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Methodology for the Monitoring and Control of the Alterations Related to Biodeterioration and Physical-Chemical Processes Produced on the Paintings on the Ceiling of the Polychrome Hall at Altamira

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Abstract: On the surface of the Cave of Altamira's prehistoric paintings, a series of active deterioration processes are evident, leading to significant alterations of this invaluable heritage. This study proposes a comprehensive methodology for the systematic recording and management of these alterations. To achieve this, advanced microphotogrammetric monitoring techniques are employed, allowing for the acquisition of very high-resolution images that provide objective and quantifiable data that let us determine the evolution of the alterations. By comparing these images with those from earlier campaigns, the study tracks changes. The data collected through this protocol has helped with the development of new research avenues to understand, among the many alteration processes that impact paintings, the dynamics of water and fluid mechanics affecting the conservation of Cave of Altamira. These investigations help clarify how, why, and at what rate degradation processes such as pigment migration, washing, and bacterial colonization occur. The insights gained from these techniques inform indirect conservation measures aimed at reducing the deterioration of the cave art, located both on the Polychrome ceiling and throughout the rest of the Cave of Altamira. The results underline the importance of regular monitoring and the application of precise, non-invasive techniques to protect rock art from continued degradation. This research provides a model for similar conservation initiatives at other vulnerable heritage sites.

Keywords: preventive conservation; deterioration; microphotogrammetry; cave art conservation; heritage preservation; non-invasive monitoring; physico-chemical alterations

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1. Introduction

The Cave of Altamira, located in Santillana del Mar, Cantabria, Spain, is one of the most iconic archaeological sites in the world, recognized for its exceptional Paleolithic paintings. This site, inscribed as a UNESCO World Heritage Site in 1985, offers invaluable insights into the cultural practices of early humans and serves as a key reference point for studies on prehistoric art and human evolution. The cave extends about 290 m, featuring various chambers, including the renowned Polychrome Hall (Figure 1b), where the most famous paintings are located (Figure 1). Discovered in 1868, the cave's significance was solidified in 1879 when Marcelino Sanz de Sautuola and his daughter María identified its ancient paintings. Although first met with scepticism, the authenticity of these artworks was confirmed by the scientific community in 1902, establishing Altamira as a critical site for understanding the Upper Paleolithic period [1–3].

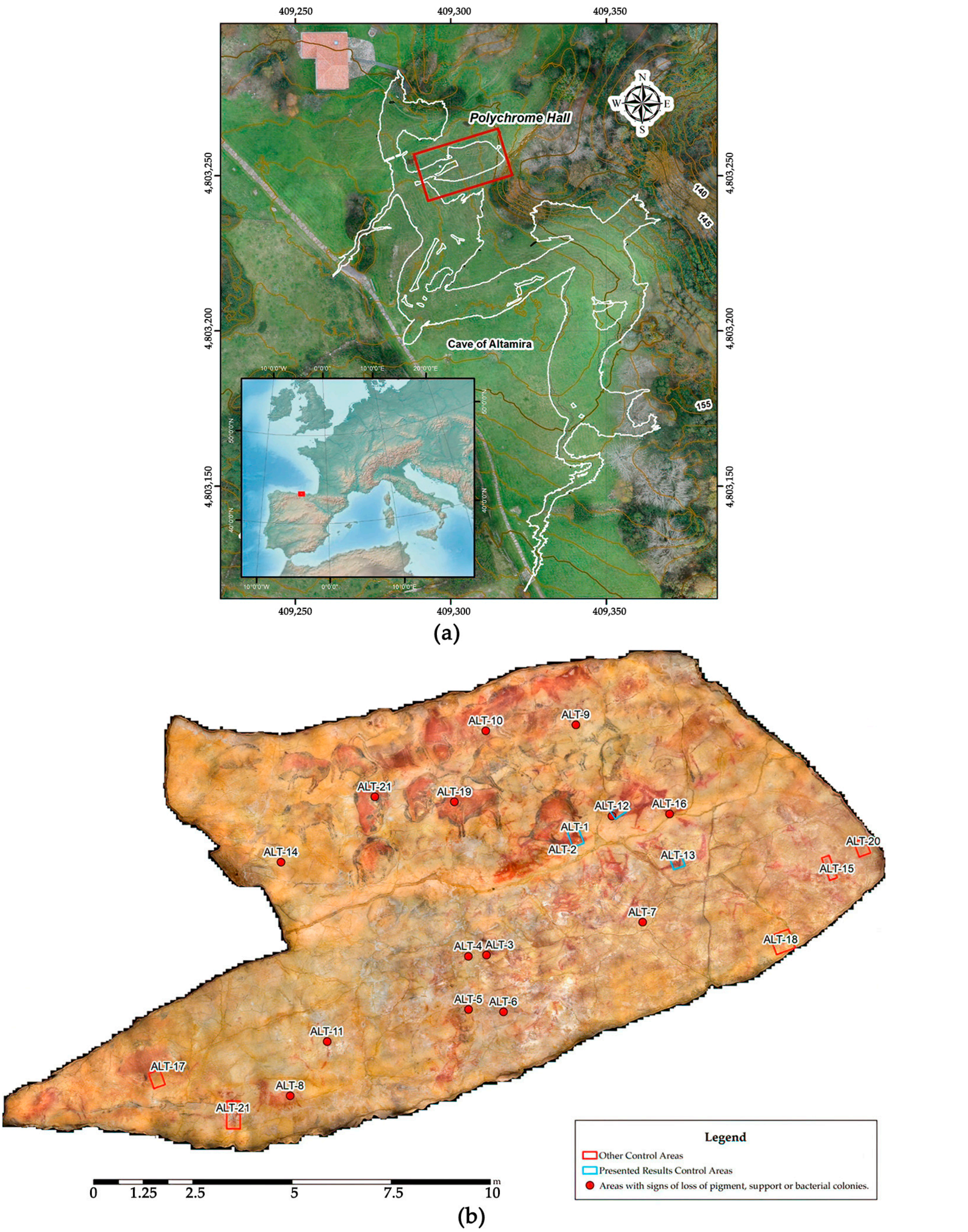


Figure 1. (**a**) Location map of the Cave of Altamira with the Projection of the Cave on the orthoimage, indicating in a red frame the position of (**b**) the Polychrome Hall with the key areas of interest for conservation efforts, including the zones most affected by active deterioration processes.

Altamira's geological context presents significant conservation challenges. The cave's limestone structure, while integral to the preservation of the paintings, is also its greatest vulnerability. Geologically, Altamira is situated in the upper part of the Altamira Formation of the Middle and Upper Cenomanian, a sequence detailed by [4]. This formation has a total thickness ranging between 13.5 and 15 m, consisting of seven stratigraphic levels characterized by alternating layers of calcarenite and limestone with thin marl intercalations. The limestone bench of the Polychrome layer, where the most notable paintings are located, is 60–70 cm thick [5,6].

This complex stratigraphy, with various subunits of calcarenite and limestone, makes the rock susceptible to natural deterioration processes. The cave's limestone substrate is riddled with fissures, fractures, and diaclases that have historically facilitated water infiltration, a critical factor in the degradation of the paintings. Furthermore, particles observed as creamy-beige, initially thought to be fragments of the bedrock, were revealed through SEM analysis to be clayey materials rich in Na, K, Al, P, S, Cl, and Fe, with abundant Si and O. These particles often display a lumpy texture with microcracks, indicative of desiccation and shrinkage processes typical of clayey sediments. More detailed analysis has identified that some of these particles contain Ca oxide. Although SEM analysis does not quantify carbon accurately, the high carbon peak in combination with oxygen suggests the presence of $CaCO_3$.

The structural and compositional complexities of Altamira's rock are key to understanding its vulnerability, as this mineral composition, combined with structural instability, predisposes the cave to natural evolutionary processes that increase the risk of collapse and endanger the preservation of the paintings.

The conservation of the Altamira paintings is complex due to the interplay of multiple deterioration processes, primarily linked to the cave's hydrology, geology, and microbiology, and which give rise to several relevant alterations (Figure 2). Among the most pressing concerns relating to conservation are the following [7,8]:

- Microkarst and the dissolution of the limestone substrate: The paintings are applied to a limestone surface, which is highly susceptible to dissolution by water containing dissolved CO_2. The acidic nature of this water gradually erodes the limestone, weakening the adhesion of pigments and leading to their detachment from the rock surface.
- Pigment erosion and transport: Water infiltrating through the cave's network of cracks and fissures plays a significant role in the erosion and transport of pigments. This is particularly problematic in the Polychrome Hall, where the Ceiling is directly exposed to infiltrating waters, resulting in the gradual dissolution and loss of pigments.
- Carbonate precipitation: Infiltration water, under certain environmental conditions, precipitates carbonates onto the painted surfaces, forming crusts that hide the Palaeolithic painting and engravings. If unchecked, these carbonate deposits can cover the paintings, making them difficult to study and appreciate art.
- The peeling and flaking of painted surfaces: The Polychrome Hall is characterized by high relative humidity and persistent water presence on much of the rock surface. Fluctuations in these environmental parameters can lead to the flaking of painted surfaces, as variations in humidity reduce the adhesion and cohesion of the pigments, causing them to peel away.
- Microbial colonization: The accumulation of microorganisms on the painted surfaces poses a significant risk to the preservation of the artworks. These microorganisms can lead to the transformation of pigments or the underlying rock through chemical reactions driven by their metabolic processes. Microbial biofilms can create microenvironments that promote further degradation of the paint or the supporting rock.
- Fragmentation and spalling: The detachment of rock fragments, including the calcite layers supporting the paintings, is another significant threat. This fragmentation can lead to the partial or complete destruction of the artworks, particularly in areas already weakened by environmental factors.

