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TESIS DOCTORAL

Integración y procesamiento de técnicas no
destructivas para el estudio y conservación
de cuevas con arte rupestre

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Resumen

El arte rupestre paleolítico de la Cueva de Altamira representa un patrimonio cultural de incalculable valor, con una antigüedad estimada de entre 35.600 y 14.000 años, lo que la convierte en una de las manifestaciones artísticas más antiguas de la humanidad. Estas pinturas, caracterizadas por su fragilidad y vulnerabilidad a factores naturales y antropogénicos, han sobrevivido gracias a condiciones ambientales específicas, aunque actualmente enfrentan desafíos significativos para su conservación. La preservación de estos vestigios milenarios demanda el desarrollo de estrategias de conservación preventiva que permitan una intervención mínima, maximizando la protección y sostenibilidad del sitio. Reconociendo su excepcional valor, la Cueva de Altamira fue declarada Patrimonio de la Humanidad por la UNESCO en 1985, formando parte del conjunto de cuevas con arte rupestre del norte de España que fueron incluidas en la lista en 2008.

En este contexto, la investigación propuesta tiene un enfoque pionero metodológico de integración de métodos mediante una implementación de un innovador sistema de teledetección geomática que combina técnicas avanzadas de LE3D, vehículos aéreos no tripulados, georradar y sistemas de posicionamiento global. Estas metodologías integradas ofrecen un potencial nuevo de cartografiado sistemático en 3D de las estructuras kársticas, las fracturas y las condiciones ambientales de la cueva, permitiendo un análisis detallado de la interacción entre las características geológicas, las pinturas rupestres que alberga y los elementos bióticos que colonizan el techo. La combinación de los datos generados ha revelado información crucial sobre los flujos de agua y el intercambio gaseoso, factores fundamentales para la conservación a largo plazo. Este enfoque multidisciplinario refuerza la capacidad de gestión y seguimiento de parámetros de la Cueva de Altamira, ofreciendo una base sólida para la toma de decisiones en la preservación de su arte rupestre.

Abstract

The Paleolithic rock art of the Cave of Altamira represents a cultural heritage of incalculable value, with an estimated age ranging between 35,600 and 14,000 years, making it one of the oldest artistic expressions of humanity. These paintings, characterized by their fragility and vulnerability to natural and anthropogenic factors, have survived thanks to specific environmental conditions, although they face significant conservation challenges. The preservation of these millennia-old remains requires the development of preventive conservation strategies that enable minimal intervention while maximizing the site's protection and sustainability. Recognizing its exceptional value, the Cave of Altamira was declared a UNESCO World Heritage Site in 1985, and in 2008 it became part of the group of caves with rock art in northern Spain included on the list.

In this context, the proposed research adopts a pioneering methodological approach by integrating various methods by implementing an innovative geomatic remote sensing system that combines advanced 3D laser scanning, unmanned aerial vehicles, ground-penetrating radar, and global positioning systems. These integrated methodologies offer new potential for systematic 3D mapping of karstic structures, fractures, and environmental conditions within the cave, allowing for a detailed analysis of the interaction between geological features, the rock art, and the biotic elements colonizing the ceiling. The combination of the generated data has revealed important information about water flows and gas exchange, key factors for long-term conservation. This multidisciplinary approach enhances the capacity for management and monitoring of the Cave of Altamira's parameters, providing a solid foundation for decision-making in the preservation of its rock art.

Resum

L'art rupestre paleolític de la Cova d'Altamira representa un patrimoni cultural d'incalculable valor, amb una antiguitat estimada entre els 35.600 i els 14.000 anys, cosa que la converteix en una de les manifestacions artístiques més antigues de la humanitat. Aquestes pintures, caracteritzades per la seua fragilitat i vulnerabilitat davant factors naturals i antropogènics, han sobreviscut gràcies a condicions ambientals específiques, encara que actualment s'enfronten a desafiaments significatius per a la seua conservació. La preservació d'aquests vestigis mil·lenaris exigeix el desenvolupament d'estratègies de conservació preventiva que permeten una intervenció mínima i maximitzen la protecció i sostenibilitat del lloc. Reconeixent el seu valor excepcional, la Cova d'Altamira va ser declarada Patrimoni de la Humanitat per la UNESCO en 1985, i el 2008 va ser incorporada al conjunt de coves amb art rupestre del nord d'Espanya incloses en la llista.

En aquest context, la investigació proposada adopta un enfocament metodològic pioner mitjançant la integració de mètodes a través de la implementació d'un sistema innovador de teledetecció geomàtica que combina tècniques avançades d'escaneig làser 3D, vehicles aeris no tripulats, georadar i sistemes de posicionament global. Aquestes metodologies integrades ofereixen un nou potencial per al cartografiat sistemàtic en 3D de les estructures càrstiques, les fractures i les condicions ambientals de la cova, permetent una anàlisi detallada de la interacció entre les característiques geològiques, les pintures rupestres que alberga i els elements biòtics que colonitzen el sostre. La combinació de les dades generades ha revelat informació clau sobre els fluxos d'aigua i l'intercanvi gasós, factors fonamentals per a la conservació a llarg termini. Aquest enfocament multidisciplinari reforça la capacitat de gestió i seguiment de paràmetres de la Cova d'Altamira, oferint una base sòlida per a la presa de decisions en la preservació del seu art rupestre.

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1. Estado del arte

La Cueva de Altamira, reconocida como uno de los enclaves más emblemáticos del arte rupestre paleolítico, alberga una colección de pinturas y grabados de gran relevancia histórica y cultural, considerados un patrimonio invaluable a nivel mundial, con una antigüedad estimada de entre 35.600 y 14.000 años. Desde su descubrimiento en el siglo XIX, Altamira ha sido objeto de estudio y conservación constante debido a la fragilidad intrínseca de las obras y su exposición a diversos agentes de deterioro. Las pinturas, realizadas con pigmentos minerales sobre las superficies irregulares de la cueva, han sufrido procesos de degradación acelerados por factores naturales y antropogénicos, que han afectado tanto a la estructura geológica de la cueva como a las condiciones microambientales que garantizan su preservación.

Ubicada en Santillana del Mar, Cantabria, la cueva forma parte del sistema kárstico del Macizo de Altamira, compuesto por calizas del Cretácico superior. Este sistema ha sido modelado por procesos de disolución kárstica, dando lugar a una compleja red de fracturas, fisuras y cavidades subterráneas. La interacción entre la geología de la cueva y los procesos ambientales es un factor determinante en la conservación del arte rupestre, ya que las filtraciones de agua, los cambios en la humedad relativa y la dinámica de los gases en el interior afectan la estabilidad de los pigmentos y la integridad de las superficies rocosas.

Entre los principales riesgos geológicos se encuentran la infiltración de agua a través de fisuras, que contribuye a la disolución de carbonatos y a la formación de depósitos calcáreos sobre las pinturas, así como la posibilidad de colapsos estructurales debido a la actividad tectónica y a la erosión diferencial del macizo. Además, la conexión con el exterior permite fluctuaciones en la concentración de dióxido de carbono (CO_2), afectando la solubilidad del carbonato de calcio y favoreciendo la cristalización de minerales en las capas pictóricas.

Ante los desafíos mencionados, el estudio del marco geológico y microambiental de Altamira resulta esencial para el desarrollo de estrategias de conservación efectivas. La integración de modelos tridimensionales, datos geofísicos y análisis climáticos permite identificar las zonas más vulnerables y diseñar planes de seguimiento continuo que contribuyan a la preservación del arte rupestre. En este sentido, la integración de tecnologías de teledetección geomática emerge como un componente esencial para la documentación, el análisis y la mitigación de los factores de riesgo presentes en la cueva.

1.1. Introducción

La presente tesis, titulada "Integración y procesamiento de técnicas no destructivas para el estudio y conservación de cuevas con arte rupestre", ha sido elaborada en formato de compendio de artículos. Los artículos se han adaptado al formato de tesis, y se han respetado las políticas editoriales correspondientes para su difusión en abierto.

La conservación de la Cueva de Altamira constituye un desafío de gran relevancia científica y patrimonial. Desde su descubrimiento en 1868 y su reconocimiento científico en 1902, la cueva ha sido objeto de sucesivas investigaciones destinadas a comprender la evolución de sus condiciones microambientales y los factores que afectan la estabilidad de sus pinturas rupestres. No obstante, la preservación de Altamira se enfrenta a desafíos constantes debido a la naturaleza dinámica y compleja de los sistemas kársticos, caracterizados por su interacción con factores geológicos, hidrológicos, climáticos y biológicos.

Las cuevas kársticas, como Altamira, son sistemas abiertos en los que las interacciones con el entorno exterior generan variaciones en la temperatura, la humedad y la circulación de gases. Estas variaciones pueden incidir en la preservación del arte rupestre al inducir procesos de condensación, infiltración hídrica y precipitación de sales en las superficies pintadas. La Cueva de Altamira, emplazada en un macizo calcáreo senil, ha experimentado a lo largo del tiempo procesos de dolinización, lo que ha dado lugar a la formación de fracturas y cavidades que inciden negativamente en su estabilidad estructural.

Además de los procesos geológicos naturales, la actividad humana ha influido en la evolución microambiental de la cueva. El incremento en el número de visitantes durante el siglo XX, en conjunto con ciertas intervenciones de conservación realizadas con anterioridad, alteró el equilibrio natural del sistema, acelerando la disolución de carbonatos y favoreciendo la proliferación de microorganismos. Estos efectos han sido identificados en diversas investigaciones, lo que ha llevado a la implementación de medidas restrictivas de acceso.

En el año 2002, se tomó la decisión de cerrar al público la cueva, tras detectarse variaciones en los niveles de dióxido de carbono y humedad, lo que evidenciaba una alteración de sus equilibrios naturales. Desde entonces, se ha implementado un programa riguroso de seguimiento ambiental, basado en el análisis de flujos de aire, dinámica de infiltración hídrica y evolución de las condiciones microclimáticas. Los resultados de estos estudios han permitido avanzar en la comprensión de las interacciones entre los factores naturales y antropogénicos que afectan a la caverna, proporcionando datos clave para desarrollar estrategias de conservación preventiva adaptadas a la complejidad del entorno kárstico.

1.1.1. Objeto de la investigación

Tras numerosos estudios llevados a cabo, persisten interrogantes fundamentales sobre la evolución de las condiciones microambientales en la cueva y su impacto acumulativo en la conservación de las pinturas rupestres. Existen discrepancias en cuanto a la influencia de la ventilación natural, la interacción entre flujos de aire y humedad, y la incidencia de la actividad microbiana en la degradación de los pigmentos.

Asimismo, se evidencia la necesidad de profundizar en el análisis del impacto del cambio climático sobre la estabilidad de la cavidad y sus manifestaciones artísticas, con el propósito de desarrollar estrategias efectivas de conservación. Investigaciones recientes han evidenciado variaciones en los niveles de humedad y temperatura en diferentes sectores del macizo kárstico, lo que podría tener repercusiones en la estabilidad estructural de la cueva a largo plazo.

Por lo tanto, el propósito de la presente tesis doctoral radica en abordar las deficiencias en el conocimiento identificadas mediante la implementación de tecnologías de documentación geomática y geofísica, integrando múltiples herramientas para obtener una caracterización precisa y multidimensional de la Cueva de Altamira. El enfoque metodológico de esta investigación se basa en la documentación del karst, con un énfasis particular en el estudio de la montera de la Sala de los Polícromos. En este contexto, se han aplicado técnicas avanzadas como el escaneo láser 3D, la fotogrametría de alta resolución y el georradar para detectar fracturas, discontinuidades estructurales y zonas de infiltración hídrica.

Además, se ha estudiado el movimiento del agua por tensión superficial y los procesos de humectación y secado dentro del macizo kárstico, analizando cómo estas dinámicas influyen en la migración de pigmentos, la cristalización de sales y la estabilidad estructural de la cueva. Los estudios llevados a cabo han evidenciado que la integración de datos geofísicos y geomáticos no solo permite identificar áreas de posible colapso, sino también comprender de manera más profunda los mecanismos involucrados en el deterioro del arte rupestre.

La integración de estas herramientas ha facilitado la generación de modelos tridimensionales de alta precisión, esenciales para la conservación preventiva de Altamira, ya que proporcionan una base sólida para la toma de decisiones informadas y la implementación de estrategias de mitigación adaptativas. Este planteamiento integrado supone un avance significativo respecto a estudios previos, al proporcionar una visión más completa de la interacción entre factores geológicos, hidrológicos y estructurales en la evolución del sitio.

1.1.2. Objetivos

Esta investigación aborda las problemáticas identificadas como prioritarias para la conservación de la Cueva de Altamira, basadas en los principales factores de riesgo documentados en estudios previos. Para ello, se han aplicado tecnologías geomáticas y geofísicas avanzadas, lo que ha permitido caracterizar con mayor precisión las dinámicas internas del karst y su efecto sobre el arte rupestre. Las áreas clave de investigación incluyen:

1. **Infiltración hídrica y disolución calcárea:** El agua se erige como uno de los principales agentes de degradación en entornos kársticos. En la cueva de

Altamira, la infiltración hídrica afecta a la estabilidad estructural del macizo kárstico y a las superficies pintadas, lo que provoca la migración de pigmentos, la disolución de carbonatos y la cristalización de sales. Los estudios recientes han demostrado que el movimiento del agua por tensión superficial en el techo de la Sala de Polícromos influye directamente en los ciclos de humectación y secado, intensificando los procesos de deterioro. La integración del georradar con múltiples frecuencias (100, 400 y 900 MHz en el exterior; 400, 900 MHz, 1600 MHz y Dual 300/800 MHz en el interior) ha permitido identificar con mayor detalle las rutas de infiltración y los puntos críticos de acumulación de agua.

2. **Deterioro microbiológico:** La proliferación de microorganismos en áreas con alta humedad constituye un factor crítico en el proceso de deterioro del arte rupestre. Numerosos estudios han puesto de manifiesto que la presencia de bacterias, hongos y algas se ve influenciada por las variaciones en la humedad relativa y por la acumulación de compuestos orgánicos en la superficie de las pinturas. La implementación de la fotogrametría de alta resolución en estudios recientes ha facilitado la detección del crecimiento y la distribución de colonias microbianas, proporcionando información valiosa para el desarrollo de estrategias de control y mitigación más eficaces. Este enfoque ha demostrado que el biodeterioro está influenciado por factores ambientales y alteraciones en la dinámica de ventilación, así como por la interacción con materiales pigmentados.
3. **Estabilidad estructural y deformaciones:** El macizo kárstico que alberga la Cueva de Altamira presenta un sistema de fracturas y discontinuidades cuya evolución debe ser controlada con alta precisión, debido al riesgo de colapso parcial y su posible impacto en las pinturas rupestres. La combinación del georradar y láser escáner 3D ha demostrado ser fundamental para el cartografiado de fracturas, permitiendo detectar deformaciones estructurales, huecos internos y zonas de mayor vulnerabilidad con mayor resolución que en estudios previos. Esta información resulta esencial para la evaluación del estado de la montera de la Sala de Polícromos y la previsión de deformaciones potenciales que puedan comprometer la integridad del sitio.
4. **Influencia de factores climáticos y antropogénicos:** Las fluctuaciones en las condiciones microambientales de la cavidad, ocasionadas por factores climáticos y actividades antrópicas, han ocasionado alteraciones substanciales en la dinámica de CO₂ y la circulación del aire. Estudios históricos han evidenciado que el aumento en la afluencia turística durante el siglo XX provocó un desequilibrio en la homeostasis natural del sistema kárstico, incrementando la tasa de disolución de carbonatos y favoreciendo el crecimiento de microorganismos en las paredes decoradas. Aunque la restricción de accesos ha mitigado parcialmente este impacto, el cambio climático emerge como un factor de riesgo emergente, debido a la intensificación de eventos de precipitación extrema y al

aumento de la humedad ambiental, lo que acentúa los procesos de disolución y filtración.

1.1.3. Metodología propuesta

En respuesta a los factores de riesgo identificados y a las lagunas de conocimiento detectadas en estudios previos, la presente tesis doctoral se ha estructurado en torno a los siguientes contenidos prioritarios, centrados en la aplicación de tecnologías geomáticas y geofísicas para la documentación, evaluación y conservación de la Cueva de Altamira:

A. Documentación Geométrica Avanzada:

La generación de modelos tridimensionales de alta precisión resulta fundamental para comprender la evolución morfológica de la cueva y evaluar los riesgos de colapso estructural. En el presente estudio, se integrarán diversas técnicas geomáticas, mediante la combinación de:

- Sistemas globales de navegación por satélite (GNSS, *Global Navigation Satellite System*): Aplicado en el exterior de la cueva para la georreferenciación precisa de los modelos y la correlación entre las estructuras internas y externas.
- Vehículos aéreos no tripulados (UAV, *Unmanned Aerial Vehicle*): Utilizados para la modelización del relieve exterior, facilitando el análisis de la interacción entre el entorno superficial y el sistema subterráneo.
- Escaneo Láser 3D (LE3D): Para capturar la morfología interna de la cueva con una resolución subcentimétrica, permitiendo identificar deformaciones y fracturas en el macizo kárstico.
- Fotogrametría de Alta Resolución: Esencial para documentar los paneles decorados y zonas de biodeterioro con una resolución submilimétrica, permitiendo el seguimiento del estado de conservación de las pinturas rupestres y la detección de alteraciones superficiales invisibles al ojo humano.

Esta combinación de técnicas permitirá la integración de datos geomáticos en plataformas de análisis espacial, facilitando el seguimiento a largo plazo y la detección de cambios morfológicos en la cueva.

B. Evaluación Geofísica y Análisis del Macizo Kárstico:

El estudio geofísico del macizo kárstico resulta imperativo para comprender la estructura interna de la cueva y detectar cavidades ocultas o zonas de debilidad que puedan comprometer su estabilidad. Para ello, se implementará la técnica no invasiva de georradar (GPR) mediante con un amplio rango de frecuencias, adaptadas a distintos niveles de penetración y resolución:

- Frecuencias de 100, 400 y 900 MHz en el exterior: Permiten analizar las capas superficiales y profundas del macizo kárstico de la cueva, detectando cavidades y principales fracturas profundas que puedan afectar la integridad del sistema.
- Frecuencias de 1600 MHz, 900 MHz, 400 MHz y Dual 300/800 MHz en el interior: Ofrecen un análisis de alta resolución de las capas próximas al techo de la Sala de Polícromos, permitiendo identificar discontinuidades (fracturas, diaclasas, planos de estratificación, despegues), oquedades y zonas de humedad.

La integración de datos geofísicos en modelos tridimensionales ofrecerá una visión integrada de las capas y estructura de la cueva, proporcionando información clave para anticipar riesgos y desarrollar estrategias de conservación preventiva.

C. Análisis del Movimiento del Agua y Estudio de Humedades:

La dinámica hídrica en el macizo kárstico constituye un factor determinante que incide tanto en la estabilidad estructural de la cueva como en la degradación del arte rupestres. En el contexto específico de la Cueva de Altamira, el comportamiento del agua se manifiesta a través de dos dinámicas diferenciadas pero interconectadas: la infiltración de agua desde el exterior y el desplazamiento de agua a través de la tensión superficial en el techo de la Sala de los Polícromos. La presente tesis doctoral tiene como objetivo principal abordar ambos fenómenos con el fin de comprender mejor su impacto y contribuir a la conservación.

- **Infiltración y dinámica hídrica interna:** El agua de infiltración representa el flujo descendente que atraviesa el macizo kárstico desde el exterior hacia el techo de la Sala de Polícromos. Este proceso es fundamental en la redistribución de humedades y puede inducir procesos de disolución de carbonatos y debilitar las formaciones rocosas. La utilización de GPR con múltiples frecuencias (100, 400 y 900 MHz en el exterior; 400, 900 MHz, 1600 MHz y Dual 300/800 MHz en el interior), procesado en 2D y 3D permitirá trazar estas rutas de infiltración, proporcionando información sobre cómo el agua se desplaza a través de las capas rocosas hasta alcanzar las superficies decoradas. La identificación de las principales rutas de infiltración es esencial para establecer medidas de conservación preventiva.
- **Delimitación de la cuenca de captación y análisis de las cuencas hidrográficas del Techo:** El estudio de la cuenca de captación del techo de la Sala de Polícromos delimitará las zonas donde el agua se acumula tras la infiltración. Esta delimitación es fundamental para detectar áreas susceptibles de cristalización de sales y disolución de carbonatos, factores clave en el deterioro de las pinturas. El modelado tridimensional de los datos geofísicos del techo y la fotogrametría de alta resolución permitirán evaluar cómo la geomorfología influye en el flujo y la retención de agua, proporcionando información valiosa para la conservación preventiva.

- **Movimiento del agua por tensión superficial en el techo de Polícromos:**

Tras alcanzar el techo de la Sala de Polícromos, el agua se desplaza predominantemente por tensión superficial, distribuyéndose lateralmente sobre las superficies rocosas. Este tipo de flujo, aunque menos evidente que el goteo, tiene un impacto significativo en las pinturas rupestres al favorecer la redistribución de humedad y la formación de biofilm. Este fenómeno propicia la cristalización de sales y el crecimiento de microorganismos, incrementando el riesgo de biodeterioro en las superficies pintadas. La comprensión de este proceso es crucial para diseñar medidas de control que prevengan la degradación del patrimonio.

Este análisis combinado permitirá comprender mejor los mecanismos a través de los cuales el agua influye en los procesos de deterioro y proporcionará una base científica para desarrollar estrategias de conservación que aborden tanto los procesos de infiltración como los de tensión superficial.

D. Análisis del biodeterioro y actividad microbiana:

El biodeterioro representa una de las principales preocupaciones en la conservación del arte rupestre en la Cueva de Altamira. Diversos microorganismos, incluyendo bacterias, hongos y algas, han demostrado la capacidad de degradar tanto los pigmentos como las capas superficiales de la roca. Este estudio se enfoca en analizar estos procesos mediante técnicas que permitirán una comprensión más profunda del impacto biológico en la conservación del sitio. Se emplearán:

- **Fotogrametría de alta resolución:** Esta metodología será fundamental para documentar el crecimiento y distribución de las colonias microbianas en la superficie de las pinturas. El uso de imágenes de alta resolución facilitará la detección de cambios sutiles en la superficie pintada y proporcionará un registro visual del avance del biodeterioro a lo largo del tiempo.
- **Evaluación del impacto en los pigmentos:** Se correlacionarán los resultados microbiológicos con datos estructurales y geofísicos para evaluar cómo la actividad biológica influye en la alteración de los pigmentos y en la formación de biofilm. Estudios previos han demostrado que ciertas bacterias pueden capturar CO₂ dentro del entorno de la cueva, exacerbando los procesos de disolución de carbonatos y contribuyendo a la inestabilidad del sustrato.
- **Relación con variables ambientales:** Las fluctuaciones en la humedad relativa, la temperatura y las concentraciones de CO₂ son factores clave en el crecimiento de microorganismos. La influencia de estas variables permitirá comprender mejor cómo las condiciones microambientales afectan la proliferación de colonias biológicas y, en consecuencia, el estado de conservación del arte rupestre.

Este enfoque permitirá desarrollar estrategias de control más específicas y efectivas para mitigar el biodeterioro y preservar la integridad de las pinturas.

1.1.4. Relevancia del problema y contribución de la investigación

Este estudio destaca por su capacidad para integrar múltiples metodologías geomáticas y geofísica en un solo modelo de análisis tridimensional, estableciendo un precedente en el campo de la conservación del arte rupestre. A diferencia de estudios previos que han aplicado tecnologías individuales o a lo sumo dos o tres tecnologías combinadas como el LE3D, GPR o UAV, esta investigación combina un rango sin precedentes de frecuencias de radar y datos geomáticos para documentar, de manera simultánea, tanto el exterior como el interior de la Cueva de Altamira.

La aplicación de GPR con múltiples frecuencias —100, 400 y 900 MHz en el exterior; y 400, 900 MHz en modalidad 2D, junto con 1600 MHz y antena dual de 300/800 MHz en 3D en el interior— ha permitido obtener una visión altamente detallada de la estructura interna del macizo kárstico. Esta combinación de frecuencias ha facilitado la detección precisa de discontinuidades, oquedades y zonas de humedad, con una resolución excepcional. La variedad de frecuencias empleadas ha facilitado el análisis de diferentes profundidades y la correlación de datos estructurales con información geofísica, superando las limitaciones de penetración y resolución observadas en estudios anteriores.

Además, el uso de fotogrametría de alta resolución y el LE3D ha permitido generar modelos tridimensionales del techo de la Sala de Polícromos, aportando información crítica sobre la morfología del sustrato rocoso y su evolución a lo largo del tiempo. Estos modelos han revelado el movimiento del agua por tensión superficial en la superficie del techo, un fenómeno asociado a la redistribución de humedades y a la proliferación de microorganismos, contribuyendo al biodeterioro de las pinturas.

El enfoque multidisciplinar de esta tesis doctoral no solo permite evaluar los factores de riesgo de manera integral, sino que también proporciona un modelo replicable para otros enclaves rupestres con características similares. Al combinar tecnologías avanzadas y análisis basados en evidencia científica, Altamira se consolida como un referente internacional en el desarrollo de estrategias de conservación preventiva. La metodología aplicada puede ser adoptada en otras cuevas con problemas de infiltración hídrica, deformaciones estructurales y biodeterioro, estableciendo un nuevo estándar en la gestión sostenible del patrimonio subterráneo.

En el marco del Plan de Conservación Preventiva de la Cueva de Altamira vigente en la cueva, este estudio se alinea con las líneas de acción establecidas para el análisis de variables geomorfológicas y estructurales, más que para el monitoreo continuo de condiciones ambientales. La documentación precisa de la cuenca de captación del techo de la Sala de Polícromos y el análisis de la dinámica hídrica interna han permitido generar nuevas estrategias de gestión sostenible, orientadas a mitigar el impacto de los factores naturales y antropogénicos en la conservación del arte rupestre.

Este estudio no solo profundiza en la comprensión de los procesos de deterioro que afectan a la Cueva de Altamira, sino que también sienta las bases para el desarrollo de

modelos predictivos y protocolos de intervención preventiva más eficaces. La integración de datos geomáticos y geofísicos en un único modelo tridimensional supone un avance significativo en el ámbito de la conservación del patrimonio cultural, al facilitar una interpretación más precisa de las dinámicas internas del macizo kárstico y su impacto en el arte rupestre.

El estado del arte ha puesto de manifiesto que, a pesar de los notables avances en la documentación y conservación de cuevas con arte paleolítico, persisten importantes carencias en la integración de datos geomáticos, microambientales y analíticos en modelos de gestión preventiva. En este contexto, la presente tesis doctoral propone un enfoque metodológico integral y multidisciplinario, orientado a superar estas limitaciones mediante la aplicación de tecnologías avanzadas. Con ello, se busca mejorar sustancialmente la capacidad de análisis, planificación y toma de decisiones, contribuyendo a reforzar las estrategias de conservación a largo plazo tanto en Altamira como en otros enclaves rupestres de valor patrimonial comparable.

1.2. Antecedentes

1.2.1. Evolución de los estudios sobre la Cueva de Altamira

La preservación de la Cueva de Altamira ha sido objeto de análisis ininterrumpidos desde su descubrimiento en 1868, con el propósito de comprender los procesos naturales y antropogénicos que inciden en su estabilidad. A lo largo del tiempo, la evolución de las metodologías utilizadas para documentar y analizar la cueva ha permitido avances significativos en la identificación de factores de riesgo y en el diseño de estrategias de conservación.

Desde los primeros levantamientos topográficos hasta la implementación de tecnologías geomáticas avanzadas en el siglo XXI, la documentación de la cueva ha experimentado una notable transformación. Los estudios iniciales se centraron en la representación cartográfica y la ilustración de las manifestaciones rupestres, mientras que las investigaciones recientes han incorporado técnicas de LE3D, GPS, GNSS, UAV y fotogrametría de alta resolución, lo que ha permitido generar modelos tridimensionales precisos y evaluar la estabilidad estructural de la cavidad con un grado de detalle sin precedentes.

A continuación, se exponen los principales hitos en la documentación y conservación de Altamira.

Siglo XIX: Descubrimiento y primeras exploraciones científicas

- **1868:** Descubrimiento de la cueva por Modesto Cubillas Pérez, marcando el inicio de su estudio y reconocimiento como un sitio de interés arqueológico.
- **1880:** Marcelino Sainz de Sautuola publica *Breves apuntes sobre algunos descubrimientos prehistóricos de la provincia de Santander*, que incluye la primera planimetría de la cueva a escala 1:2000 y un dibujo del techo de los Polícromos.
- **1880:** El diario *El Impulsor* de Santander difunde públicamente los hallazgos de Sautuola, incrementando el interés por la cueva.
- **1880:** José Escalante y González, profesor de instituto, realiza la primera fotografía del techo de los Polícromos, iluminándolo con luz eléctrica mediante baterías. Estas imágenes, actualmente desaparecidas, supusieron un avance en la documentación visual del arte rupestre.
- **1881:** Tras la controversia sobre la autenticidad de las pinturas, el profesor E. Harlé visita la cueva y elabora un croquis detallado de su planta y alzado longitudinal, aportando una visión más técnica y estructurada del sitio.

Siglo XX: Desarrollo de la documentación gráfica y primeras iniciativas de conservación

- **1902:** E. Cartailhac y H. Breuil reproducen mediante acuarelas las figuras de la cueva, fortaleciendo el reconocimiento científico internacional de Altamira.
- **1911:** Publicación de *Les Cavernes de la Région Cantabrique* por E. Cartailhac, H. Breuil y L. Sierra, con una extensa recopilación de ilustraciones y fotografías que consolidan el interés arqueológico de la cueva.
- **1921:** Alberto Corral elabora un plano detallado de la cueva a escala 1:1.250, mejorando la comprensión de su estructura interna.
- **1925:** Instalación de energía y luz eléctrica en la cueva, lo que modificó significativamente sus condiciones microambientales.
- **1935:** H. Breuil y H. Obermaier publican *La Cueva de Altamira en Santillana del Mar*, una obra de referencia con dibujos y fotografías fundamentales para el estudio del arte rupestre.
- **1941:** Gonzalo Bringas documenta las modificaciones estructurales en la Sala de Polícromos, incluyendo la construcción de muros artificiales para limitar el acceso y proteger las pinturas.
- **1959:** Erich Pietsch y el Instituto de Geodesia Aplicada de Frankfurt/Main realizan la primera fotogrametría del techo de los Polícromos, marcando un hito en la documentación tridimensional de la cueva.
- **1962:** Se entrega la primera réplica del techo de los Polícromos al *Deutsches Museum* de Múnich.
- **1963:** Se entrega una réplica idéntica al Museo Arqueológico Nacional de Madrid, permitiendo al público apreciar el arte rupestre sin dañar el original.
- **1975:** La empresa de topografía Foestra, bajo la dirección de Agustín Gómez Obregón, realiza una nueva planimetría y secciones detalladas de la cueva.
- **1977:** El Instituto Geográfico y Catastral, dirigido por Luis Domingo Clavo, implementa un levantamiento topográfico de la Sala de Polícromos mediante técnicas de fotogrametría terrestre.
- **1978:** J.A. Cebrecos realiza un fotomosaico del techo de la Sala de Polícromos con motivo del centenario del descubrimiento de la cueva y sus pinturas, proporcionando una visión gráfica completa del techo decorado.
- **1979:** El Instituto Geográfico Nacional (IGN) lleva a cabo un levantamiento altimétrico del techo de la Sala de Polícromos mediante fotogrametría, mejorando la precisión de los datos sobre su morfología.

- **1981:** La Subdirección General de Arqueología, con Antonio Esteban a la cabeza, realiza un conjunto completo de topografías que contribuyen al conocimiento estructural de la cueva.
- **1981:** El equipo liderado por M. Hoyos, en colaboración con A. Bustillo, A. García, C. Martín, R. Ortiz y C. Suazo, presenta un informe técnico encargado por el Ministerio de Cultura titulado Características geológico-kársticas de la Cueva de Altamira. Este estudio constituye uno de los primeros análisis integrales sobre la morfología del macizo y la dinámica de los procesos de alteración del soporte rocoso en la cueva, sentando las bases para investigaciones posteriores en conservación y geología del karst.
- **1986:** El Proyecto Nacional de Documentación de Arte Rupestre, dirigido por Sergio Ripoll, Fernando Piñón y José Latova (Equipo Norte), ejecuta una exhaustiva campaña de documentación gráfica y topográfica en la cueva.
- **1991-1992:** Manuel Hoyos Gómez publica en los actos de la mesa redonda hispano-francesa de Colombres los resultados de un estudio comparativo sobre los procesos de alteración del soporte y pintura en varias cuevas con arte rupestre del norte de España, entre ellas Altamira. Estas contribuciones destacan la vulnerabilidad del arte paleolítico frente a factores microambientales y geológicos, e introducen por primera vez un enfoque sistemático sobre los riesgos asociados a la condensación, cristalización de sales y proliferación microbiana en entornos subterráneos decorados.
- **1993-1994:** La empresa Proart S.A. realiza una réplica tridimensional del techo de los Polícromos para un parque temático en Isobe-cho Sakazaki (Japón), utilizando los datos de altimetría de 1979 del IGN y la colaboración de los profesores Pedro Saura, Pedro Martínez y Matilde Múzquiz de la Universidad Complutense de Madrid.
- **1994:** En el marco del foro Altamira en peligro, Manuel Hoyos presenta una serie de consideraciones preliminares sobre los riesgos estructurales y ambientales de la cueva, destacando la necesidad de evaluar el macizo mediante técnicas geofísicas. En este contexto, se realizan los primeros estudios de sondeos eléctricos verticales (SEV) y tomografía de resistividad en el entorno de la Sala de Polícromos, con el objetivo de caracterizar el espesor de la cobertura rocosa, detectar fracturas y evaluar la posible conexión entre el exterior y las galerías decoradas. Estos estudios pioneros abrieron el camino para la posterior incorporación de técnicas de GPR en la cueva.
- **1997-1998:** Pedro A. Saura fotografía en detalle el techo de la Sala de Polícromos para su reproducción, capturando con gran fidelidad las condiciones de las pinturas.

