this pattern is read together with the lithological distribution, a further nuance emerges: the most frequently studied substrates (granite, sandstone and limestone) do not behave identically, since cracking and scaling effects appear to be over-represented on hard, open-air lithologies such as granite and sandstone, whereas limestone and calcite more commonly figure in cases dominated by soot and other deposits, mostly in cave contexts. This suggests that the interaction between fire intensity, site setting and host rock properties plays a decisive role in determining whether fire leaves primarily depositional, mechanical or chromatic signatures on rock-art surfaces. Scoring system for fire related damage to rock art.

The concentration of observations on deposits, discolouration, cracks and scaling in the results discussed above indicates that a relatively small set of fire-related damage types recurs across diverse contexts. However, these degradation patterns are still described in heterogeneous and largely qualitative ways. Given this recurrence of fire-related damage types, and adapting terminology from the ICOMOS glossary on stone deterioration patterns (ICOMOS, 2016), we propose a preliminary ordinal scoring system for fire-related damage to rock art. The aim is to provide a structured vocabulary that can be applied consistently in field recording, laboratory studies and experimental work, allowing results from sites as different as Whoopup Canyon (Tratebas et al., 2004), Chauvet-Pont d’Arc (Salmon et al., 2019, 2021) or San Salvador de Coruxo (Pozo-Antonio et al., 2020) to be compared more directly.

4.1. Scoring system for fire degradation patterns in rock-art

We recognise the four main fire degradation sub-classes based on the ICOMOS glossary: Deposits (soot, ash, tarry residues); Discolouration (pigment bleaching, reddening, heat halos, non-soot surface darkening); Cracks (micro-cracking, fracturing, warping and buckling of surfaces); and Scaling (scaling, spalling, exfoliation and flaking of surfaces), which were highlighted in the results section accordingly. Each class is scored on a four-level ordinal scale from 0 (absent) to 3 (severe), based on observable field criteria. The detailed descriptions of the scoring system for each class are presented in Table 2. For deposits, which include soot, ash and tarry residues, the extensive soot accumulations described in several cave studies we analysed would correspond to deposit scores of 2–3 (moderate to severe), whereas the largely aesthetic changes observed in the study of Pozo-Antonio et al. (2020) for example would be scored as 1 (mild) despite clear residue presence.

Meanwhile, discolouration patterns such as reddened backgrounds around engravings, as reported in some analysed open-air site studies, would be scored as 2 (moderate), while heavy bleaching of painted surfaces in post-fire comparisons would be scored 3 (severe) due to the loss of the paintings themselves. Observed micro-cracking and fabric disruption documented in experimental heating studies, particularly in open-air sites, would correspond to a score of 2 (moderate), while the severe cracking and block separation visible in high-severity burns would naturally mark the upper end of the scale as a score of 3 (severe).

Table 2
ICOMOS-based classification table for fire degradation patterns observed in rock-art.