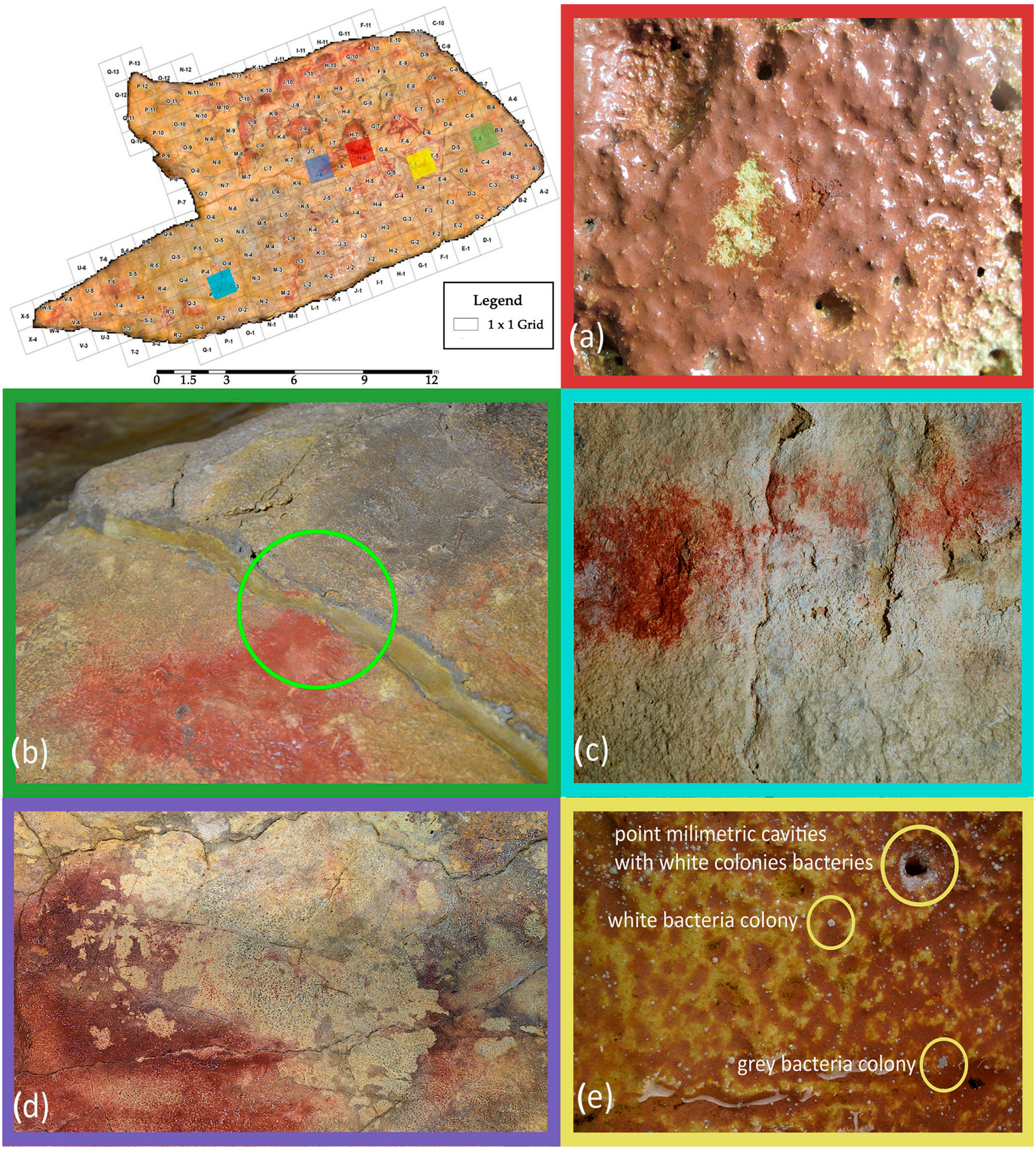


Figure 2. Main alterations associated with active deterioration processes on the surface of the Polychrome ceiling (**a**) Corrosion and dissolution of the limestone substrate (red box), (**b**) erosion and pigment transport by seepage water (green box), (**c**) encrustation, carbonate precipitation (light blue box), (**d**) detachment and scaling (purple box), and (**e**) biological colonization (yellow box).

These deterioration processes have the potential to cause either a partial or total destruction of the paintings, with their intensity and progression heavily influenced by specific environmental variables existing in the cave. The conservation environment within the cave is inherently unstable, with the interaction of various deterioration agents (CO_2

levels, temperature, and humidity) complicating efforts to predict and control potential damage [9–13]. The unstable nature of the conservation environment, where even minor interventions can have irreversible consequences, underscores the importance of accurate monitoring to enable us to put proactive conservation strategies into practice [13–19].

The microclimate in the Cave of Altamira, however, presents unique seasonal challenges. Temperature within the cave is affected by thermal oscillations transmitted from the exterior through the variable thickness of the rock above each room. This rock thickness buffers and delays the thermal wave, with annual oscillation intensity going down in rooms where the ceiling rock is thicker. Also, the presence of interconnected rooms, fissures, and cracks within the karst system creates thermal gradients within the cave, with specific effects on air circulation patterns. Thus, between the months of December to May there is a positive thermal gradient exists, where temperatures increase progressively from the hall to the crossing and then to the Polychrome Hall. As cold air is denser, it usually settles at lower levels, causing a natural flow of cool air from the entrance to the cave's interior. This airflow reaches maximum intensity in February, the coldest external month, cooling the Polychrome Hall and potentially decreasing CO_2 concentrations there. From June to November, a reverse negative thermal gradient forms, wherein temperatures decrease from the entrance hall to the crossing and then to the Polychrome Hall. This arrangement reduces gravitational air movement, thus stabilizing the air layers within the cave.

Gas exchange, primarily for CO_2 and radon, is strongly seasonal, following these temperature-driven airflow patterns. CO_2 concentrations average around 3000–3300 ppm annually, peaking in summer as gaseous exchange with the exterior intensifies due to thermal gradients and moisture levels in the cave's fissures. Winter sees minimal air exchange, while spring and autumn mark transition phases where degassing and recharging processes begin, respectively, following seasonal shifts. The research [20] further analyses these dynamics, emphasizing the critical role of ventilation fluctuations in the Polychrome Hall.

Relative humidity in the cave is consistently high, close to 100%, with slight temperature variations. These slight variations in the room conditioned by seasonal patterns condition the conservation strategies [21–25].

Periodic and systematic monitoring of the control areas located on the surface of the Polychrome Ceiling, where some of the best-known paintings are located, has revealed several critical alterations linked to the aforementioned deterioration processes. Among these, the most pressing issue affecting the paintings is the washing and erosion of their mineral components. While pigment particle dissolution and transport have been observed in certain areas for years, recent monitoring has provided clear evidence of pigment particles migration and destruction associated with specific drip points in some specific areas of the Polychrome Ceiling.

Over the past few decades, deterioration processes directly linked to water infiltration, along with indirectly related factors such as CO_2 concentration, temperature fluctuations, and humidity levels, have contributed to significant damage to the paintings. One particularly affected area, identified as ALT1, is within the H-6 grid of the Polychrome Ceiling (Figure 1b). This area, covering approximately 1 m^2, lies beneath the hind legs of one of the large polychrome bison and has been subject to repeated episodes of water dripping and pigment washing away. These drips have led to pigment migration and loss.

Detailed studies have indicated that the surface of the Polychrome Ceiling contains a discontinuous clay film, sometimes carbonated, which lies between the limestone substrate and the paint layers. This clay layer is susceptible to internal stress due to the slight but significant fluctuations in humidity, leading to a loss of adhesion of the pigments to the supporting rock. Environmental humidity contributes to the dissolution of carbonates, as the accumulation of water on the limestone surface facilitates mineral decomposition reactions. Also, the physical and chemical properties of infiltrating water, which carries CO_2 and other nutrients from the soil, exacerbate the dissolution of the limestone, further weakening the pigment's adhesion [25–28].

Despite the advancements in monitoring and understanding these processes, significant challenges remain in the conservation of Altamira's paintings. The rate of deterioration observed in recent years, especially in control area ALT1, indicates that the current conservation measures may not be sufficient to halt or reverse the damage caused by the washing processes associated with infiltration and condensation water. This situation highlights the need for ongoing research and the development of new techniques to better understand and mitigate the factors contributing to the degradation of these valuable paintings.

This study aims to contribute to improving and clarifying the diagnosis of the state of conservation of the cave by using advanced microphotogrammetric techniques to monitor and document the ongoing biodeterioration and physico-chemical alterations in the Cave of Altamira. By providing a detailed, high-resolution analysis of these alterations or deteriorations, the study seeks to offer insights that can inform proactive conservation measures, making sure the Cave of Altamira paintings are preserved for future generations. Applying these techniques, combined with a thorough understanding of the cave's hydrology and environmental dynamics, represents a significant advance in the conservation of the Altamira cave and by extension also of Cultural Heritage.

The significance of this work lies not only in its contribution to the preservation of a singular cultural treasure but also in its potential to serve as a model for similar conservation efforts worldwide. By addressing the complex interplay of geological, hydrological, and biological factors that threaten the integrity of cave art, this study advances our understanding of how to effectively monitor and mitigate these threats. The findings of this research will be invaluable for curators, and stakeholders responsible for the preservation of the Cultural Heritage sites, offering new tools and methodologies for safeguarding these irreplaceable works of human history.

2. Materials and Methods

Accurate georeferencing (Figure 3) is essential when documenting caves, particularly those with rock art, due to the complexity and sensitivity of these environments [29]. The geographical referencing of features within caves is challenging because of their enclosed spaces, irregular surfaces, and environmental conditions [30]. In the context of remote sensing and rock art conservation, georeferencing becomes even more critical when conducting change detection especially when the variations we are trying to detect and control are sub-millimetric [31]. Small deviations in spatial accuracy can significantly distort the results of such studies, making it difficult to accurately monitor changes over time. Accuracy is important when using technologies like photogrammetry or 3D laser scanning to observe changes in rock art or even in the morphology of the cave itself because we are in living and changing environments over time, where new mineral precipitates are formed while others are dissolved and destroyed.

2.1. Creation of Reference Frame for Micro-Photogrammetry

First, to accurately perform change detection, the creation of a reference frame is essential [30]. The combined use of Global Navigation Satellite System (GNSS), microgeodetic networks and 3DTLS ensures the development of a precise, georeferenced model of the cave, which is important for monitoring both structural integrity and rock art preservation [32–36]. This georeferencing process involves several critical steps to guarantee the accuracy of data collection in the case of the Cave of Altamira.

- GNSS static and real-time kinematic (RTK) positioning: Techniques, such as static positioning or RTK, are applied outside the cave to establish a global reference frame [37,38]. At Altamira, a network of points was created using three TOPCON Hyper II (Topcon Corporation, Tokyo, Japan) receivers [39], which formed the basis of the geodetic reference system. The European Terrestrial Reference System 1989 (ETRS89) was used to create this reference frame. The reference frame had a mean accuracy of 1.7 cm, providing the foundation to integrate geospatial data from inside the cave with regional or global cartographic systems.