- **1998-2000:** El Centro Nacional de Información Geográfica (CNIG), bajo la dirección de Benjamín Piña, Antonio Mañero y Francisco Pascual, realiza trabajos de topografía y fotogrametría para la creación de la Neocueva. Pedro Saura y Matilde Múzquiz, de la empresa TRAGACANTO, se encargan de la reproducción del techo.

Siglo XXI: Tecnologías Avanzadas de Documentación y Conservación

Con el avance de las tecnologías geomáticas, el siglo XXI ha representado un punto de inflexión en la conservación de la Cueva de Altamira. Los proyectos más relevantes incluyen:

- **2012-2014:** Redacción y ejecución del *Plan de Investigación para la Conservación Preventiva y Régimen de Acceso a la Cueva de Altamira*, liderado por la Secretaría de Estado de Cultura y el IPCE, bajo la dirección de Gaël de Guichen. Este plan estableció un modelo pionero de seguimiento basado en estudios geofísicos y sensores ambientales.
- **2013:** Implementación de dos proyectos clave:
 - **Documentación geométrica de la cueva y su entorno**, ejecutada por GIM Geomatics, S.L., bajo la dirección de Vicente Bayarri. Este proyecto utilizó LE3D y GNSS para crear un modelo tridimensional de alta resolución.
 - **Generación de una ortoimagen de alta resolución del techo de los Polícromos**, llevada a cabo por Actividades y Servicios Fotográficos, S.L., bajo la dirección de José Latova. Este trabajo permitió evaluar el estado de conservación y realizar comparaciones históricas de las condiciones del techo.

Estos avances han permitido mejorar la comprensión de la evolución morfológica de la cueva y evaluar los riesgos asociados a procesos de degradación.

1.2.2. Antecedentes en otras cuevas

La conservación de las cuevas que contienen arte rupestre y la documentación de los sistemas kársticos han experimentado una notable evolución gracias a la integración de técnicas geomáticas. Métodos como GNSS, LE3D, UAV, GPR y fotogrametría de alta resolución han permitido generar modelos tridimensionales de gran precisión, evaluar la estabilidad estructural de las cavidades y analizar los procesos de deterioro que afectan a las pinturas rupestres.

A lo largo de los años, múltiples estudios han empleado estas tecnologías de manera combinada para mejorar la documentación y conservación de cuevas. Sin embargo, pocos han integrado simultáneamente las cinco técnicas y ninguno ha logrado una

combinación tan amplia de frecuencias de GPR para documentar tanto el exterior como el interior de una cueva, como en Altamira.

A continuación, se presentan casos representativos en los que se han aplicado mediante la integración de diversas metodologías:

- **Cueva de Lascaux, Francia:** Se utilizó escaneo LE3D y fotogrametría para generar modelos digitales de la cueva, lo que ha permitido su estudio sin intervención directa y facilitado la creación de réplicas virtuales. Esta documentación resultó clave para comprender la evolución ambiental dentro de la cavidad y minimizar riesgos de conservación.
- **Cueva de Chauvet, Francia:** Para estudiar las pinturas de más de 36.000 años de antigüedad, se empleó un enfoque similar al de Lascaux, combinando LE3D y fotogrametría de alta resolución. Estos métodos han permitido analizar las obras sin contacto directo, reduciendo el impacto antropogénico. En esta cueva, además se empleó GPR de 400 MHz para evaluar la estabilidad del techo y las formaciones geológicas internas.
- **Monte de El Castillo, España:** En el Monte de El Castillo se ha llevado a cabo un exhaustivo estudio geomático que incluye vuelos UAV para la modelización del relieve, así como el LE3D de cinco de sus cuevas más representativas. En las cuevas de El Castillo, Las Monedas y La Pasiega, se ha aplicado teledetección hiperspectral combinada con fotogrametría de alta resolución para la documentación del arte rupestre y el análisis del biodeterioro. Esta técnica ha permitido identificar pigmentos no visibles al ojo humano, detectar alteraciones químicas en los soportes rocosos y evaluar la presencia de colonias microbianas, proporcionando información clave para la conservación de los paneles decorados y el desarrollo de estrategias preventivas más eficaces.
- **Grutas de Mogao, China:** En este complejo de cuevas budistas se ha implementado una estrategia de conservación basada en LE3D y fotogrametría, permitiendo la digitalización de los murales sin riesgo de alteración.
- **Cueva Meziad, Rumanía:** Se han utilizado LE3D y GNSS para capturar la complejidad estructural de la cueva con alta precisión, lo que ha permitido adoptar medidas de conservación antes de la realización de excavaciones arqueológicas.
- **Sistema kárstico de Carlsbad Caverns (EE.UU.):** Se aplicaron antenas de 100 MHz para cartografiar el desarrollo de cámaras subterráneas y evaluar el riesgo de colapso en ciertas zonas del macizo.
- **Cueva del Arco, Cieza, España:** Se combinaron los resultados de una antena GPR de 25 MHz y LE3D. La aplicación del GPR con antenas de distintas frecuencias ha permitió detectar cavidades ocultas, fracturas y cambios en la composición del macizo rocoso, proporcionando datos esenciales para la evaluación de la estabilidad estructural de la cueva.
- **Cueva de Praileaitz, España:** Fue objeto de estudios geofísicos empleando antenas de 200 y 400 MHz destinados a evaluar su potencial arqueológico y la

estabilidad del macizo kárstico. Mediante la aplicación de GPR en la entrada principal, se detectaron niveles excavables de entre 6 y 10 metros de profundidad, sugiriendo la presencia de depósitos arqueológicos intactos. Además, en una nueva entrada descubierta en 2014, los estudios indicaron que el espesor de los sedimentos superaba los 10 metros, lo que refuerza la hipótesis de la existencia de restos del Paleolítico superior y del Musteriense.

- **Cueva de Pozalagua, España:** En esta cavidad perteneciente al sistema kárstico de Peñas de Ranero (Vizcaya), se emplearon técnicas de escaneo LE3D y GPR con antenas de 400 MHz para documentar su morfología interna y su relleno sedimentario. Los estudios permitieron establecer la estratigrafía de los depósitos en relación con los cambios climáticos, identificar distintos tipos de sedimentos asociados a procesos de meteorización de la dolomía y a su sistema de fracturación, así como correlacionar la hidrología con las morfologías internas. Además, se propuso un origen geológico común entre la Cueva de Pozalagua y la cercana Torca del Carlista, aportando claves relevantes para la comprensión evolutiva del sistema kárstico regional. El trabajo demuestra la utilidad de la integración entre métodos geomáticos y geofísicos para el análisis estructural y paleoambiental de cavidades.
- **Cueva de la Orquídea, Xalapa, México:** Fue estudiada mediante una antena GPR de 300 MHz para el cartografiado de oquedades subterráneas. Gracias a esta técnica, se ha logrado una caracterización detallada de la estructura interna de la cueva, revelando la disposición de tres cámaras interconectadas y detectando fracturas en el macizo rocoso.
- **Complejo de Atapuerca, España:** Fue objeto de un estudio mediante una antena de 270 MHz para detectar partes desconocidas de las cavidades. La aplicación de esta técnica ha permitido identificar cavidades ocultas, conductos sedimentados y estructuras subterráneas no documentadas previamente, proporcionando información clave sobre la configuración interna del sistema kárstico.

Como han demostrado los antecedentes en otras cuevas, la combinación de tecnologías geomáticas resulta eficaz en la documentación y conservación del patrimonio subterráneo. No obstante, la metodología implementada en Altamira constituye un avance significativo al integrar de manera simultánea cinco técnicas geomáticas además de emplear un rango de frecuencias de GPR sin precedentes, tanto en el exterior como en el interior de la cueva.

Este enfoque innovador establece los fundamentos para un nuevo estándar en la documentación de entornos kársticos y la preservación del arte rupestre, estableciendo un modelo replicable para la gestión de otros yacimientos patrimoniales.

1.3. Resultados de la revisión de la literatura: avances y vacíos de conocimiento

La revisión de la literatura científica ha evidenciado avances significativos en el ámbito de la conservación de cuevas con arte rupestre, así como en el uso de tecnologías geomáticas y geofísicas para la documentación y seguimiento de su estado. No obstante, se han identificado ciertas lagunas en el conocimiento que justifican la necesidad de integrar un mayor número de técnicas geomáticas y frecuencias de GPR para una comprensión más profunda de ciertos procesos de deterioro. Por consiguiente, a continuación se presentan los progresos más relevantes y las áreas donde se requiere mayor investigación.

Avances en la documentación geomática y análisis estructural

El perfeccionamiento de los métodos de documentación geomática ha sido un aspecto fundamental para la conservación del patrimonio subterráneo. Estudios previos han demostrado que la combinación de tecnologías como el LE3D, UAV y sistemas GNSS permite generar modelos tridimensionales georreferenciados de alta precisión, esenciales para el análisis de la estructura del karst y su evolución morfológica.

En cuevas emblemáticas como Lascaux y Chauvet (Francia), se ha empleado LE3D y fotogrametría para documentar el estado de las pinturas rupestres sin contacto físico, minimizando el riesgo de deterioro. En la Cueva de El Castillo (España), la integración de teledetección hiperespectral y fotogrametría ha permitido identificar colonias microbianas y pigmentos invisibles al ojo humano.

Sin embargo, ningún estudio previo ha logrado integrar simultáneamente un rango tan amplio de tecnologías y frecuencias de radar como el planteado en esta tesis doctoral. En el caso de Altamira, se han empleado cinco técnicas combinadas: LE3D, UAV, GNSS, fotogrametría de alta resolución y GPR con frecuencias múltiples (100, 400 y 900 MHz en el exterior; 400, 900 MHz, 1600 MHz y Dual 300/800 MHz en el interior). Esta combinación permite obtener no solo un modelo geométrico completo, sino también una caracterización estructural y ambiental más detallada del macizo kárstico.

Este enfoque representa una innovación metodológica, ya que, hasta la fecha, en otras cuevas, las frecuencias de GPR utilizadas han sido limitadas y no se han correlacionado sistemáticamente con datos microambientales y geofísicos para anticipar procesos de deterioro.

Comprensión de los factores de deterioro y procesos microclimáticos

El estado de conservación del arte rupestre en Altamira está intrínsecamente relacionado con las condiciones microclimáticas internas de la cueva. Variables como la humedad relativa, la temperatura y la concentración de CO₂ influyen directamente en la estabilidad de los pigmentos y en los procesos de disolución de carbonatos.

Estudios previos en otras cuevas, como Chauvet (Francia) y las Grutas de Mogao (China), han demostrado que los ciclos de condensación-evaporación propician la cristalización de sales, afectando a largo plazo la integridad de las pinturas. En Altamira, estas dinámicas se ven acentuadas por la infiltración hídrica desde el exterior hacia el techo de la Sala de los Polícromos, donde el agua se desplaza por tensión superficial y facilita la proliferación de colonias microbianas en las superficies pintadas.

A pesar de estos avances, sigue siendo necesario comprender mejor cómo interactúan estos factores en el largo plazo y cómo el cambio climático podría amplificar sus efectos. Este vacío de conocimiento justifica la implementación de modelos más complejos que integren datos estructurales y microambientales para anticipar y mitigar los procesos de deterioro.

Impacto del cambio climático en la conservación de la cueva

El cambio climático se ha identificado como un factor de riesgo emergente en la conservación del arte rupestre. Las alteraciones en los patrones de precipitación y las variaciones térmicas están afectando la dinámica hidrogeológica de las cuevas, incrementando la infiltración de agua y acelerando la disolución de la roca caliza.

Estudios recientes en el Sistema Kárstico de Carlsbad Caverns (EE.UU.) han mostrado cómo las precipitaciones extremas aumentan el riesgo de colapso en ciertas zonas del macizo. De manera similar, en Altamira, se ha observado que las variaciones en el flujo de agua y la acumulación en las cuencas hidrográficas del techo de los Polícromos incrementan el riesgo de cristalización de sales y deterioro de los pigmentos.

Este contexto subraya la necesidad de desarrollar estrategias de conservación adaptativas, incluyendo:

- Seguimiento hidrogeológico en tiempo real para evaluar los efectos del agua sobre los paneles decorados.
- Sistemas de drenaje pasivo para minimizar la acumulación de humedad en áreas críticas.
- Modelos predictivos que anticipen cambios estructurales en el karst ante escenarios climáticos futuros.

Seguimiento del biodeterioro y actividad microbiana

El crecimiento de microorganismos en las superficies pintadas representa un desafío importante para la conservación del arte rupestre. Bacterias, hongos y algas proliferan en ambientes con alta humedad y acumulación de compuestos orgánicos, degradando progresivamente los pigmentos y la roca soporte.

Las tecnologías implementadas en Altamira ofrecen un enfoque más exhaustivo en comparación con otras cuevas pues integran estudios de fotogrametría de alta

resolución, teledetección hiperespectral y espectrometría Raman en la documentación del arte y por ende de los procesos de biodeterioro.

Estos métodos han permitido no solo identificar los puntos de mayor actividad biológica, sino también correlacionar su evolución con las condiciones microambientales y los flujos de agua por tensión superficial en el techo de los Polícromos.

1.3.1. Desafíos Abordados en la Presente Investigación

Esta investigación ha abordado múltiples desafíos específicos, integrando herramientas geomáticas y geofísicas para evaluar y mitigar los riesgos descritos. Entre las principales innovaciones se encuentran:

- Primera integración simultánea de cinco técnicas geomáticas: LE3D, UAV, GNSS, GPR y fotogrametría de alta resolución para la creación de modelos tridimensionales completos del karst de Altamira.
- Aplicación de GPR con múltiples frecuencias: 100, 400 y 900 MHz en el exterior; 400 y 900 MHz en modo 2D; y 1600 MHz junto con antenas duales de 300/800 MHz en 3D en el interior para una caracterización precisa de las estructuras internas del macizo, incluyendo discontinuidades, estratificación y trayectorias de flujo hídrico.
- Estudio de la cuenca de captación del techo de los Polícromos, identificando el impacto de la tensión superficial y el movimiento del agua en la distribución de humedades y el biodeterioro.
- Protocolo fotogramétrico para el control del crecimiento microbiano y el seguimiento de las alteraciones en los pigmentos.

2. Metodología

Este capítulo presenta una visión general del flujo de trabajo desarrollado en la investigación para el estudio integral de la Cueva de Altamira, basado en la integración de técnicas avanzadas de teledetección geomática. Si bien la metodología específica de cada técnica se describe en detalle en los artículos científicos que componen esta tesis, a continuación, se expone el enfoque metodológico general, incluyendo los objetivos de cada procedimiento, el proceso de integración de datos en un modelo tridimensional unificado, así como los criterios de precisión y validación empleados.

El flujo de trabajo se organiza en una secuencia de etapas interrelacionadas, tal y como se puede apreciar en el diagrama que aparece a continuación, que abordan tres ámbitos principales de actuación: la caracterización vertical y del entorno próximo a la cueva, el estudio del interior de la cavidad, y el análisis detallado de la montera. Todas las tareas se desarrollan a partir de una red geodésica de referencia, lo que garantiza la georreferenciación precisa de los datos y su integración coherente en un modelo tridimensional unificado.

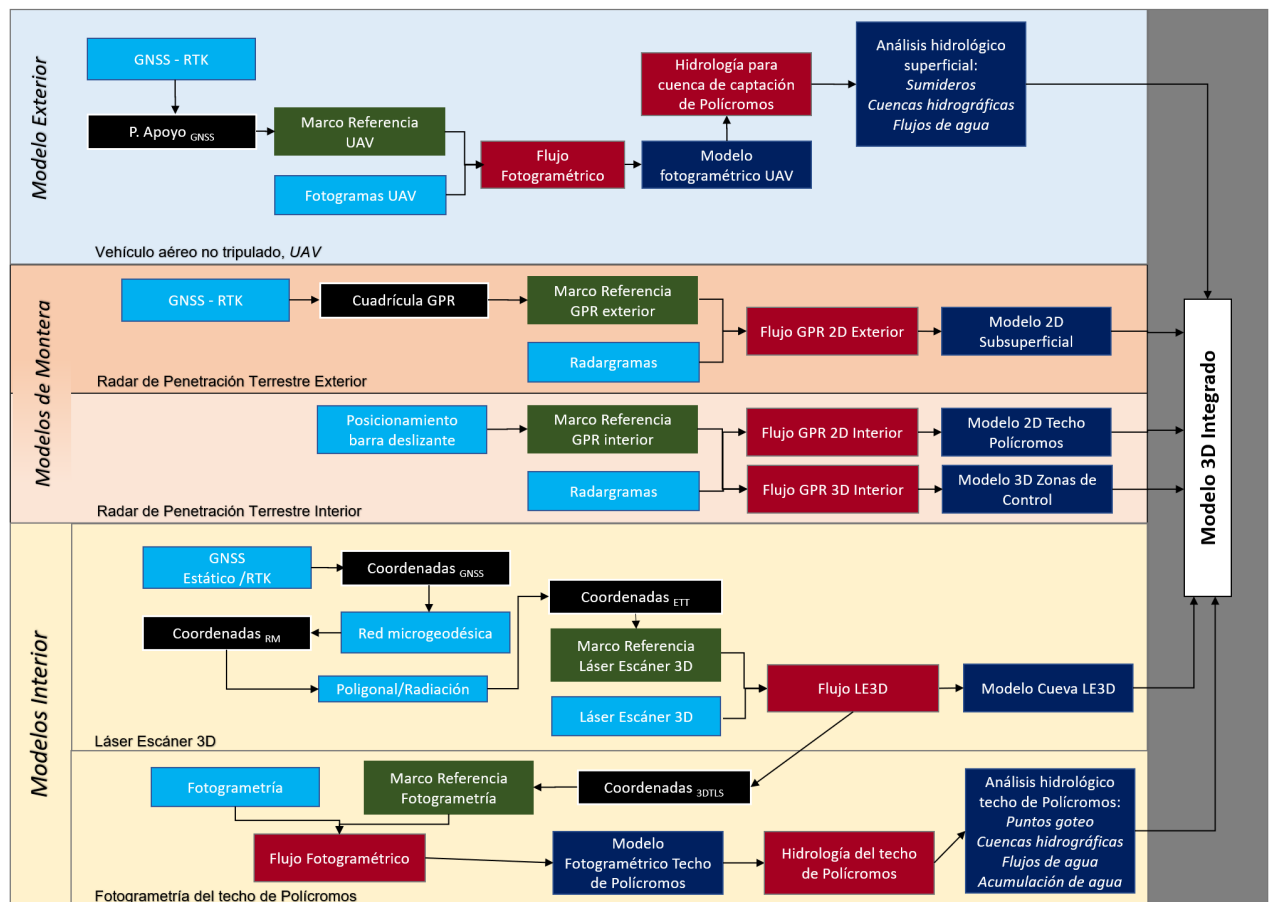


Figura 1: Diagrama de flujo general del procedimiento metodológico aplicado en el estudio de la cueva de Altamira.

Cada parte del proceso se detalla en diferentes publicaciones especializadas según su enfoque específico:

- Para una visión integral de las tecnologías de teledetección y su aplicación en la conservación preventiva del arte rupestre, se recomienda consultar la **Publicación 1**, que describe la integración de escaneo LE3D, UAV, GPR y GNSS en la creación de un modelo tridimensional exhaustivo.
- Los aspectos relacionados con la evaluación estructural del karst y el análisis de las condiciones del techo de la Sala de Polícromos se tratan en la **Publicación 2**, que combina GPR, LE3D y fotogrametría UAV para modelar fracturas y rutas de humedad.
- Los estudios sobre la dinámica de la humedad en el sistema kárstico y su impacto en la conservación de las pinturas rupestres se desarrollan en la **Publicación 3**, utilizando múltiples sensores y análisis de radar.
- La migración de pigmentos y los procesos de deterioro asociados a la infiltración de agua en las pinturas prehistóricas de la Sala de Polícromos se abordan en la **Publicación 4**, donde se emplean GPR y fotogrametría de alta resolución.
- La cartografía de las dinámicas de humedad mediante GPR de múltiples frecuencias y su relación con la conservación de las pinturas se detalla en la **Publicación 5**, proporcionando un modelo replicable para otros sitios patrimoniales.
- Por último, la **Publicación 6** presenta una metodología integral para el seguimiento y control de alteraciones por biodeterioro y procesos fisicoquímicos, utilizando microfotogrametría y LE3D para rastrear cambios en las pinturas y el sustrato rocoso.

A continuación, se presenta un breve resumen de la metodología general y de las principales técnicas geomáticas y geofísica empleadas en esta investigación. Aunque aquí se expone una visión global del enfoque adoptado, la descripción detallada de cada procedimiento, así como los resultados específicos obtenidos, pueden consultarse en los artículos científicos que conforman esta tesis doctoral.

2.1. Establecimiento de redes geodésicas de referencia

2.1.1. Sistema GNSS (*Global Navigation Satellite System*)

Se implementó una red geodésica de referencia precisa en el entorno de la Cueva de Altamira mediante el uso de receptores GNSS estáticos y cinemáticos en tiempo real (RTK). Se utilizaron tres receptores TOPCON Hyper II para definir un marco de coordenadas homogéneo basado en el *European Terrestrial Reference System 1989* (ETRS89), con una precisión media de 1,7 cm, proporcionando una base sólida para integrar datos geoespaciales tanto del interior como del exterior de la cueva.

Este sistema permitió garantizar una ubicación precisa de los puntos de control en el exterior de la cavidad, integrar datos provenientes de otras tecnologías de teledetección geomática y minimizar errores de alineación espacial en el modelo tridimensional final.

2.1.2. Estación Topográfica Total (ETT) y redes microgeodésicas

Dentro de la cueva, donde las señales GNSS no penetran, se observó y ajustó una poligonal con 16 vértices utilizando una Estación Total Topcon GPT-7503 que se cerró con un error angular de 0,0218 g y un error lineal menor de 0,005 m.

Desde las 16 bases de la poligonal se radiaron 66 puntos que se materializaron por clavos o dianas distribuidos por toda la cueva. Dichos puntos se escanearon y modelaron por mínimos cuadrados para generar observaciones de triangulación entre los de cada base. Los lados comunes se promedian ponderadamente y se ajustan formando una red microgeodésica, sirviendo las coordenadas ajustadas de base para la georreferenciación de los escaneos tridimensionales.

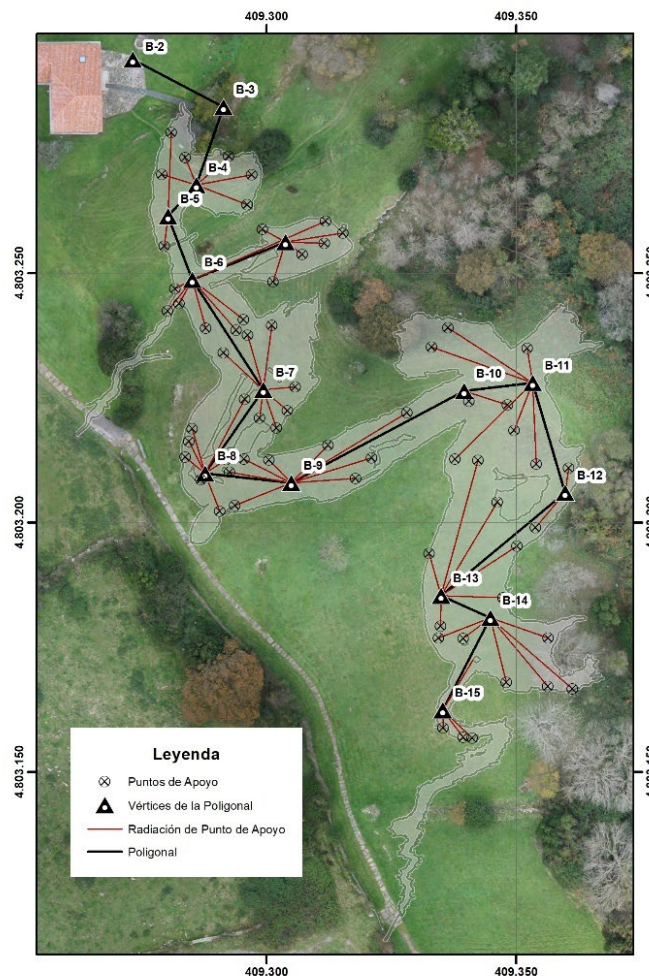


Figura 2: Representación de las bases de la poligonal principal levantada mediante ETT, junto con los elementos radiados desde cada una de ellas.

2.2. Escaneo láser 3D

El LE3D se implementó para documentar con alta resolución la geometría interna de la Cueva de Altamira, con especial énfasis en el techo y las paredes de la Sala de Polícromos. Para ello, se empleó un escáner FARO FOCUS X-130, realizando aproximadamente 300 escaneos distribuidos estratégicamente a lo largo de la cueva. Este procedimiento generó una nube de puntos densa y coherente, alcanzando una precisión de 2,7 mm para el 95 % de los puntos medidos.

El escaneo permitió capturar con detalle la morfología interna de la cueva, tanto el techo y paredes de la Sala de Polícromos, donde se encuentran las pinturas rupestres más sensibles como el resto de la cueva, proporcionando un modelo tridimensional integral del entorno subterráneo.

Los datos recabados fueron empleados para cartografiar fracturas, fisuras y otras irregularidades geométricas significativas, con el propósito de evaluar la estabilidad estructural del macizo kárstico. Asimismo, se utilizaron para identificar deformaciones en el techo que podrían influir en la dinámica de infiltración de agua y la distribución de humedad.

El LE3D, además de constituir la base geométrica precisa para el análisis estructural, también resultó fundamental para integrar datos procedentes de otras técnicas, como la fotogrametría del techo de los polícromos, las campañas de biodeterioro y la posición de las antenas GPR, pues dichos datos se georreferenciaron a partir de las nubes de puntos.

Esta sinergia de datos facilitó la creación de un modelo tridimensional unificado, integrando información geomática y geofísica para comprender mejor las interacciones entre el sistema kárstico, las condiciones ambientales y el estado de conservación de las pinturas rupestres.

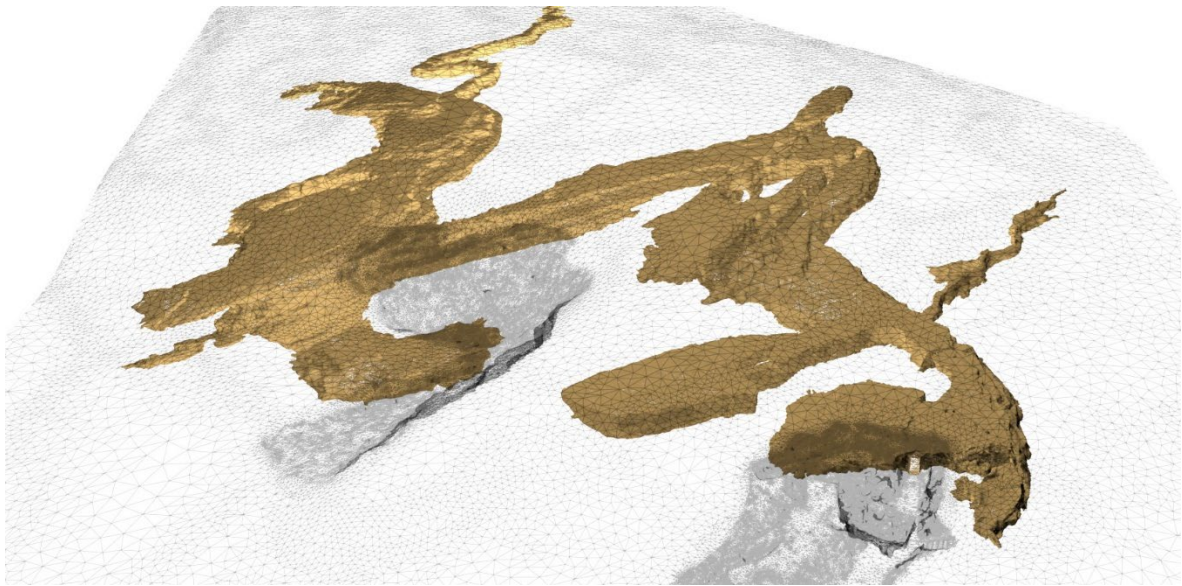


Figura 3: Integración del modelo tridimensional de la cueva con la malla de triángulos generada para la superficie exterior.

2.3. Fotogrametría

2.3.1. Fotogrametría aérea mediante vehículos aéreos no tripulados

Para la caracterización geomorfológica del entorno superficial de la Cueva de Altamira se llevaron a cabo vuelos fotogramétricos con un dron TOPCON Intel Falcon 8+, equipado con una cámara Sony A7R Mark II de formato completo y un objetivo Sony Sonnar T FE 35 mm F/2.8. Esta configuración permitió capturar imágenes de alta resolución con un tamaño de muestreo en terreno (*Ground Sample Distance, GSD*) de 2 cm. En total, se obtuvieron más de 4800 fotografías cubriendo un área aproximada de 40 hectáreas.

Para garantizar la precisión geométrica del modelo, se midieron 52 puntos de control en tierra (GCP) con tecnología RTK-GNSS, y se emplearon otros 40 puntos adicionales para control de calidad, logrando un error medio de 1,76 cm. A partir de estos datos, se generaron ortomosaicos, modelos digitales de superficie (DSM) y nubes de puntos densas, permitiendo la identificación de dolinas, sumideros, fracturas y otros elementos clave del sistema kárstico superficial, así como su posible conexión estructural con las cavidades subterráneas. Los detalles se pueden consultar en la publicación 1.



Figura 4: Modelo fotogramétrico generado a partir de vuelos UAV sobre la montera de la cueva de Altamira.

2.3.2. Fotogrametría terrestre del techo de la Sala de Polícromos

En el interior, se realizaron dos niveles de fotogrametría terrestre para el techo de la Sala de Polícromos:

1. **Fotogrametría general del techo de la sala de Polícromos:** Se realizó una fotogrametría de conjunto del techo decorado, alcanzando una resolución espacial de 200 micras. Este modelo fue georreferenciado a partir de la nube de puntos obtenida mediante escaneo LE3D, lo que permitió integrarlo con el resto de los datos geomáticos y facilitar su análisis en el modelo 3D general de la cavidad.

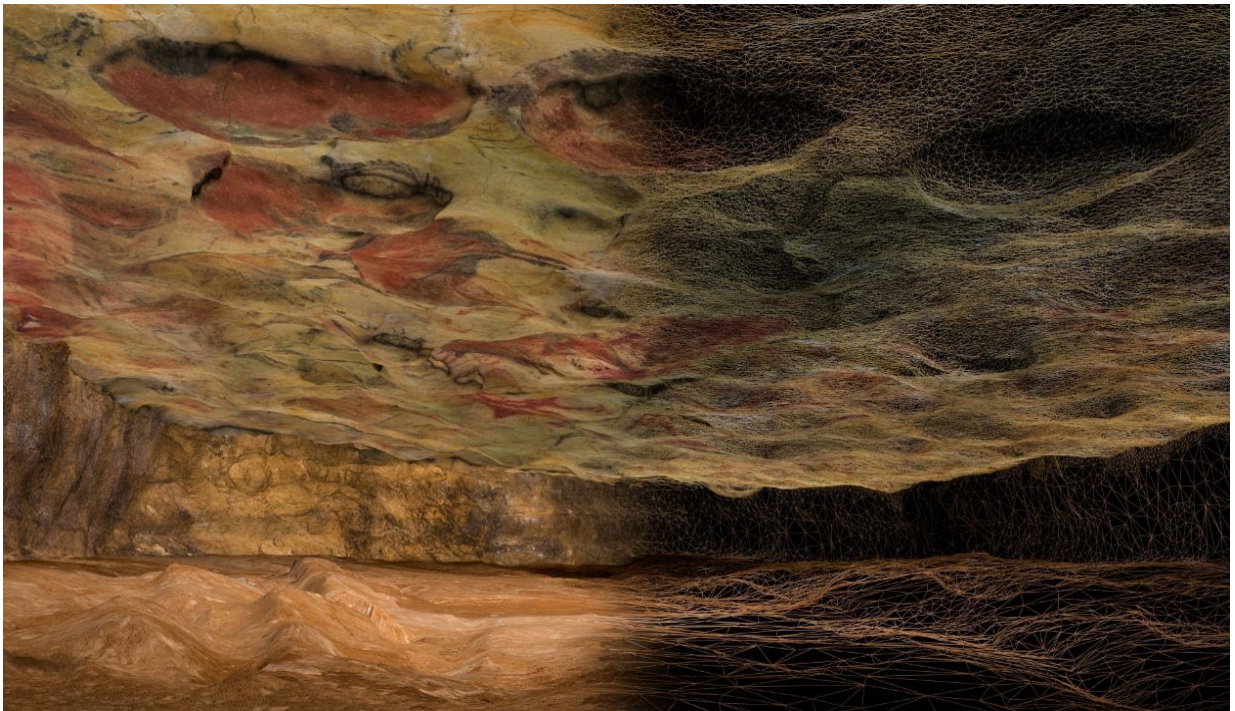


Figura 5: Modelo fotogramétrico de la Sala de Polícromos: a la izquierda, modelo con textura aplicada; a la derecha, representación de la malla empleada en la generación del modelo general.