ICOMOS Degradation Family	Fire-damage Type Class	Score (0–3)	Operational definition (field use)	Typical indicators and notes
DISCOLOURATION & DEPOSIT	Deposits (Soot, ash, tarry residues)	0	None – no visible fire-related deposits on the rock surface or motifs.	Clean rock surface, no darkening or coating that can be attributed to fire.
		1	Mild – thin or patchy deposits that do not significantly obscure motifs or engraved lines.	Light grey/black smudges, small patches, underlying motifs clearly legible.
		2	Moderate – continuous or thicker deposits partially obscuring motifs or altering their legibility.	More extensive dark coatings, some motifs partly hidden or harder to see.
		3	Severe – heavy deposits fully obscuring motifs or substantially altering surface appearance.	Thick black/grey layers, laminated soot, motifs invisible; may trap moisture or salts; often on ceilings/overhangs.
	Discolouration (Pigment bleaching, reddening, heat halos, non-soot surface darkening)	0	None – no perceptible colour changes attributable to fire.	No obvious difference between exposed and sheltered areas or pre-fire imagery.
		1	Mild – slight colour shifts visible locally, but motifs remain clearly legible.	Subtle reddening or lightening; contrast essentially preserved.
		2	Moderate – noticeable bleaching or reddening reducing motif contrast, but motif outline still discernible.	Clear halos around engravings, noticeably faded pigments; figures still recognisable.
		3	Severe – strong colour changes leading to partial or near-complete loss of motif visibility.	Background and pigment colours converge; motifs very hard to distinguish or effectively lost.
CRACK & DEFORMATION	Cracks (Micro-cracking, open fractures, warping & buckling of surfaces)	0	None – no fire-related cracks distinguishable from background jointing or natural bedding.	Only pre-existing structural joints; no new crack sets associated with burned areas.
		1	Mild – localised hairline cracks or slight deformation confined to small areas; motifs not disrupted.	Fine surface cracks or slight curvature in limited zones; motifs intact.
		2	Moderate – more extensive crack networks or localised warping intersecting motifs; increased risk of future detachment.	Cracks cut through figures, small blocks beginning to separate; noticeable but not yet catastrophic.
		3	Severe – wide open cracks, block separation or strong deformation compromising panel stability.	Large open fractures, displaced blocks, warped surfaces; risk of collapse or major loss of decorated surface.
DETACHMENT	Scaling (spalling, exfoliation & flaking of decorated surface)	0	None – no fire-related loss of surface material detectable.	No fresh scars, no accumulations of new flakes attributable to fire.
		1	Mild – small flakes or limited scaling outside motif areas.	Minor fresh chips, thin flake loss on margins or non-decorated zones.
		2	Moderate – partial loss of decorated surface (e.g. parts of figures) or extensive spalling of adjacent rinds.	Missing segments of motifs, sizeably spalled zones; detached fragments present at panel base.
		3	Severe – extensive or complete removal of decorated surface and/or substantial panel thinning.	Large areas of lost rock art, deep exfoliation fronts, major thinning of the decorated layer; often co-occurs with severe cracking.

Finally, the common spalling of weathering rinds and varnish described by [Tratebas et al. \(2004\)](#) or [Pillans and Fifield \(2013\)](#) would correspond to detachment scores of 3 (severe), whereas minor flaking observed after low-temperature events would be scored as 1 (mild).

We emphasise that the proposed system is ordinal and operational, designed for reproducible recording rather than as a direct physical measure of energy input or material loss. Its main value lies in providing a common structure that can be used across post-fire surveys, laboratory case studies and experimental burns. Although most existing studies treat discolouration qualitatively, this scheme invites more systematic use of repeatable criteria and, where possible, colourimetry measurements. In future work, damage scores can be calibrated against micro-structural, mineralogical and mechanical measurements, such as those already reported for soot layers, weathering rinds and heated granite, to refine thresholds and link qualitative assessments more tightly to quantitative change.

4.2. Methodological analysis

The methodological landscape of research on fire degradation in rock art, as observed in the reviewed articles, is complex. However, it can be systematically examined by grouping similar approaches into seven broad groups/categories. These include micro-analytical, chronometric, stratigraphic, fire simulative, landscape scale, archival and qualitative methods, as well as synthetic/review studies. Assessing these approaches highlights both their contributions and their limitations in advancing the understanding of fire degradation in rock art.

Collectively, they reveal areas where current methodologies are robust, particularly in reconstructing fire-rock interactions and deterioration mechanisms, as well as significant gaps, especially in the predictive assessment of future fire damage. This overview provides a solid framework for understanding the current state of research in this field.

4.2.1. Micro-analytical approaches

Studies which approach the microscopic and microstructural scales use high resolution tools such as optical microscopy, scanning electron microscopy, Raman spectroscopy, Fourier transform infrared spectroscopy and thin section microstratigraphy to characterize pigments, soot, varnish, weathering rinds and mineral phases on rock art surfaces ([Hedges et al., 1998](#); [Tratebas et al., 2004](#); [Gheco et al., 2017](#); [Pozo-Antonio et al., 2018](#); [Figueiredo et al., 2020](#); [Pozo-Antonio et al., 2020](#); [Moya-Canoles et al., 2021](#); [Richard et al., 2024](#)). In some cases, they also include cosmogenic nuclide measurements, varnish microstratigraphy and detailed mineralogical work on gypsum, oxides and other salts to reconstruct long term weathering histories ([Pillans and Fifield, 2013](#); [Dorn and Whitley, 2021](#); [Gagan et al., 2022](#)). The strengths of these methods lie in their sensitivity, enabling the differentiation of soot from pigment, the identification of specific mineral phases, and the detection of subtle thermal transformations that indicate whether rock surfaces reached particular temperature thresholds during fire events. When combined with dating techniques, they also allow for the establishment of absolute or relative chronologies of events, as described in [Richard et al. \(2024\)](#) when dating soot layers in a stalagmite at Points Cave or the layered fire, paint and gypsum sequences