- Microgeodetic network with total station (TTS): Since GNSS signals cannot penetrate the cave's interior, a microgeodetic network was established using a TOPCON GPT-7503 (Topcon Corporation, Tokyo, Japan) Total Station [40]. This network linked several high-precision targets within the cave, distributed across 16 traverse stations and adjusted to compensate for angular and linear closure errors. This setup ensured high accuracy, with the adjusted traverse having an angular error of 0.0218 g and a linear error in X, Y, and Z of less than 0.005 m.
- The placement of high-precision targets: A total of 66 reference targets were distributed throughout the cave to ensure a comprehensive coverage of significant structural areas, including those featuring Palaeolithic rock art. These checkerboard targets served as control points, measured precisely using the Total Station. They formed the basis for georeferencing the 3D scans obtained by 3D Terrestrial Laser Scanning (3DTLS).
- 3DTLS: For the surface mapping of the cave's structure, a FARO FOCUS X-130 (Faro Technologies Inc., Lake Mary, FL, USA) laser scanner [41] was used to create a highly detailed point cloud. Around 300 scans were performed, capturing the cave's surfaces with an accuracy of 2.7 mm for 95% of the points. These scans generated a comprehensive model of the cave, revealing essential structural features and rock art details.
- The co-registration of point clouds: The point clouds generated by 3DTLS were co-registered [30], meaning they were aligned to the microgeodetic control points (the installed targets). This step made sure the scans from different locations within the cave were spatially consistent with each other, resulting in a unified, georeferenced point cloud that accurately captured the cave's entire geometry.
- The integration of GNSS, TTS, and 3DTLS data: The final step in the georeferencing process was to align the cave's interior 3D point cloud with the external GNSS-based reference frame [31]. This integration was important for merging the internal cave model with external geographic information, such as terrain models generated by TOPCON Intel Falcon 8+ (Topcon Corporation, Tokyo, Japan) Drone surveys. The result was a complete, georeferenced 3D model of the Cave of Altamira, supporting both structural analysis and rock art preservation
- Ground control points (GCPs) extraction: From the co-registration of point clouds, two datasets of GCPs were extracted, derived from the point cloud with a mean Ground Sampling Distance (GSD) of 1–2 mm. This high-resolution point cloud allowed for the precise extraction of GCPs without the need for physical targets, which are not allowed on the delicate Polychrome Ceiling due to conservation restrictions. Also, this method significantly improved accuracy compared to traditional Total Station methods, which typically achieve a precision of 5–7 mm. One dataset was used for calibrating the 3D model, making sure all scanned data aligned with the microgeodetic reference framework, while the second dataset was used for validation. These GCP datasets were essential to the change detection process, helping with the accurate monitoring of structural changes over time.
- Polychrome Ceiling photogrammetry: In 2014, a dedicated photogrammetry campaign documented the Polychrome Hall ceiling with sub-millimetre resolution [42]. This effort complemented the laser scanning and produced a 3D digital model of the Ceiling with about 200 million polygons. The photogrammetric support for this campaign involved detecting homologous points, extracted from the 3D laser scanner's point clouds, which served as GCPs for model calibration and validation. Specifically, 80 control points were strategically placed throughout the Hall, half of which were used to validate the model. These high-resolution images were collectively adjusted, resulting in a point cloud of approximately 11 billion points, which was filtered down to 3.5 billion points to generate a detailed 3D model.

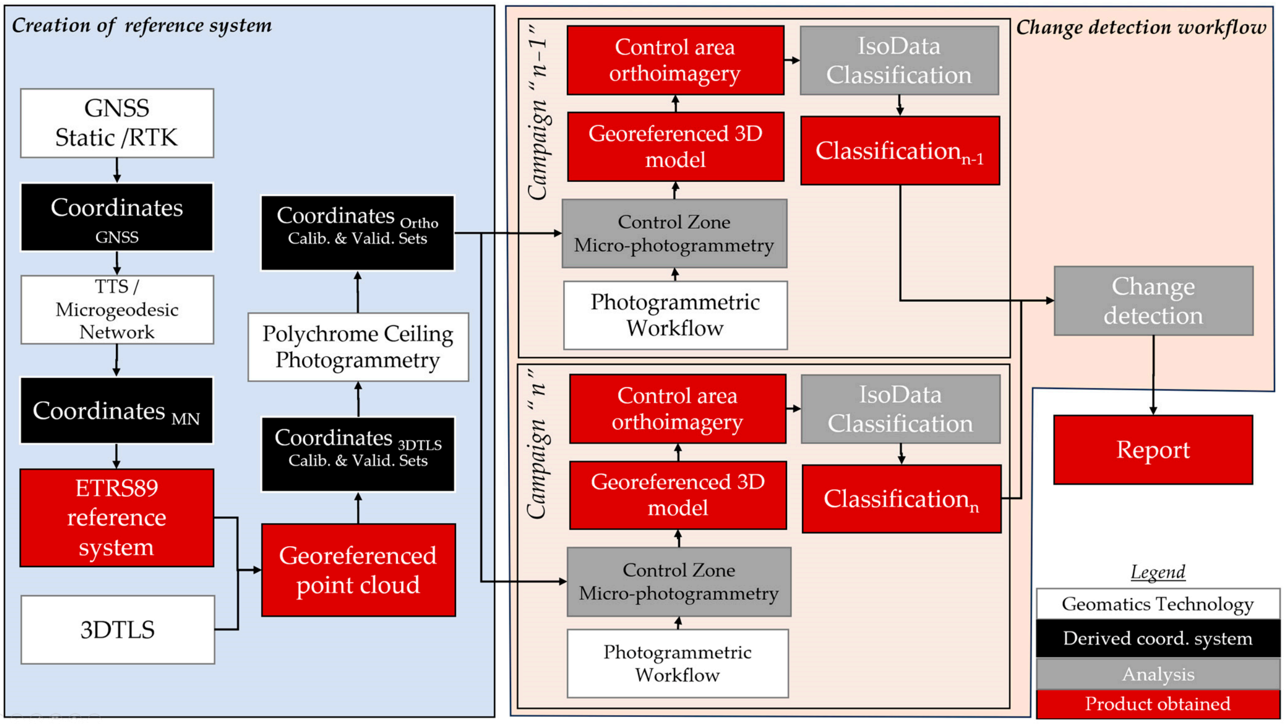


Figure 3. General workflow diagram.

2.2. Change Detection Workflow

These techniques allow for the precise monitoring of surface alterations, enabling curators to detect changes in pigment loss, microbial growth, or surface erosion or microkarst. The change detection process can be divided into two main parts: micro-orthoimage generation and the change detection process.

To guarantee the proper conservation of the representations, we adhered to the access protocols established in the Research Programme for the Preventive Conservation and Access Regime of the Altamira Cave for all work presented here [43]. The monitoring and control of the environmental conditions are carried out by measuring stations in different areas that monitor the parameters of the cave in real time. In parallel, the microenvironment generated in the workplace is monitored every minute with a high-resolution, high-precision datalogger to verify that the increase in temperature never exceeds 0.3° above the initial value. The work inside the Polychrome Hall is carried out by 2 people, who enter the room twice a year for a maximum of 60 min. The lighting equipment for this work strictly follows the standards established by the PCP. LED light is used which has a low thermal emission, with low colour temperature and lux levels of less than 50 lux.

2.2.1. Micro-Orthoimage Generation

- Image acquisition: High-resolution images are captured using a Sony (Sony Corporation, Tokyo, Japan) A7R Mark II camera with a 90 mm lens, making sure detailed features of the cave's surface are recorded. The lighting system is important for image clarity, especially in the humid environment of the cave where moisture on the rock surfaces can cause unwanted reflections. To address this, an F & V (F & V Europe B.V., Helmond, The Netherlands) HDR-300 LED ring light equipped with a 45–135° polarizing filter is used, while a circular polarizer is fitted to the camera lens. This setup allows for cross-polarization, a technique in which the polarizers on the light source and the camera are oriented at 90 degrees to each other. Cross-polarization effectively eliminates surface reflections or "glints" caused by water or moisture on the cave walls, as only light waves vibrating in a specific direction pass through both filters. This significantly enhances the visibility of the underlying textures and features of the rock surface by suppressing specular reflections and glare, which can obscure details. A milk diffuser is also applied to the light source to ensure even illumination, further reducing harsh shadows or hotspots that could interfere with the image quality and subsequent analysis.

To create a 3D model of the cave surface, overlapping images are taken to ensure stereoscopic coverage. For each section of interest, at least nine images are captured with 70% longitudinal and 30% transverse overlap. To maintain these overlaps precisely, a double-axis slider (Figure 4), capable of covering 1 m^2, was designed. This setup allows for an accurate reconstruction of the 3D surface, enabling the precise detection of even the most subtle changes in features such as pigment loss or biological growth.

(**a**) (**b**)

Figure 4. (**a**) Double-axis slider during image acquisition of ALT13 control zone. (**b**) Sony A7R Mark II camera with a 90 mm lens and cross-polarizing light.

- Control area orthoimage: The images captured during each campaign are processed to generate a detailed 3D model of the control zone's surface. This process has evolved significantly from the initial campaigns. Currently, images are taken in RAW format and then developed using a SpiderCheckr colour calibration chart [44], which ensures accurate colour management. This is essential for consistent colour reproduction, allowing for precise colour comparison between different campaigns. Such comparisons are important for detecting subtle changes in the surface, such as pigment alterations or the appearance of new biological growth.

Once the images are developed, they undergo a photogrammetric workflow. This workflow utilizes the 3D coordinates established from the full orthoimage model as a reference, making sure the newly generated 3D model of the control zone is precisely aligned with previous datasets. This alignment is critical for accurate comparative analysis, as it allows for the detection of even minor changes in the cave's surface features over time.

The final step involves creating a high-resolution orthoimage of the control area, achieving a pixel resolution of at least 50 µm. This level of detail is enough for general surface monitoring and enables the detection of small-scale changes, such as the growth of bacterial or fungal colonies and the slight migration of pigments associated with the thin film of water that occasionally covers the ceiling of the room. The detailed orthoimage provides a comprehensive view of the extent and nature of any deterioration, supporting ongoing conservation efforts and helping with the precise tracking of changes over successive campaigns.

2.2.2. Change Detection

Change detection is a critical part of monitoring the state of preservation [45,46], specially where subtle surface alterations can indicate significant conservation issues [47,48]. The primary goal of this process is to accurately identify and measure changes over time, letting curators detect and assess surface deterioration, biological growth, and pigment migration. The steps followed are standard [49,50] in remote sensing and permit creating a robust classification of surface materials, conducting a detailed change detection analysis, and performing statistical assessments to ensure the integrity of the data and support the long-term preservation of the cave's cultural heritage.

- Data alignment: Once the orthoimages are created, they are co-registered to a common reference frame to make sure any detected changes between campaigns are the result of actual surface alterations rather than misalignments during data collection. This step is critical for accurate comparison, enabling the identification of both subtle and significant changes on the control areas. The co-registration process aligns the newly acquired datasets with reference models from earlier campaigns, ensuring consistency and reliability in the measurements.
- Classification using the IsoData algorithm: After data alignment, the next step involves applying the IsoData classification algorithm [51] to the generated orthoimages. This unsupervised classification technique automatically groups pixels into clusters based on their spectral properties, effectively categorizing different surface materials. The output classes are then assigned specific labels such as different types of pigment (categorized by colour), fungal growth, bacterial colonies, rock without pigment, and areas with glints (marked as no data).
    1. Initial classification: The algorithm iteratively adjusts the cluster centroids and reassigns pixels to different classes based on their spectral distance until optimal cluster separation is achieved. This step is crucial for creating distinct categories that accurately reflect the surface materials and biological elements present on the cave walls.
    2. Class assignment and naming: Once the clustering process is complete, each class is manually reviewed and assigned a name according to its characteristics. For example, classes may be named "Red Pigment", "Black Pigment", "Fungal Growth", "Bacterial Growth", "Exposed Rock", and "Glints" (no data). This manual assignment makes sure the automated classification aligns with the actual surface conditions observed in the cave.
    3. Separability analysis: To ensure the classification's accuracy, a separability analysis is conducted. This analysis measures the statistical distance between classes, determining the degree of overlap and making sure each class is sufficiently distinct from the others. A high separability score indicates that the classes are well-defined and that the producer accuracy is robust. This step is essential for validating the classification results and ensuring reliable data for subsequent analysis.
- 2D change detection: After the classification is complete, a pixel-by-pixel change detection analysis is performed to identify shifts between classes across different campaigns (Figure 5). This analysis compares each pixel's class assignment from one campaign to the next, calculating the frequency and nature of changes, such as pigment loss, microbial growth, or alterations in surface composition. This method provides detailed information on how surface materials have evolved over time, offering insights into the dynamics of deterioration processes.