2. **Fotogrametría de alta resolución para control de biodeterioro:** En áreas específicas, como zonas con crecimiento de microorganismos, se alcanzó una resolución de 50 micras. Esto permitió:
- Detectar manchas, velos microbianos y otras evidencias de biodeterioro con gran detalle.
 - Observar procesos activos como la migración de pigmentos y reacciones físico-químicas en la superficie pictórica.
 - Establecer una base visual comparativa para el seguimiento temporal de los efectos del microclima y la eficacia de las intervenciones de conservación.

A continuación se presenta el diagrama que resume el procedimiento seguido para el control de cambios en el techo de la Sala de Polícromos. Los detalles técnicos y metodológicos completos pueden consultarse en el Artículo 6 de esta tesis.

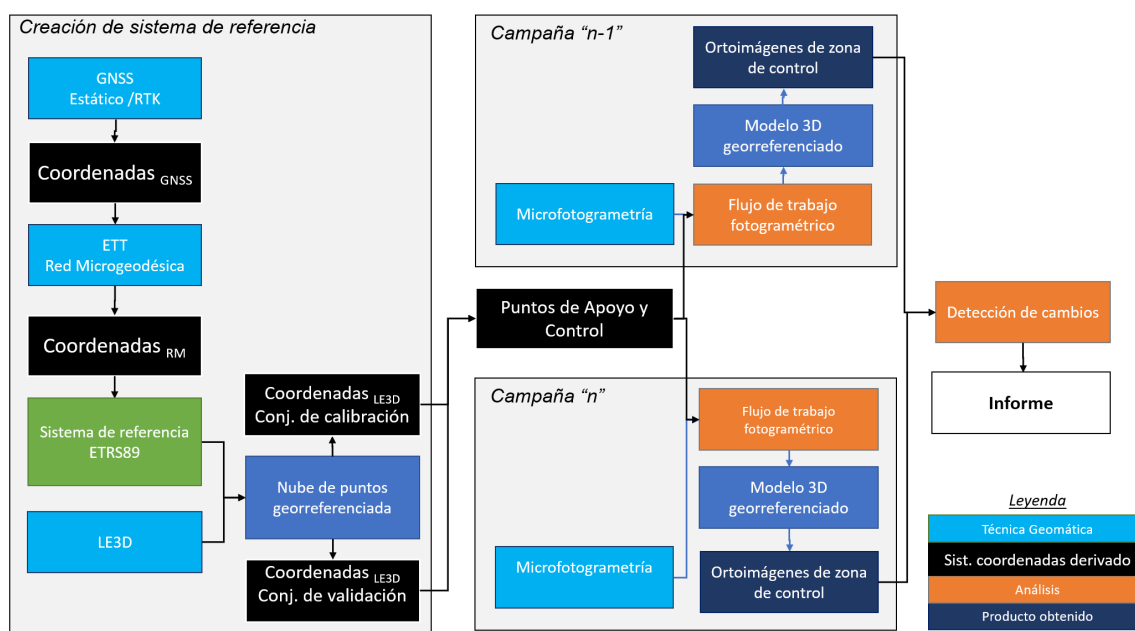


Figura 6: Diagrama de flujo correspondiente a las campañas de seguimiento microbiológico realizadas en la Sala de Polícromos.

2.4. Radar de penetración terrestre

La implementación del GPR en la Cueva de Altamira se concibió con el propósito de investigar la estabilidad estructural, las dinámicas hídricas y las discontinuidades del subsuelo. Para ello, se emplearon antenas de diversas frecuencias en emplazamientos específicos, tanto en el exterior como en el interior de la cueva, con el propósito de obtener una comprensión multiescalar del sistema kárstico y su interacción con el entorno subterráneo. La elección de cada antena se llevó a cabo con el propósito de abordar diferentes profundidades y resoluciones, adecuadas para el análisis de fracturas, rutas de infiltración de agua y la integridad del macizo rocoso. Los detalles se pueden encontrar en los artículos 1, 2 y 3 que componen la presente tesis.

2.4.1. Desde el exterior hacia la Sala de Polícromos

- Antena de 100 MHz:
 - Objetivo: Caracterización de las estructuras profundas del karst, fracturas y discontinuidades principales.
 - Ubicación: Aplicada sobre el terreno kárstico del complejo de la cueva de Altamira.
 - Profundidad y Resolución: Alcanzó una profundidad de hasta unos 6 metros con una resolución a escala centimétrica.
 - Hallazgos: Se cartografiaron fracturas, zonas de despegue y cavidades principales que podrían comprometer la estabilidad general del macizo y su relación con las galerías internas.

- Antena de 400 MHz:
 - Objetivo: Detección más detallada de discontinuidades y flujos de infiltración hídrica.
 - Ubicación: Aplicada en superficie sobre la Sala de Polícromos.
 - Profundidad y Resolución: Alcanzó aproximadamente unos 4 m de profundidad, permitiendo identificar flujos de infiltración de agua que conectan el exterior con el interior de la cueva.
 - Hallazgos: Se detectaron flujos de infiltración que influyen en la dinámica de humedad y en el transporte de nutrientes, esenciales para comprender el deterioro por humedad.
- Antena de 900 MHz:
 - Objetivo: Caracterización superficial de alta resolución en la zona del lapiaz.
 - Ubicación: Utilizada para la capa más superficial donde se desarrolla la zona de lapiaz sobre la Sala de Polícromos.
 - Profundidad y Resolución: Alcanzó una profundidad de aproximadamente unos 2 m con alta resolución, idóneo para detectar discontinuidades a superficie y puntos de entrada de agua superficiales.
 - Hallazgos: Se identificaron puntos críticos de entrada de agua que alimentan la humedad subsuperficial y pueden influir en la conservación de las pinturas.

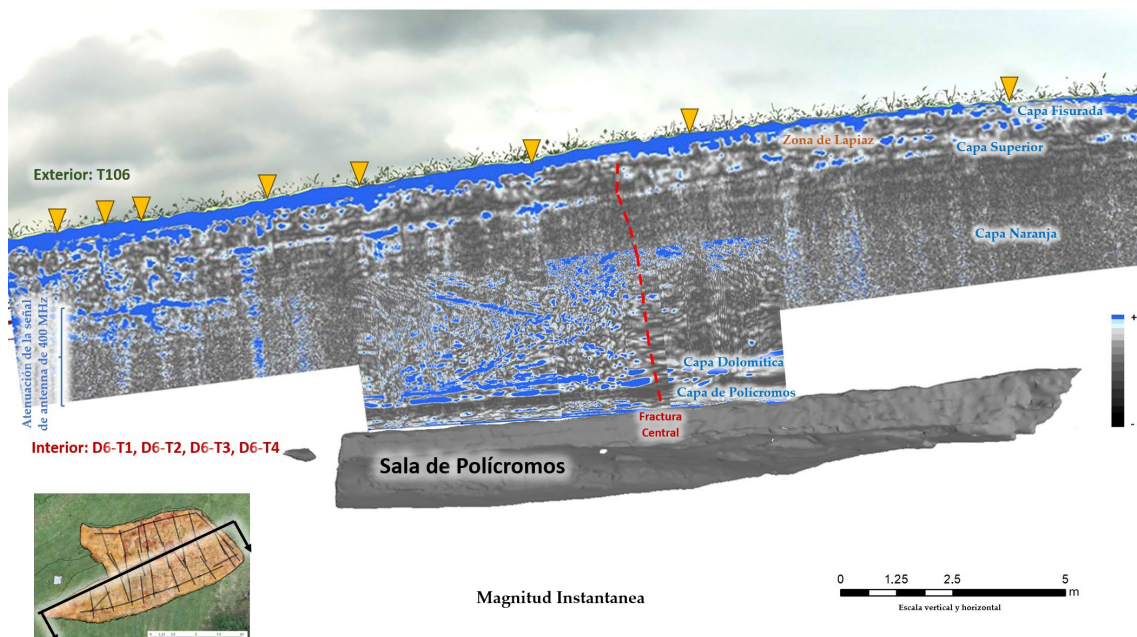


Figura 7: Sección transversal con el atributo de magnitud instantánea derivado de perfiles, que muestra las principales zonas de infiltración de agua o vías de circulación en la capa superior a la Sala de Polícromos. Se observa una fractura central que se extiende desde la zona de lapiaz (capa fisurada) hasta la superficie basal de dicha sala (indicada con línea discontinua roja). Se han marcado los sumideros superficiales que coinciden o se aproximan a la traza de los perfiles (triángulos ocre). También se indican las zonas de atenuación de la señal con la antena de 400

MHz y la correlación entre los perfiles de reflexión y las unidades estratigráficas de la capa superior.

2.4.2. Desde el interior hacia el exterior

Los detalles metodológicos de este subapartado se desarrollan en los artículos 2 y 3 para el caso de las antenas analógicas y los procesados en 2D, y en los Artículos 4 y 5 en lo relativo al procesamiento 3D mediante antenas de 1600 MHz y sistema Dual 300/800 MHz.

- Antenas de 400 MHz y 900 MHz:
 - Objetivo: Caracterizar el estado estructural del techo y las paredes de la Sala de Polícromos.
 - Ubicación: Aplicadas en el techo de la Sala de Polícromos, con perfiles orientados según las principales líneas de fractura.
 - Profundidad y Resolución:
 - La antena de 400 MHz alcanzó unos 4 metros de profundidad, permitiendo la detección de discontinuidades.
 - La antena de 900 MHz proporcionó una mayor resolución para discontinuidades más superficiales, con una profundidad de hasta 1,5 metros.
 - Hallazgos: Se identificaron fracturas y zonas potencialmente inestables, información crucial para la conservación estructural del techo de la cueva.
- Antena Dual de 300/800 MHz:
 - Objetivo: Crear mapas tridimensionales de la distribución de humedad y los flujos de descenso del agua.
 - Ubicación: Aplicada en dos zonas críticas de la Sala de Polícromos, incluyendo el área de control ALT1.
 - Profundidad y Resolución:
 - La frecuencia de 300 MHz permitió una mayor penetración (unos 5 metros) para cartografiar los flujos del agua subterránea.
 - La frecuencia de 800 MHz ofreció una mejor resolución para detectar zonas de humedad más cercanas a las pinturas, con una penetración de unos 2,5 m).
 - Hallazgos: Se observó cómo el agua se desplaza y se acumula en las discontinuidades del macizo rocoso, influyendo en la migración de pigmentos y en el crecimiento de biofilms.

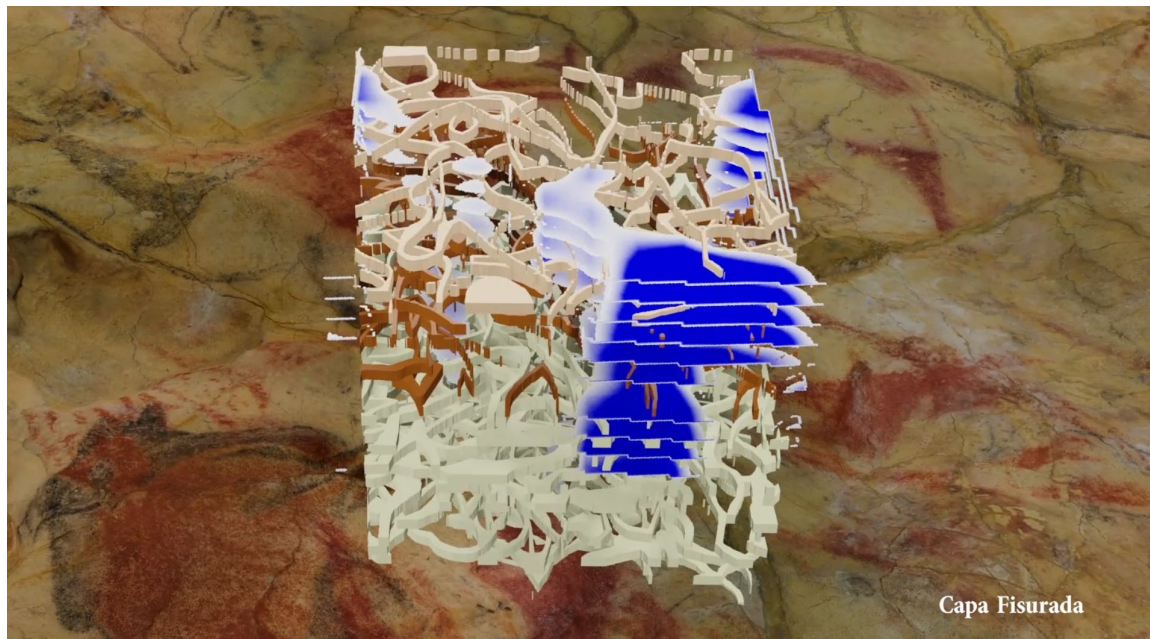


Figura 8: Vista en perspectiva de las discontinuidades que revelan zonas con mayor humedad, representadas mediante un gradiente de color azul a blanco, a través de los diferentes estratos del techo de la Sala de Polícromos. Los datos fueron obtenidos con tres antenas GPR: una de 1.6 GHz para los primeros 50 cm, una de 800 MHz para profundidades de hasta 1.2 m y otra de 300 MHz para profundidades de hasta 4.9 m.

- Antena de 1.6 GHz:
 - Objetivo: Análisis de muy alta resolución de microfracturas y discontinuidades muy próximas a la superficie basal de la capa de Polícromos.
 - Ubicación: Aplicada en el área de control ALT1 del techo de la Sala de Polícromos.
 - Profundidad y Resolución: Alcanzó entre 0,4 y 0,5 metros de profundidad con resolución subcentimétrica.
 - Hallazgos: Detectó fracturas muy próximas a la superficie basal de la capa de Polícromos, complementando la información obtenida con el LE3D y la fotogrametría. De esta manera se pudo analizar las interacciones entre las capas-y los biofilms que afectan a los pigmentos rupestres.

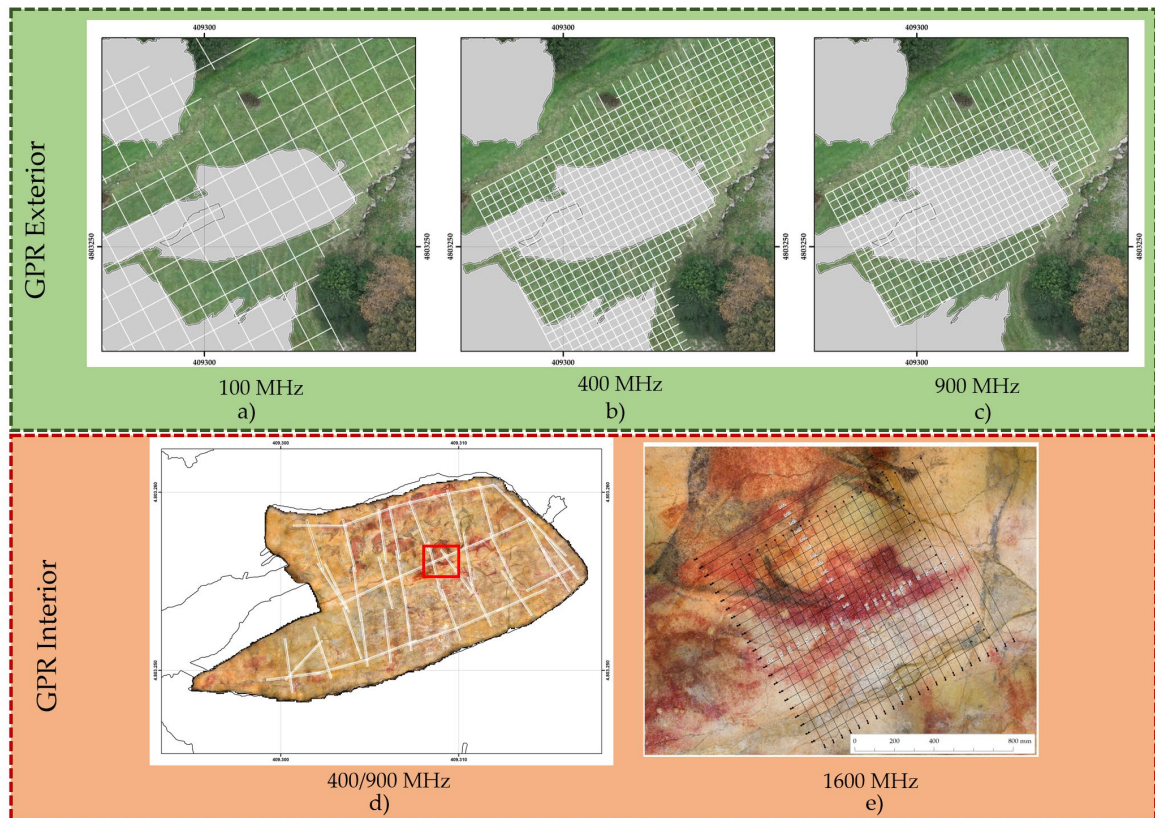


Figura 9: Visión general de los estudios realizados con GPR en la cueva de Altamira y el techo de la Sala de Polícromos: (a) malla exterior de 100 MHz con retícula de 3×3 m, (b) malla exterior de 400 MHz con retícula de 1×1 m, (c) malla exterior de 900 MHz con retícula de 1×1 m, (d) perfiles interiores con antenas de 400 y 900 MHz (indicados con líneas blancas), y localización del área ALT1 (cuadro rojo), (e) malla interior de 1.6 GHz con paso de 5×5 cm.

2.5. Integración y modelado tridimensional

El proceso de integración fue diseñado para abarcar múltiples escalas, desde el entorno kárstico general hasta detalles submilimétricos en áreas críticas, asegurando la fiabilidad en los diferentes rangos de escala.

2.5.1. Proceso de integración del modelo 3D

- Marco de referencia y ajuste geoespacial:
 - Materialización y observación: Se estableció un marco de referencia mediante GNSS y ETT, proporcionando una base georreferenciada precisa para todos los datos geomáticos. Este sistema permitió un posicionamiento exacto de cada elemento dentro del macizo kárstico.
 - Ajuste y alineación: Las nubes de puntos generadas por el LE3D se alinearon con los datos de GNSS y ETT, garantizando la coherencia

espacial de los diferentes niveles de detalle, desde el entorno kárstico general hasta las microfracturas en el techo de la Sala de Polícromos.

- Integración de datos multimodales:
 - Modelos Fotogramétricos: Los modelos fotogramétricos de alta resolución se apoyaron sobre las nubes de puntos del LE3D, permitiendo disponer de un modelo 3D detallado de la superficie rocosa y las pinturas de la sala de Polícromos. Los datos se emplearon para la identificación de alteraciones en los pigmentos y zonas afectadas por biodeterioro.



Figura 10: Modelo fotogramétrico de alta resolución de la sala de Polícromos

- Perfiles de GPR: Los datos de GPR, obtenidos con antenas de múltiples frecuencias (100, 400, 900, 1600 MHz y dual 300/800 MHz), se integraron en el modelo tridimensional para cartografiar la distribución de fracturas, rutas de infiltración y acumulaciones de humedad. La combinación de estos datos proporcionó información sobre cómo el agua se desplaza a través del macizo kárstico y cómo interactúa con las pinturas rupestres.
- Creación de modelos multiescala:
 - Escala General del Sistema Kárstico: El entorno kárstico circundante se modeló a gran escala para evaluar la estructura global y las rutas de

infiltración de agua desde el exterior hacia el techo de la Sala de Polícromos.

- Detalle Submilimétrico en Zonas Críticas: Estos modelos fueron esenciales para analizar microfisuras, humedad superficial y distribución de colonias microbianas. Se puede dividir en dos zonas:
 - Techo de la sala de Polícromos: Se realizó una fotogrametría con un tamaño de píxel de $200 \times 200 \mu\text{m}^2$ para toda su extensión.
 - Zonas de control: De extensiones más reducidas, entorno a 1 m^2 , el tamaño de píxel de estas zonas de especial interés es de $50 \times 50 \mu\text{m}^2$

2.5.2. Resultados del modelo 3D integrado

El modelo tridimensional final generado permite disponer de una herramienta sin precedentes para la gestión y conservación del complejo de Altamira, pues se puede disponer de las rutas de infiltración de agua, zonas de acumulación de humedad y biodeterioro así como de la distribución y profundidad de las principales fracturas.

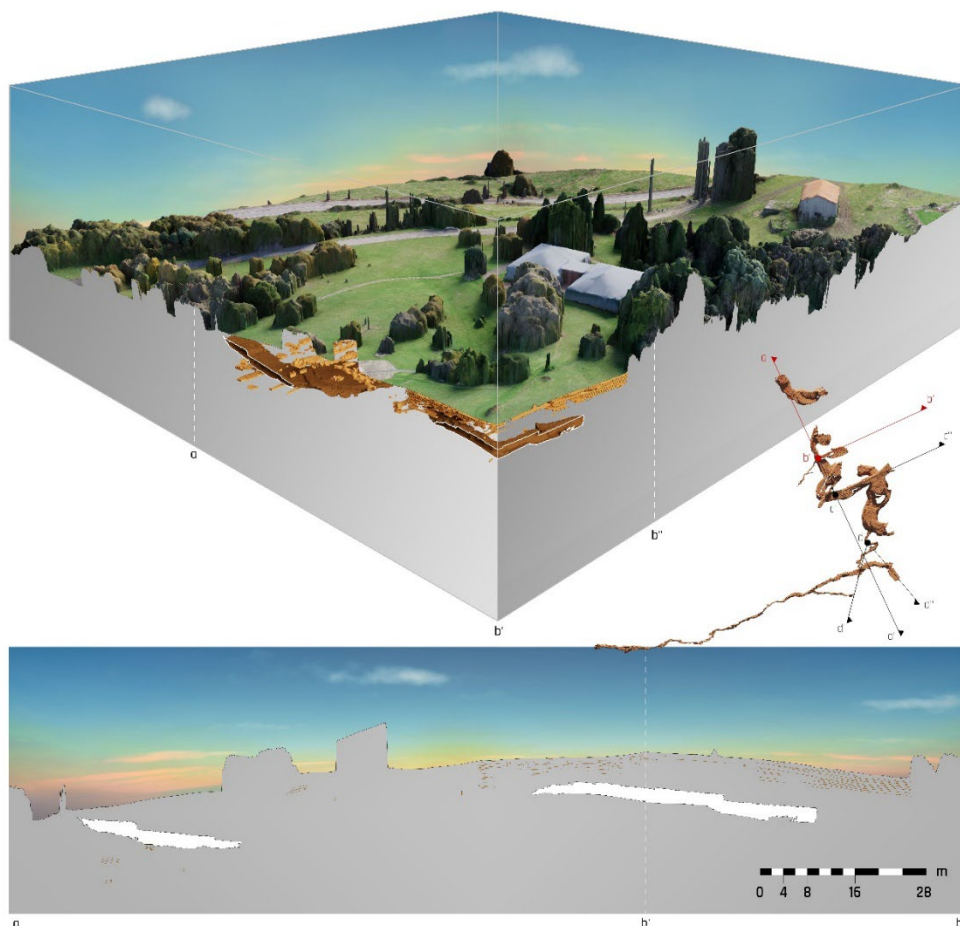


Figura 11: Sección del modelo integrado y desarrollo del mismo de la cueva de Altamira, Estalactitas y la Castañera, con datos procedentes de UAV, LE3D y GPR.

2.6. Análisis y validación de resultados

La validación de los modelos se llevó a cabo mediante un enfoque multidisciplinar que combinó mediciones in situ y diferentes análisis.

2.6.1. Cartografía de flujos de agua y gases

El objetivo de esta cartografía fue representar las rutas de agua y el intercambio gaseoso en diferentes condiciones ambientales. Los resultados indicaron:

- Las rutas de infiltración detectadas con GPR mostraron cómo el agua influye directamente en las dinámicas de humedad dentro de la Sala de Polícromos, afectando los procesos de lixiviación de carbonatos y la migración de pigmentos.
- Se cartografiaron los flujos de aire y gases, revelando patrones de ventilación y condensación estacionales. Estos patrones exacerban el deterioro de las pinturas en áreas específicas, particularmente en el techo y los puntos de goteo identificados, como el área de control ALT1.

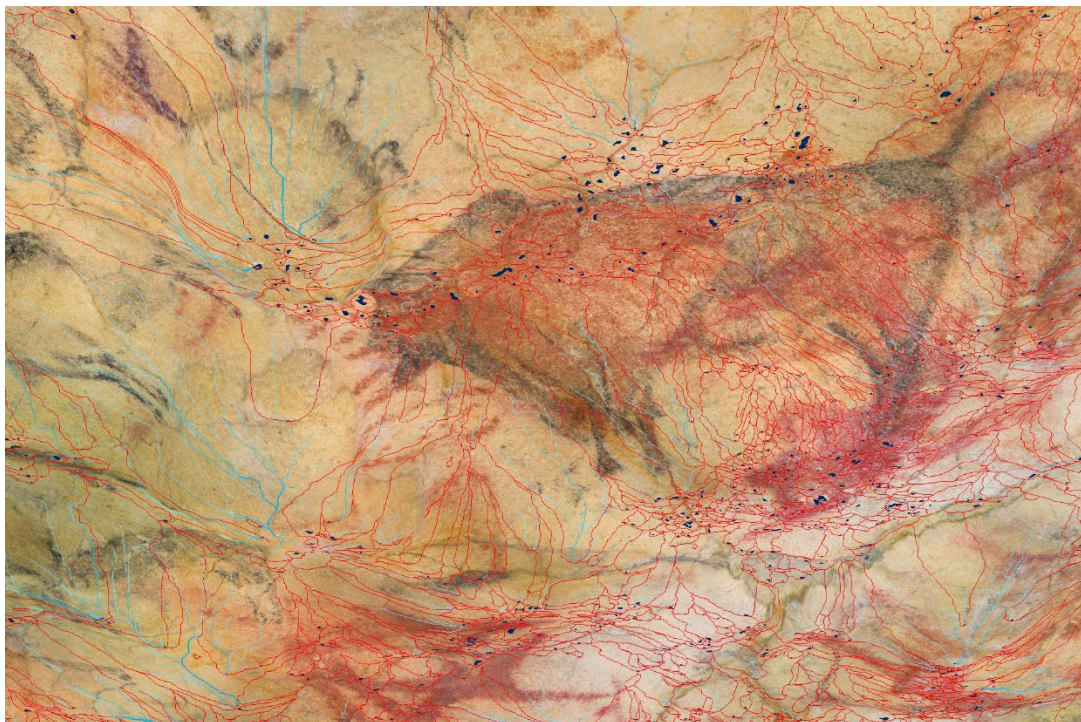


Figura 12: Vista general del modelo 3D de las cuencas hidrográficas del techo (en rojo) de la Sala de Polícromos, mostrando flujos de agua (en azul) y puntos de goteo (en azul oscuro).

2.6.2. Validación mediante observaciones in situ

Se instalaron sensores de humedad y temperatura en puntos estratégicos del techo y las paredes de la Sala de Polícromos para comparar las predicciones del modelo con datos empíricos. Los resultados fueron:

- Los datos validados confirmaron que las áreas con mayor acumulación de humedad coincidían con las rutas de infiltración detectadas mediante GPR y con los puntos de mayor concentración de colonias microbianas.
- La monitorización continua reveló fluctuaciones estacionales significativas en el microclima de la cueva, destacando la necesidad de ajustar el modelo periódicamente para reflejar estos cambios. Durante los meses de invierno (noviembre a mayo), se observó una reducción de la ventilación y un aumento de la concentración de CO₂, mientras que en verano (junio a noviembre) se evidenció el efecto inverso debido a los gradientes térmicos.

2.6.3. Seguimiento del biodeterioro y lixiviación de pigmentos

Se realizó un seguimiento del crecimiento de microorganismos y la lixiviación de pigmentos en el techo de la Sala de Polícromos a través de varias técnicas complementarias:

- **Fotogrametría de alta resolución:** Esta técnica documentó la evolución de colonias microbianas y su correlación con la acumulación de humedad en puntos específicos. Se observó un crecimiento más acelerado en las zonas cercanas a los puntos de goteo activos, como ALT1, donde el agua transportaba nutrientes y provocaba la lixiviación de pigmentos.
- **Modelos de humedad:** Los mapas tridimensionales mostraron cómo las áreas con mayor lixiviación de pigmentos coincidían con las zonas de alta humedad y tensión superficial del agua. Esto incrementó el riesgo de pérdida de pigmentos debido a la acción disolvente del agua rica en CO₂.

2.6.4. Conclusiones del análisis validado

El análisis y la validación de resultados confirmaron que la integración de datos multiescala y multimodales es esencial para abordar problemas complejos en la conservación de Altamira. Entre los hallazgos clave se incluyen:

- **Rutas de infiltración de agua:** Se identificaron claramente las principales rutas de infiltración desde el exterior hacia el techo de la Sala de Polícromos, evidenciando la influencia de las condiciones hidrogeológicas en la dinámica de lixiviación y biodeterioro.
- **Acumulación de humedad y biodeterioro:** Las zonas con mayor acumulación de humedad coincidieron con los puntos de proliferación microbiana, demostrando una correlación directa entre ambos factores.
- **Migración y pérdida de pigmentos:** Las áreas de mayor lixiviación mostraron una pérdida significativa de pigmentos a lo largo del tiempo, destacando la necesidad de implementar estrategias de conservación preventiva específicas en estas zonas.

- **Impacto estacional en el microclima:** Los datos de monitorización indicaron que los cambios estacionales en la ventilación y la humedad relativa influyen considerablemente en la estabilidad del microclima de la cueva. Este hallazgo subraya la necesidad de ajustar las estrategias de conservación según las condiciones estacionales para reducir el impacto en las pinturas rupestres.

Este enfoque multidisciplinar no solo confirmó la exactitud de los modelos generados, sino que también demostró ser una herramienta fundamental para la planificación y ejecución de estrategias de conservación preventiva en la Cueva de Altamira.

3. Publicaciones científicas

Este capítulo presenta un resumen de cada una de las seis publicaciones científicas que conforman el compendio de la tesis. Cada publicación aporta hallazgos clave que contribuyen a la comprensión y conservación del arte rupestre en la Cueva de Altamira, aplicando tecnologías de teledetección geomática para documentar, analizar y monitorear el entorno kárstico y las condiciones estructurales de la cueva. A continuación, se describe el enfoque, métodos y principales resultados de cada estudio:

Publicación 1: Integration of Remote-Sensing Techniques for the Preventive Conservation of Paleolithic Cave Art in the Karst of the Altamira Cave - "Integración de técnicas de teledetección para la conservación preventiva del arte rupestre en Altamira"

Resumen: Esta publicación detalla el diseño y la implementación de un sistema integral de teledetección geomática para el monitoreo de la Cueva de Altamira, combinando escaneo LE3D, UAVs, GPR y GNSS. Los resultados destacan cómo la integración de estos métodos permite la creación de un modelo tridimensional exhaustivo que documenta tanto las características superficiales de la cueva como su estructura geológica. Esta combinación de datos ha permitido cartografiar zonas de riesgo con precisión, identificando áreas vulnerables de intercambio de gases y posibles rutas de infiltración de agua.

Principales Contribuciones:

1. Innovación Metodológica:
 - Integra tecnologías avanzadas como 3DTLS, GPR y UAV para un enfoque multidimensional en la conservación del patrimonio cultural subterráneo.
 - Desarrolla un modelo cartográfico 3D de alta precisión que incluye detalles geológicos y topográficos.
2. Conservación y Gestión:
 - Proporciona datos fundamentales para realizar un seguimiento de procesos de deterioro como biodeterioro y fisuras estructurales.
 - Identifica vías de intercambio gaseoso y flujo de agua, permitiendo una planificación preventiva más efectiva.
3. Resultados Técnicos:

- Creación de mapas que miden el grosor de las capas superpuestas y detectan estructuras como sumideros y fracturas con una resolución milimétrica.
- Detección de discontinuidades clave en la capa superior de la Sala de Polícromos, vinculadas a dinámicas de agua e inestabilidad estructural.

4. Aplicaciones Futuras:

- Establece una base para estudios similares en otros sistemas kársticos con arte rupestre.
- Contribuye a la implementación de estrategias de conservación que minimicen el impacto humano y climático en el patrimonio cultural subterráneo.

Publicación 2: *A Multimodal Research Approach to Assessing the Karst Structural Conditions of the Ceiling of a Cave with Palaeolithic Cave Art Paintings: Polychrome Hall at Altamira Cave (Spain)* - "Un enfoque de investigación multimodal para evaluar las condiciones estructurales kársticas del techo de una cueva con pinturas rupestres paleolíticas: Sala de Polícromos de la Cueva de Altamira (España)"

Resumen: Este artículo aborda la evaluación de las condiciones estructurales del karst sobre el techo de la Sala de Polícromos de la cueva de Altamira, España, mediante un enfoque multimodal que integra tecnologías de teledetección y análisis geomático. Utilizando GPR, LE3D y fotogrametría UAV, los investigadores cartografiaron y modelaron las características estructurales del techo, incluyendo fracturas, fisuras y zonas de humedad.

El análisis reveló que las discontinuidades verticales juegan un papel crucial en el flujo de agua desde el entorno externo hacia el interior de la cueva, un factor determinante en la conservación del arte rupestre. Además, se identificaron patrones en la migración de agua y acumulaciones de humedad que afectan las pinturas prehistóricas. Estas metodologías no invasivas proporcionan información crítica para la conservación preventiva y la gestión patrimonial.

Principales Contribuciones:

1. Metodología Avanzada:

- Integra GPR, fotogrametría UAV y LE3D para generar modelos 3D precisos de la cueva y su entorno.
 - Introduce el análisis de atributos de radar para mejorar la identificación de discontinuidades geológicas.
2. Conservación y Monitoreo:
- Identificación de vías de flujo de agua hacia el techo de la Sala de Polícromos.
 - Evaluación del impacto de la humedad en la estabilidad estructural y las pinturas rupestres.
3. Resultados Específicos:
- Detección de discontinuidades críticas en la estructura del techo que facilitan la infiltración de agua.
 - Modelado de las rutas de migración de humedad para prever posibles daños en las pinturas.
4. Implicaciones para la Gestión Patrimonial:
- Proporciona un marco replicable para la conservación de otras cuevas con arte rupestre.
 - Apoya la toma de decisiones basadas en datos para mitigar riesgos ambientales y estructurales.