reconstructed at Alero Cachaco by [Moya-Cañoles et al. \(2021\)](#).

However, these methods are typically invasive, requiring micro-sampling from rock-art panels or adjacent surfaces. Their insights are also highly localized, limited to the scale of individual samples or panels, which makes it challenging to extrapolate results to the site or regional level. Interpretation can be complex, often constrained by local geology and fire history, thereby limiting broader generalization across different archaeological contexts. In practice, these microanalytical approaches are particularly well suited to investigating deterioration mechanisms, for example distinguishing wildfire-induced heat effects from water-driven erosion (e.g. Mougas and the Burrup Peninsula), differentiating soot deposition from pigment (e.g. Alero Cachaco, El AltoAncasti and Cova Eiros) or linking these alterations to secondary processes such as salt efflorescence and exfoliation (e.g., Sulawesi and North-Central Chile).

4.2.2. Chronometric approaches

Chronometric approaches in the reviewed studies use fire-related materials as chronological anchors for fire-affected rock-art, particularly through accelerator mass spectrometry (AMS) radiocarbon dating and Uranium-Thorium (U-Th) dating of areas containing soot ([Hedges et al., 1998](#); [Steelman et al., 2017](#); [Dorn and Whitley, 2021](#); [Moya-Cañoles et al., 2021](#); [Richard et al., 2024](#)). These studies address residual carbon derived from past fire events that infiltrate cave floors and wall surfaces, often requiring correction strategies based on these dating techniques. Such methods provide robust chronological frameworks for dating both art production and past fire events, sometimes linking repainting phases or soot deposition episodes to specific periods. When combined with stratigraphic approaches, they enable the reconstruction of complex sequences, such as painting phases followed by soot deposition, gypsum formation and subsequent repainting, effectively transforming layered wall deposits into dated histories of use and alteration. The combined application of U-Th and radiocarbon dating, as demonstrated in [Richard et al. \(2024\)](#) also permits cross-validation of fire episodes against broader paleoenvironmental records, situating rock-art activity within broader environmental and climatic contexts.

At the same time, contamination risks are significant: soot and carbon from unrelated fires may infiltrate pigments and substrate surfaces, meaning that the obtained dates can reflect the most recent heating or soot deposition episode rather than the original moment of image creation if stratigraphic relationships are not carefully established. Sample sizes are usually small, analytical costs are high, and ethical constraints limit destructive sampling, especially on iconic panels. These approaches have been primarily applied to dating charcoal-based paintings and establishing minimum ages for engravings (e.g. Cova Eiros), reconstructing the timing of human presence and fire use in relation to artistic activity (e.g. Points Cave and Alero Cachaco), and assessing both the potential and limitations of radiocarbon dating in fire-rich cave contexts ([Hedges et al., 1998](#)). Over time, a clear methodological shift can be observed, from dating any available carbon to more selective and rigorous strategies that distinguish between pigment, soot and natural carbonates or oxalates. Increasingly, fire-related by-products, such as soot layers and soot-bearing stalagmites, are used as chronometers in their own right, sometimes independently of a direct association with the imagery.