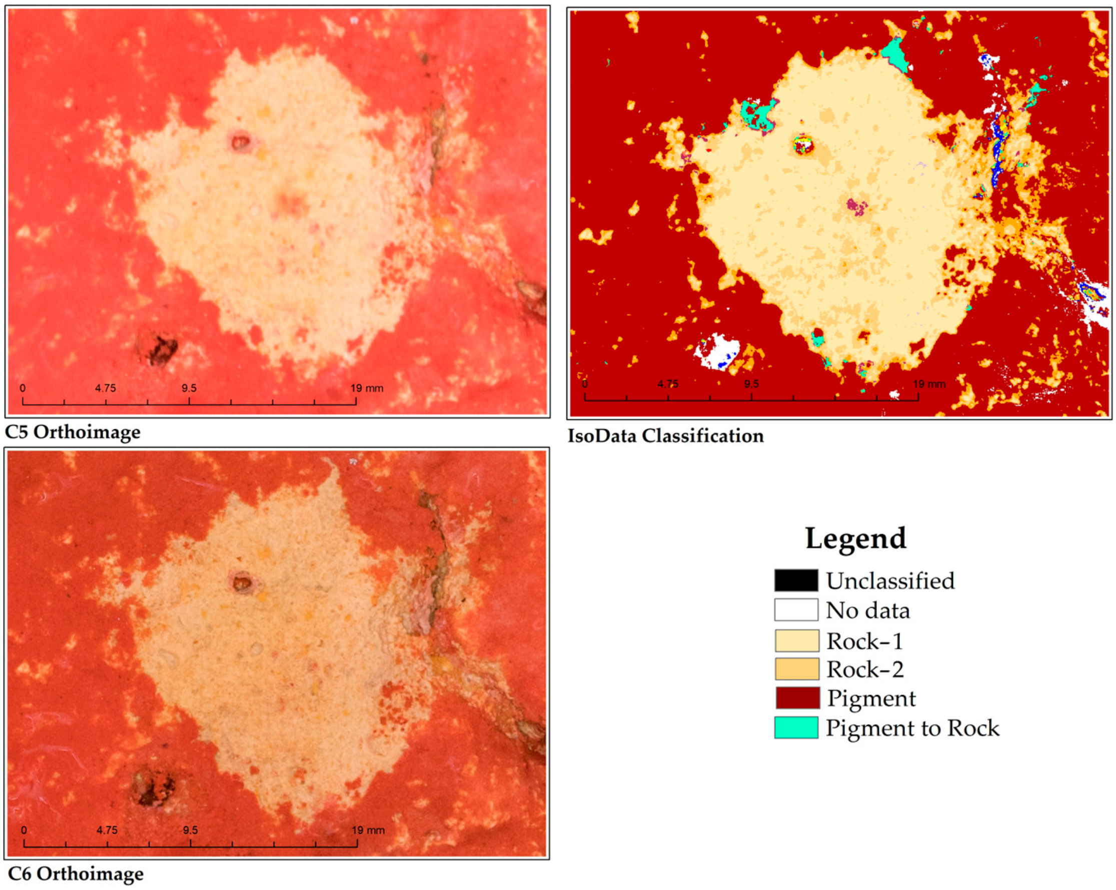


Figure 5. Orthoimage for campaigns 5 and 6 and the IsoData classification with the class pigment to rock represented in blue.

- Statistical analysis: Once the change detection is completed, statistical analyses are conducted to quantify the changes in specific control zones. For example, the analysis may reveal the percentage of pixels that have shifted from “Red Pigment” to “Rock” indicating pigment erosion, or from “Rock” to “Fungal Growth”, suggesting biological colonization. These statistics provide both general trends and localized data, enabling a comprehensive understanding of the affected areas.

3. Results

3.1. Detection and Documentation of Deterioration Processes

The systematic and periodic monitoring of the ALT1 control zone and other areas on the ceiling of the Polychrome Hall have been essential in detecting and documenting the ongoing deterioration processes affecting the cave paintings. These efforts reveal the direct impacts of water infiltration, including the erosion and washing away of mineral components from the limestone substrate, which contribute to pigment migration and loss. Recent XRD studies [52] on red pigments from the ALT1 sign and other claviform symbols in the Polychrome Hall provide a deeper understanding of the pigment composition. The primary red colouring agent is hematite, typically accompanied by variable amounts of goethite. The XRD analyses highlight hematite as the dominant mineral phase, with quartz and calcite also present. Iron (Fe) serves as the principal element in the red pigments, with additional trace elements detected, including P, S, Cl, K, Ti, V, Cr, Mn, Co, Cu, Zn, Pb, As, Br, Rb, Sr, Zr, and Nb.

Raman spectroscopy studies [53] on pigments from various pictorial elements—including a large bison near the entrance to the Polychrome Room, central claviform symbols, and large doe at the rear of the room—confirm hematite (Fe_2O_3) as the primary pigment. Calcite is also frequently identified in the spectra, suggesting that it may either result from natural carbonate precipitation on the painted surfaces or Raman signals reflecting the underlying limestone substrate.

This comprehensive chemical and mineralogical profile underscores the inherent vulnerability of these iron oxide-based pigments to environmental changes and aligns with earlier findings on the Fe-based pigments in northern Spanish cave art, thus enhancing our understanding of pigment stability and deterioration mechanisms within the unique microenvironment of the Cave of Altamira [54,55].

These deterioration processes are particularly pronounced in the ALT1, ALT12, and ALT15 (Figures 1b and 6) zones, where a loss of pigment particles has been observed, caused by washout through the infiltration water that accedes mainly through fractures and fissures associated with the large central fracture that crosses the Ceiling from west to east. These areas are associated with some of the red signs on the ceiling of the Polychrome Hall, and are particularly vulnerable to the effects of water infiltration. As for ALT13, although it is close to the other control areas mentioned above, and although it has been affected by the same processes in the past, it is more now affected by an increase in bacterial colonies.

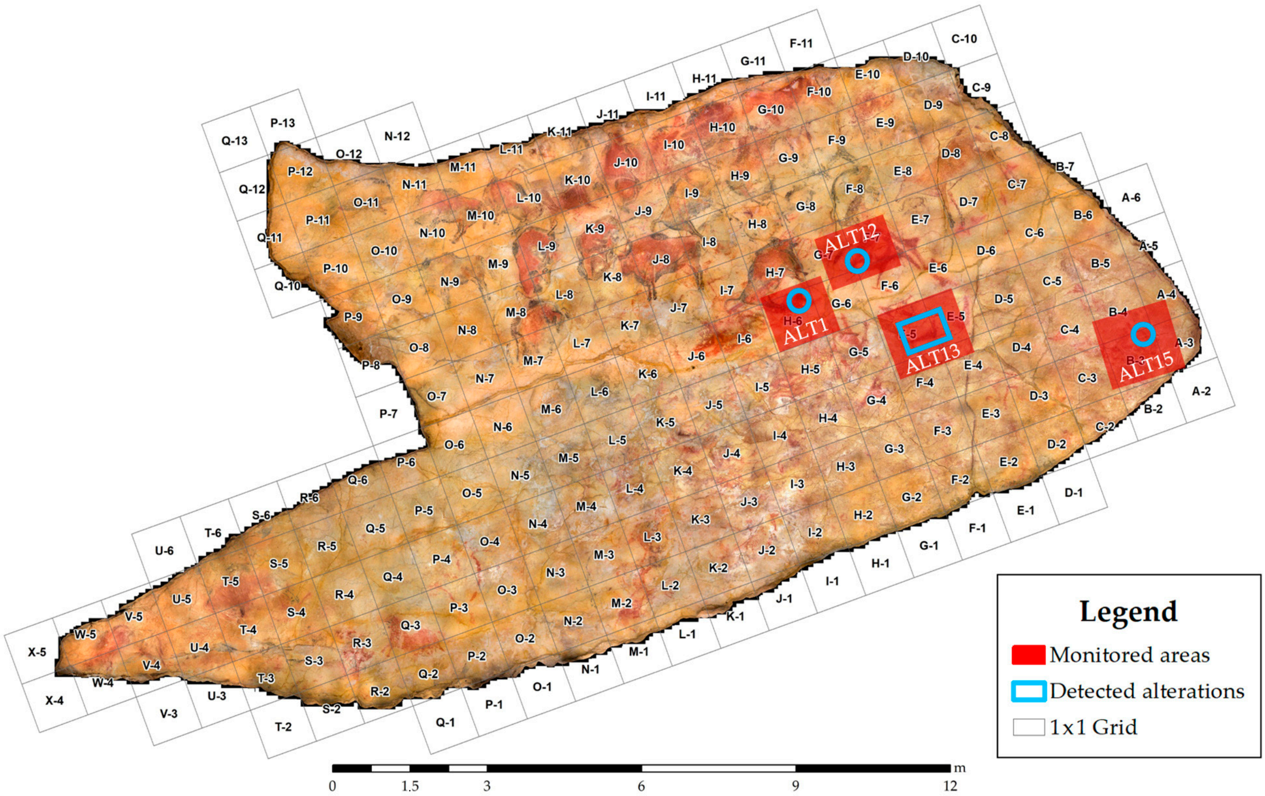


Figure 6. Control areas with their designation and the conservation hotspots or critical areas that we monitor and control more exhaustively.

3.2. Impact of Water Infiltration on Pigment Migration

The study of water infiltration patterns within the Polychrome Ceiling has helped to understand the mechanisms behind pigment migration. Water flows across the Polychrome Ceiling, picking up and redistributing pigments from one area to another. This migration process is critical as it removes pigment from its original location and redeposits it elsewhere, complicating conservation efforts.

The following image (Figure 7) establishes a comparison of ALT12 through a photograph taken on 5th May 2014 and another taken recently. Visually, it may appear that the photograph corresponding to 2022 shows a greater amount of pigment and consequently a smaller washed-out surface. To understand this process in all its complexity, we must consider that the surface of the ceiling is bathed in a film of moving water which remains on it by surface tension, which acts as a transport vehicle for the paint itself and other deposits (clays and small fragments of limestone), dragging them to the drip point. On ALT12, the dragged pigment accumulates at the dripping point and prevents the already very relevant surface without pigment that has been generated at the same point, due to the repetition of these dragging and washing processes, from being seen. The process described is cyclical and constant, it is not limited to the specific day on which the droplet is detected to be saturated with pigment particles, and consequently this characteristic means that we consider it a much more serious process. This mechanism described for ALT12 is also observed in other monitored areas of the Polychrome Ceiling.