Publicación 3: *Multisensory Analysis of the Moisture Course of the Cave of Altamira (Spain): Implications for Its Conservation*" Análisis Multisensorial del Curso de Humedad de la Cueva de Altamira (España): Implicaciones para su conservación "

Resumen: El artículo aborda los problemas de conservación de la cueva de Altamira, un sitio del Patrimonio Mundial de la UNESCO, debido a los efectos de la humedad y el agua en su interior. Utilizando técnicas avanzadas de percepción remota, como el LE3D y el GPR, se evaluaron los flujos de humedad y las vías de infiltración desde el entorno externo hasta el interior de la cueva. Estas herramientas permitieron identificar características críticas como fracturas, fisuras y patrones de infiltración que impactan directamente la estabilidad de las pinturas rupestres de la Sala de Polícromos.

El estudio destaca la influencia de las capas geológicas sobre la dinámica del agua y su impacto en las pinturas, enfatizando la importancia de las fracturas centrales y la infiltración directa de agua en el proceso de conservación.

Principales Contribuciones:

1. Innovación Metodológica:
 - Uso de técnicas de múltiples sensores para cartografiar flujos de humedad en el sistema kárstico.
 - Introducción de transformaciones como la de Hilbert en los datos GPR para analizar la humedad y discontinuidades.
2. Análisis de Factores Críticos:
 - Evaluación del papel de la capa dolomítica en la regulación de la humedad y su impacto en las pinturas.
 - Identificación de las fracturas principales que actúan como canales para la infiltración de agua.
3. Implicaciones para la Conservación:
 - Cartografiado preciso de puntos de goteo que arrastran pigmentos y alteran las pinturas.
 - Identificación de rutas de infiltración para implementar estrategias de mitigación.
4. Aplicaciones Globales:
 - Establecimiento de metodologías replicables para la conservación de sitios similares.
 - Integración de análisis geoespaciales y técnicas de percepción remota en la gestión patrimonial.

Publicación 4: *Remote Sensing and Environmental Monitoring Analysis of Pigment Migrations in Cave of Altamira's Prehistoric Paintings* "Análisis por teledetección y monitorización ambiental de las migraciones de pigmentos en las pinturas prehistóricas de la Cueva de Altamira"

Resumen: El estudio utiliza tecnologías avanzadas de percepción remota, como el GPR y la fotogrametría, para cartografiar y analizar los procesos de migración de pigmentos en las pinturas prehistóricas de la Sala de Polícromos de la cueva de Altamira. Los investigadores identificaron rutas de infiltración de agua que impactan directamente en

la estabilidad de los pigmentos, especialmente en zonas sensibles como el área de control ALT1. Los datos revelaron cómo los procesos de lavado, migración y desprendimiento de pigmentos están vinculados con patrones específicos de humedad e infiltración.

El artículo destaca la importancia de correlacionar los resultados del análisis geoespacial con los factores microclimáticos y antropogénicos, subrayando los efectos adversos de las intervenciones humanas históricas, como el uso de mortero hidráulico en fisuras. La integración de tecnologías no invasivas permite desarrollar estrategias preventivas y sostenibles de conservación para este patrimonio cultural único.

Principales Contribuciones:

1. Avances Metodológicos:
 - Uso de GPR de alta frecuencia y fotogrametría para crear modelos tridimensionales precisos que documentan flujos de humedad e infiltración.
 - Estandarización de metodologías para correlacionar dinámicas de agua con degradación de pigmentos.
2. Conservación Preventiva:
 - Identificación de rutas críticas de infiltración de agua que afectan los pigmentos.
 - Propuestas de soluciones indirectas para revertir procesos de deterioro activos.
3. Resultados Técnicos:
 - Cartografiado de puntos de goteo específicos que contribuyen a la erosión y pérdida de pigmentos en el techo de la Sala de Polícromos.
 - Análisis mineralógico que detalla la composición y vulnerabilidad de los pigmentos de hematita frente a factores climáticos y químicos.
4. Implicaciones para la Gestión Patrimonial:
 - Mejora del entendimiento de las interacciones complejas entre factores ambientales y antropogénicos en sitios con arte rupestre.
 - Base para implementar medidas de conservación que optimicen la sostenibilidad del patrimonio cultural.

Publicación 5: *Tracking Moisture Dynamics in a Karst Rock Formation Combining Multi-Frequency 3D GPR Data: A Strategy for Protecting the Polychrome Hall Paintings in Altamira Cave* - " Seguimiento de la dinámica de la humedad en una formación rocosa kárstica combinando datos de GPR 3D multifrecuencia: Una estrategia para proteger las pinturas policromas de la cueva de Altamira"

Resumen: Este artículo utiliza radares de penetración terrestre de múltiples frecuencias para cartografiar las dinámicas de humedad en la Sala de Polícromos de la cueva de Altamira. Mediante antenas de 1.6 GHz, 800 MHz y 300 MHz, se identificaron características geológicas clave, como fisuras, fracturas y capas sedimentarias que afectan la infiltración de agua y, por ende, la preservación de las pinturas rupestres.

El análisis permitió cartografiar flujos específicos de agua y zonas críticas de acumulación de humedad, vinculadas a procesos de deterioro en los pigmentos debido al transporte capilar y la filtración a través de discontinuidades estructurales. Este enfoque no invasivo proporciona información valiosa sobre la conectividad hidrogeológica del sistema kárstico, lo que permite proponer estrategias de conservación específicas para minimizar el impacto del agua en las pinturas.

Principales Contribuciones:

1. Innovación Técnica:
 - Uso combinado de antenas de múltiples frecuencias para generar modelos tridimensionales de diferentes resoluciones que diferencian estructuras a varias profundidades.
 - Aplicación de transformaciones como la de Hilbert (atributo de magnitud instantánea) para identificar zonas de humedad con mayor precisión.
2. Resultados Críticos:
 - Identificación de fracturas y microcanales que actúan como rutas de infiltración hacia las pinturas.
 - Caracterización de zonas de mayor contenido de humedad que coinciden con puntos de goteo y migración de pigmentos.
3. Conservación Aplicada:
 - Propuesta de estrategias preventivas basadas en el monitoreo de humedad en áreas críticas como ALT1.

- Desarrollo de un modelo replicable para evaluar dinámicas de humedad en otros sitios patrimoniales.
4. Impacto en la Gestión Patrimonial:
- Contribución a la comprensión de las interacciones geológicas e hidrológicas en sistemas kársticos.
 - Establecimiento de una base para políticas de conservación informadas por datos de alta resolución.

Publicación 6: 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 - "Metodología para el Seguimiento y Control de las Alteraciones Relacionadas con el Biodeterioro y los Procesos Físico-Químicos Producidos en las Pinturas del Techo de la Sala de Polícromos de Altamira"

Resumen: Este artículo presenta una metodología integral para monitorear y gestionar las alteraciones relacionadas con el biodeterioro y los procesos físico-químicos que afectan las pinturas rupestres de la Sala de Polícromos en la cueva de Altamira. Utilizando técnicas avanzadas de microfotogrametría y LE3D, se documentaron con alta precisión los cambios en las pinturas y el estado del sustrato rocoso. La metodología permite rastrear dinámicas clave como la migración de pigmentos, el lavado por infiltración de agua y la colonización bacteriana.

El análisis reveló patrones de deterioro asociados con agentes ambientales (agua y CO₂) y factores biológicos (bacterias). Además, se propusieron medidas preventivas como la gestión de la infiltración de agua y el control de condiciones microambientales. Este enfoque destaca la importancia de estrategias no invasivas y proactivas para preservar este patrimonio cultural de valor incalculable.

Principales Contribuciones:

1. Innovaciones Metodológicas:
 - Implementación de microfotogrametría y LE3D para controlar alteraciones a nivel submilimétrico.
 - Desarrollo de un marco replicable para el seguimiento continuo de pinturas rupestres en condiciones dinámicas.

2. Resultados Críticos:

- Identificación de rutas de infiltración de agua responsables de la migración de pigmentos.
- Correlación entre colonización bacteriana y procesos de lavado de pigmentos en puntos de goteo específicos.

3. Conservación Preventiva:

- Propuesta de acciones indirectas como el desvío de flujos de agua para reducir el lavado de pigmentos.
- Estrategias para mitigar la colonización bacteriana mediante el control de la humedad y nutrientes.

4. Impacto en la Gestión Patrimonial:

- Provisión de datos objetivos y cuantificables para informar decisiones de conservación.
- Contribución al diseño de políticas de gestión sostenibles para la preservación de sitios de arte rupestre.

Cada una de estas publicaciones contribuye al objetivo general de la tesis, demostrando la efectividad de las tecnologías de teledetección geomática para documentar y conservar el arte rupestre en la Cueva de Altamira, y proponiendo un modelo de conservación que pueda aplicarse en otros sitios de relevancia cultural.

4. Resultados y discusión

La investigación interdisciplinar en la Cueva de Altamira ha generado una serie de hallazgos significativos sobre la conservación de su arte rupestre paleolítico, destacando el papel central de las tecnologías de análisis y monitoreo para abordar los retos que enfrenta este patrimonio cultural. Los principales resultados arrojados de la presente investigación han sido:

4.1. Evaluación estructural y dinámicas del karst

El estudio inicial sobre las condiciones estructurales del karst subyacente a la Sala de Polícromos reveló que las discontinuidades verticales y las fracturas juegan un papel crucial en la infiltración de agua desde el exterior hacia el interior de la cueva. Este flujo de agua, documentado mediante el uso de GPR, LE3D y fotogrametría UAV, ha permitido identificar áreas críticas de acumulación de humedad que comprometen la estabilidad del techo y las pinturas rupestres. Además, los resultados del modelado 3D han mostrado cómo estas fracturas están relacionadas con la evolución geológica del karst y la dinámica de colapso que afecta a la integridad estructural de la cueva. Este enfoque también ha permitido cartografiar el grosor de las capas superpuestas y determinar las zonas de mayor vulnerabilidad a derrumbes, lo cual resulta esencial para el desarrollo de estrategias de conservación preventiva.

4.2. Dinámicas de humedad y conservación preventiva

Complementando este análisis estructural, el estudio multisensorial de las dinámicas de humedad proporcionó evidencia detallada de los patrones de infiltración y migración de agua, así como de su impacto directo en la preservación de los pigmentos. La combinación de datos obtenidos con GPR y transformaciones avanzadas como la de Hilbert permitió identificar rutas específicas de infiltración, corroboradas con puntos de goteo observados en la Sala de Polícromos. Este estudio también identificó la presencia de zonas de acumulación de agua temporal que generan microclimas locales adversos para las pinturas rupestres. La comparación con modelos anteriores permite una mejor comprensión de los ciclos estacionales de humedad y su relación con el transporte de minerales solubles, que contribuyen a la formación de costras y deposiciones perjudiciales.

4.3. Migración de pigmentos y biodeterioro

Un aspecto clave documentado es la migración de pigmentos en las pinturas, vinculada a la infiltración de agua y los procesos de lavado por capilaridad. El análisis de pigmentos en zonas críticas, como el área ALT1, demuestra que las rutas de flujo de agua están directamente asociadas con la pérdida de pigmentos debido a factores ambientales. La integración de otras técnicas espectrales permitió detectar la composición química de los pigmentos y evidenciar el impacto de la humedad en su estabilidad, incluyendo alteraciones no visibles a simple vista. Además, el seguimiento microambiental revela

que el biodeterioro, facilitado por la alta humedad y la presencia de nutrientes, contribuye significativamente al deterioro de las pinturas. Las bacterias y microorganismos identificados actúan como catalizadores de procesos químicos que erosionan los materiales, afectando tanto a los pigmentos como al soporte rocoso.

4.4. Integración de tecnologías y su impacto

La combinación de tecnologías no invasivas como el GPR de múltiples frecuencias, la microfotogrametría, el LE3D y el análisis hiperespectral ha sido fundamental para generar modelos tridimensionales precisos y detallados del entorno de la cueva. Estos modelos han permitido correlacionar dinámicas ambientales y estructurales con la conservación del arte rupestre. En particular, el uso de GPR de alta frecuencia ha sido clave para cartografiar las rutas de flujo y las zonas de acumulación de agua, mientras que las técnicas de fotogrametría han aportado información crucial sobre los cambios fisicoquímicos en los pigmentos. Esta integración también ha permitido identificar puntos de conexión entre el interior de la cueva y el entorno externo, como fracturas y fisuras que facilitan el intercambio de gases y humedad.

4.5. Propuestas para una conservación sostenible

Los estudios concluyen con recomendaciones para implementar estrategias de conservación sostenibles, como el manejo de la infiltración de agua mediante la desviación de flujos en áreas críticas y el control de las condiciones microambientales para mitigar el biodeterioro. En este contexto, se sugiere la aplicación de barreras geotécnicas y el uso de morteros compatibles que permitan un sellado efectivo sin alterar la dinámica natural del karst. Además, se destaca la necesidad de realizar monitoreos constantes y actualizaciones periódicas de los modelos 3D para anticipar y mitigar los riesgos. La colaboración interdisciplinaria entre geólogos, conservadores, científicos ambientales y especialistas en tecnologías de la información resulta esencial para garantizar la preservación a largo plazo de la Cueva de Altamira.

En conjunto, los seis estudios destacan cómo las tecnologías avanzadas y los enfoques multidisciplinares pueden transformar la manera en que se gestiona y preserva el patrimonio cultural. Estos hallazgos no solo ofrecen soluciones específicas para Altamira, sino que también proporcionan un modelo replicable para otros sitios de importancia histórica y artística, asegurando que este legado cultural se conserve para las generaciones futuras.

5. Conclusiones, recomendaciones y futuras líneas de investigación

5.1. Conclusiones

La investigación realizada en la Cueva de Altamira ha demostrado la efectividad de las técnicas de teledetección geomática para la conservación preventiva del arte rupestre en entornos kársticos complejos. Estas metodologías han permitido abordar problemas de conservación desde una perspectiva integral, cubriendo tanto el entorno geológico como las condiciones microambientales que afectan directamente a las pinturas rupestres. A continuación, se presentan las principales conclusiones derivadas del estudio:

1. Integración multiescala y multidimensional: La combinación de datos obtenidos mediante GNSS, LE3D, fotogrametría, UAVs y GPR ha permitido generar un modelo 3D integrado de alta precisión, que abarca desde la escala del sistema kárstico hasta detalles submilimétricos de las pinturas. Este modelo ha sido fundamental para comprender las interacciones entre las fracturas geológicas, las rutas de infiltración hídrica y los procesos de deterioro biológico y químico en la cueva.
2. Identificación de áreas críticas: El uso de GPR y LE3D ha permitido detectar fracturas activas y zonas de acumulación de humedad que representan riesgos significativos para la estabilidad estructural del macizo rocoso y la conservación de las pinturas rupestres.
3. Seguimiento del biodeterioro: La fotogrametría de alta resolución fue clave para documentar la expansión de colonias microbianas en zonas críticas, así como para rastrear la migración de pigmentos en las pinturas debido a la infiltración de agua. Estos datos han proporcionado una base visual y cuantitativa para evaluar los efectos de las condiciones microambientales sobre el deterioro de los pigmentos.
4. Validación de resultados: Las mediciones *in situ* de humedad y temperatura confirmaron la precisión de las simulaciones de flujos de agua y gases del modelo 3D. La monitorización continua reveló cambios estacionales en el microclima de la cueva, mostrando la necesidad de adaptar las estrategias de conservación a estas fluctuaciones temporales.
5. Eficiencia de las técnicas no invasivas: El uso de técnicas no invasivas, como el LE3D, el GPR y la fotogrametría, ha demostrado ser fundamental para documentar la cueva de manera precisa y exhaustiva sin dañar las pinturas ni el entorno natural. Este enfoque asegura la integridad del sitio y minimiza el impacto de las intervenciones humanas.
6. Establecimiento de un modelo replicable: La metodología implementada establece un modelo replicable que puede ser aplicado en otros sitios de arte

rupestre con características similares, contribuyendo al desarrollo de estrategias de conservación preventiva a nivel global.

5.2. Recomendaciones

A partir de los hallazgos obtenidos, se presentan las siguientes recomendaciones para la gestión y conservación de la Cueva de Altamira:

1. Implementación de un sistema de control continuo:
 - Se recomienda la instalación de sensores permanentes de humedad, temperatura y CO₂ en áreas clave de la cueva para poder modelar las condiciones microambientales de toda la cueva en tiempo real.
 - Integrar estos datos en un sistema de gestión geoespacial que permita alertar sobre cambios críticos que puedan afectar la estabilidad de las pinturas.
2. Mantenimiento y actualización del modelo 3D:
 - Actualizar periódicamente el modelo tridimensional de la cueva con nuevos datos obtenidos mediante técnicas de teledetección, especialmente después de eventos climáticos extremos o intervenciones humanas.
 - Utilizar el modelo para realizar simulaciones predictivas sobre el impacto de diferentes escenarios ambientales.
3. Estrategias de mitigación del biodeterioro:
 - Implementar medidas específicas para controlar el crecimiento microbiano, ajustando los niveles de humedad y aplicando tratamientos no invasivos en áreas afectadas.
 - Establecer un protocolo de inspección regular del techo de la Sala de Polícromos para identificar signos tempranos de deterioro biológico o químico.
4. Control de la infiltración de agua:
 - Analizar la posibilidad de diseño de sistemas de drenaje en el entorno externo del karst para reducir la infiltración de agua en las galerías internas.
 - Realizar intervenciones no invasivas en fracturas y fisuras detectadas como rutas principales de infiltración.
5. Educación y sensibilización:
 - Desarrollar programas educativos para informar al público sobre la fragilidad del arte rupestre y la importancia de las medidas de conservación preventiva.
 - Utilizar visualizaciones basadas en el modelo 3D para comunicar de manera efectiva los riesgos y las acciones de preservación.
6. Colaboración interdisciplinar:
 - Fomentar la colaboración entre geólogos, arqueólogos, biólogos, ingenieros y especialistas en teledetección para desarrollar enfoques más integrales.
 - Establecer redes de investigación internacional para compartir metodologías y resultados relacionados con la conservación del patrimonio rupestre.

5.3. Futuras líneas de investigación

El propósito de la presente tesis doctoral es proporcionar respuestas a una serie de interrogantes fundamentales que contribuirán a una gestión más sostenible y efectiva de la Cueva de Altamira y otros enclaves rupestres de alto valor patrimonial. A pesar de los avances logrados en el campo de la documentación geomática, los análisis geofísicos y los estudios de biodeterioro, aún persisten importantes brechas de conocimiento. Las preguntas abiertas más relevantes que se plantean son las siguientes:

- **Impacto del cambio climático y factores ambientales:**
 - ¿Cómo influirá el cambio climático en la estabilidad estructural y microambiental de la cueva a largo plazo, particularmente ante la intensificación de eventos de precipitación extrema y variabilidad térmica?
 - ¿De qué manera afectará el aumento de CO₂ y la temperatura ambiental a los procesos de disolución de carbonatos y a la infiltración hídrica en el techo de la Sala de Polícromos?
 - ¿Podrían desarrollarse estrategias de conservación adaptativas que mitiguen los efectos del cambio climático sobre las pinturas rupestres y el macizo kárstico?
- **Interacción entre procesos microambientales y biodeterioro:**
 - ¿Cómo interactúan las dinámicas de humedad, temperatura y concentración de CO₂ con la proliferación de microorganismos y el biodeterioro de los pigmentos?
 - ¿Cuál es el papel del agua en movimiento por tensión superficial en la distribución y crecimiento de colonias microbianas sobre las superficies pintadas?
 - ¿Es posible desarrollar estrategias de control microbiológico basadas en cambios microambientales sin alterar el equilibrio natural de la cueva?
- **Dinámica hídrica y estabilidad estructural:**
 - ¿De qué manera afectan las rutas de infiltración hídrica y las cuencas de captación en el techo de Polícromos a la estabilidad estructural del macizo kárstico y al estado de conservación del arte rupestre?
 - ¿Cómo puede contribuir el análisis multiescala del movimiento del agua a comprender mejor los procesos de disolución de carbonatos y cristalización de sales?

- ¿Hasta qué punto los patrones de goteo identificados con GPR y el modelado tridimensional pueden predecir el riesgo de colapso en zonas críticas de la cueva?
- **Integración y modelización predictiva:**
 - ¿Es posible integrar datos de LE3D, GPR, GNSS y fotogrametría en una sola plataforma SIG que permita controlar cambios estructurales y microambientales en tiempo real?
 - ¿Podrían los modelos predictivos basados en inteligencia artificial y aprendizaje automático anticipar zonas de deterioro antes de que el daño sea irreversible?
 - ¿De qué manera se podrían optimizar las estrategias de conservación mediante la simulación de escenarios futuros basados en datos multiescala y multimodal?
- **Conservación preventiva y acceso sostenible:**
 - ¿Qué impacto tiene el acceso humano controlado en las condiciones microambientales de la cueva y cómo puede ser gestionado de manera sostenible?
 - ¿Podrían las estrategias de monitoreo no invasivas proporcionar datos suficientes para mantener el equilibrio entre la conservación y el acceso público limitado?
 - ¿Cómo podrían replicarse los métodos desarrollados en Altamira en otros enclaves rupestres con condiciones geológicas y ambientales similares?

Responder a estas preguntas será crucial no solo para optimizar la gestión y conservación de la Cueva de Altamira, sino también para sentar las bases de nuevos estándares científicos y técnicos replicables en otros enclaves patrimoniales con arte rupestre en contextos kársticos. Estas cuestiones no solo abren vías de investigación específicas, sino que orientan el desarrollo de metodologías avanzadas que permitirán anticipar escenarios de riesgo, mejorar las estrategias de conservación preventiva y reforzar el enfoque interdisciplinar en la protección del patrimonio subterráneo. Es por ello que, a partir de los desafíos identificados, se proponen las siguientes líneas futuras de investigación:

1. Análisis predictivo del cambio microambiental:
 - Ampliar las simulaciones del modelo 3D para incluir proyecciones de largo plazo sobre los efectos del cambio climático en las condiciones internas de la cueva.
 - Desarrollar modelos basados en inteligencia artificial para prever patrones de deterioro y evaluar la efectividad de diferentes estrategias de mitigación.
2. Optimización de las técnicas de teledetección:

- Investigar el uso de nuevas tecnologías, como el escaneo láser aerotransportados (LiDAR) y sensores hiperespectrales, para mejorar la resolución y eficiencia de la documentación.
 - Evaluar la aplicación de sensores portátiles para realizar mediciones en tiempo real durante inspecciones de campo.
3. Transferencia de metodología a otros sitios:
- Aplicar las técnicas desarrolladas en Altamira a otros enclaves de arte rupestre para validar su eficacia en contextos diferentes.
 - Comparar los resultados obtenidos en distintos sitios para identificar patrones comunes y ajustar las estrategias de conservación.
4. Estudios de interacción biológica y química:
- Profundizar en el análisis de la interacción entre los microorganismos presentes en la cueva y los pigmentos rupestres.
 - Desarrollar tratamientos que minimicen el impacto de estas interacciones sin alterar la composición original de las pinturas.

En conjunto, estas conclusiones y recomendaciones resaltan la importancia de adoptar un enfoque multidisciplinar, tecnológicamente avanzado y adaptativo para garantizar la preservación a largo plazo del arte rupestre de Altamira y otros sitios patrimoniales similares.

6. Bibliografía

A continuación, se presenta una recopilación de las fuentes y referencias académicas utilizadas a lo largo del estudio, incluyendo las publicaciones científicas que conforman el compendio de la tesis, estudios de conservación de patrimonio, y literatura sobre las tecnologías de teledetección empleadas.

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7. Publicaciones

Publicación 1: Integration of Remote-Sensing Techniques for
the Preventive Conservation of Paleolithic Cave Art in the
Karst of the Altamira Cave



Article

Integration of Remote-Sensing Techniques for the Preventive Conservation of Paleolithic Cave Art in the Karst of the Altamira Cave

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Abstract: Rock art offers traces of our most remote past and was made with mineral and organic substances in shelters, walls, or the ceilings of caves. As it is notably fragile, it is fortunate that some instances remain intact—but a variety of natural and anthropogenic factors can lead to its disappearance. Therefore, as a valuable cultural heritage, rock art requires special conservation and protection measures. Geomatic remote-sensing technologies such as 3D terrestrial laser scanning (3D TLS), drone flight, and ground-penetrating radar (GPR) allow us to generate exhaustive documentation of caves and their environment in 2D, 2.5D, and 3D. However, only its combined use with 3D geographic information systems (GIS) lets us generate new cave maps with details such as overlying layer thickness, sinkholes, fractures, joints, and detachments that also more precisely reveal interior–exterior interconnections and gaseous exchange; i.e., the state of senescence of the karst that houses the cave. Information of this kind is of great value for the research, management, conservation, monitoring, and dissemination of cave art.

Keywords: cultural heritage; rock art; geomatics; data processing; 3D terrestrial laser scanner; global navigation satellite systems; UAV photogrammetry; ground penetrating radar; cultural management; mapping



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1. Introduction

Recently, remote-sensing techniques have been used for underground cultural heritage sites to improve traditional documentation such as terrestrial photogrammetry [1–4], to create orthoimages series and virtual reality scenarios [5–9], and in the case of hyperspectral remote-sensing, to recover rock-art paintings invisible to the naked eye or covered by calcite, dirt, or soot [10–16], which are themselves helpful for understanding the stratigraphy of the rock art panel [17–20].

From a remote-sensing viewpoint, caves are characterized by particular conditions, such as complex access, confined spaces, high humidity, constant temperature, absence of natural light, a potential relationship between the interior and the exterior, etc. [4,21].

Separately, photogrammetric unmanned aerial vehicle (UAV) flights can provide accurate terrain models [22,23], 3D terrestrial laser scanner (3D TLS) surveys provide detailed and correct cave models, while ground-penetrating radar (GPR) provides information on the particularities of the rock mass under investigation.

It is the combined use of these tools that enables the generation of new cartographic information on the features of cave karst complexes, such as rock thickness, fractures, joints, sinkholes, cave seepage, water dripping, stability analysis, and gaseous exchanges, which are valuable for conservation studies of the cave.

The Altamira Cave is an exceptional cultural heritage site that is internationally recognized as a masterpiece of History of Art, being added to the UNESCO World Heritage List in 1985. It is in Santillana del Mar (Cantabria) and is 296 m long, widening in some areas, such as the Polychrome Hall. It is the first cave in which the existence of rock art from the Palaeolithic period was identified (Figure 1).

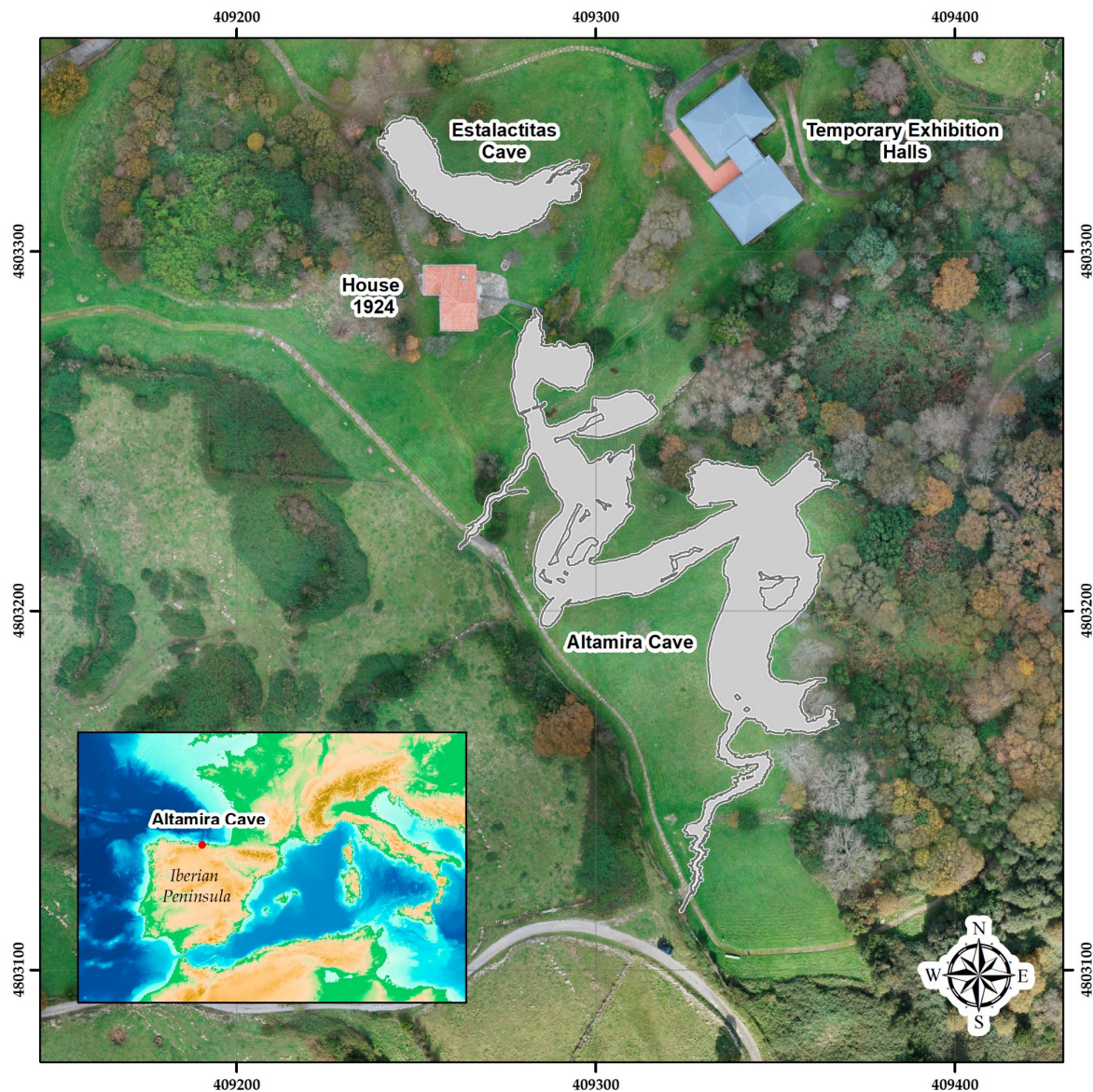


Figure 1. Location map and the surroundings of Altamira Cave. The cave is located in Santillana del Mar, Cantabria, Spain.

The cave was discovered in 1868, while the cave art was discovered in 1879 by Marcelino Sanz de Sautuola and his daughter María. The authenticity of the cave paintings was accepted by the scientific community in 1902 [24,25]. It has paintings and engravings that were made from over 35,000 years ago to 14,000 years ago, among which the set of polychrome bison stands out.

Since its discovery, it has been the object of special conservational attention and care. It is in the upper part of an ancient karst (Figure 2a) that has a tendency to disappear by collapse and subsidence: due to the tabular structure of the limestone and the steep slope of the fracture planes, the geological evolution of Altamira is more marked by a series of gravitational collapses of the limestone rock layers than by the circulation of water [26].

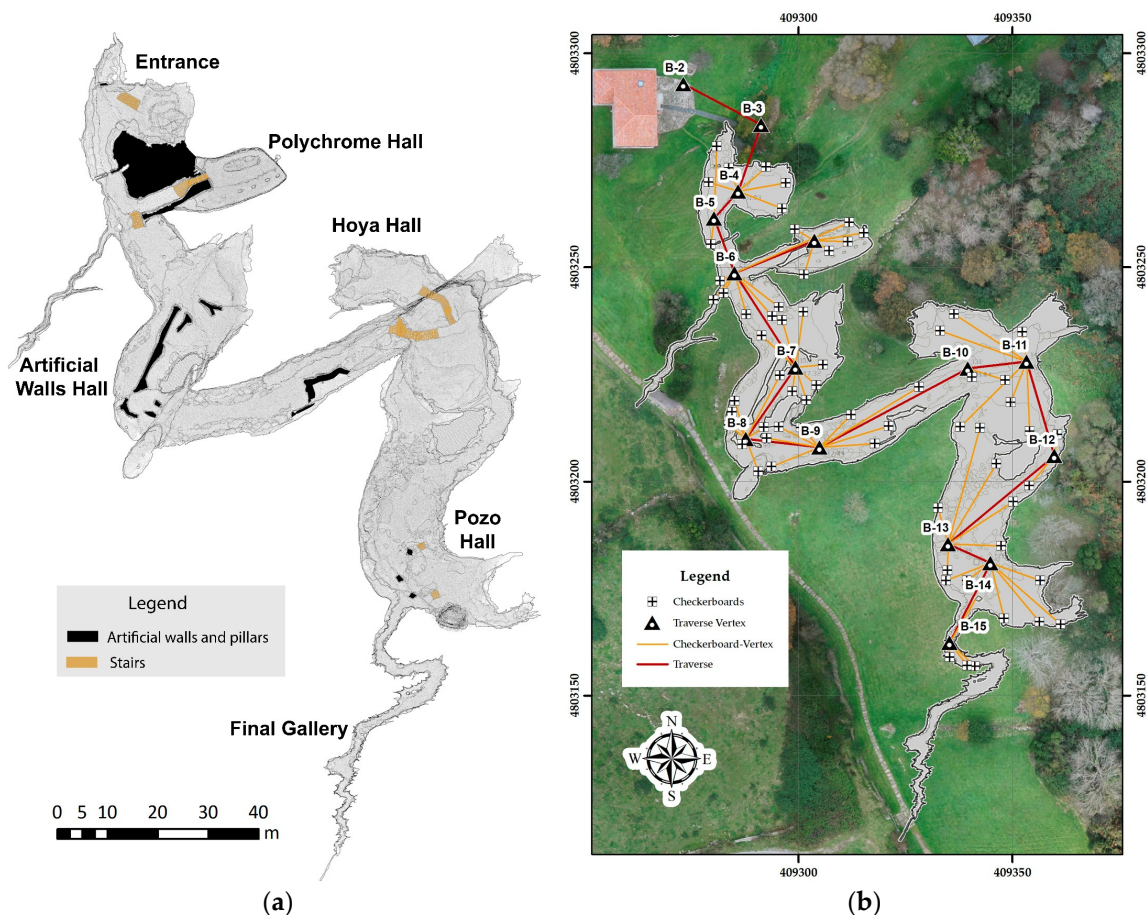


Figure 2. (a) Map of the interior of the Cave including gallery names, artificial walls, pillars, and stairs. (b) Map of the traverse and reference checkerboards, including the traverse station from which they radiate.