4.2.3. Stratigraphic approaches

Stratigraphic approaches treat caves and shelters as integrated depositional systems in which sediments, soot layers and sequences of painted or engraved superpositions are considered within a unified analytical framework. These approaches involve stratigraphic excavation of floor deposits, the analysis of superimpositions and stylistic sequences, and the spatial study of panel distribution. In the reviewed studies, they are often combined with microanalytical and chronometric methods to provide a more comprehensive understanding of site formation and use ([Gheco et al., 2017](#); [Gheco, 2020](#); [Moya-Cañoles et al.,](#)

[2021](#)). The advantage of these approaches is their holistic view, as they attempt to connect art making, fire events, occupation episodes or broader social practices through time and allow cross validation between multidisciplinary, such as correlating wall soot layers with dated floor hearths. They are particularly strong for interpreting repainting, palimpsests and shifts in occupation intensity, since they can read changes in panel composition against changing hearth patterns and sediment inputs. Their main disadvantages are practical: they are methodologically heavy, requiring excavation permits, multi-year campaigns and genuinely multidisciplinary teams, and they often result in richly detailed but highly site-specific case studies whose broader generalizability is limited. Chronological precision also depends on the density of dates and the integrity of stratigraphy, both of which can be compromised by later quarrying or disturbance, as [Richard et al.](#) note for Points Cave. A clear trend is the movement toward multidisciplinary frameworks that combine spatial, stratigraphic, microanalytical and chronological data, and toward treating fire as part of the occupation history and social practice of a place rather than only as a physical threat to art.

4.2.4. Fire simulation approaches

Studies aiming to predict potential fire degradation generally follow two main methodological paths: either through controlled burns ([Gunn and Whear, 2009](#)), or through numerical simulations of fire events ([Salmon et al., 2019, 2021](#)). Numerical simulations are particularly notable, as they provide quantitative temperature fields and surface thresholds within realistic geometries, enabling researchers to link observed thermo-alterations to specific heating regimes, for example, experimental calibrated thresholds where rubification occurs above 250 °C and grey colouration at 350–400 °C ([Salmon et al., 2019, 2021](#)). These simulations are also non-destructive, making it possible to test hypothetical fire scenarios in protected sites that cannot ethically be reproduced in-situ.

However, such models require careful calibration and are sensitive to assumptions about fuel type, moisture, ventilation, wall thermal properties, and boundary conditions. To date, their primary application has been archaeological interpretation, informing hearth size, function and placement, rather than for proactive conservation risk assessment.

4.2.5. Landscape scale approaches

Landscape scale studies step away from individual panels to consider many sites across archaeological regions, usually after major wildfires. Methodologically, they combine postfire archaeological surveys with fire intensity predictors such as topography, vegetation and fuel moisture ([Sefton, 2011](#); [Pozo-Antonio et al., 2020](#); [Friggens et al., 2021](#)). These methods excel in understanding landscape scale patterns and at identifying settings where fire damage in rock-art is more likely to occur, which is relevant for fire management planning, helping to assess where protective measures might need to be prioritized. Another positive is the fact that they are non-invasive and repeatable, relying on field observations of fire-affected areas combined with remotely sensed (or modelled) environmental data. The main limitations of this approach for rock-art are that the damage metrics used so far can be quite coarse: on [Friggens et al.](#) for example the classification for site burn severity following a fire event was simply unburned, (2) low (scorched or lightly burned), (3) moderate, or (4) high (severely burned), based on site observational data. And in this example too, rock-art was just one type of site among many and was never analysed separately from rock field houses and other small masonry structures. Not only that but burn severity is usually an ecological proxy based on vegetation consumption rather than a direct measurement of rock surface temperatures or pigment alteration, and no study yet links these landscape predictors to experimentally derived damage thresholds for rock art bedrock. We can see the growing use of predictive models to map vulnerability at scale, but so far with only a weak connection to microscale deterioration data (a core strength of previously highlighted methodology approaches),

leaving a gap between landscape modelling and rock-art conservation.