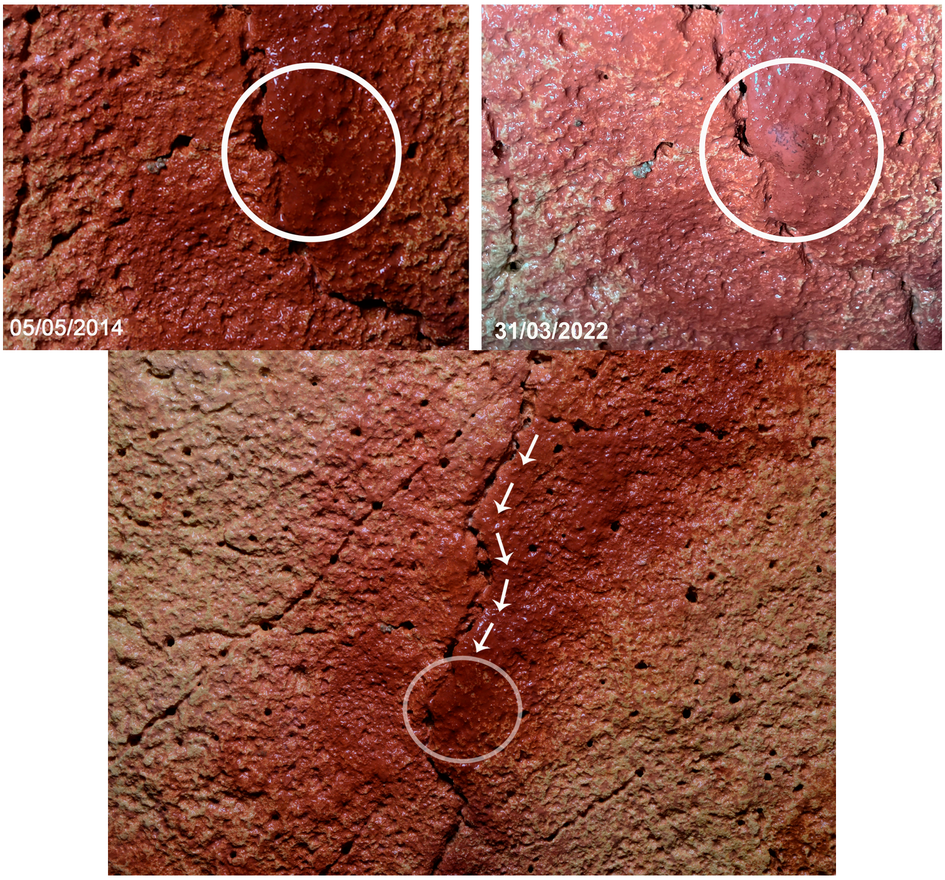


Figure 7. Comparison of the drip point with paint drop corresponding to ALT12 (years 2014–2022) and proposed water flow with pigment carry-over to the drip point. The white circles indicate the drop point with pigment drag. The arrows show the path of the water and its drag of pigment to the drop point.

The analysis reveals that the pigment carried away by the water is not destroyed in its entirety but that some of it is retained elsewhere on the Ceiling itself during the process of water infiltration. This dynamic movement of pigment, driven by water infiltration, poses a major challenge to conservation efforts, as it requires continuous adaptation to the changing conditions of the Ceiling surface.

The superposition of this data with the changes observed in the pigment distribution has provided a clear visualization of the impact of water infiltration (Figure 8). Understanding these patterns is crucial for developing effective conservation strategies that address both the loss and redistribution of pigments. The redistribution of pigments complicates conservation efforts, and conditions art research because some of the painting is located in places other than the place it originally occupied.

Figure 8. Area of the ceiling of the Polychrome Hall affected by a marked lack of support. The areas highlighted in blue indicate a lack of supporting rock. Within these highlighted areas the washed pigment, washed away by the water, has been redeposited.

The implications of this water infiltration are significant. Although the presence of water and humidity is fundamental and has guaranteed the good conservation of the paintings in both the Polychrome Hall and the rest of the cave, it is no less true that the implications that water infiltration plays in the degradation processes of the paintings are relevant. By monitoring these infiltration patterns and understanding the conditions that lead to pigment migration, curators receive the necessary tools to try to predict future alterations and minimize pigment loss. By tracking these infiltration patterns and understanding the conditions that lead to pigment migration, curators can better predict and mitigate future pigment loss.

3.3. Documentation of Bacterial Colonization and Reduction

The monitoring of the ALT13 control zone on a large claviform on the south side of the Polychrome Hall, close to the central fracture, has provided valuable data on the relationship between the presence of microbial activity and the indirect preventive conservation measures that have been applied for years in the cave and its external environment. On this sign, a large number of white bacterial colonies that partially cover the painting, has been historically documented [56–59]. The monitoring we have been carrying out using high-resolution photogrammetry has shown a significant reduction since 2015 in both the number of bacterial colonies and their size (Figure 9).

Using a newly developed method for change detection, we have quantified this reduction with high precision. For example, in a specific 411 cm^2 area of ALT13, a 0.67% reduction in bacterial coverage was recorded over ten months in 2019. A similar analysis in another area of ALT13 showed an even greater reduction of 0.854%. This decrease in bacterial activity may be related to the preventive conservation measures that have been put into practice at Altamira over the last few years. These indirect actions are applied both inside, trying to reduce the presence of particles and hydroaerosols that enter the Polychrome Hall, as well as outside, through the systematic control of vegetation.

The detailed analysis of these bacterial colonies, including their expansion, consolidation, and eventual reduction, has provided relevant information to understand the relationship between bacterial colonies and the microenvironmental dynamics of the Polychrome Hall and by extension the whole cave. This data is essential for understanding the role of microorganisms in the degradation process and for developing strategies to manage or mitigate their impact on the paintings.

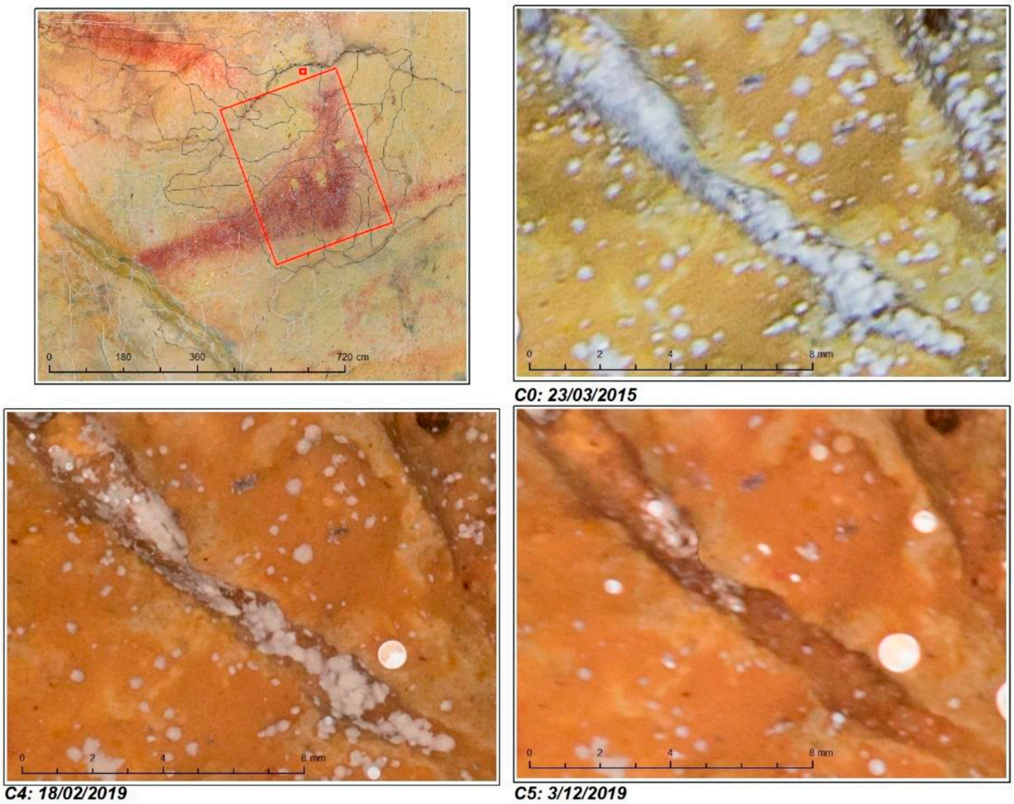


Figure 9. Changes in white bacterial colonies at one of the monitoring points within the ALT13 control zone. It shows a significant reduction in the number and size of bacteria colonies from 2019. The large red rectangle in the first figure indicates the control area location and the small rectangle the location of the detail images.

Integrating microbial data with the patterns of pigment loss and redistribution has revealed potential correlations between water infiltration and bacterial colonization. These observations also confirm that some of the bacterial colonies are not fixed to the supporting rock or even to the pigment, but displace with the help of the sheet of water moving by surface tension that bathes the surface of the ceiling (Figure 10). For example, areas with active water flows usually show more significant bacterial activity, which in turn accelerates the degradation of the painted surfaces. This finding suggests that managing water infiltration may also help control bacterial growth, thus reducing the rate and risk of deterioration.

Figure 10. Presence of white bacterial colonies on the pigment in the ALT13 control area. The bacterial colonies are directly related to the water film bathing the surface, which also involves migration and pigment washing processes. Each unit of the graphic scale is equivalent to 1 cm.

The results from the ALT13 control zone underscore the importance of monitoring microbial activity as part of the overall conservation strategy. The reduction in bacterial colonies in certain areas suggests that it may be possible to mitigate some of the biological factors contributing to the degradation of the paintings. However, the persistence of bacterial activity in other areas indicates that this remains a significant challenge [21,57–59].

3.4. Detailed Analysis of ALT1 Control Zone

3.4.1. ALT1_1 Subzone

ALT1_1 is one of the drip points within our ALT1 monitoring area [23]. At ALT1_1 the recurrent occurrences of pigment migration and washout produced in part by seepage water have demanded almost continuous monitoring of the area. The deterioration begins with a loss of pigment adhesion to the limestone due to microkarst processes. The infiltration of water through cracks and fissures in the rock causes the pigment particles to be progressively washed away by the water and carried to the drip point, which becomes loaded with paint. The accumulation of pigment in the drop of water increases progressively until it can no longer keep it and the paint precipitates, generating the appearance of a lagoon or increasing the perimeter of an existing lagoon that has been generated previously in processes the same as the one described (Figure 11). These events that lead to the destruction of pigment occur repeatedly at the same point; they are cyclical.