The first writings in the local and national press reported the existence of collapses throughout the cave. Faced with this structural instability in some parts of the cave at the beginning of the 20th century, important transformations were proposed, such as the raising, in the vestibular area, of a large stone wall to act as a support for the strata of the ceiling, which was threatening to collapse. This intervention, which definitively isolated the Polychrome room from the rest of the cavity, has generated some of the micro-environmental conservation problems that continue to this day. Subsequent interventions focused on trying to reverse the infiltration of rainwater through the network of fissures and fractures in the cave, which is the main problem for the conservation of the paintings. Artificial walls were built inside the cave (Figure 2a), some cracks were filled with hydraulic mortar, and a layer of Portland cement was spread over the exterior surface [27].

The current state of conservation of Altamira results from structural geological problems due to the accumulation over time of multiple transformations and micro-environmental disturbances. Refurbishment works, changes in the external and internal soils, archaeological excavations, mass visits, and other activities have generated conservation conditions different from those that the cave had before its discovery, where its substantial conservation

was caused by its low water infiltration rate and its stable microclimatic conditions, the latter being caused by its natural closure [28].

The most worrying factors in the conservation of the Altamira cave concern deterioration processes related to geological structural stability and infiltration water, as well as biodeterioration and human presence. To understand their dynamics and to minimize the alterations generated by them, it is necessary to develop effective conservation strategies aimed at controlling the different agents of deterioration. The water that enters the cave through the network of fissures and fractures in the overlying layer plays an important role in the processes of dissolution and dragging of the supporting rock. The processes of microcorrosion, loss of adhesion, cracking, washing, and loss of support are worrying and are still active today.

Knowing and studying the underlying dynamics of these processes hypothetically associated with the destruction of paint at Altamira is essential to design strategies to control each alteration agent and the interactions between them.

The aim of this research was to improve the understanding of the karst system surrounding Altamira Cave by combining remote-sensing technologies for its preventive conservation, thus contributing to decision-making for its management.

An exhaustive and combined study of remote-sensing techniques was carried out, after which we performed 3D cartography to integrate the exterior, the inner topography of the cave, and the main discontinuities and karst features detected around. As we will show, this 3D integrated mapping is a crucial tool for monitoring the main fluid flows into the cave and other conservation purposes.

In the paper, Section 2 shows the data sources integrated to carry out the study, i.e., GNSS in different operational modes, 3DTLS for the geometrical characterization of the cave, a UAV flight to model the terrain, and GPR for the overlying layer. Each subsection describes the accuracies achieved with each method. Section 3 shows the results obtained from integrating two or more techniques and how to visualize them. Finally, Section 4 contains the discussion.

2. Materials and Methods

Caves with rock art are formed by the dissolution of limestone rock by slightly acidic water, which may involve processes of chemical and geological activity, tectonic forces, and atmospheric influences. They are irregular in shape and variable in extent, so it is necessary to integrate different georeferenced remote-sensing techniques to derive new cartographies and generate new information on the cultural heritage element [29].

The flowchart that follows first required the creation of a reference frame, which was observed using the static mode of GNSS, obtaining an average error of 1.7 cm at the vertices. This reference frame was observed and adjusted as a microgeodetic network, obtaining an average accuracy of 1.1 cm in the determination of vertex coordinates.

The UAV flight was georeferenced by GNSS in RTK mode. Fifty-two control points were taken throughout the area and 40 points were taken to validate the model. The result of the validation points was an error of 2.1 cm in planimetry and 2.8 cm in elevation.

The GPR grids were staked using GNSS in RTK mode. To keep the direction constant, a canvas was attached to each grid. From these efforts, the three models were generated and then integrated to be analyzed as a whole (Figure 3).

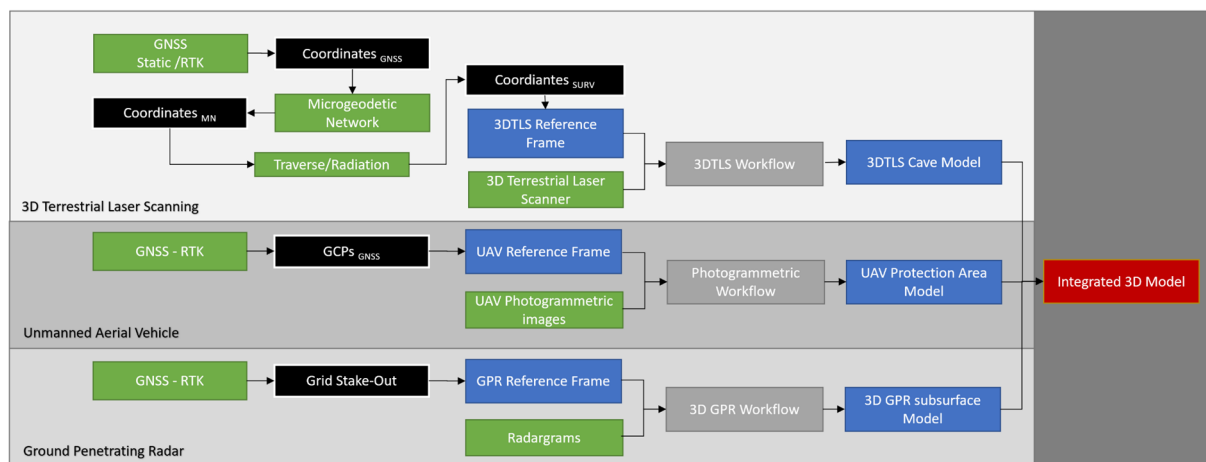


Figure 3. General workflow scheme followed in this study.

2.1. Global Navigation Satellite System (GNSS)

GNSS (Global Navigation Satellite System) refers to the set of satellite navigation system technologies that provide geospatial positioning with autonomous global coverage.

The origins of GNSS date to the 1970s with the development of the US military GPS (Global Positioning System), which, through a network of satellites, a GNSS receiver can determine its position in four dimensions (longitude, latitude, altitude, and time) [30].

In September 2013, a network of points was created using three TOPCON Hyper II [31] receivers simultaneously, 2 of which were moved to other vertices after 1 h of observation to create the reference frame, which was the beginning of the traverse of the cave. The geodetic reference system used to create the reference frame was the European Terrestrial Reference System 1989 (ETRS89).

The software Topcon Tools [32] was used to calculate observed phase changes to form the differencing observation equations, perform the least-squares adjustment, and output the adjusted baseline vector components. The mean accuracy of the reference frame was 1.7 cm.

GPR grids were staked out by using the Real Time Kinematic (RTK) mode. The RTK positioning technique is based on the carrier solution of the signals transmitted by the global navigation satellite systems GPS; in our case, Glonass and Navstar. A reference station provides instantaneous corrections for mobile stations, which brings the obtained accuracy to the centimeter level. The base station retransmits the phase of the carrier it measured, and the mobile units compare their own phase measurements with that received from the reference station. This lets the mobile stations calculate their relative positions with millimeter accuracy, with their absolute relative positions being related to the base station coordinates. This technique requires the availability of at least one reference station with known coordinates that has a GNSS receiver and a radio transmitter modem. The station generates and transmits differential corrections for the stations, which use the data to precisely determine their positions [33,34].

2.2. 3D Terrestrial Laser Scanning

Having an accurate cartographic model of a cave is important when knowledge-based prediction models need to be estimated from georeferenced parameters such as microbiological, climatic, hydrochemical, geomorphological, etc. that are highly correlated either between them or with what happens in the exterior [18].

Starting from a vertex of the reference frame “b-2” (Figure 2b), a closed traverse back-and-forth was made that was adjusted and compensated through the cave using a TOPCON GPT-7503 total station [35]. Sixteen traverse stations were needed, and the total length was 430 m. The angular closure error was 0.0218°, and the linear closure error was $X = -0.001$ m, $Y = -0.005$ m, $Z = 0$.

A total of 66 checkerboards distributed around the cave were radiated from the vertices of the traverse; these are the reference system of the 3D laser scanner, on which the scans are georeferenced. (Figure 2b).

The field campaign was carried out in December 2013; a FARO FOCUS X-130 [36] was used, and 300 scans were required. Calibrated spheres were used as tie points and the traverse checkerboards as references, which were adjusted with an accuracy of 2.7 mm for 95% of the points (Figure 2a) [37].

This new model updated the traditional values of the Altamira cave, which are as follows:

- Length: 296.5 m (20 longer)
- Area: 11,390.9 m²
- Volume: 9372.7 m³

The 3D model enabled us to obtain, apart from the classical cartographies of plant and section planes, other cartographies such as the height of roofs, floors, and galleries.

2.3. Unmanned Aerial Vehicle

Currently, the use of drones for surveying and mapping work is widespread. Drones allow surveys of large areas to be carried out with high reliability in a shorter time than using traditional techniques such as Topographic Total Stations (TTS) and GNSS. UAVs make it possible to obtain something fundamental for our model, which is to have continuous, sufficiently precise information of the entire work area, including places that are difficult to access: in our case, the sinkholes [38–40].

The platform selected for the execution of the photogrammetric flights was a TOPCON Intel Falcon 8+ Drone [41], on which a Sony A7 R Mark ii full-frame camera [42] was mounted with a Sony Sonnar T* FE 35 mm F/2.8 lens. The flights were carried out with the flight-planning system in a simple and fast way.

To reach a ground sample distance (GSD) of 2 cm, the flight-planning system was used to obtain measurements throughout the entire cave environment (40 Ha). More than 4800 pictures were taken, 52 Ground Control Points (GCP) were measured with RTK-GNSS to reference the flight, and another 40 points were measured for quality control. The mean error of the control points was 1.76 cm.

This allowed us to obtain 2D information such as orthoimages, 2.5D information such as a Digital Surface Model, which was filtered to remove trees to obtain a Digital Elevation Model (DEM), and 3D information such as point clouds and a 3D model of the whole area. The 3D model of the cave environment (40 Ha) was created at a definition of 12 million triangles textured with 8 textures of 8192 × 8192 pixels (Figure 4), while the model of the area next to the cave (4 Ha) was created with 4 million polygons and 4 textures of 8192 × 8192 pixels, which is the model we used for integrating the rest of the data. Both models were exported to .Obj, a geometry definition file format, to be integrated with other data.

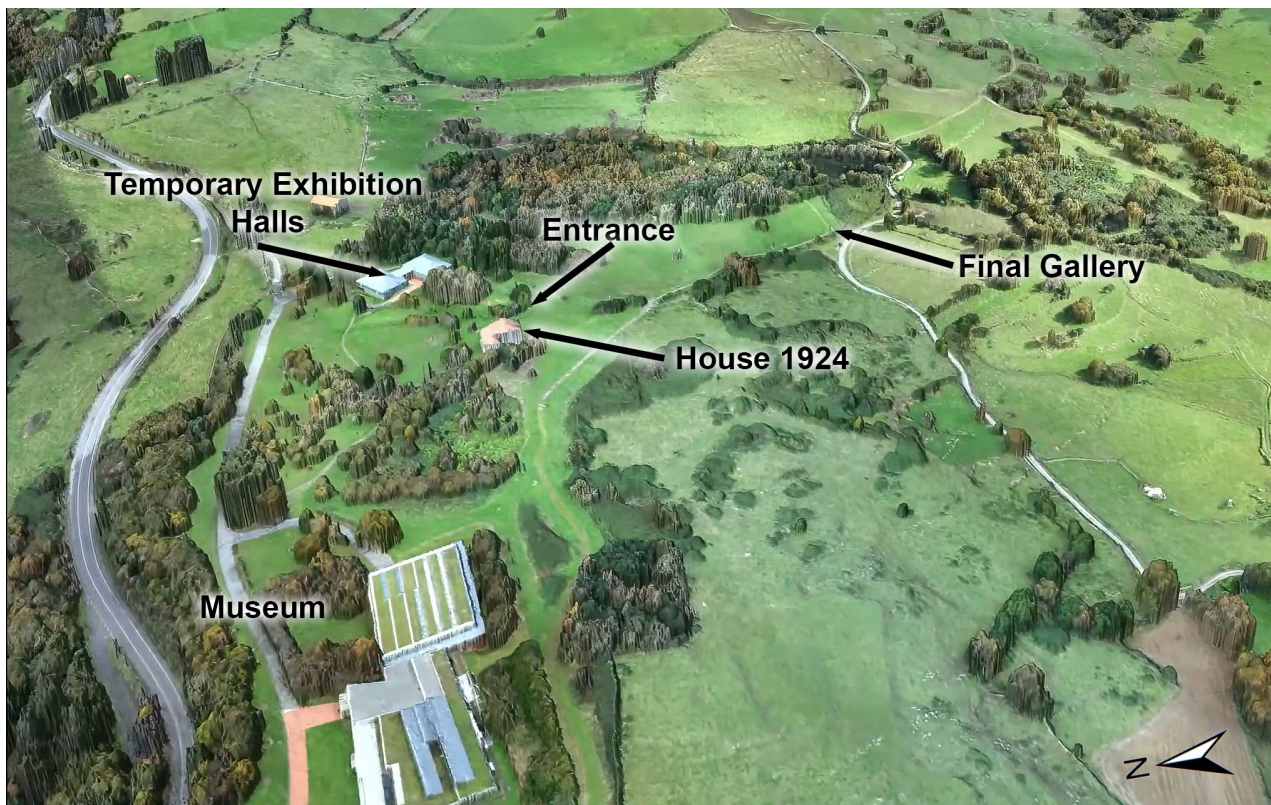


Figure 4. View of the 3D model derived from UAV photogrammetric flight of the surroundings of Altamira Cave.

2.4. Ground-Penetrating Radar

Ground-Penetrating Radar (GPR) is commonly used in the investigation of the internal structure of rock masses, which are generally defined as mechanically discontinuous, anisotropic and heterogeneous environments [43–45]. GPR provides continuous, high-resolution information on the internal structure of a rock mass and its physical properties in both vertical and lateral directions [46–49]. The data recorded with the GPR (radargrams) depend on the transmission of the electromagnetic wave in the medium and the amount of energy reflected, diffracted, or critically refracted by the medium. Therefore, the propagation of a wave depends on the electromagnetic properties (magnetic permittivity, electrical conductivity, and dielectric permittivity) of the medium through which it is transmitted and the contrast of these electromagnetic properties with those of other media.

In a rock-mass survey, GPR is used to map discontinuities, mainly fractures, joints, cavities, detachments, and bedding planes [50–54]. To study the features of a karstic system, the GPR technique is useful for mapping and assessing rock discontinuities [55–60].

2.4.1. Field Data Acquisition

It was necessary to collect data from the whole site of the Altamira Cave and its surroundings. A three-dimensional (3D) GPR methodology was carried out to pinpoint and define the existence and geometry of the main discontinuities and fractures in the karst system where the cave is located. One feature of GPR surveying is the inevitable decrease in resolution with depth. The frequency of the antenna is a crucial choice. Different resolutions and penetration depths can be achieved using antennas with different nominal center frequencies: higher resolution and shallower penetration depths are typically obtained with higher frequency antennas, while deeper penetrations and lower resolution are achieved with lower frequency antennas [61,62]. A commercial GPR equipment SIR-3000 (GSSI) was used for the study. In this study, we present the results of three GPR grids.

- In order to pinpoint discontinuities and karst structures in deep layers, a 100 MHz nominal center frequency antenna was used for the area in and around Altamira Cave. The 100 MHz antenna was able to penetrate to depths of about 10 m in the study area, and a centimeter resolution could be achieved [63,64]. The design of the GPR profile grid mainly took into account the dimensions and directionalities of a series of karst structures and faults, in some cases extending over more than half a kilometer, mapped in previous studies in the Altamira Cave area [65,66]. Therefore, a profile grid for GPR data acquisition was designed with equidistant 2D orthogonal lines, spaced every 3 m, with respect to a longitudinal axis that was, in turn, perpendicular to the main fracture directions in the Altamira Cave area, as described in these previous studies. Every 2D profile line was topographically georeferenced by GNSS (Figures 5 and 6).



Figure 5. The location of GPR profile grid (orthogonal 2D profiles spaced every 3 m) in the Altamira Cave site, carried out with the 100 MHz antenna.

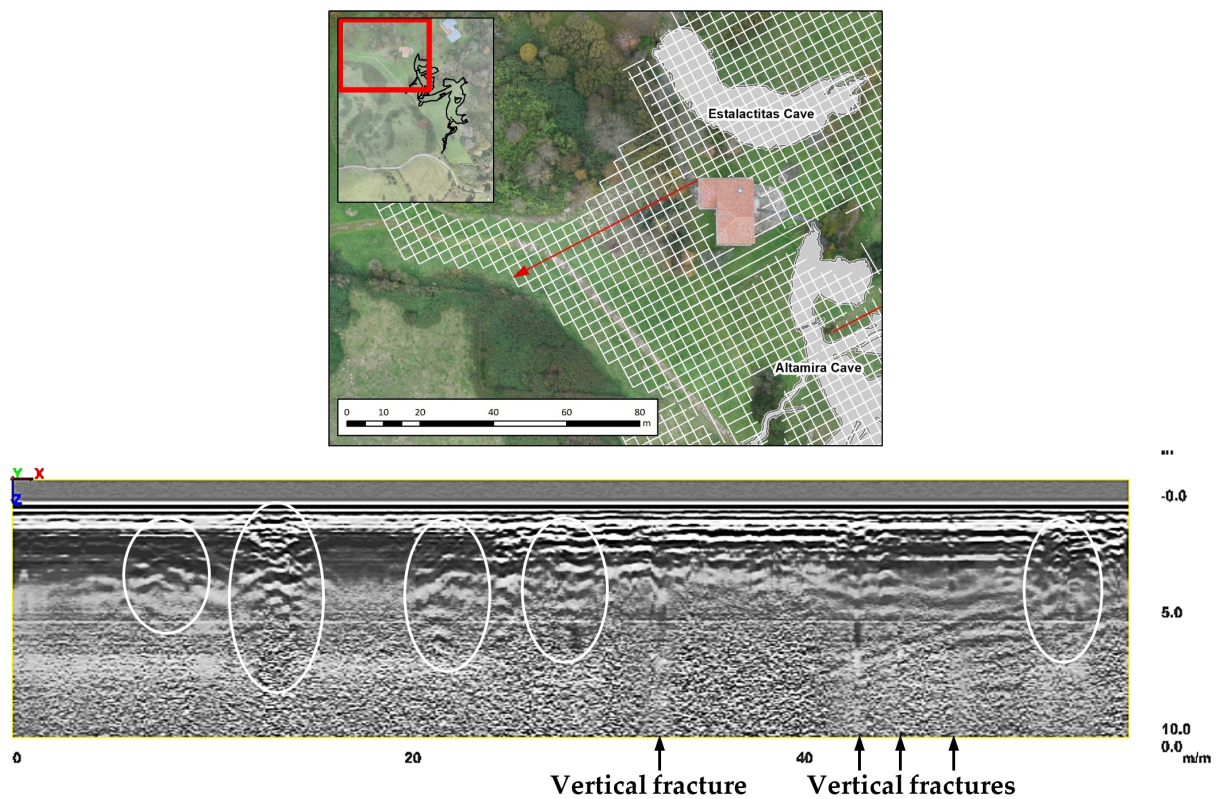


Figure 6. Radargram recorded with the 100 MHz antenna. Profile Z2-85 above shows discontinuities in the rock mass: several sinkholes (indicated by white ovals) and vertical fractures. This radargram also shows the attenuation of the electromagnetic wave in the last meters of depth.

- Due to the importance of the cave paintings on the Polychrome Hall ceiling for the Cave of Altamira, it was considered necessary to study the first meters of its overlying rock strata and its lapiés area in greater detail and at a higher resolution. Two GPR profile grids were planned in the Polychrome Hall area:
 - A profile grid for the study of its strata in the first meters using a 400 MHz nominal center frequency antenna to identify discontinuities and karst structures. The 400 MHz antenna was able to penetrate to depths of about 4 m in the study area, with centimeter resolution [67].
 - A profile grid for the study of its lapiés zone using a 900 MHz nominal center frequency antenna to define the lapiés groove system. The 900 MHz antenna was able to penetrate to depths of about 1.5 m in the study area with a centimeter resolution [68].

These two grids were designed according to the extensive system of lineaments in the exterior and interior of Altamira Cave, mainly in the form of joints and with predominant directions N45, N68, N110, N168, and N-S [69]. Accordingly, both profile grids for GPR data acquisition were designed with equidistant 2D orthogonal lines, spaced every 1 m, with respect to a longitudinal axis that was, in turn, perpendicular to the main joints directions in the Polychrome Hall area, as described in the aforementioned previous study. Every 2D profile line was topographically georeferenced by GNSS (Figures 7 and 8).

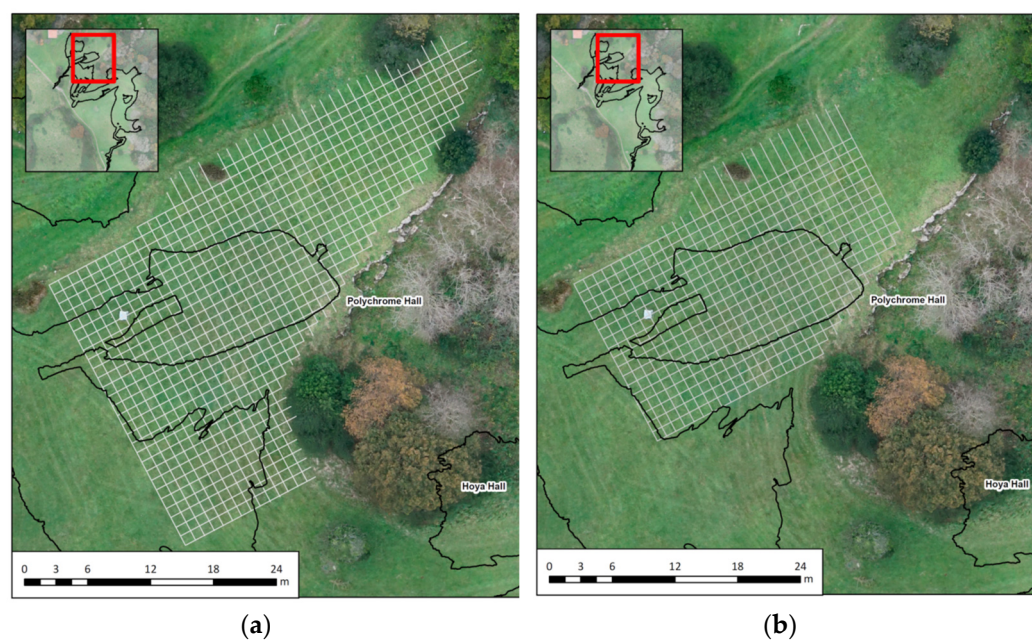


Figure 7. The location of GPR profile grids (orthogonal 2D profiles spaced every 1 m) in the overlying rock strata and the lapiés zone of the Polychrome Hall ceiling, carried out with the (a) 400 MHz and (b) 900 MHz antennas.

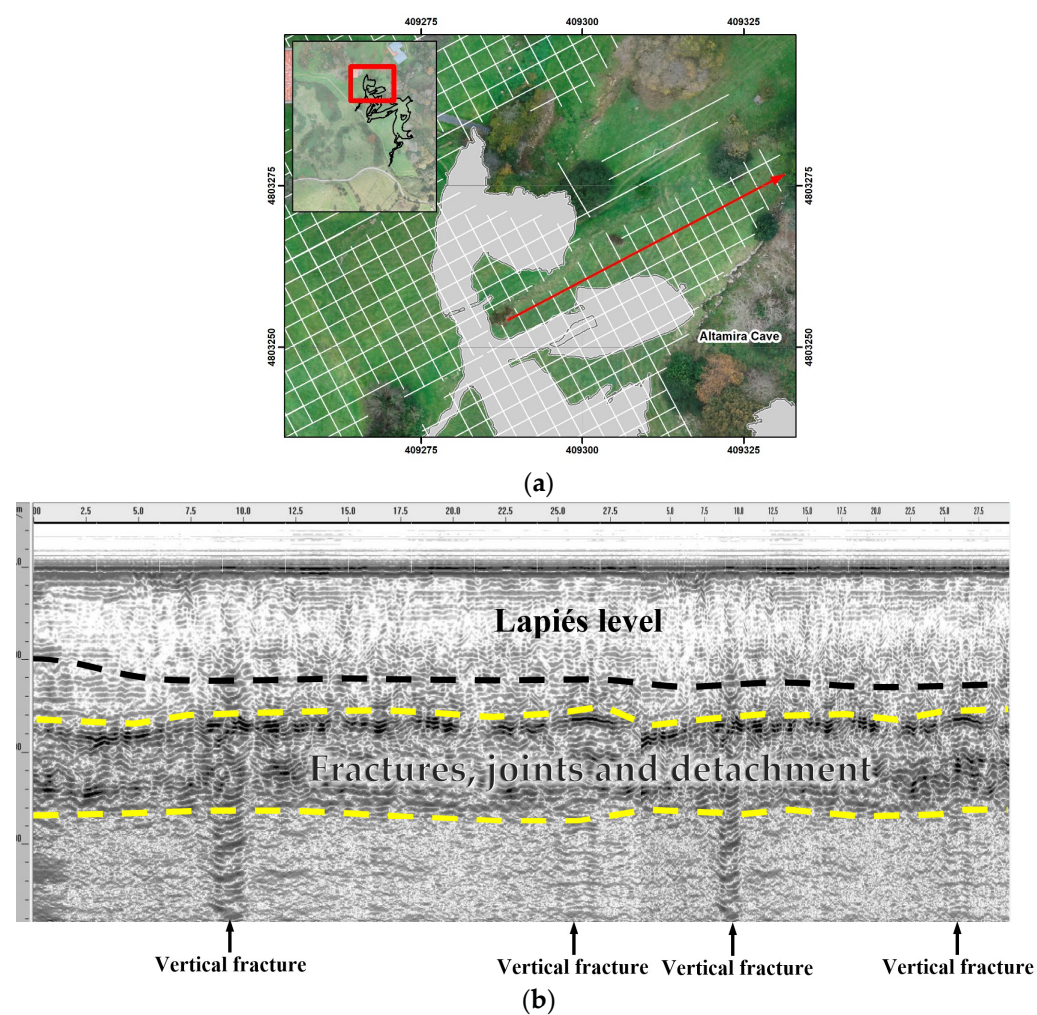


Figure 8. Cont.

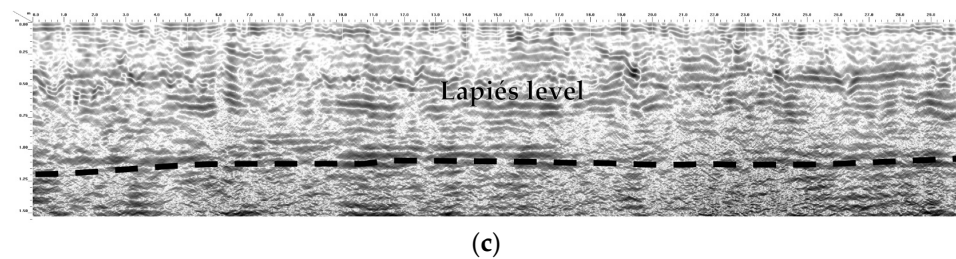


Figure 8. (a) Location and (b) radargram (profile T-97) recorded with the 400 MHz antenna, in which two levels of discontinuities in the rock mass were detected. The first and more superficial level corresponds to the lapiés (delimited with a black dashed line), and the second corresponds to a zone of fractures, joints, and detachments (delimited with a yellow dashed line). Vertical discontinuities corresponding to vertical fractures were also detected. (c) Radargram (profile T-97) recorded with the 900 MHz antenna, in which discontinuities with better resolution were detected at the lapiés level (delimited with a black dashed line). Vertical discontinuities corresponding to vertical fractures and rock pinnacles separated by grooves were also detected.

In the field campaign, 454 profiles were recorded: 329 profiles totalling 20,850 m² were surveyed with the 100 MHz antenna, 76 profiles totalling 850 m² with the 400 MHz antenna, and 49 profiles totalling 550 m² with the 900 MHz antenna.

2.4.2. Data Processing

Velocity Estimation

The GPR reflection data was acquired in the same week under very similar weather conditions with no rainfall. Thus, the subsurface moisture conditions in this investigated area could be considered almost constant for the investigated depth during the acquisition of the GPR field data. This velocity estimation assumption was made for the velocity-to-depth conversions, considering that possible changes in subsurface conditions could cause velocity variations that would affect these velocity-to-depth conversions [61,69].

The average velocity of the GPR wave was determined by the hyperbola fitting method on a set of hyperbolas recorded in different profiles, obtaining an average velocity value of 11.17 cm/ns. The dielectric permittivity (ϵ) was calculated to be 7.2, according to the following equation for low-loss media [61,62]:

$$\epsilon = \left(\frac{c}{v} \right)^2$$

where v is the electromagnetic wave velocity and c is the velocity of light in free space ($c \approx 29.97$ cm/ns).

This value was applied for the calculation of the processed depths in the investigated site of Altamira Cave.

Selected Processing Flow

Post-acquisition processing procedures were applied to the raw field GPR data sets to produce amplitude maps and rendered 3D images with all reflection profiles in the grids [61,62,69]. In this study, a data-processing procedure was applied to the raw data sets using RADAN 7.6 software (Geophysical Survey Systems, Inc., GSSI). The main processing steps are shown in Figure 9. The first step was a 1D processing consisting of zero-time correction (time-zero adjustment). After this, the 2D processing was applied to the reflection profiles according to these steps: (i) background removal; (ii) bandpass filters; (iii) linear amplitude gains; (iv) a time-to-depth conversion based on the calculated velocity average for the overlying rock strata. Next, each processed reflector profile was aligned within the grids described, with corresponding topographic corrections, to produce 3D horizontal amplitude maps and isosurface images (isoamplitude surface rendering).

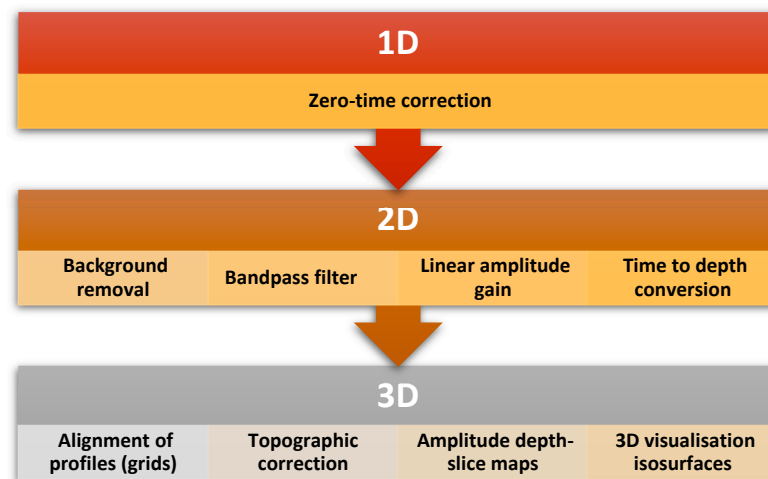


Figure 9. Flowchart of the main processing steps applied to raw reflection data collected by GPR in this study.

3. Results

3.1. Integration of UAV and 3DTLS

First, the UAV terrain model was integrated with the 3DTLS model of the cave because all information is georeferenced. From this, the surface position of the galleries and the proximity of the ceiling to the exterior terrain could be analyzed (Figure 10).

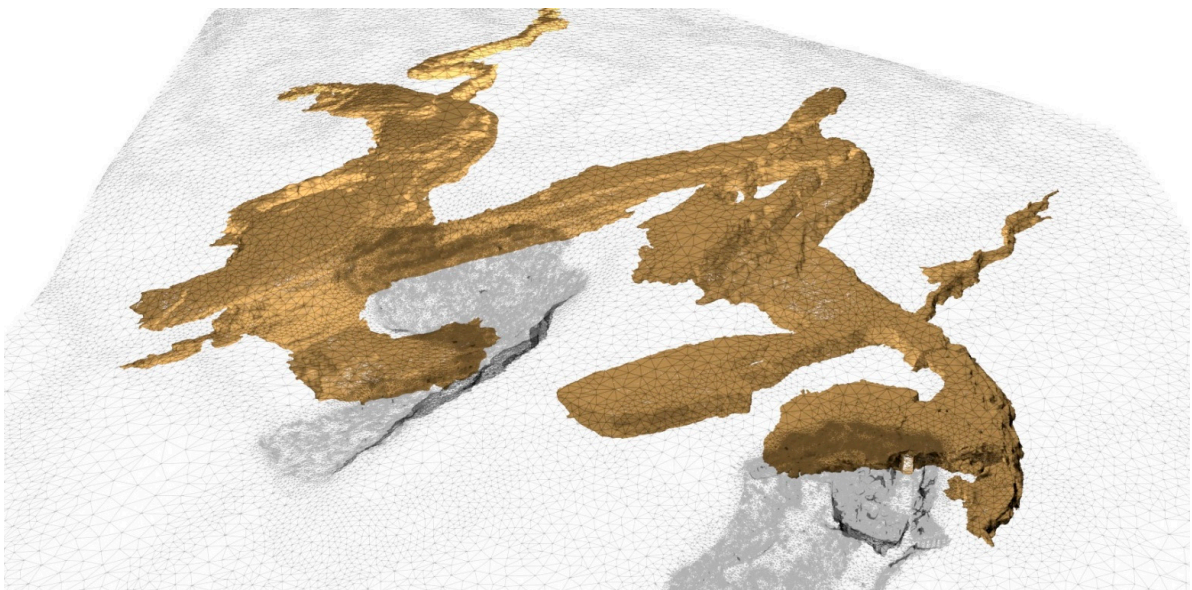


Figure 10. Visualization of the 3D model of the cave below a low-detail mesh obtained from UAV model.