4.2.6. Archival and qualitative approaches

Archival and qualitative approaches reconstruct the history of fire and damage to rock-art sites through documents, images and testimonies rather than direct material analysis. They draw on expedition reports, field notes, contemporary accounts, and also image material from early drawings, watercolour copies or historical photographs (Gagan et al., 2022; Harde, 2023). These methods are valuable because they capture long-term changes over decades in the absence of systematic monitoring, allowing researchers to track the progression of soot accumulation, peeling or exfoliation. They can also help identify the origins of fire events associated with observed degradation patterns, information often inaccessible to purely physical or microanalytical studies. While non-invasive and applicable in areas where access is restricted or the art is completely obscured, these approaches have clear limitations: they do not provide direct material analysis of soot or substrates, cannot easily distinguish visual obscuration from physical or chemical alteration, and rely on irregular documentation potentially uncertain chronology and completeness. Their use is therefore most effective at sites with prior documentation and where contemporary activity is a major driver of fire risk.

4.2.7. Synthesis/review articles

Synthesis and review oriented studies do not introduce new empirical data but instead compile and compare results from multiple case studies to develop conceptual frameworks and management guidance. Common methods involve literature review, comparative synthesis across host rocks and pigment types, and translation of scattered, often technical findings into more accessible guidance. The strength of this approach lies in its ability to translate diverse and often highly specialized technical work into pragmatic overviews, such as recommending vegetation clearance, describing rock-art bedrock differences or highlighting particularly vulnerable pigment types. These syntheses also play an important role in identifying recurring knowledge gaps, such as the persistent lack of quantitative temperature threshold data or the limited understanding of how specific pigments respond to repeated heating and soot exposure. Their main limitations are that they depend on the quality and geographic scope of the underlying empirical literature, risk perpetuating existing biases or gaps, and typically remain qualitative in their approach to fire scenarios.

4.2.8. Overview of methodological groups

Across these seven methodological groups, several observations emerge when the approaches are considered collectively. First, multi-disciplinary integration is becoming increasingly standard: many recent studies, particularly by Gheco (2020) and by Moya-Cañoles et al. (2021), deliberately combine microanalytical, chronometric and stratigraphic methods rather than relying on a single approach, using this integration to build richer narratives of fire damage, rock-art and site occupation. Second, soot deposition is central in cave-painting contexts, with highly consistent analytical methods but conceptually fragmented interpretations: in different studies, soot appears as a datable substrate (Hedges et al., 1998; Richard et al., 2024), a damaging obscuring that effectively erases imagery (Gagan et al., 2022; Harde, 2023) and even as a socially constitutive material that structures repainting practice over millennia (Moya-Cañoles et al., 2021). Third, fire sources are increasingly differentiated: recent research identifies a range of prehistoric hearths, wildfires, domestic fires, religious fires and even industrial or agricultural emissions, each with distinct spatial and chemical signatures (Gagan et al., 2022; Harde, 2023; Moya-Cañoles et al., 2021; Tratebas et al., 2004). Fourth, despite software and numerical modelling and some experimental calibrations, temperature thresholds remain a persistent weakness in the reviewed literature: most conservation-oriented rock-art studies do not link observed damage to quantified temperature/exposure regimes, leaving a gap between fire behaviour

modelling and material vulnerability. Finally, these issues point to a more fundamental challenge concerning scales of analysis, where fire-related impacts operate across disconnected levels: at the micro-scale, they involve physicochemical alterations of pigments and substrates; at the panel or site scale, they are shaped by patterns of human activity such as hearth placement, ventilation and repeated occupation; and at the regional scale, they reflect broader processes including wildfire regimes, vegetation dynamics and landscape history. While micro-analytical and landscape-scale approaches can coexist (Pozo-Antonio et al., 2020), they are rarely bridged methodologically. Rock-art often falls between these scales, being neither fully integrated into landscape models nor consistently linked to sample explicit degradation thresholds. This factor highlights a need for development of methodological frameworks that can link micro-analytical approaches to site formation processes and, in turn, to regional fire histories, thereby bridging currently disconnected scales of approach.