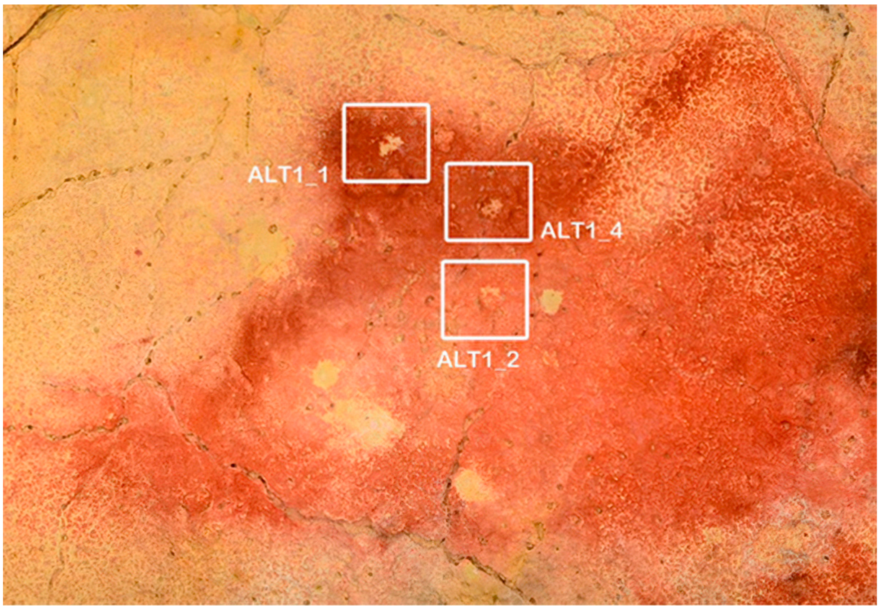
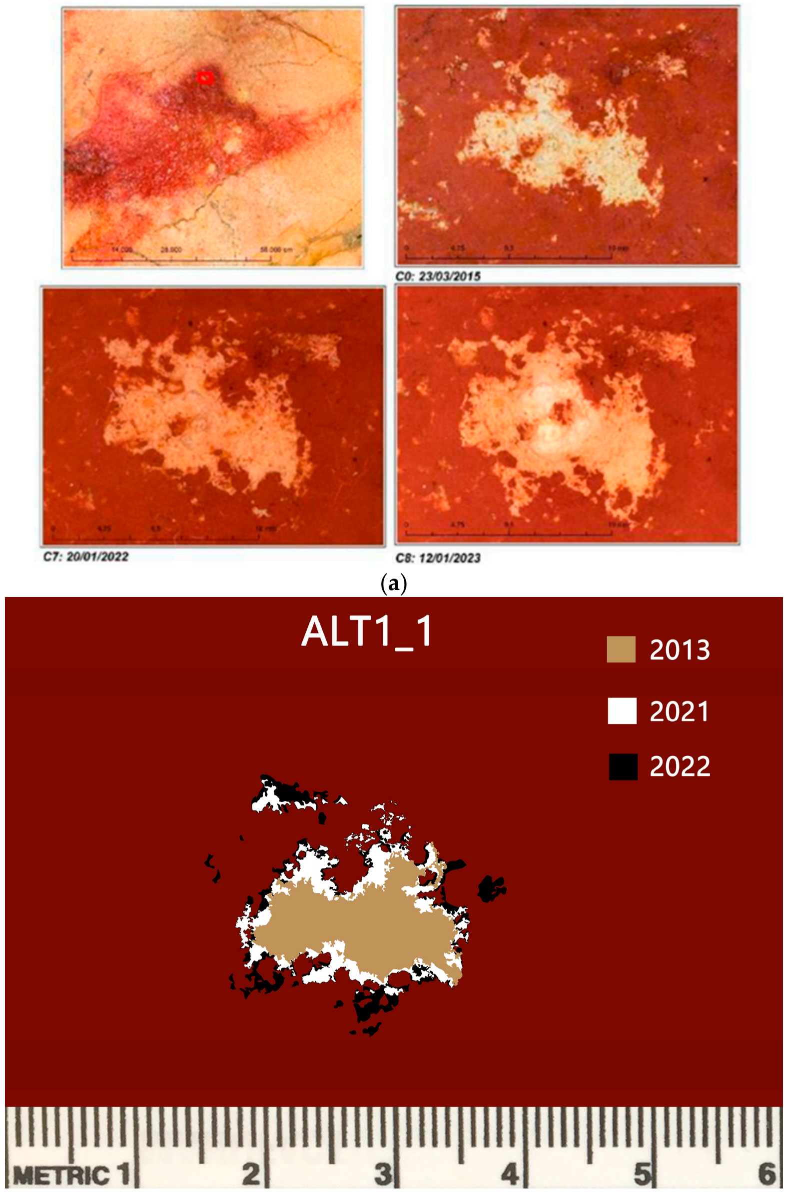


Figure 11. Control area ALT1 showing the three active drip points where carry-over and pigment loss associated with water dripping has been documented.

A comparison of the ALT1_1 area since 2013 has been carried out to understand its behaviour over the last years (Figure 12a). The evolution in the morphology of the lagoon during these years of analysis shows that the processes of washing, migration, or dragging of the pigment are still active. A detailed analysis of the evolution over the last few years shows that the perimeter areas delimiting the surface of the lagoon have been washed out (Figure 12b).

As it can be appreciated in Figure 12b, the lagoon has increased in size, but it has not grown considerably in relation to the amount of pigment we have recorded in our beakers located perpendicular to the drip point (Figure 13).



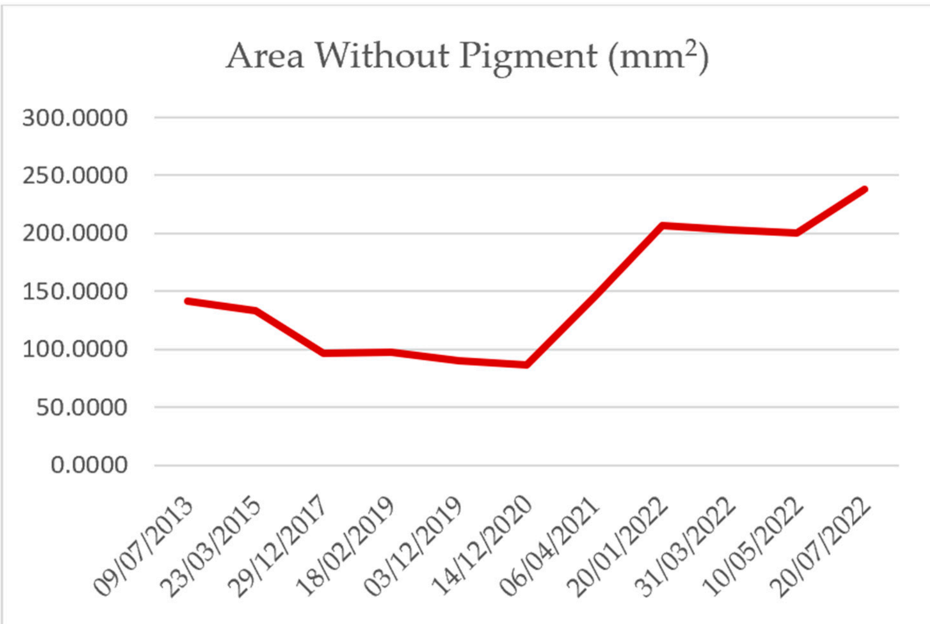
(**a**)

(**b**)

Figure 12. (**a**) Evolution of the surface area of the lagoon corresponding to drip point ALT1_1 from 2015 to 2023. (**b**) The image below shows the damage map and comparisons in relation to the years 2013, 2021, and 2022.

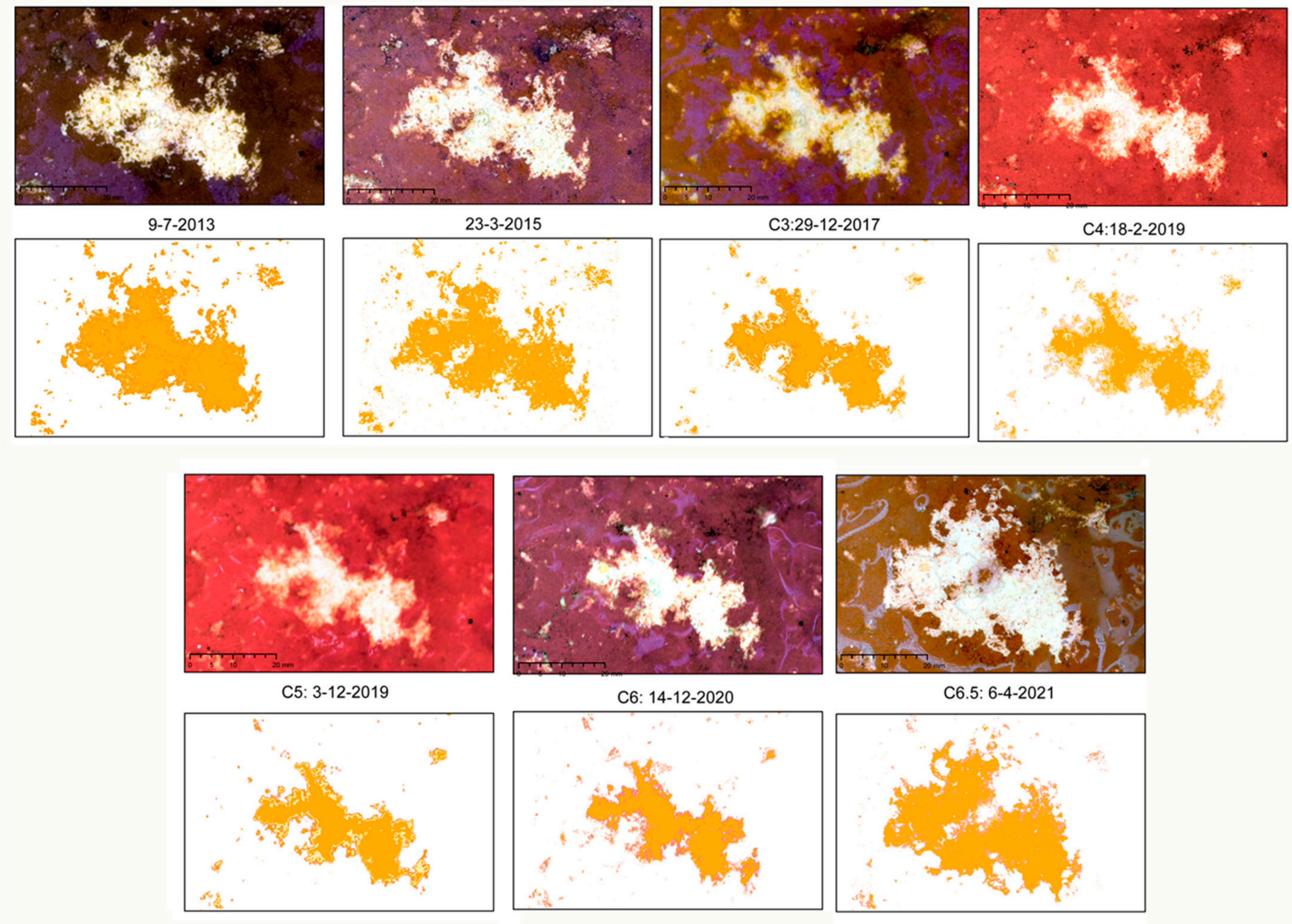
The explanation is reflected in Figure 14 and Table 1. If the size of the area lacking pigment since 2013 is quantified, it can be seen that the ALT1_1 area has been loading up with pigment until the fall episode occurred at the beginning of April 2021. This repositioned pigment that has accumulated during these eight years has lost its attachment to the supporting rock and is floating in the water film. Therefore, the loss of pigment that we have quantified is not only that which comes from the drip zone known as ALT1_1 but also from other points of the Ceiling, although it ends up dripping on ALT1_1. We therefore conclude that the amount of pigment destroyed is much more considerable than what the perimeter of the lagoon shows at first glance.