A cartography was created with the overlying layer thickness of the cave (Figure 11) [29]. These maps consist of a raster with a resolution of $1 \times 1 \text{ cm}^2$, in which each pixel has the minimum distance between the ceiling of the cave and the ground recorded by the UAV flight for each pair of XY coordinates [70].

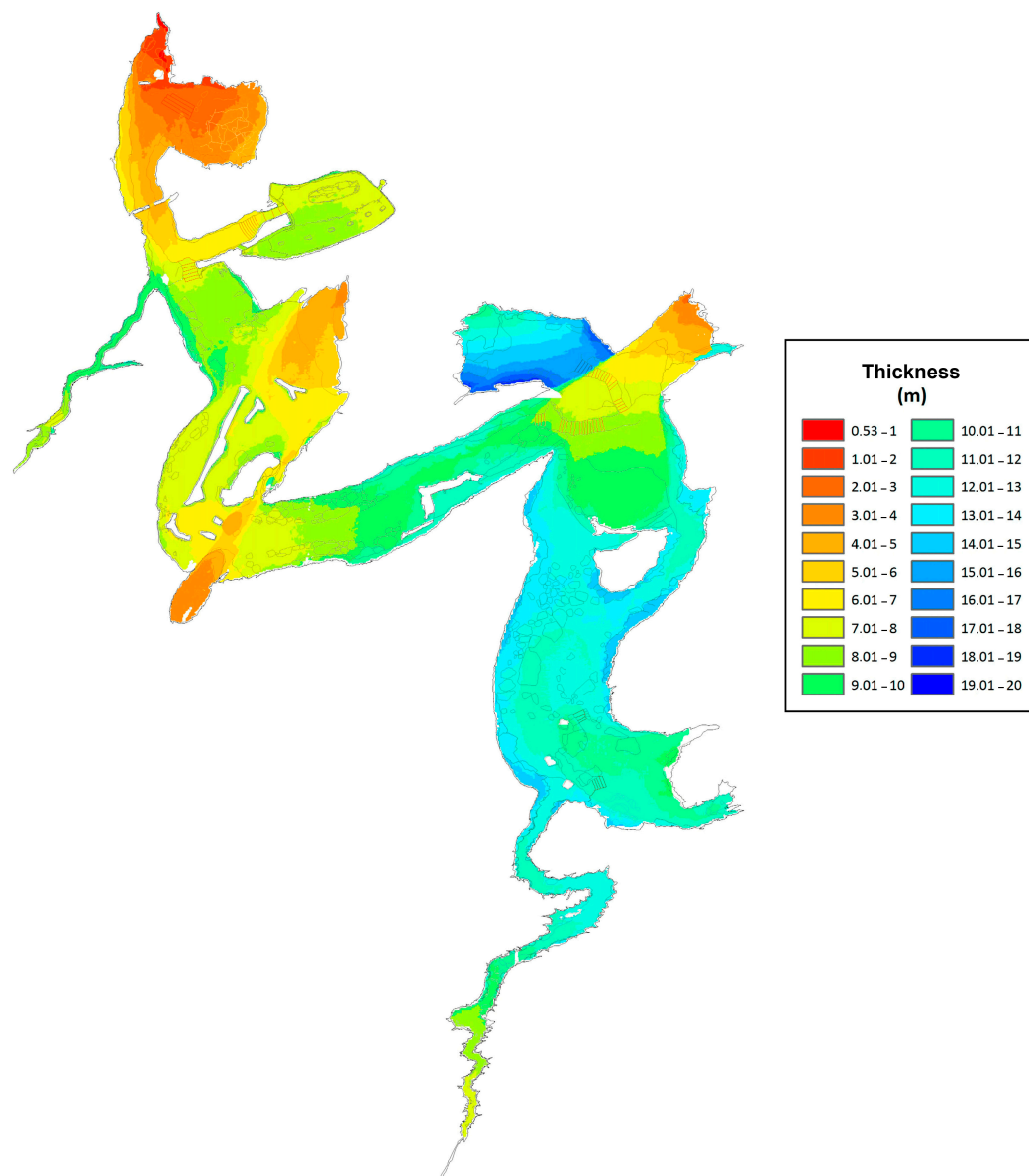


Figure 11. Overlying layer thickness model of Altamira Cave.

3.2. Integration of UAV and GPR

After processing the data recorded with the three central frequency antennas (100 MHz, 400 MHz and 900 MHz), we obtained 3D isosurface models with significant discontinuities in the overlying layer of the Altamira Cave bed and with higher resolution in the layer overlying the Polychrome Hall.

3.2.1. Results from the Overlying Layer of the Altamira Cave Site Derived from the 100 MHz Antenna

Subvertical reflectors and vertical diffractions were mapped and recorded in the GPR profiles that correspond to internal discontinuities in the rock mass (fractures, joints, detachments, bedding planes, etc.). Some of the vertical/subvertical discontinuities, with great in-depth development, were only a few meters from the surface. These vertical/subvertical discontinuities represent important accesses/pathways for the exchange processes between the interior of the cave and the exterior. Mainly, these vertical/subvertical discontinuities were detected in the following areas (Figure 12):

- The surrounding sinkholes (cave entrance, areas of Hoya Hall and El Pozo).

- The Polychrome Hall.
- The Stalactites Cave.
- The Hoya Hall.
- The artificial walls.
- An area to the NW where a house and a cowshed with its dunghill were located.
- The end zone of the westernmost branch line.

In addition, this GPR survey pinpointed several sinkholes in two areas (Figure 12):

- To the northwest of the Altamira Cave, specifically on the road to the south of the Museum building and where buildings and constructions demolished (house, bar, stable, and a dunghill) were located.
- In the end zone of the westernmost branch line of Altamira Cave.

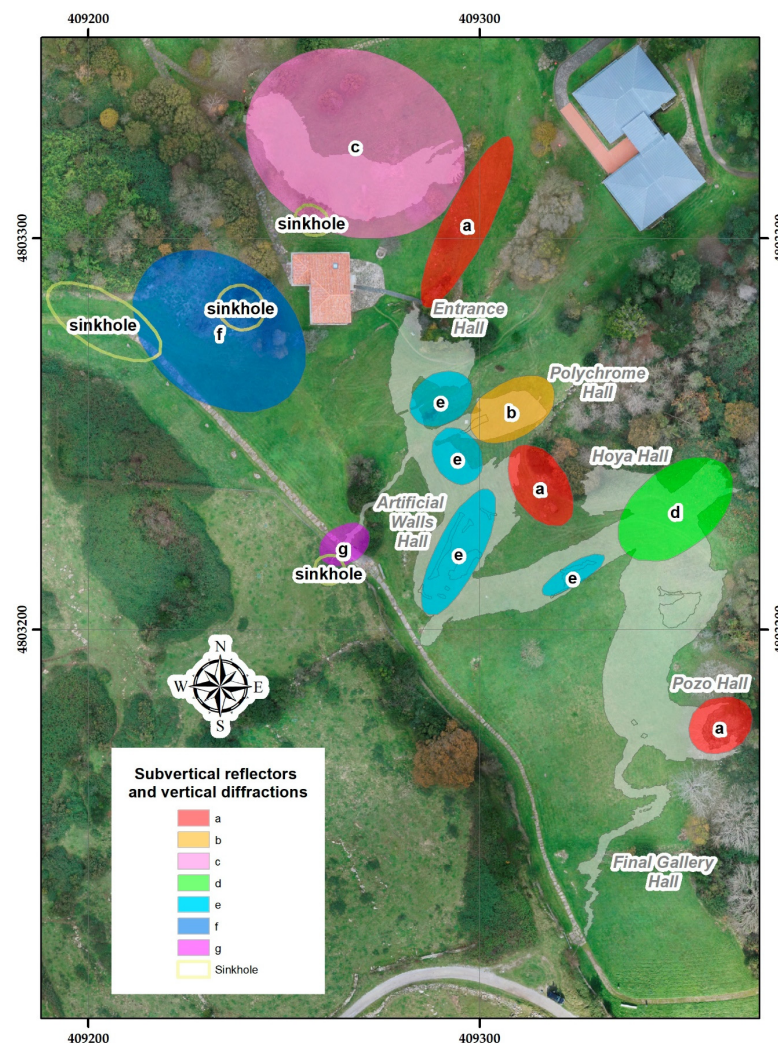


Figure 12. Zonal distribution map of subvertical reflectors and vertical diffractions (fractures) from GPR profiles in the rock massif of Altamira Cave: (a) the surrounding sinkholes, cave entrance, areas of Hoya Hall and Pozo Hall; (b) the Polychrome Hall; (c) the Cave of the Stalactites; (d) the Hoya Hall; (e) the artificial walls; (f) an area to the NW where a house and a cowshed with its dunghill were located; (g) the end zone of the westernmost branch line. Sinkhole areas pinpointed by GPR in the rock massif of Altamira Cave are indicated by yellow ovals.

The existence of vertical/subvertical discontinuities (fractures) detected in the Hoya Hall area would justify the construction of the artificial walls at the beginning of the 20th century.

This mapping has revealed discontinuities in specific areas of the Cave de Altamira that suggest that in past times, the extension of the Cave was greater than it is today and that it had several entrances/accesses.

3.2.2. Results from the Overlying Layer of the Polychrome Hall Derived from the 400 MHz and 900 MHz Antennae

The 3D model from the data recorded with the 400 MHz center frequency antenna indicated two levels containing a large number of high amplitude reflectors and vertical diffractions in the first few meters of depth of the overlying layer (Figure 13):

- A first level from the surface to a depth of about 1.20 m, which corresponds to the lapiés zone.
- A second level located in a variable interval between 1.70 m and 2.80 m depth, which may correspond mainly to the existence of fractures, joints, and an extended zone of detachments.

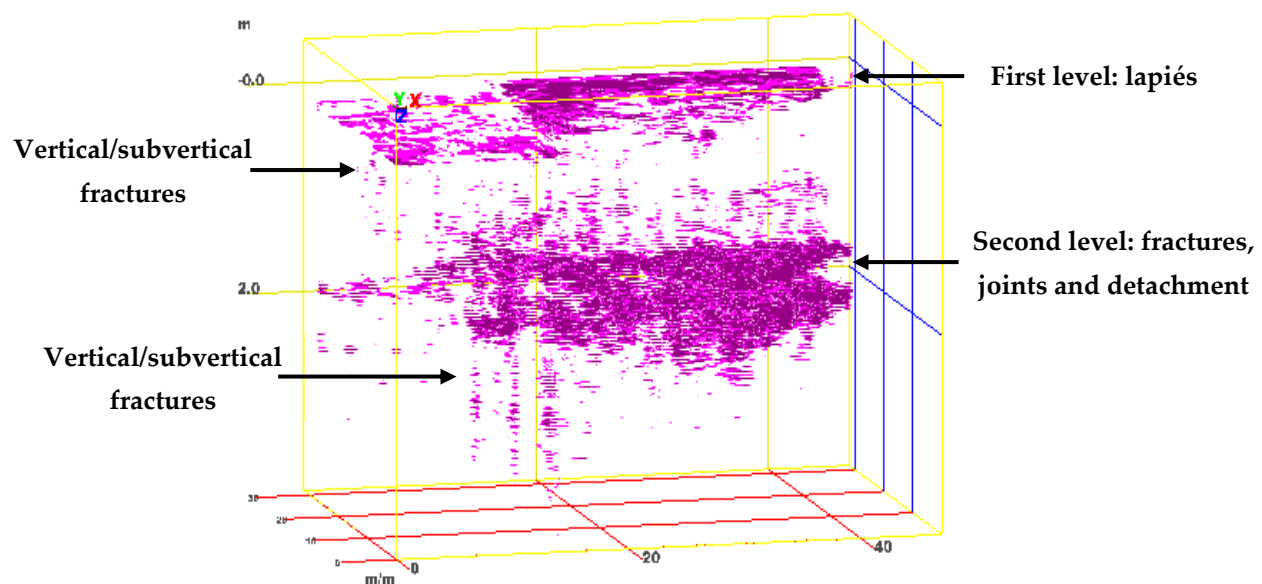


Figure 13. 3D amplitude isosurface model of the main discontinuities in the overlying layer of the Polychrome Hall with the 400 MHz antenna, showing the two levels of discontinuities (lapiés zone—fractures, joints, and detachment zone) and the vertical fractures.

A presence of a number of vertical/subvertical discontinuities (fractures) connecting these two levels and extending in depth (>3.80 m depth) was also detected. These mapped discontinuities represent significant access/pathways for the exchange processes between the interior of the Polychrome Hall and its external environment.

The second level was detected only to the north and east of the projection of the Polychrome Hall (Figure 14). This level could represent an area of water load located at a higher level than the ceiling of the Polychrome Hall, i.e., there is a probability of a local and temporary generation of a hanging aquifer where water from the surrounding area would build up on possible impermeable levels at its base. It is also necessary to consider the possibility that in times of high exterior–interior exchange, many particles deposited there may end up inside the Polychrome Hall.

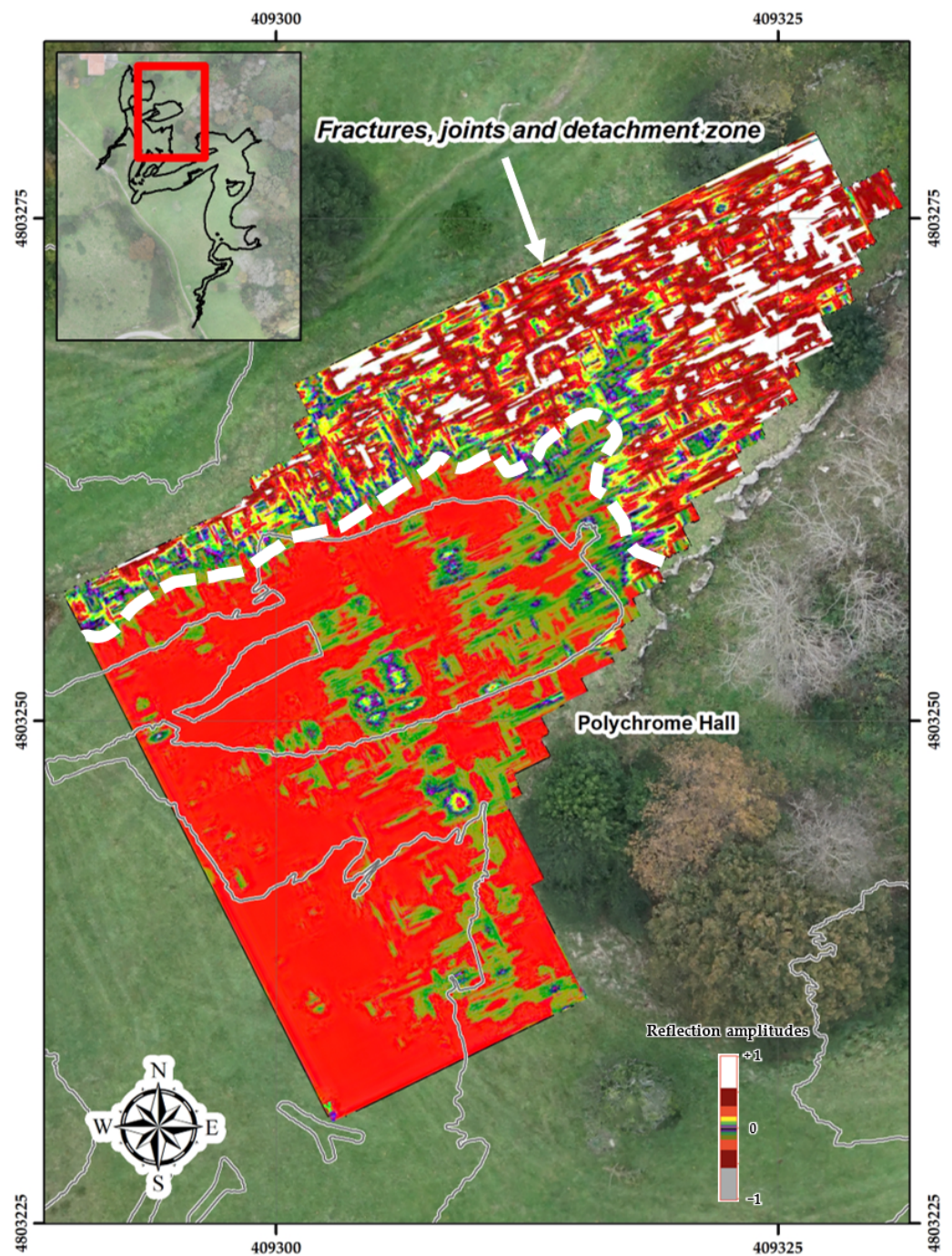


Figure 14. Amplitude slice, 2.20 m depth with the 400 MHz antenna, showing the fracture, joint, and detachment zone (marked in white) on the vertical projection of the Polychrome Hall. This zone of discontinuities is located only to the north and east of the Polychrome Hall projection.

In addition, this second level could contribute to the direct and lateral infiltration (impervium) of water into the horizons that make up the geological structure of the overlying layer of Polychrome Hall. This is the case in three of the vertical fracture zones observed and coincides with the temporary contributions of water in the walls of the Polychrome Hall, with two of them being located in its north wall and one of them in its south wall, as shown in Figure 15.

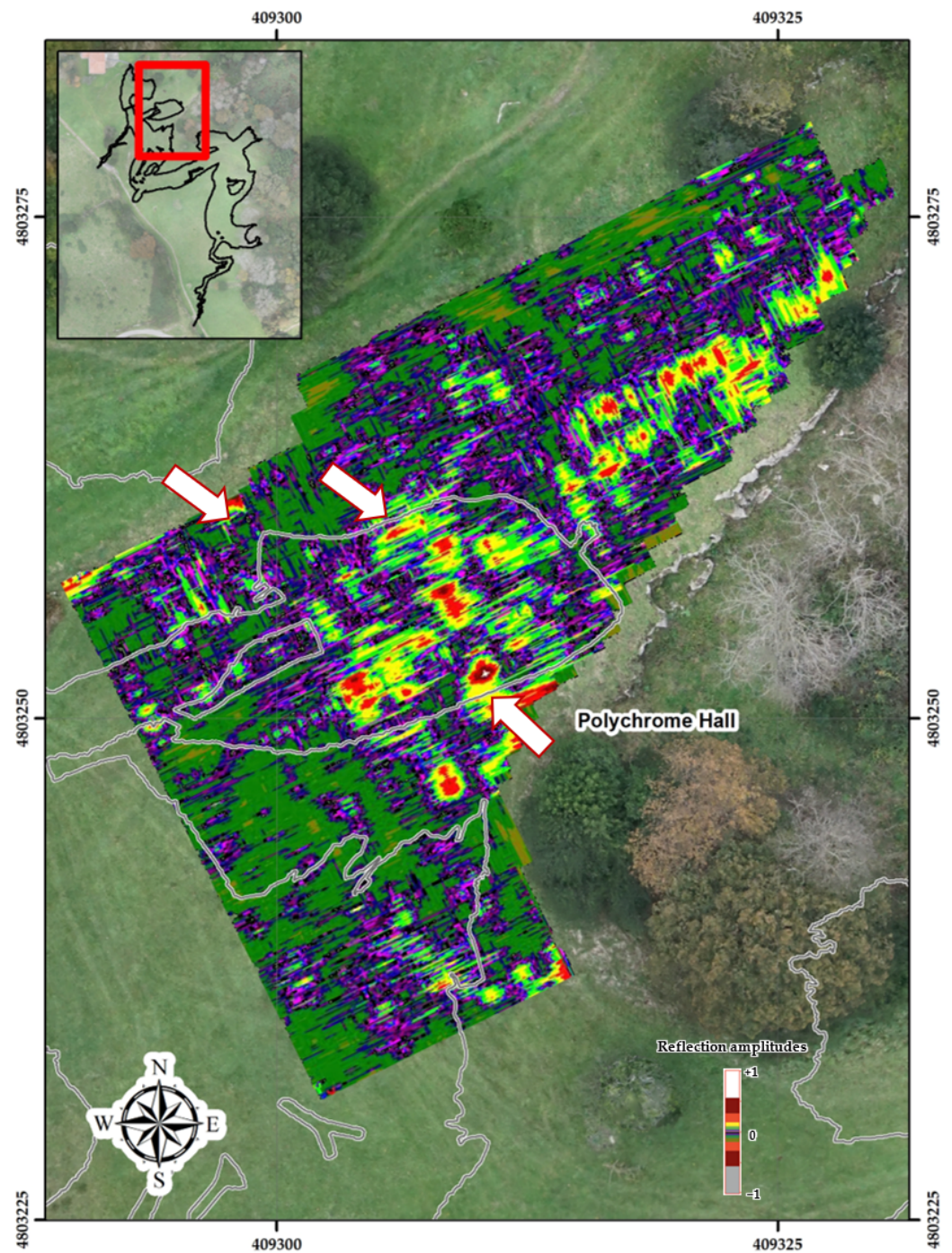


Figure 15. Amplitude slice, 3.50 m depth with the 400 MHz antenna, showing with white arrows the locations of the projections of the vertical/subvertical fractures that correspond to the 3 zones of temporary water inflow observed in the interior of the Polychrome Hall. Two of them are on the north wall and one is on the south wall.

In addition, the existence of this detachment level (level of high-amplitude reflectors), which borders the Polychrome Hall to the north and east, could be related to

- the decision at the beginning of the 20th century to construct the artificial walls to the north and east of the Polychrome Hall, or
- the current topography of the surface above Polychrome Hall, reflecting a change in orientation and slope that tilts towards the NE on the surface, which coincides with the surface projection of this detected level of high amplitude reflectors (Figure 16), or

- the distensive processes caused by the collapse of the sinkholes surrounding the north and southeast of the Polychrome Hall [65–68,71].

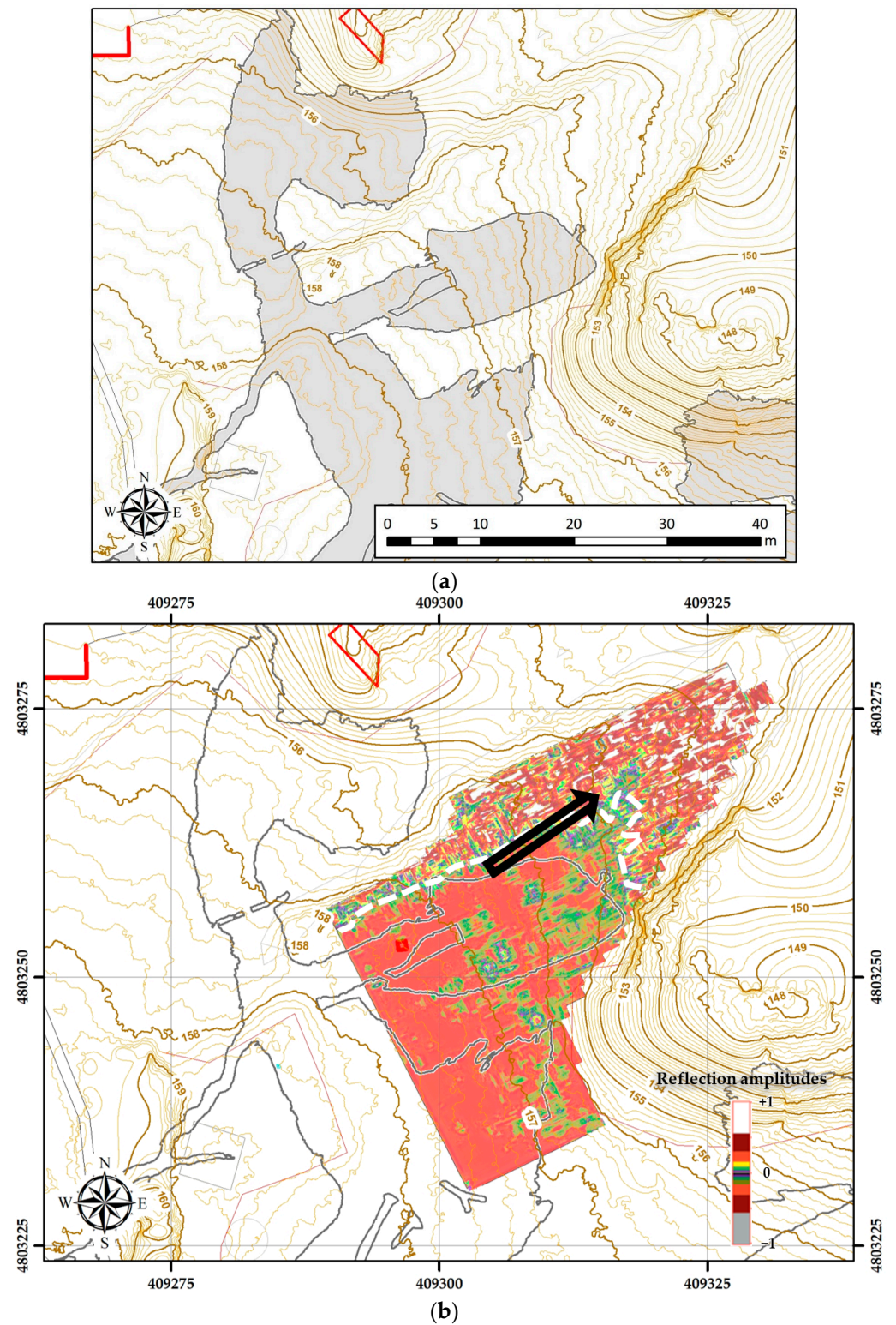


Figure 16. Projection of the Polychrome Hall on the topographic map, showing a change of orientation and slope (indicated with black arrow) that tilts to the NE (a), and which also corresponds to the projection of the second level of discontinuities in its amplitude depth slice (2.20 m depth) (b).

In summary, we observed that the overlayer of Polychrome Hall is more affected by fracturing in its northern and eastern areas. Similarly, its fracturing increases from west to east.

The 900 MHz center frequency antenna was used for the 3D study of the lapiés area of the Polychrome Hall. In this study, a large number of high-amplitude reflectors were recorded and mapped from the surface to about 1.20 m depth. These high-amplitude reflectors correspond to the rugged water-modeled limestone surface, consisting of rock pinnacles separated by grooves. The lineaments of this groove complex in the lapiés derived from 3D mapping agree with the predominant directions of the joint system (N45, N68, and N168) mapped in the Polychrome Hall rock outcrops [68]. (Figure 17). This lapiés area represents a permeable soil system that allows both runoff and infiltration of water, as well as the flow of gases.

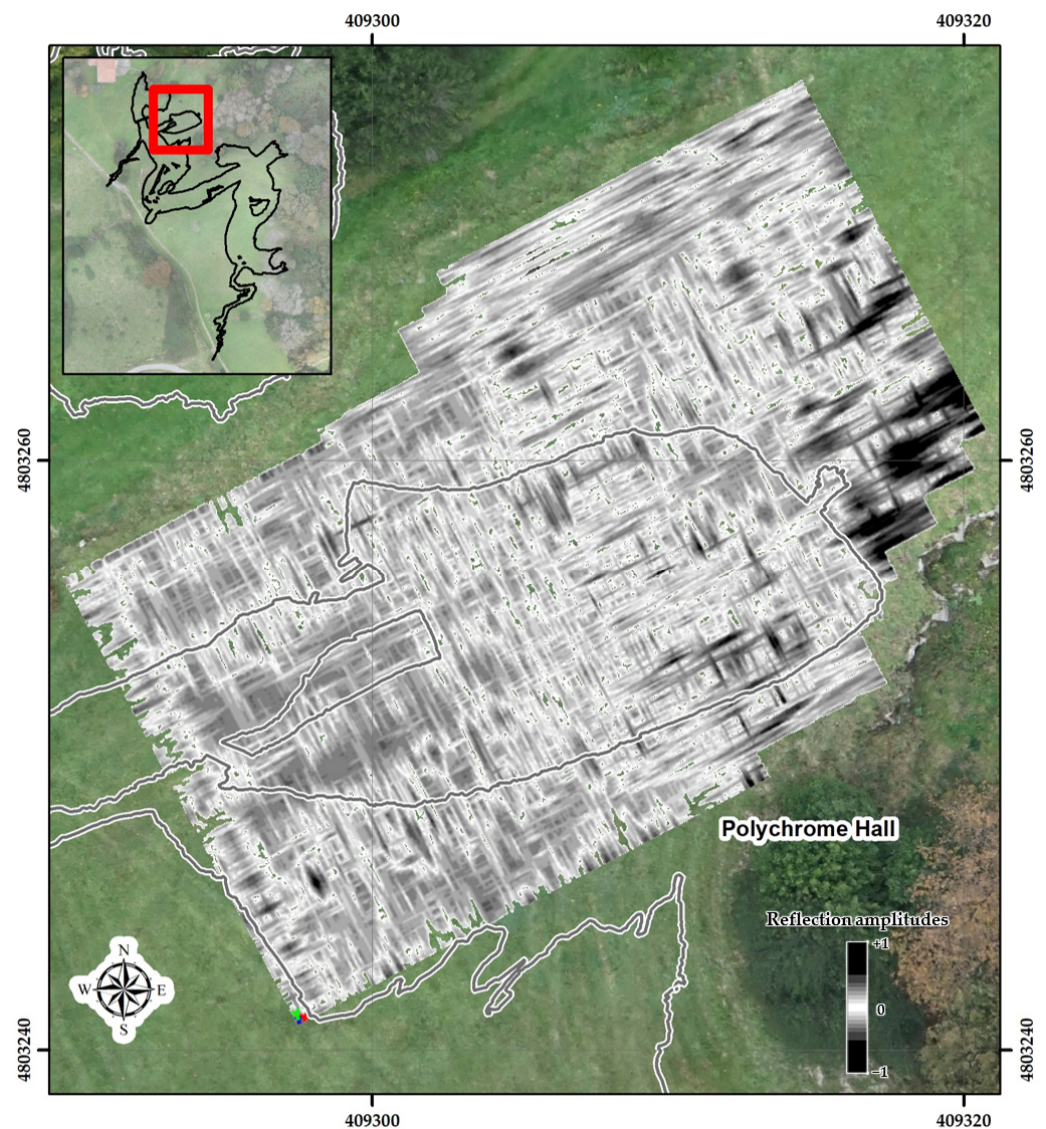


Figure 17. Amplitude slice, 0.45 m depth with the 900 MHz antenna, showing the mapped lapiés groove system in the overlying layer of the Polychrome Hall. It can be seen that the lineaments of this system of lapiés grooves, derived from the 3D mapping, agree with the orientations of the main lineaments of the joints (N45, N68, and N168) [67].

3.3. Visualization of the Integration of UAV, 3DTLS, and GPR

The 3D GPR model derived from the 100 MHz antenna recordings provides information about the most important discontinuities in the Altamira Cave karst system up to a depth of about 8 m (Figure 18).

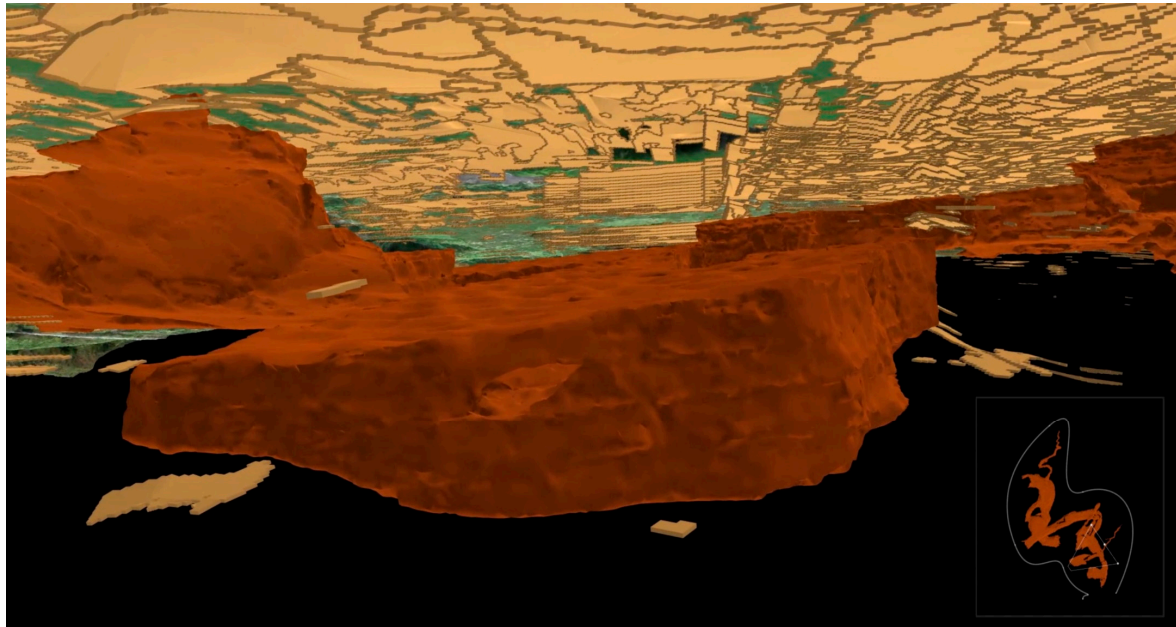
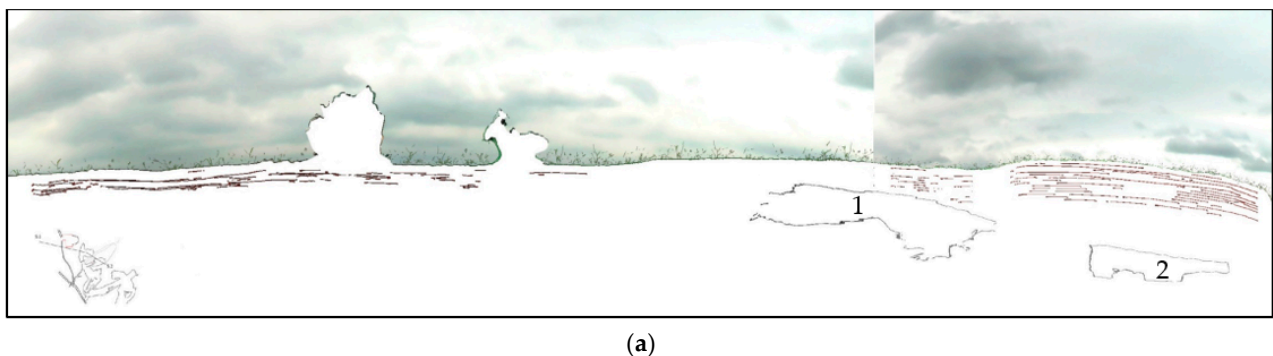


Figure 18. Image of integrating the UAV model, 3DTLS and GPR (100 MHz antenna), showing the discontinuities in the Polychrome overlying layer (in light brown) and the backside of the Polychrome Hall (in dark brown).