5. Conclusions

Climate change is accelerating the physical, chemical, and biological processes that threaten rock-art preservation, yet research on fire-related degradation remains at an early stage, particularly concerning its interaction with rock-art. While vulnerabilities of archaeological sites to rising sea levels, storms, and glacial retreat are well documented, studies on fire impact have only gained significant attention in recent years, especially from 2020 onwards. Research has spanned regions including Argentina, Australia, the United States of America, and Spain, revealing a global concern but also revealing a gap between investment in rock-art protection and the limited understanding of fire-related damage. Research on fire-related damage to rock-art remains largely focused on small-scale anthropogenic fires. Under these conditions, most studies concentrate on topics such as rock-art dating, or the reconstruction of pre-Common Era societal practices, often analysing soot-related damage on cave paintings. Fewer studies explicitly address rock-art preservation, and this area of research presents a wider array of scenarios. These studies typically examine open-air sites and rock shelters, which are more exposed to natural fires, and reveal a wide variety of decay patterns, including flaking, spalling, fracturing and discolouration. Lithology also contributes to this variability: while rock-art in granite and limestone is common in the reviewed literatures (and in cultural heritage studies more broadly), sites on less common bedrock remain largely unexplored.

The reviewed studies on fire degradation of rock art predominantly focus on soot deposition in caves or shelters containing archaeological paintings. While soot analysis is a consistent element, methodologies and objectives vary widely, often emphasizing chronology and site use rather than direct damage assessment. Collectively, these studies demonstrate the potential of current approaches: field-based post-fire observation can map deposits, cracking, spalling and discolouration across panels and landscapes; laboratory analyses reveal microstructural and mineralogical changes in weathering rinds and varnishes; and chronological techniques situate fire events within broader occupation histories. At the same time, these works highlight key limitations. Most investigations are opportunistic, conducted after fires have occurred, and rely on qualitative descriptions or specific categories. Quantitative, standardised assessments/ scoring of damage severity is rare, and there is limited integration between field observations, laboratory analyses and explicit conservation thresholds.

Most studies of fire impacts on rock-art have focused on post-event analyses, examining sites after damage has already occurred. Consequently, most methodologies have been developed for cases where rock-art was already affected or lost, whether due to small-scale anthropogenic fires or historical wildfires. This highlights a notable scarcity of approaches aimed at predicting fire impacts or developing simulation models, tools that would be crucial for understanding and mitigating risks in sites not yet affected, particularly in regions prone to future

wildfires. This imbalance is especially evident in the near absence of prospective or experimental work. With few exceptions, such as controlled burns and a small number of laboratory heating and simulation studies, methodologies that anticipate fire impacts are limited. Systematic monitoring before and after planned burns, or experimental replication of fire effects on rock-art media, is rare. Fire-simulation approaches that integrate controlled heating, detailed recording of deposits, discolouration, cracking, and detachment, along with laboratory analyses of rock physical and mechanical responses to high temperatures, remain largely unstandardized or absent. Without carefully designed experiments and pre- or post-fire protocols, translating observations from past events into predictive tools for risk assessment and conservation planning is extremely challenging. There is a clear opportunity to expand research on fire-induced decay in rock-art by simulating varying fire conditions, such as temperature, duration and intensity, and examining their effects on different types of bedrock. Such studies could broaden the range of lithologies investigated, particularly less commonly studied substrates, and incorporate mechanical and physical analyses of rock properties. This approach would support tailored conservation strategies for different regions and, alongside predictive models, enable more effective risk assessment and protection measures. Collaboration between fire management professionals, archaeologists, and conservationists is essential to ensure that research findings are translated into practical safeguards. While progress has been made in protecting rock art from wildfires, the lack of comprehensive studies on fire impacts remains a critical gap. Current methodologies provide robust tools for describing and analysing specific aspects of fire impact, but they are fragmented across disciplinary and thematic lines. Addressing this gap requires dedicated research efforts and interdisciplinary research efforts. By enhancing our understanding of how fires affect rock-art, we can better protect these irreplaceable cultural treasures for future generations.

Author contributions

Amélia Dionísio, Gustavo Paneiro and Thierry Aubry contributed to the study conception, design, and supervision. Methodology was conceptualized by Amélia Dionísio, Gustavo Paneiro and João Senra. Data collection and analysis was performed by João Senra. The first draft of the manuscript was written and reviewed by all authors, who also commented on previous versions of the manuscript. All authors read and approved the final manuscript.

CRedit authorship contribution statement

João Senra: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Thierry Aubry:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Conceptualization. **Gustavo Paneiro:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Amélia Dionísio:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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