Figure 13. Beakers located perpendicular to the active drip points within the ALT1 control zone. These beakers, designed to capture and quantify the pigment carried by the water droplets, revealed that the visible gap in the ceiling represents only a part of the total pigment lost, as part of the pigment recorded comes from areas bordering the lagoon itself, which access the drip point by migration of the pigment through the sheet of water.



(**a**)

Figure 14. *Cont*.



(**b**)

Figure 14. (**a**) Graph showing the evolution of pigment washout loss at drip point ALT1_1 (**b**) Evolution of the active drip zone corresponding to ALT1_1. The morphology of the lagoon, i.e., the area devoid of pigment, is highlighted in yellow over the years of monitoring.

Table 1. Quantification of the area affected by pigment loss during the different monitoring campaigns (2013–2022).

Campaign	Date	Nº Pixels	% to C0	Surface mm^2
C0	9 July 2013	88,758	100.00%	142.0120
C1	23 March 2015	83,186	93.72%	133.0980
C3	29 December 2017	60,252	67.88%	96.4035
C4	18 February 2019	61,220	68.97%	97.9515
C5	3 December 2019	56,198	63.32%	89.9163
C6	14 December 2020	54,053	60.90%	86.4848
C6.5	6 April 2021	90,909	102.42%	145.4540
C7	20 January 2022	129,467	145.87%	207.1480
C7.3	31 March 2022	126,980	143.06%	203.1680
C7.5	10 May 2022	125,025	140.86%	200.0401
C7.7	20 July 2022	149,077	167.96%	238.5226

3.4.2. ALT1_2 and ALT1_4 Subzones

Similar deterioration patterns have been documented in ALT1_2 and ALT1_4 at drip points (Figure 15). Although the monitoring period for these areas is shorter than for ALT1_1, the data indicate that these subzones are undergoing the same cyclical process of pigment washing, migration, and loss. The water drips in these areas have also led to significant pigment destruction, with newly formed lagoons or the expansion of existing ones clearly observable.

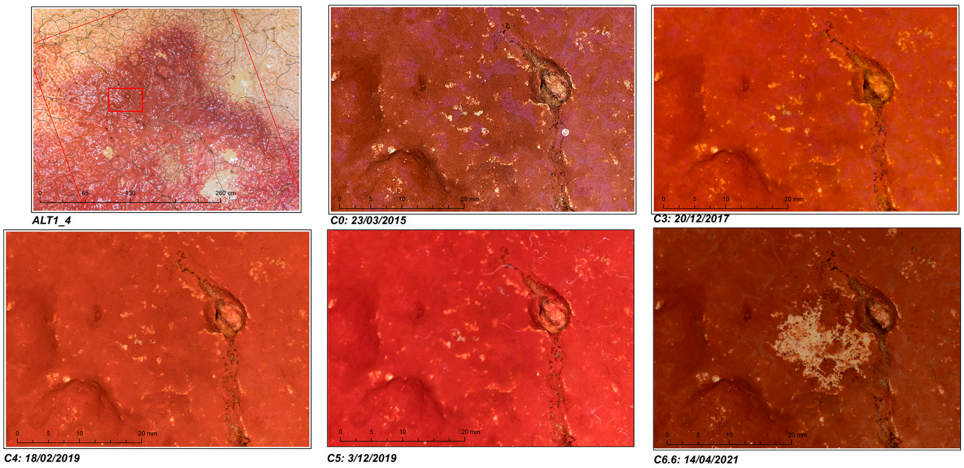


Figure 15. ALT1_4. The figure highlights the water flows involved in pigment transport and destruction. The large red rectangle in the first figure indicates the control area location and the small rectangle the location of the detail images.

The analysis of ALT1_2 and ALT1_4 drip points indicates that these areas are at a critical juncture, with the potential for rapid and irreversible pigment loss if the current trends continue. Nearby areas (Figure 16) have started to show preliminary signs of pigment detachment, similar to those observed in ALT1_1, ALT1_2, and ALT1_4 (indicated by black circles).

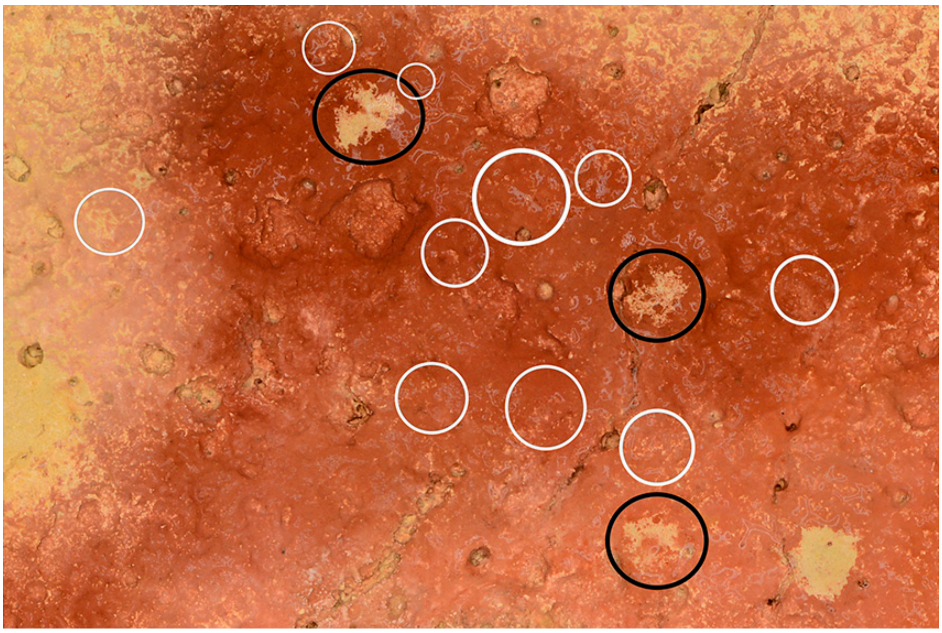


Figure 16. The analysis of ALT1_2 and ALT1_4 subzones. White circles in the figure indicate nearby areas showing preliminary signs of pigment detachment, similar to patterns observed in ALT1_1, ALT1_2, and ALT1_4, which are marked by black circles.

The cyclical nature of pigment destruction in these subzones is evident, with each cycle of water infiltration leading to further pigment loss. The continued expansion of the lagoons within these subzones highlights the urgent need for targeted conservation efforts to prevent further degradation.

3.5. Implications and Future Monitoring

The data collected in this study clearly indicate that the deterioration processes affecting the ALT1 control zone are ongoing and are intensifying. Integrating water infiltration patterns, pigment migration, and microbial activity analyses has provided a comprehensive understanding of the complex interplay of factors contributing to the degradation of the paintings. The precise quantification of pigment loss, the tracking of water and other relevant factors such as CO2 concentration-induced pigment migration, and the documentation of microbial colonization all point to the need for enhanced and continuous monitoring efforts.

Future monitoring should focus on refining the methods used in this study, with particular emphasis on understanding the microenvironmental conditions that contribute to the ongoing deterioration. While the current study has provided valuable insights into the factors driving pigment loss and microbial colonization, further research is needed to develop more effective conservation strategies that can be adapted to the dynamic conditions within the cave.

The results of this study underscore the critical importance of continuous and detailed monitoring of the Ceiling surface where the paintings are located. The advanced techniques employed here, such as high-resolution microphotogrammetry and 3D laser scanning, provide invaluable tools for detecting and understanding the complex interplay of factors that threaten these irreplaceable works of art. Continued vigilance and the adaptation of conservation strategies will be essential to preserving the Altamira paintings for future generations.

The findings suggest that the development of new conservation measures may be required to prevent further degradation in areas like ALT1_1, ALT1_2, and ALT1_4, where the rate of pigment loss is worrying. This study highlights the need for a more integrated approach to conservation that considers both the physical and biological factors at play. By continuing to refine and expand the monitoring techniques, we can develop more effective conservation strategies that respond to the dynamic conditions within the cave, ensuring the long-term preservation of this invaluable Cultural Heritage.

4. Discussion

The results analyse the alterations affecting the paintings on the ceiling of the Polychrome Hall, relating these deteriorations to the active processes of degradation. Through the application of high-resolution monitoring techniques such as microphotogrammetry, photogrammetry, and 3D laser scanning, we have documented the migration and loss of pigment in some of the control zones such as ALT1, ALT12, and ALT15, as well as the evolution of the bacterial colonies arranged in the control zone ALT13. These alterations, associated with cyclical and continuous deterioration processes, have been related to infiltration and condensation water as well as CO_2 concentration levels and a series of other environmental factors in the cave.

4.1. Preventive Conservation Measures

The strategies used in Altamira's conservation are rooted in the concept of Preventive Conservation, a comprehensive approach to the preservation of Cultural Heritage. Preventive conservation is defined as a systematic method aimed at identifying, evaluating, detecting, and controlling the risks of deterioration that cultural interest sites face, with the ultimate goal of reducing these risks by addressing their root causes—typically external factors. This approach is critical in the case of Altamira, where the preservation of the cave's prehistoric paintings is threatened by a variety of environmental and anthropogenic factors.

In the context of Altamira, preventive conservation strategies are focused on eliminating or mitigating the causes of deterioration. The only viable long-term preservation strategy is to control the environmental and biological agents responsible for the degradation of the paintings, which could otherwise reinitiate or accelerate these processes in the future.

The periodic and systematic monitoring of the ALT1 control zone, alongside other sensitive areas within the Polychrome Hall (Figure 1b, has enabled the early detection and documentation of direct alteration processes in the cave paintings. These alterations, particularly those related to the washing and erosion of the mineral components of the rock substrate, have been quantitatively measured. The results indicate significant pigment migration and loss at several critical points within the ALT1 control zone. This systematic documentation confirms the ongoing nature of these deterioration processes and allows for the precise tracking of their progression over time.

4.2. Shifts in Conservation Conditions

The conservation conditions of the Cave of Altamira have undergone significant changes since its discovery, differing markedly from those that existed when the cave remained sealed. Before its discovery, Altamira maintained a high degree of preservation due to its low water infiltration rate, which was a result of its tabular structure and stable microclimatic conditions that had been consistent since the natural sealing of the cave approximately 13,000 years ago [4]. During this sealed period, natural deterioration processes, though present, were relatively slow. These processes, which began with the creation of the paintings, were significantly less impactful until the cave was reopened and exposed to external influences.

The reactivation and acceleration of these deterioration processes in recent times are closely tied to the cave's discovery and the subsequent human interventions and activities, including the influx of visitors [4]. These activities have introduced new environmental dynamics into the cave, which have significantly altered its natural internal conditions. Increased water infiltration, changes in humidity and temperature, as well as the sometimes very high CO_2 concentrations have contributed to the fact that the deterioration processes detected are still fully active.

Given these changes, the conservation strategies currently applied in Altamira are designed to address these newly introduced risks. Preventive conservation measures, as outlined in the *Programa de Investigación para la Conservación Preventiva y Régimen de Acceso de la Cueva de Altamira* (Research Program for Preventive Conservation and Access Regime of Cave of Altamira), aim to monitor, identify, and mitigate the risks associated with these environmental changes induced in many cases by human action [22]. This program includes the *Plan de Conservación Preventiva* (PCP), which serves as a comprehensive framework encompassing all necessary means and actions to ensure the proper conservation of the Cave of Altamira and its rock art.