This model, showing the 3D amplitude isosurfaces, has been integrated with the UAV and 3DTLS models in Blender, an open-source 3D computer graphics software [72], to manage data and determine the spatial relationships between them by measuring or making sections (Figure 19) with variable thickness.

A video (Figure 20) showing the remarkable discontinuities recorded during the geophysical campaign in the karstic formation of the Altamira Cave was also rendered.



(a)

Figure 19. *Cont.*



(b)

Figure 19. (a) Section of the integrated model in the Entrance Hall (1) and Polychrome Hall (2) area showing terrain, GPR (brown), and 3DTLS (grey) models. (b) Section with 6 m far plane of the integrated model in the Entrance Hall (1) and Polychrome Hall (2) area showing terrain, GPR (brown), and 3DTLS (grey) models.

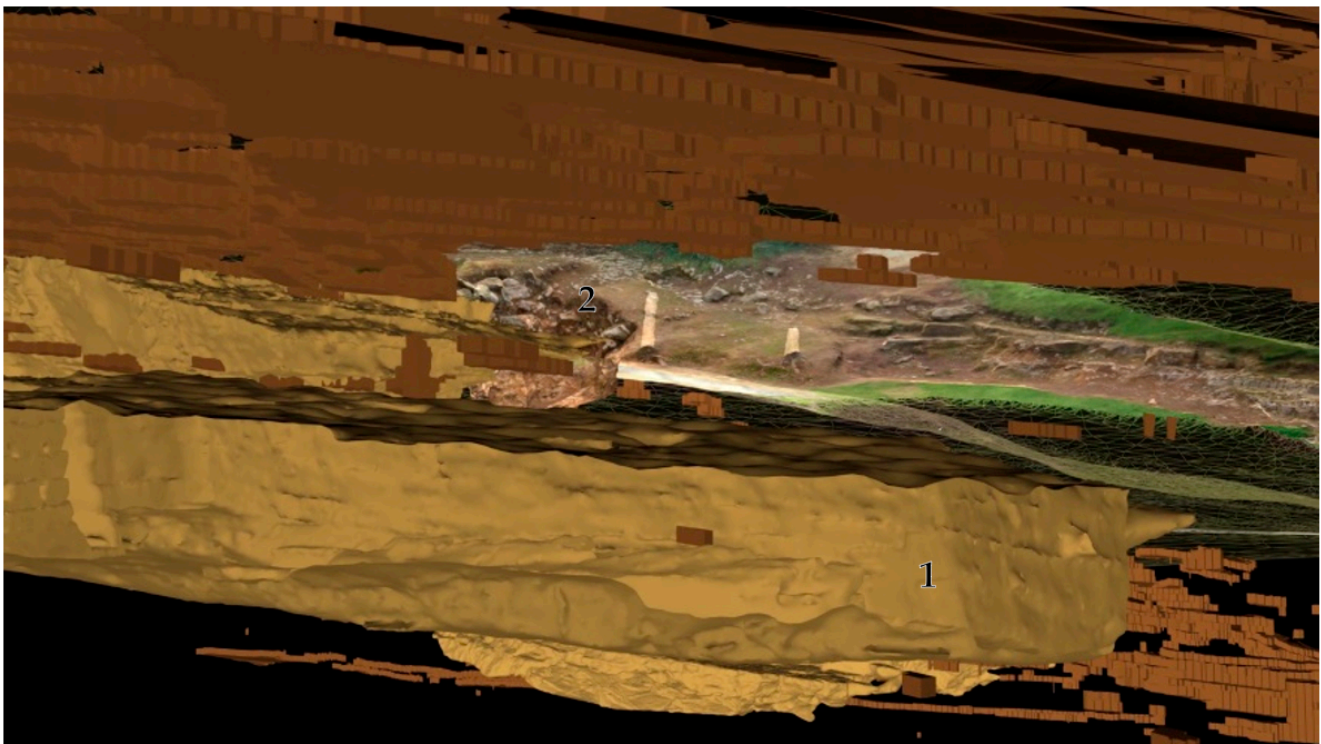


Figure 20. Video capture of integrating the UAV model, 3DTLS, and GPR (100 MHz antenna), showing discontinuities in the Polychrome Hall (1) and the exterior excavation (2).

4. Discussion

Geologically speaking, Altamira Cave is in a senile state with a clear tendency to disappear through natural evolution, given that the processes of destruction are more important than those of sedimentation [26]. The existence of an important network of fissures, fractures, joints, and displacements present from the top of the cave to the cave ceilings themselves affects cave stability and conditions important changes in the circulation of infiltration water, generating relevant alterations on the painting such as flaking, washing/erosion, and the concretion of carbonates [73,74].

The criteria used for the management and custody of Altamira Cave have led to the application of measures aimed at protecting the cave, its paintings, and its surroundings to guarantee their correct conservation. The research and conservation work in the cave, within the framework of its Preventive Conservation Plan, is aimed at gaining a better

understanding of the active deterioration processes to establish a detailed diagnostic procedure that facilitates indirect conservation actions.

Accurate georeferencing is key for integrating remote-sensing techniques in order to derive useful information from the cultural heritage, since it allows us to see the relationships between different parts of the cave with the exterior and how the soil is preserved. The study carried out on the mountain where Altamira Cave itself is located posed a research challenge of great relevance for the cave's conservation: to determine the exact access routes and the trajectories of the infiltration water which, through the lines of fractures, fissures, and joints, access the different parts of the cave, especially the Polychrome Hall.

Integrating GNSS, 3DTLS, UAV photogrammetry and GPR permits a rapid, accurate, and reliable recording of complex features such as caves or cavities [18]. This information can be used to derive cartography such as floor plans, contour lines, longitudinal and cross sections, and three-dimensional analysis such as the height or thickness of galleries, or analyze and map the system of fractures from the exterior to almost the cave ceiling. Very significant vertical and subvertical fractures were detected, as well as the connections between these fractures and joints, establishing the access routes for infiltration water and relating them to the drip points located on the ceilings of the cave. All this information on moisture that is directly or indirectly associated with the main fractures and fissures mapped has been linked to many of the drip points involved in processes of erosion, flaking, disintegration, and washing away by dissolution of some of the mineral components present in the cave ceilings [75].

This model integration supports the decision-making of cave managers by enabling them to engage with advanced predictive models and simulations within a knowledge-based system.

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Data Availability Statement: The research data supporting this publication are not publicly available. The data was collected by GIM Geomatics as part of the research and conservation studies of the Cave. These data are kept in the Museo Nacional y Centro de Investigación de Altamira. A video showing the results of this study is available in: <https://youtu.be/YGU2mE8-rNg>.

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Publicación 2: A Multimodal Research Approach to
Assessing the Karst Structural Conditions of the Ceiling of a
Cave with Palaeolithic Cave Art Paintings: Polychrome Hall
at Altamira Cave (Spain)

Article

A Multimodal Research Approach to Assessing the Karst Structural Conditions of the Ceiling of a Cave with Palaeolithic Cave Art Paintings: Polychrome Hall at Altamira Cave (Spain)

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Abstract: Integrating geomatics remote sensing technologies, including 3D terrestrial laser scanning, unmanned aerial vehicles, and ground penetrating radar enables the generation of comprehensive 2D, 2.5D, and 3D documentation for caves and their surroundings. This study focuses on the Altamira Cave's karst system in Spain, resulting in a thorough 3D mapping encompassing both cave interior and exterior topography along with significant discontinuities and karst features in the vicinity. Crucially, GPR mapping confirms that primary vertical discontinuities extend from the near-surface (Upper Layer) to the base of the Polychrome layer housing prehistoric paintings. This discovery signifies direct interconnections helping with fluid exchange between the cave's interior and exterior, a groundbreaking revelation. Such fluid movement has profound implications for site conservation. The utilization of various GPR antennas corroborates the initial hypothesis regarding fluid exchanges and provides concrete proof of their occurrence. This study underscores the indispensability of integrated 3D mapping and GPR techniques for monitoring fluid dynamics within the cave. These tools are vital for safeguarding Altamira, a site of exceptional significance due to its invaluable prehistoric cave paintings.

Keywords: ground penetrating radar; data integration; mapping; karst system; rock discontinuities; cultural heritage; rock art; preventive conservation; geomatics; cultural management



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1. Introduction

Prehistoric art, an extraordinary manifestation documenting detailed facts and co-existing animal species in Palaeolithic times, is often found in caves within evolving karst systems housing unique microhabitats. These special and fragile artworks have faced preservation challenges due to tourism pressures. The Upper Palaeolithic, spanning 40,000–10,000 years ago, marked a significant era characterized by the emergence of anatomically modern humans (*Homo sapiens*) and extraordinary advancements in technology, art, and culture. This period witnessed the flourishing of cave paintings, sculptures, and personal ornaments, reflecting an evolving capacity for abstract thought and symbolic representation.

The Altamira cave has one of the most important pictorial and artistic cycles of the Upper Palaeolithic period. The cave was used for several periods during 22,000 years of occupation, from about 36,500 years ago until 13,000 years ago, when the main entrance to the cave was sealed by a collapse [1,2]. This cave is in Santillana del Mar, Cantabria, Spain (Figure 1), and was declared a World Heritage Site by UNESCO in 1985. The recognition of such universal values brought with it the responsibility to ensure its preservation [3–7].

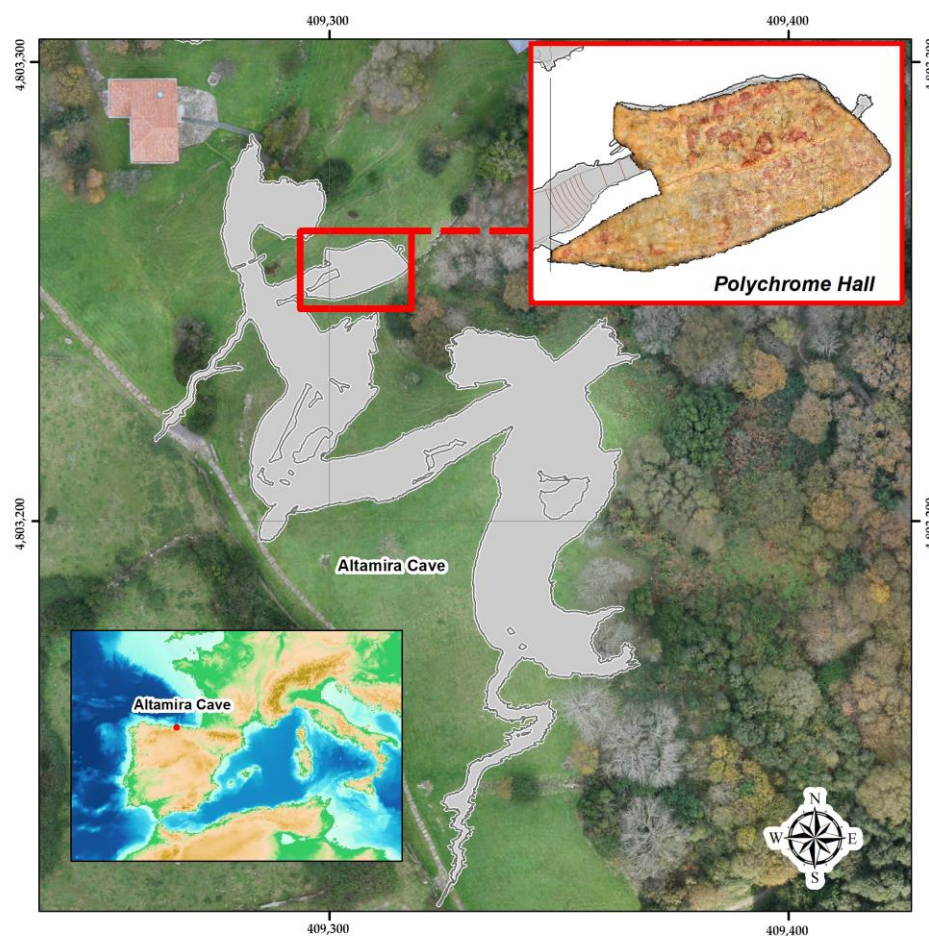


Figure 1. Geographic location of Altamira cave (Cantabria, Spain) and location of the main elements in the surrounding area.

The cave is part of a common geological and landscape environment. Altamira, with other caves close to it, such as the cave of Stalactites and the cave of Castañera, arise as consecutive episodes in the evolution of the karst, with Altamira, in the uppermost part of the karst, being the oldest. Understanding its relationship with the environment is fundamental to explaining the influence this system of karst galleries can have on the physical and chemical equilibria of Altamira and the stability of the microclimatic conditions in the cave [8].

The cave embodies a unique karstic environment essential to understanding its preservation. It is within a senile Pliocene-age karst that features a tubular, polygenic structure affected by geological and structural processes, notably fracturing, resulting in cavities that are formed through gravitational collapses [9]. Due to its proximity to the surface, the cave remains reliant on rainfall infiltration for water supply, with minimal in-cave circulation due to the rock's low permeability. The network of fissures, fractures, and detachments present from the top of the cave to the ceilings themselves affect the general conservation of the cave as they present a risk to its stability due to the possibility of gravitational collapse [10].

The Polychrome Hall's ceiling within Altamira cave adds another layer of complexity. It is formed by a limestone stratum sloping to the south, separated from the surface by a modest limestone layer. The surface hosts prehistoric paintings but is affected by microcorrosion processes, forming small millimetre-sized domes, while clay films with sporadic carbonate content adhere to the roof. Most intriguingly, the cave is above the maximum reach of lateral infiltrated water from higher areas, emphasizing that the water source for this unique environment is primarily confined to localized rainfall infiltration. Altogether, Altamira's intricate geological and environmental features underscore the

paramount importance of studying its immediate surroundings to preserve its cultural and natural heritage.

The preservation of cave paintings at Altamira under optimal conditions due to low natural infiltration and entrance collapse was disrupted by human discovery and visits, irreversibly changing the cave's ecosystem [11,12]. Natural alteration in the paintings began at creation and has remained consistent, with current conservation concerns tied to inevitable geological and hydrogeochemical deterioration processes [13]. Altamira's Polychrome Hall paintings on the ceiling face added complexity in preservation and the application of documentation techniques like GPR, photogrammetry, and hyperspectral remote sensing owing to their horizontal arrangement and vulnerability to washing. The main deterioration affecting the conservation of the paintings is the loss of pigment through washing, which has occurred over millennia and has led to the alteration or disappearance of parts of the paintings, especially in the southern section of the ceiling in the Polychrome Hall [14,15].

These pigment loss processes are associated with several factors: infiltration, condensation and composition water, relief of the support, and relationship with the fracture network, which allow natural ventilation of the Polychrome Hall and the cave [16,17]. Nowadays, these loss processes are monitored using geomatics techniques [18–21] such as photogrammetry and hyperspectral remote sensing, which help not only to document pigment losses but also to try to recover veiled areas or to create a chronological stratigraphy of the art [22].

The existence of an important network of fractures and delamination present from the top of the cave to the cave ceilings themselves affected and continues to affect its stability. The gravitational landslides documented in recent times highlighted the need for building artificial walls in areas that showed significant instability in the 1940s and 1950s. Among these areas is the Polychrome Hall itself, where the ceiling is crossed by a very relevant central crack. While the aforementioned retaining walls were being built, this large central fracture, as well as other adjacent ones, were sealed with hydraulic mortar, reactivating new and relevant deterioration processes.

Water supply to the Polychrome Hall comes from direct infiltration of rainwater through the fractures; lateral contributions of infiltrated water are small.

The overlying thickness of the Polychrome Hall bedrock is between 7 and 9 m (Figure 2), with the thickness of the soil cover varying between 5 and 25 cm.

Accurate georeferencing of the interior of the cave with the exterior is crucial to preserving the geological formations, habitats, artifacts, and rock art in the cave. Knowing this information allows for the establishment of protection zones, tracking the internal microclimate of the cave, mapping safe zones, and helping with research, hence helping to achieve effective and sustainable conservation [23].

Nowadays, the use of geophysical surveys is a possible alternative to direct research methods for studying the internal rock structure in karstic complexes [24–27], particularly for studies of karst formations that feature prehistoric art [28–30]. Geophysical surveys are non-invasive and can accurately map discontinuities in the shallow subsurface [31–33].

Ground-penetrating radar (GPR) reflection profiles are commonly used to examine the internal structure of rock masses, encompassing rock matrix blocks and discontinuities. These media are typically characterized as mechanically discontinuous, anisotropic, and heterogeneous. In recent decades, GPR reflection profiles have also proven valuable for correlating contacts between stratigraphic units or identifying structural breaks (discontinuities) within geological formations, thus enhancing our understanding of subsurface complexities [34,35]. GPR is a non-destructive method that provides continuous, high-resolution information about the internal rock structure and its physical properties, both vertically and laterally [36–41].

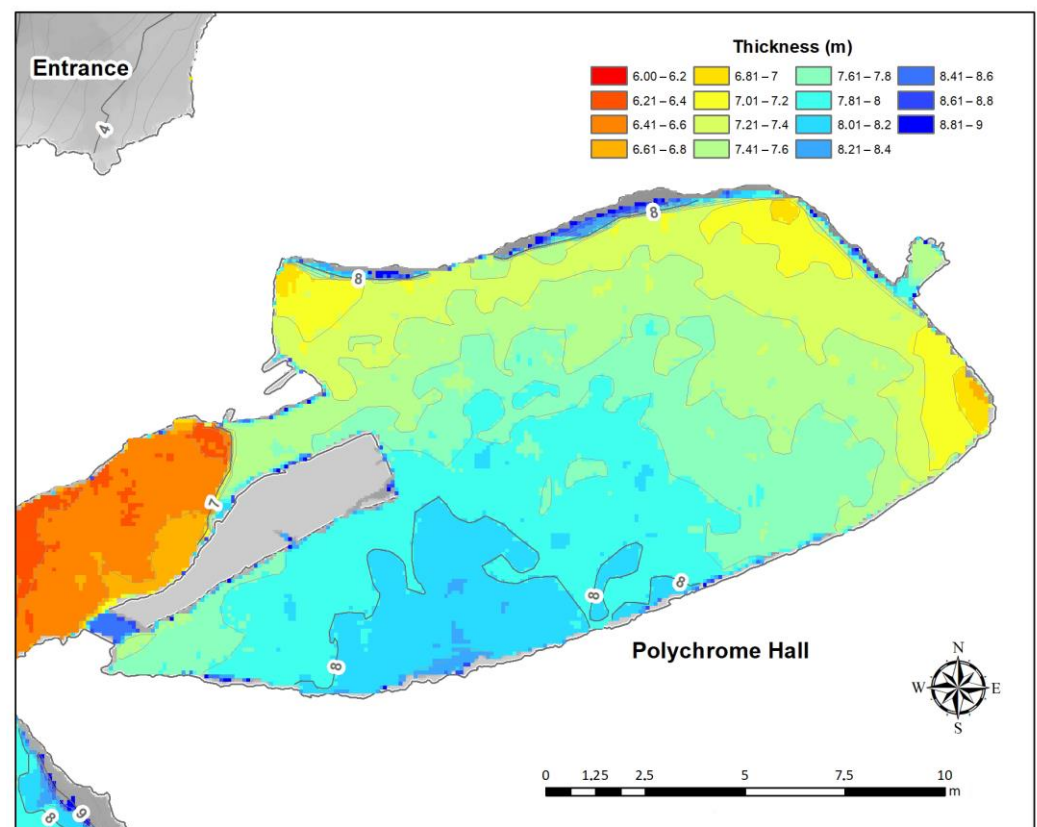


Figure 2. The thickness of the layer overlying the Polychrome Hall.

The main objective of this study was to systematically map the discontinuities within the strata overlying the Polychrome Hall to evidence their role as conduits for flow processes connecting the cavity with the external environment, an aspect previously considered only as a hypothesis. This article showcases the multidisciplinary tasks carried out to model both the thickness of the overlying layer and the water supply basin in the Altamira cave's Polychrome Hall. The aim was to confirm the consistency of the stratigraphic sequence, precisely characterizing and mapping the fractures within each package and pinpointing significant vertical fissures that facilitate direct water infiltration, thereby endangering the preservation of the invaluable paintings.

In the following parts of the study, readers can expect to delve into a comprehensive exploration of the Polychrome Hall within Altamira cave. Section 2 offers detailed insight into the technical aspects of Ground-Penetrating Radar (GPR) methodology and the specific parameters of 400 MHz and 900 MHz antennas used in the study; these serve as crucial tools for understanding the geological and hydrological dynamics in the cave. Section 3 takes us through the processing flow of GPR data and the application of hydrological tools to map water infiltration and the interconnections between the cave's exterior and interior environments. Additionally, it delves into the internal stratigraphy near the cave's surface, providing valuable information for conservation and understanding of the rock art's context. Finally, in Section 4, readers are presented with a detailed discussion of the findings. The study emphasizes the importance of elevation models, discusses the complex spatial arrangement of discontinuities in the cave, and highlights the need for ongoing conservation efforts to protect the cave's valuable art and mitigate risks of damage. Overall, these three parts offer a comprehensive journey into the geophysical and geological aspects of Altamira's Polychrome Hall, shedding light on its historical significance and the measures necessary for its preservation.

2. Materials and Methods

Caves are formed by the dissolution of limestone rock due to slightly acidic water and involve chemical and geological processes as well as tectonic forces and atmospheric influences. These caves are irregular in shape and size, requiring the use of various georeferenced remote sensing techniques to map them and obtain more information about this valuable heritage [42].

2.1. General Workflow

The data integrated into the model requires, first, a reference frame, which was generated using a Global Navigation Satellite System (GNSS) [43]. GNSS is a technology that enables global geospatial positioning through a network of satellites [44]. In 2013, a geodetic reference system was established using TOPCON Hyper II receivers [45] and the European Terrestrial Reference System 1989 (ETRS89). Topcon Tools software [46] was used to calculate observed phase changes, resulting in a reference frame with a mean accuracy of 1.7 cm in determining the coordinates of the vertices located outside the cave.

Having an accurate cartographic model of a cave is important when predicting knowledge-based models relying on georeferenced parameters like microbiological, climatic, hydrochemical, and geomorphological data [47]. These parameters often show significant correlations with each other and with external environmental factors. A closed back-and-forth traverse [48] spanning a total length of 430 m and involving 16 traverse stations was conducted within the cave. The angular closure error was 0.0218 degrees and the linear closure error was small ($X = -0.001$ m, $Y = -0.005$ m, $Z = 0$). To establish the georeferenced system for 3D laser scans, 66 checkerboards positioned throughout the cave were radiated from traverse vertices. This reference system was pivotal for the precise georeferencing of the 300 scans conducted using a FARO FOCUS X-130 [49] during the field campaign in December 2013. The scans were calibrated using spheres as tie points and checkerboards as references, resulting in an accuracy of 2.7 mm for 95% of the points to which the interior photogrammetry [47] was supported.

The exterior model of the cave was generated by an Unmanned Aerial Vehicle (UAV). UAVs have become integral tools in surveying and mapping [50–52], offering efficient and reliable means for assessing large areas in significantly less time compared with traditional techniques such as Topographic Total Stations (TTS) and GNSS. Moreover, UAVs are nowadays also integrated with thermal cameras and lamps, enabling them to perform thermographic inspections, hence expanding their capabilities in various applications [53]. In our study, we harnessed the capabilities of a TOPCON Intel Falcon 8+ Drone [54] equipped with a Sony A7 R Mark II full-frame camera [55] incorporating a Sony Sonnar T* FE 35 mm F/2.8 lens. By implementing a flight planning system, we achieved a ground sample distance (GSD) of 2 cm across the extensive cave environment (40 hectares). Over 4800 images were collected, with 52 Ground Control Points (GCPs) measured via RTK-GNSS to establish flight references. An additional 40 points were measured for quality control, yielding a mean control point error of 1.76 cm.

These photogrammetric flights enabled the acquisition of diverse spatial data, including 2D orthoimages, 2.5D Digital Surface Models (DSMs) transformed into Digital Elevation Models (DEMs) through tree removal, and 3D datasets encompassing point clouds and comprehensive models of both the cave environment (40 hectares) and its adjacent areas (4 hectares). The 3D model of the cave was composed of 12 million triangles textured with eight 8192×8192 -pixel textures. Simultaneously, the model of the neighbouring area featured four million polygons and four 8192×8192 -pixel textures serving as a foundation for data integration. Both models were exported in .Obj file format for seamless incorporation with more data sources, underscoring the versatility and precision of drone-assisted surveying in our study. All the details on integrating 3D TLS, UAVs, and exterior GPRs (Figure 3) can be found in [56].

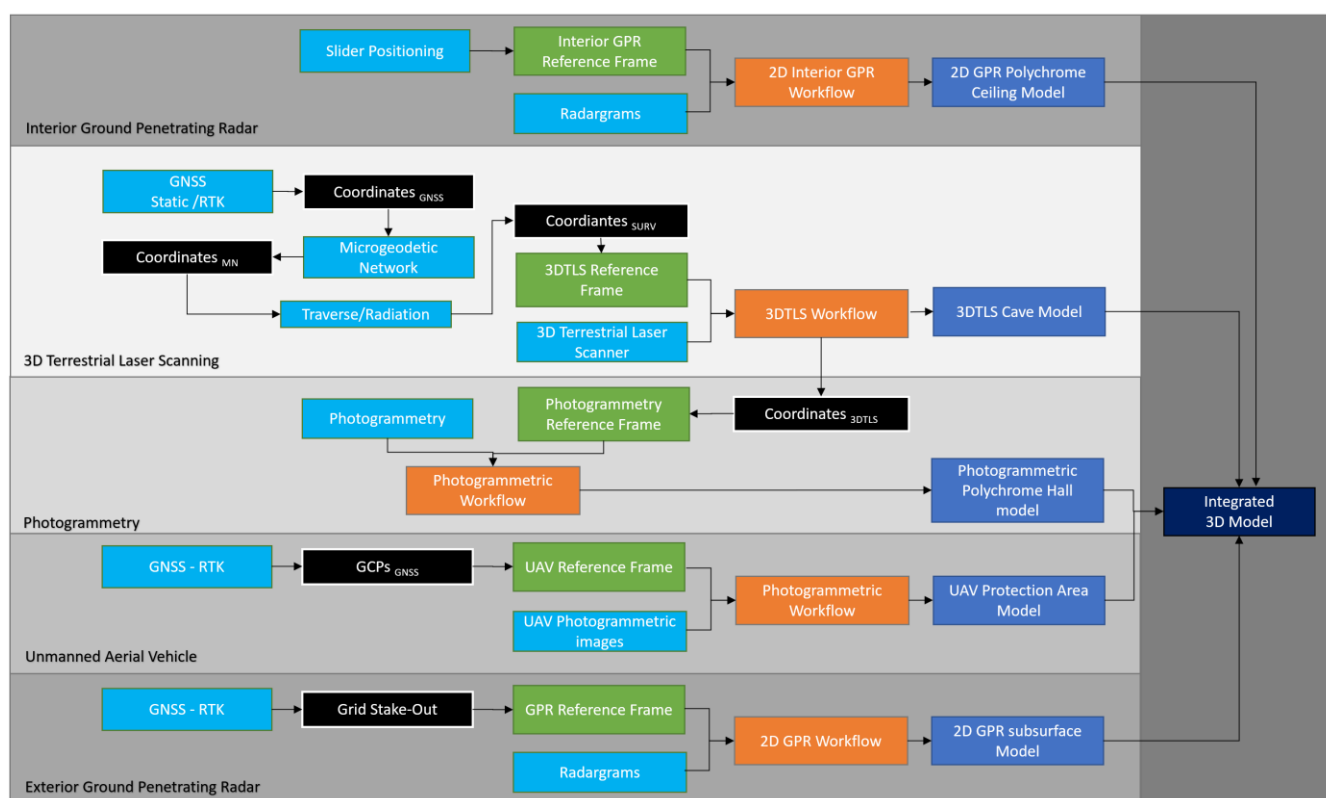


Figure 3. The general workflow followed in this study (adapted from [56]).

Previously, in 2014, a photogrammetry campaign was carried out to document the ceiling of the Polychrome Hall [57], independently of the laser scanning process, to achieve sub-millimetre resolution documentation. Besides the geometrical quality of the image, a camera capable of capturing true R-G-B colour was chosen, as the coded images were also to be used for colour analysis. For this purpose, a Hasselblad H4 D-200 MS, which can capture 8176×6132 -pixel frames with the HC 3.5/35 and HC 4/28 lenses, was used.

The minimum resolution was set to 16 pixels/mm² and the illumination system consisted of two 4800 Kelvin degree LED flat screens with an illuminance of 980 lux each (composed of 1024 LED units), which were covered with a Rosco Cinegel 3000 Tough Rolux (Roscolab Limited, London, UK) plastic diffuser.

Photogrammetric support was carried out by detecting homologous points extracted from the point clouds captured by the 3D laser scanner. A total of 80 homogeneously distributed points were used throughout the hall, half of which were used as control points for model validation. The images were adjusted in blocks and a high-density point cloud of about 11 billion points was generated from them. This was filtered and generalized to another cloud of about 3.5 billion points from which a high-resolution 3D digital model of the ceiling of about 200 million polygons was used to generate a 6 Gigapixel orthoimage and a reduced 4 million polygon version used for the integration.

2.2. Ground-Penetrating Radar

In recent decades, GPR reflection profiles have been correlated with contacts between stratigraphic units or with structural breaks (discontinuities) in geological media [42,43]. GPR studies of the internal structure of rock masses focus primarily on their discontinuities, including fractures, joints, veins, detachments, and stratification planes [58–61]. The karst system of the Altamira cave is in a senile state and is characterized by multiple discontinuities in its different strata (Figure 4) [11,62]. The information is collected by transmitting electromagnetic energy into the subsurface and recording the reflected, diffracted, or critically refracted energy from the electromagnetic discontinuities. Discontinuities in a rock

mass represent electromagnetically active contacts/interfaces to the GPR, where part of the radar pulse energy is reflected to the surface, producing a radar record as a profile (radargram). A radargram can be represented in grayscale or colour, where different shades or colours correspond to different magnitudes of the recorded wave amplitudes [63,64].

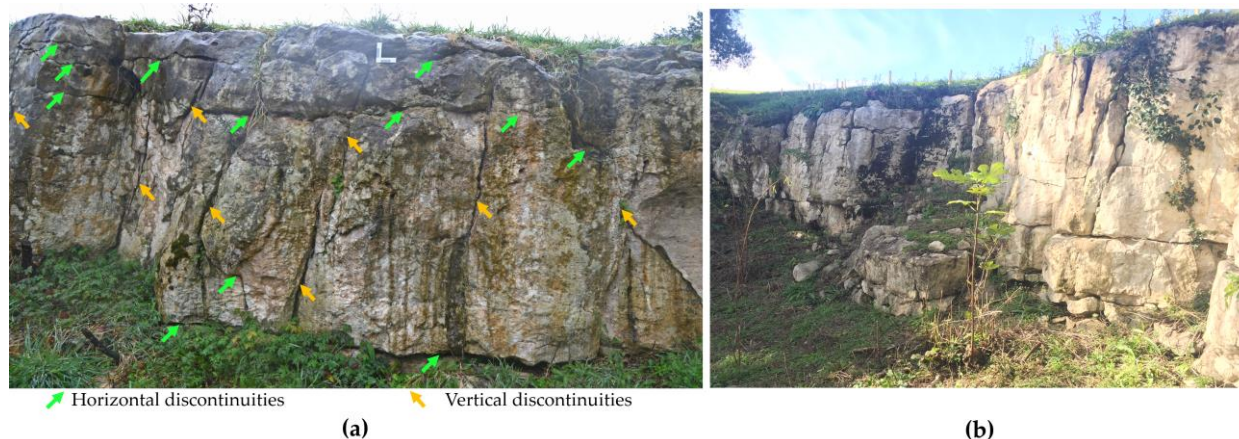


Figure 4. (a) Frontal photograph of the eastern margin of the outcrop of the layer overlying Polychrome Hall. Different vertical (yellow) and horizontal (green) discontinuities are observed in the rock mass. (b) Photograph showing the pattern of discontinuities throughout the outcrop of the overlying layer.