As part of the PCP, *Protocolo N°6: Seguimiento del Estado de Conservación* (Protocol No. 6: Monitoring the Conservation State) mandates a rigorous program of high-resolution photogrammetric monitoring across various zones within the cave, particularly focusing on the ceiling of Polychrome Hall [22]. This monitoring is essential for documenting the state of conservation of the cave's most sensitive areas and tracking the evolution of any alterations over time. The ability to objectively and quantitatively measure these changes allows for a better understanding of the factors driving the deterioration processes and helps with the development of more effective conservation strategies [4,57–65].

4.3. Accelerated Deterioration Post-Discovery

The data collected from the control area ALT1, as well as from other monitored areas of the Ceiling, indicate that the deterioration processes on the paintings are still active today. This degradation of the paintings is directly related to the internal microclimate of the cave, to external moisture inputs, and to the recent history itself, where human interaction has been critical.

The processes of pigment destruction associated with runoff and dripping water have been occurring on the paintings since almost their creation, but the reality, thanks to studies such as those presented here, is that they continue even today, and are worrying in some specific areas of the Ceiling, such as ALT1. This active degradation indicates that, despite significant efforts to minimize the impact on this valuable art, the current measures appear insufficient to fully reverse the alterations occurring on certain parts of the Polychrome Ceiling surface.

A more detailed analysis, as a result of our continuous monitoring, lets us determine that the degradation of the paint associated with our ALT1 control area is conditioned by important agents of deterioration such as water and CO_2 concentrations. The CO_2-laden water remains for long periods of time on the surface of the limestone rock, favouring mineral decomposition reactions that weaken the adhesion of the pigment to the rock [26]. As a result, the paint loses its adhesion to the support and is transported away from its original location, leading to the formation of bare areas where the pigment has been completely removed. The migration of the paint is conditioned by the presence of small interconnected depressions and fissures on the ceiling of the Polychrome Hall, forming a network of microkarstification (Figure 17). This network facilitates the movement of water and CO_2, both of which are important agents of deterioration. Water, in particular, accumulates on the surface of the limestone, favouring mineral decomposition reactions that weaken the adhesion of the pigment to the rock.

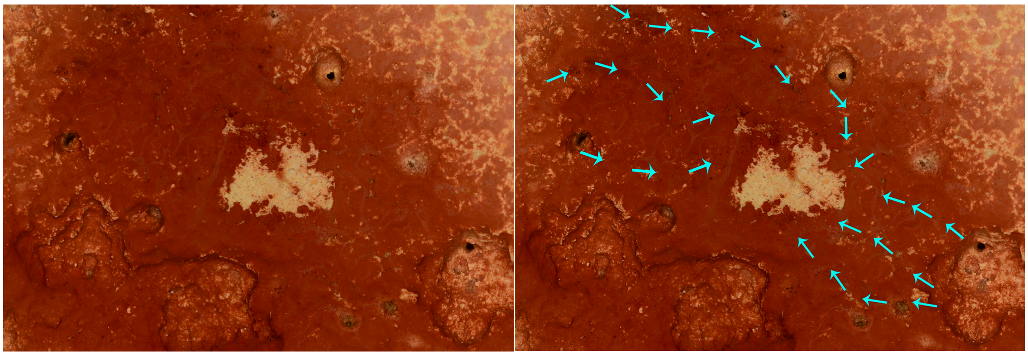


Figure 17. Migration of paint moving through small interconnected depressions and cracks within the Ceiling surface in control area ALT1. The arrows show the path of the water and its drag of pigment to the drop point.This complex process of deterioration, involving multiple environmental and biological [43] agents, is not a one-time event but rather a continuous, systematic, and recurring phenomenon. The ongoing migration of pigment through water erosion and its subsequent accumulation at various drip points underscore the need for continuous and vigilant monitoring. The study of these processes has also revealed that the alterations are more widespread than first believed, affecting not just ALT1 but also adjacent areas, further complicating the conservation efforts.

4.4. Future Research Directions and Strategic Conservation Efforts

Observations in ALT1, making a comparison during the last years of follow-up, are as follows:

- The acceleration of deterioration: The processes of flaking, disaggregation, and loss of pigment cohesion have persisted, affecting new areas beyond those previously identified (Figure 18).
- Predictive monitoring: The systematic monitoring of the cave, coupled with the detailed analysis of environmental conditions, has allowed us to predict areas of potential damage before they occur. This predictive capacity is important as it is currently allowing us to implement punctual preventive conservation actions so that water flows involved in pigment migration within ALT1 do not generate new and repeated damage to the pigment (Figure 19).

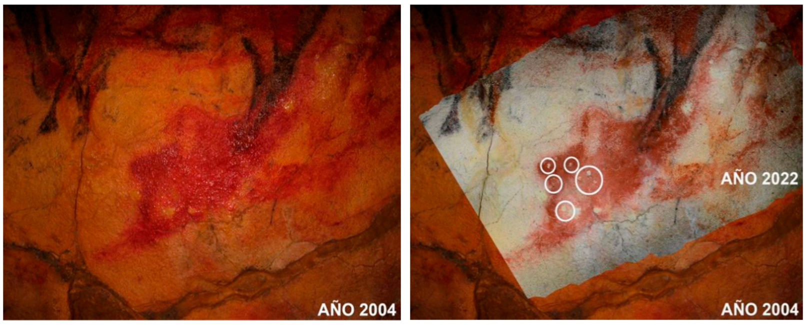


Figure 18. Comparative analysis of the red sign in ALT1 between 2004 and 2022, highlighting with white circles the significant variations related to pigment loss. The word *Año* in picture means year.

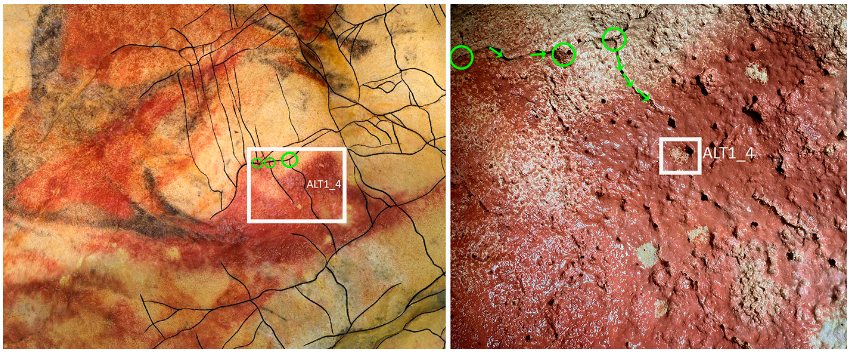


Figure 19. In the drip zone with migration of pigment ALT1_4, it has been determined which are the water flows (marked by the green arrows) that, associated with the fracture lines of the roof, generate the dragging and washing of the paint. The green circles indicate possible water circulation areas where a potential diversion would prevent migration and loss of pigment by dragging to the drip zone ALT1_4.

Although this work methodology is providing positive results resulting in minimizing certain deterioration of the painting, the conservation challenges are such that we cannot consider them to be fully satisfactory at the present time. This is why the following lines of research are proposed to enable us to develop more effective conservation strategies:

- High-resolution GPR studies: The evaluation of the state of the overlying layer from the dolomitic geological level, located barely one metre from the 'Polychrome' level where the rock art paintings are located on its basal surface. A reliable and non-destructive solution based on the use of a high-frequency GPR system will be used for this purpose. The objective will be the high-resolution survey in different control areas affected by pigment migration processes to know in detail the trajectory followed by the water from the aforementioned dolomitic layer to the Polychrome level, allowing the calculation of thicknesses, the existence of possible voids, areas of presence/absence of water, detachments, and fractures. This study should be re-applied at different times of the year to know the difference in the behaviour and movement of the water in this area of the roof of Polychromes.
- Microenvironmental dynamics: Investigate the microenvironmental dynamics related to CO_2 fluxes between the cave and the external environment. Understanding these dynamics is essential for developing strategies to manage CO_2 concentrations, which play a critical role in the chemical degradation of the limestone substrate.
- Geochemical analysis of infiltrating water: Perform in-depth geochemical analyses of the water reaching ALT1. Preliminary results suggest carbonate dissolution is occurring, which indicates that the water may not always be calcifying. Understanding the specific chemical composition of this water is vital for determining its potential to dissolve the rock substrate and contribute to pigment loss.

- Microbial influence on deterioration: Expand research on the role of microorganisms in the cave's deterioration processes, particularly their influence on CO_2 concentrations and carbonate dissolution. Previous studies, such as the work [39], have shown that certain bacterial colonies can capture CO_2 within the cave environment, potentially exacerbating the dissolution of the limestone substrate and further destabilizing the pigments.

The systematic monitoring and detailed analysis conducted within the PCP framework have proven essential in documenting and understanding the ongoing deterioration processes in Altamira. However, the acceleration of these processes in recent years indicates that the current preventive measures may not be enough to fully address the challenges posed by the complex interplay of environmental and biological factors. To mitigate further damage, it is important to expand the scope of conservation efforts and incorporate advanced scientific techniques and methodologies into the preservation strategy.

5. Conclusions

This study provides a detailed and objective analysis of the ongoing deterioration processes in the Cave of Altamira, emphasizing the need to continue this systematic monitoring but also to put new conservation strategies into practice. The preventive conservation strategies currently in place, while essential, have not proven to provide great enough mitigation of the degradation observed in recent years. The data suggest that the deterioration processes in ALT1 and other zones are becoming increasingly severe and widespread, driven by a combination of water infiltration and CO_2.

The findings of this study underscore the importance of systematic and continuous monitoring, combined with advanced analytical techniques, to predict and mitigate future damage. Integrating these monitoring efforts into a broader multidisciplinary strategic conservation plan, such as the *Plan de Conservación Preventiva*, is critical to preserving Altamira's invaluable cultural heritage. This requires the collaboration of professionals from diverse fields—ranging from geochemistry, hydrology, geotechnics, petrography/diagnostics, microbiology, and conservation/restoration—each contributing specialized knowledge toward a common goal: the protection and conservation of Altamira. By working together, these experts make sure every aspect of the cave's preservation, from biological threats to structural vulnerabilities, is thoroughly addressed, combining their knowledge to safeguard the site's future.

At Altamira, it is not possible to completely halt the deterioration processes that generate the alterations described in this study. Our real objective is to minimize deterioration by applying specific control and stabilization measures, such as those proposed here. The preservation of the Altamira paintings for future generations depends on our ability to adapt and improve these conservation strategies, responding effectively to the dynamic and changing conditions within the cave.

Author Contributions: Conceptualization, A.P. and V.B.; methodology, A.P. and V.B.; software, V.B.; validation, A.P. and V.B.; formal analysis, A.P. and V.B.; investigation, A.P. and V.B.; resources, A.P. and V.B.; data curation, A.P. and V.B.; writing—original draft preparation, A.P. and V.B.; writing—review and editing, A.P. and V.B.; visualization, A.P. and V.B.; supervision, A.P. and V.B.; project administration, V.B.; funding acquisition, V.B. All authors have read and agreed to the published version of the manuscript.

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