The penetration depth at which the GPR technique can obtain records/images of discontinuities within a rock is strongly influenced by the electromagnetic parameters within the rock mass (dielectric permittivity, electrical conductivity, and magnetic permeability). These electromagnetic parameters can indicate alterations in the rock and the presence of conducting minerals, porosity, joints, fractures, water content, and fillings within the discontinuities. Penetration is greater in rocks characterized by low electrical conductivities and magnetic permeabilities. Most geological materials and rocks are non-magnetic, thus the dielectric permittivity (dielectric constant) and electrical conductivity, in particular, play a relevant role in amplitude attenuation and effectiveness of the GPR. The attenuation factor increases with increasing conductivity of the medium. Additionally, the electromagnetic wave undergoes geometric attenuation with distance. Reflective/diffractive surfaces also contribute to signal attenuation. In summary, the degree of water saturation, water mineralization, distance, variation in porosity, and number of discontinuities all affect the propagation of electromagnetic waves in a rock mass [63–66].

The signal penetration and detection resolution of the GPR depends on the frequency of the antenna used. Higher frequency antennas offer better detection resolution, but signal attenuation also increases, resulting in less penetration into the rocks. The choice of antenna type, considering its central emission frequency, is made taking into account the detection–penetration trade-off [64,65].

In the karst of the Altamira cave, an earlier study of the layers overlying the Polychrome Hall observed attenuation of the electromagnetic wave in radargrams obtained using an antenna of 100 MHz from about 5–6 m deep [47], that is, the penetration depth reached with the 100 MHz antenna was not enough to study its full thickness (>9) (Figure 2). This attenuation of the electromagnetic wave in the layers overlying the Polychrome Hall was the main reason GPR profiles were projected on the Polychrome Hall ceiling using 400 MHz and 900 MHz antennas. Thus, radar records that complement the final meters up to the basal surface of the Polychrome Hall ceiling, which could not be studied from its outer surface using the 100 MHz antenna, would be obtained. In addition, the discontinuities and geological layers close to the basal surface of the Polychrome Hall could be studied in detail. Their study is crucial as they support the Palaeolithic paintings.

3D integration of the three UAV, 3DTLS, and exterior GPR models of the cave and its overlying layer was achieved [47]. Nevertheless, constraints associated with time limitations imposed by conservation efforts in the interior of Polychrome Hall prevented the acquisition of a continuous spaced grid that, when interpolated, would have provided the accuracy required for our purposes. As a result, we had to settle for the 2D profiles that we were able to record.

2.2.1. Field Data Acquisition: Polychrome Hall ceiling

A GSSI SIR3000 system was used in this geophysical study. Due to the morphology and dimensions of the Polychrome Hall ceiling, and considering the mobility factors inside it, profiles close to the ceiling were measured using the 400 MHz and 900 MHz central frequency antennas. Data acquisition using the 400 MHz antenna was performed in continuous mode, with a total time window (range) of 100 ns and defined by 512 samples per trace, and with IIR filter 800 MHz (low pass)–100 MHz (high pass). Data acquisition was also performed in continuous mode using the 900 MHz antenna, with a total time window (range) of 35 ns and defined by 512 samples per trace, with IIR filter 2500 MHz (low pass)–225 MHz (high pass). The profiles were transversal and parallel to the central fracture of the Polychrome Hall ceiling. Access to the Altamira cave is restricted to protect its integrity and historical value. Conservation measures have been put in place to limit the time visitors and researchers can stay in the cave to minimize their impact and prevent damage to the paintings. Due to these limitations, 46 GPR profiles 3 m in length were recorded inside the cave and used for the present study.

Recording these GPR profiles allowed us to complement the mapping and detection of discontinuities obtained from the outer surface of the Polychrome Hall using the 100 MHz antenna as described in a previous study [47], as well as record discontinuities with higher resolution in the geological levels closest to its basal surface. Measuring these discontinuities in greater detail is of great interest since the Palaeolithic paintings are located on the basal surface of the Polychrome Hall ceiling.

Several authors have conducted software simulation studies and real measurements of the optimal height of antennas relative to a surface during data collection over the last decades [66–73]. These authors concluded that the best GPR data are obtained when antennas are in contact with the ground or close to the ground. This allows the antennas to couple to the ground and ensures that the maximum amount of energy is transmitted to the subsurface. The higher an antenna is above the ground surface, the more GPR energy is reflected at the interface with the ground, and the less GPR energy is transmitted to the subsurface, greatly reducing the penetration depth. This not only reduces the response amplitude of smaller targets but also decreases the spatial resolution. Furthermore, the height of the antenna depends on its centre frequency. Higher centre frequency antennas need to be closer to the surface, while lower centre frequency antennas can operate with wider gaps between the antenna and the surface. The authors also concluded that the results generally showed optimal performance up to an antenna height of 100 cm.

GPR data were collected with the antennas air-coupled to the ceiling of the Polychrome Hall. A 3-m-long slider, on which the 400 and 900 MHz antennas focused on the ceiling were placed, was chosen due to operative limitations inside the cave (Figure 5a). An odometer was used to accurately reference the GPR profile to the source. A key aspect of the model was the georeferencing of the profiles registered inside the Polychrome Hall, which was achieved by 3D scanning of the sliders where the antennas were placed. In addition, a minimum distance of about 8 cm from the ceiling was ensured to avoid any antenna–ceiling contact that would cause damage to the cave paintings. We had to assume that the height of the antenna would affect the ceiling surface during data acquisition. To minimize this effect and take into account a minimum permitted distance to the ceiling paintings, data acquisition was performed with heights based on the centre frequency of the antenna: 10 cm height for the 1.6 GHz antenna and 25 cm height for the 400 MHz antenna. These heights allowed the antennas to be air-coupled to the ceiling to ensure the maximum

possible amount of energy transmitted to the rock mass and to reduce air-coupling effects to obtain accurate and quality GPR records [68].

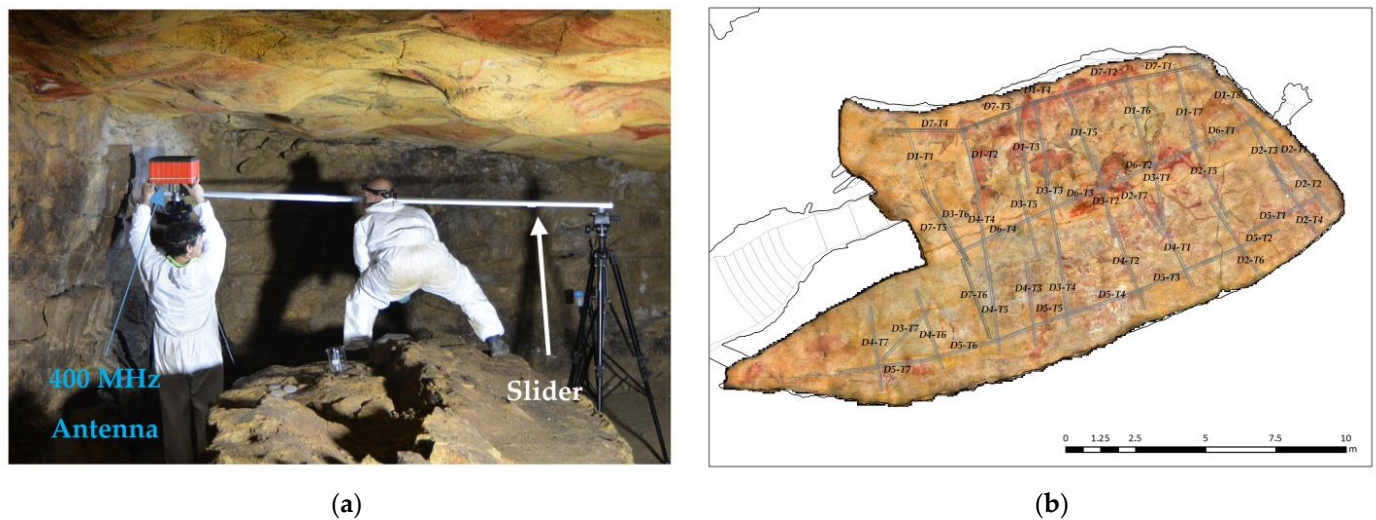


Figure 5. (a) Photograph showing the slider device used for GPR profiling. (b) Locations and names of the GPR profiles were measured using the 900 MHz and 400 MHz antennas projected on the Polychrome Hall ceiling where the central fracture and the Palaeolithic paintings on its surface were observed.

2.2.2. Data Processing

Velocity Estimation

Several hyperbolic reflections are present in different GPR profile sets measured in the ceiling area. The hyperbola fitting method was used to determine the average velocity of the GPR wave, obtaining a value of 0.109 m/ns. Dielectric permittivity (ϵ) was calculated as 7.5 using the simplified equation for low-loss media [64]:

$$v = \frac{c}{\sqrt{\epsilon_r}} \quad (1)$$

where v is the electromagnetic wave velocity and c is the velocity of light in free space ($c \approx 0.299$ m/ns).

Velocity variations are present in rock masses with discontinuities. Although measuring a single velocity value for data migration is not an optimal procedure, this value was considered acceptable after evaluating the disposition of some diffractions and observing coherence between the thicknesses of geological levels mapped at different depths in the radargrams obtained and those in earlier studies, both on the surface of the thickness of the overlying layer and on the Polychrome Hall ceiling [8,10,11]. This velocity value was used to calculate thicknesses and depths in the carbonate layers based on the parameters of each of the 400 MHz and 900 MHz antennas (Table 1). This average velocity was also used for processing the 2D GPR data in the Kirchhoff migration.

Processing Flow

Several post-acquisition radar signal process techniques can be used for GPR datasets based on proposed goals. The RADAN 7.6 software (Geophysical Survey Systems, Inc., GSSI, Nashua, NH, USA) was used in this study. The main phases for processing the GPR raw data (Figure 6) were:

The first phase is the 1D treatment consisting of the following points:

1. As in our case, when the RADAN processing software is used, the initial component of the DC signal—also known as DC shift—as well as the low-frequency trend, is

automatically removed. The DC shift is usually the first processing step/filter applied to the data after acquisition [66].

2. Zero-time correction (zero-time adjustment) is applied to remove the delay time in the first reflection to correct for the effect of the distance between the transmitting (T) and the receiving antennas (R) and possible variations in the arrival time of the direct waves. In the second phase, 2D processing was applied to the profiles based on the following points:
 1. Background filtering was applied to remove the average values on all traces on the horizontal axis (horizontal bands) based on the antennas used. The average of all traces was calculated by averaging all traces in the profile and subtracting them from each trace starting at time zero.
 2. Various bandpass filters were applied depending on the centre frequencies of the antennas used to remove high and low-frequency noise in the vertical and horizontal directions.
 3. Linear amplitude gains were applied to compensate for amplitude reduction due to the filters run. This allowed for the highlighting or enhancement of certain amplitudes.
 4. Kirchhoff migration was applied to the profiles using the calculated average velocity (0.109 m/ns) to move the reflectors to their true subsurface positions.
 5. Time-to-depth conversion was performed for the rock mass based on a calculated average velocity of 0.109 m/ns.

Table 1. Comparison of parameters of the 400 MHz and 900 MHz antennas used on the Polychrome Hall ceiling.

Parameter	400 MHz Antenna	900 MHz Antenna
Central Frequency	400 MHz	900 MHz
Frequency Range	250–600 MHz	600–1200 MHz
Wavelength in air	0.75 m	0.33 m
Wavelength ($\epsilon = 7.5$)	0.306 m	0.136 m
Minimum resolution ($\epsilon = 7.5$)	0.099 m	0.044 m
Estimated maximum depth ($\epsilon = 7.5$) $N = 20$.	1.026 m	0.456 m
Estimated maximum depth ($\epsilon = 7.5$) $N = 100$.	5.13 m	2.28 m
Ground Conditions	Less affected by challenging conditions.	Moderate attenuation under these conditions.
Advantages	Deep penetration, versatile.	Balanced depth and resolution.
Disadvantages	Lower resolution, less suitable for shallow applications.	Reduced depth compared with 400 MHz.

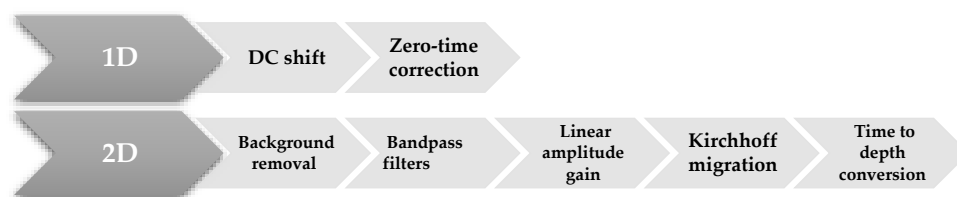


Figure 6. Flowchart of the main processing steps applied to raw reflection GPR data in this study.

3. Results

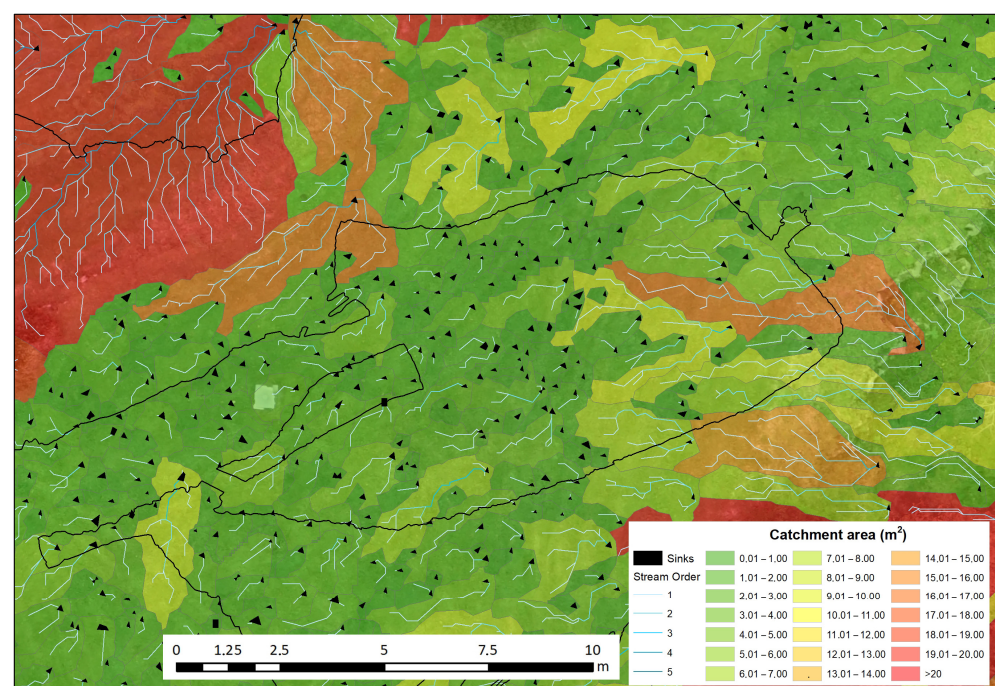
3.1. Polychrome Overlying Layer Hydrology

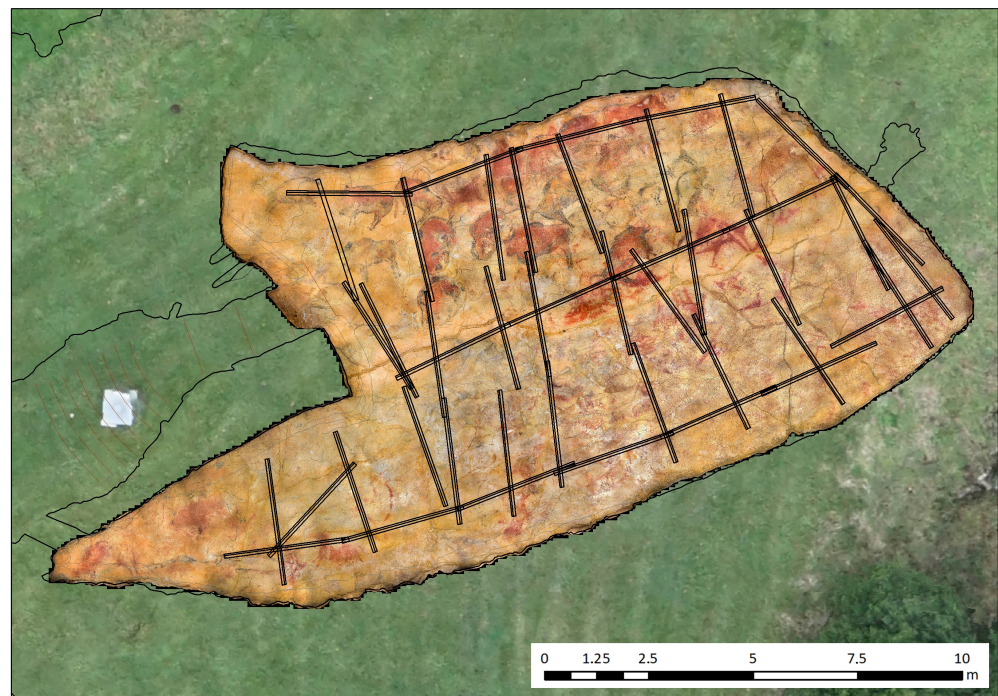
A series of hydrology tools have been used to model the flow of surface water from the DEM generated with the UAV. The aim is to understand how surface water flows in the area near the Polychrome Hall and to identify possible sinkholes through which water enters the system as well as the layout of the different streams and the extent and shape of the catchment basins.

The Polychrome Hall ceiling orthoimage [56] provides information on the parts of the ceiling that were washed by water in the past and sealed by calcium carbonate, and the areas that are still actively leaking (Figure 5b).

Hydrological tools are used to simulate the movement of water over surfaces. In the area overlying the Polychrome, water flows have been modelled to understand the origins, pathways, and destinations of water (Figure 7a,b). For this purpose, layers were generated using QGIS software [74] for these parameters [75,76]:

- **Drainage Basins:** Drainage basins, also known as watersheds, are areas of land from which all surface water flows into a common outlet such as a river. These basins are delineated by the topography of the land, with higher elevations forming the basin boundaries.
- **Catchment Basins:** Catchment basins follow the same concept as drainage basins. They are the geographical areas that contribute runoff water to a single point, usually a river or stream.
- **Flow Direction:** Flow direction in hydrology and GIS refers to the direction in which water flows across the terrain. It is a crucial part of modelling the movement of water in a digital environment.
- **Watercourses:** Watercourses are natural or man-made channels through which water flows.
- **Flow Accumulation Zones:** Flow accumulation zones are areas within a watershed where water from surrounding areas converge. These areas are typically identified by analysing the terrain and the direction of the flow of water.
- **Flow Distance:** Flow distance is the distance water travels along the terrain to reach a specific point downstream.
- **Sinks:** In hydrology, sinks are depressions or low points in the terrain where water can accumulate. These are especially interesting for our case study because they represent the points where all the captured water is introduced into the limestone package.
- **Strahler Method for Watercourse Classification [77,78]:** This is a technique used to classify the hierarchical order of watercourses within a watershed. In this method, the smallest headwater streams are designated as first-order streams. When two first-order streams converge, they form a second-order stream, and so on. This classification helps to explain the branching structure of a watershed's drainage network.





(b)

Figure 7. (a) Catchment basins classified by area and stream order according to the Strahler method [77] and vertical sinks in the Polychrome Hall. (b). Overlay of the above with the orthoimage and position of the recorded interior GPR profiles.

3.2. Internal Stratigraphy

The reflectors recorded in the GPR profiles of the Polychrome Hall were correlated with the arrangement of the strata as described in the CSIC report [8] on the detailed lithostratigraphic column representative of the layers in which the Polychrome Hall is found based on the type of lithostratigraphic series of the Santillana area [10,79]. The internal stratigraphy (Figure 8), from the ceiling of the Polychrome Hall to the surface, can be summarised as follows [8]:

- Polychrome layer: this limestone layer is about 60–70 cm thick and tapers towards the south. The base exhibits hydroplastic deformation, which is significant as the Palaeolithic paintings are at its base, taking advantage of the hydroplastic deformations' shapes.
- Dolomitic layer: this dolostone layer (10–25 cm thick) displays varying degrees of dolomitization. A thin loamy-clay intercalation separates it from the Polychrome level.
- Fissured layer: a limestone layer, about 1.1 m thick, that is visible throughout the cave. It is recognized by its unique alteration pattern characterized by vertical dissolution morphologies associated with joints.
- Orange layer: this layer consists of thin-bedded limestone (10–20 cm each) with a total thickness between 0.7 and 1 m.
- Upper layer: this layer alternates between calcarenite and limestone, with thin marl interbeds. It has a total thickness of about 2 m.

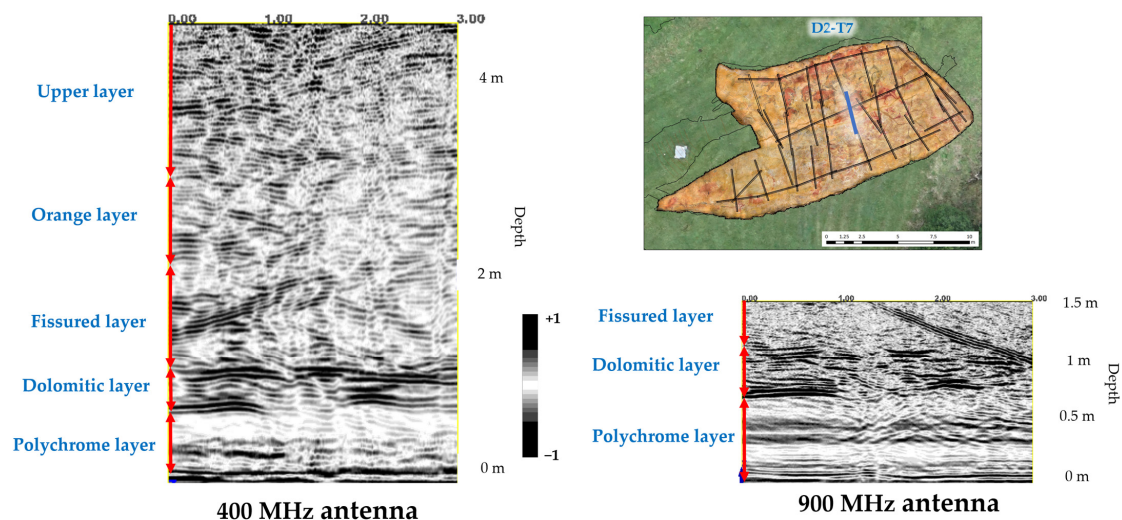


Figure 8. Radar stratigraphic interpretation of the layers overlying the Polychrome Hall (D2-T7 profile). The vertical red arrows indicate the thickness of each layer recorded on the radargram according to the descriptions of the overlying layer thicknesses [8].

3.3. Layer Overlying the Polychrome Hall

The accurate georeferencing of the interior 400 MHz antenna and the exterior 100 MHz antenna made the mapping of the layout and shape of the main vertical discontinuities possible (Figure 9). This mapping is the first evidence confirming that the main vertical discontinuities run from near the surface (Upper Layer) to the basal surface of the Polychrome layer where the prehistoric paintings are located. This implies that there are direct interconnections that facilitate the exchange of fluids between the exterior and the interior of the cave.

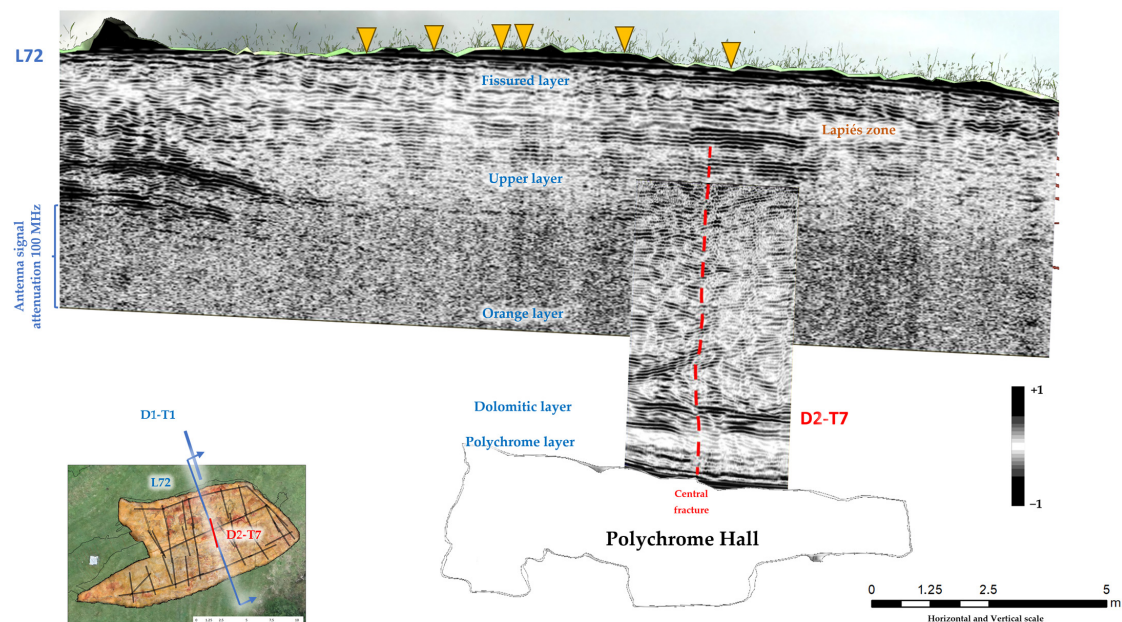


Figure 9. An example of mapping of the main vertical discontinuities obtained via precise georeferencing of the inner reflection profile D2-T7 (400 MHz antenna) and the outer reflection profile (100 MHz antenna). The central fracture goes from the lapiés zone (Fissured layer) to the basal surface of the Polychrome layer (indicated by the red dashed line). The surface sinks that coincide with the layout of these profiles are plotted (indicated by ochre triangles). The signal attenuation zone determined using the 100 MHz antenna and the correlations between both reflection profiles and the stratigraphic units of the layer overlying the Polychrome Hall are also shown.

Among the vertical discontinuities, the central fracture stands out. It runs close to the surface (lapiés area), from approximately 1.4 m depth to the basal surface of the Polychrome Hall, as shown in Figure 9.

Discontinuities in the Dolomitic layer, which is separated from the Polychrome layer by a thin loamy-clay intercalation [8], reduce the degree of waterproofing at the contact of these two layers, thus enhancing dripping on the basal surface (Figure 10b).

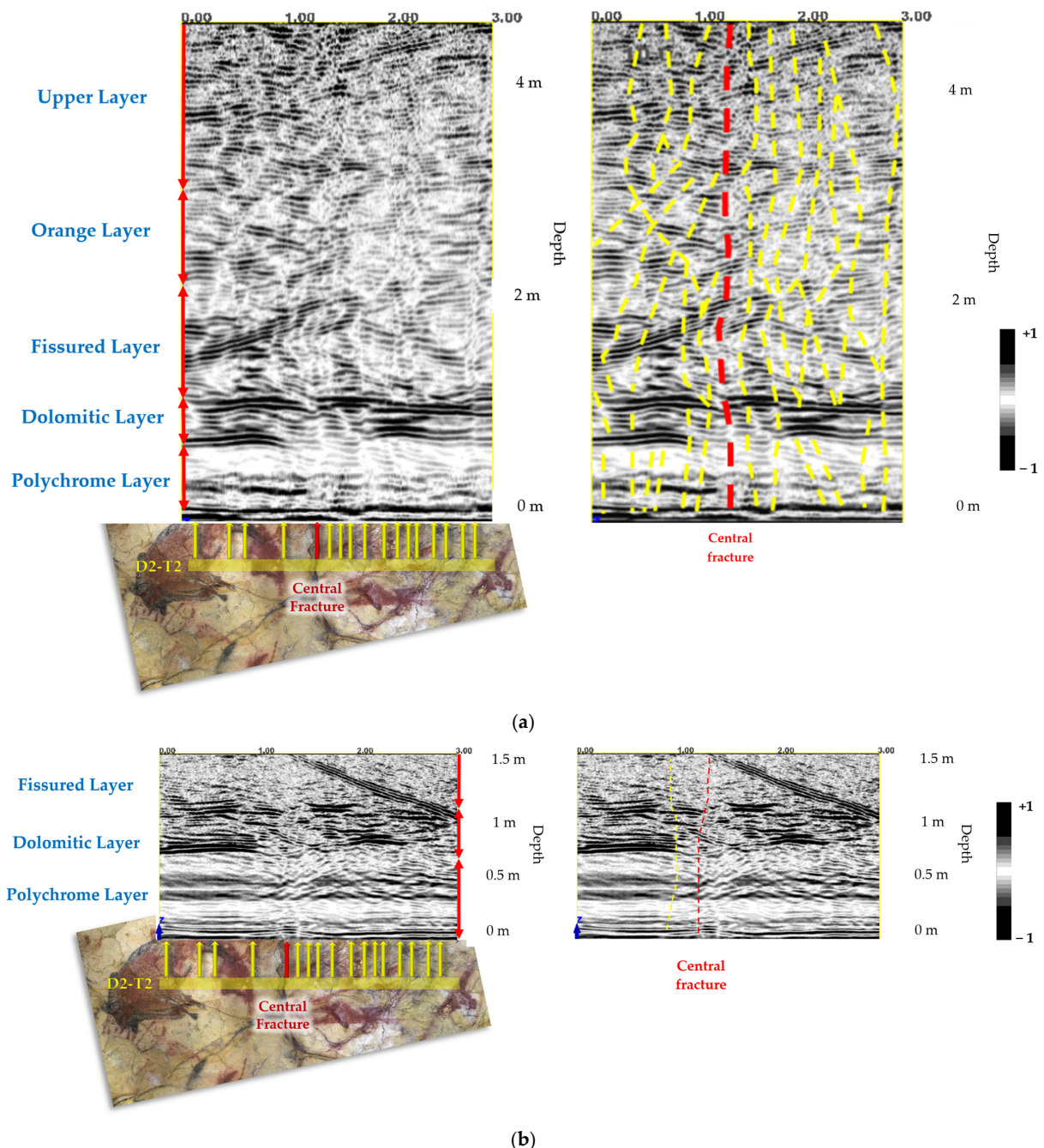


Figure 10. Profile D2-T7 interpretation of the main vertical discontinuities with the corresponding stratigraphy of the layer overlying the Polychrome Hall using (a) 400 MHz antenna and (b) 900 MHz antenna. In each of the two GPR records collected, the following are indicated: the position of the D2-T7 profile projected onto the orthoimage of the Polychrome Hall ceiling is shown using a yellow line; the thicknesses of each recorded layer are indicated by red vertical arrows; the location correlations between the main ceiling fractures and the records of the two antennas used are indicated by yellow arrows and the central fracture is highlighted with a red arrow.

In addition, the presence of internal reflectors has been detected in the Polychrome layer, between 24 cm and 47 cm deep (23 cm thick), in the profiles measured using a 900 MHz antenna (Figure 11). These reflectors may correspond to the internal characteristic of hydroplastic deformation in the Polychrome layer.

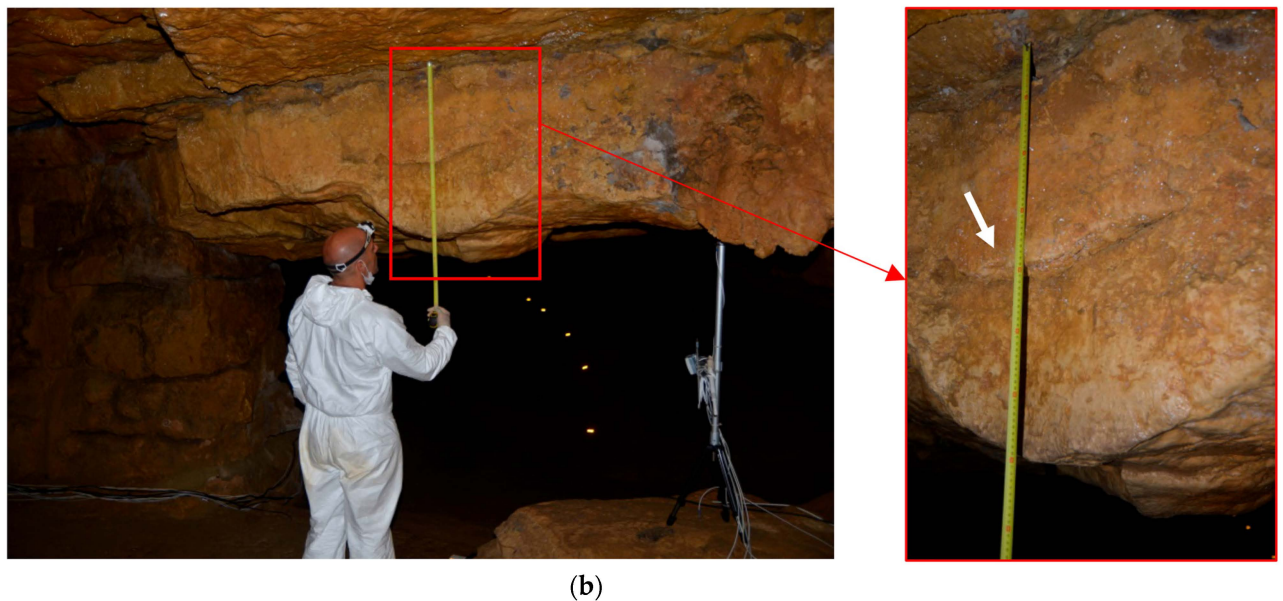
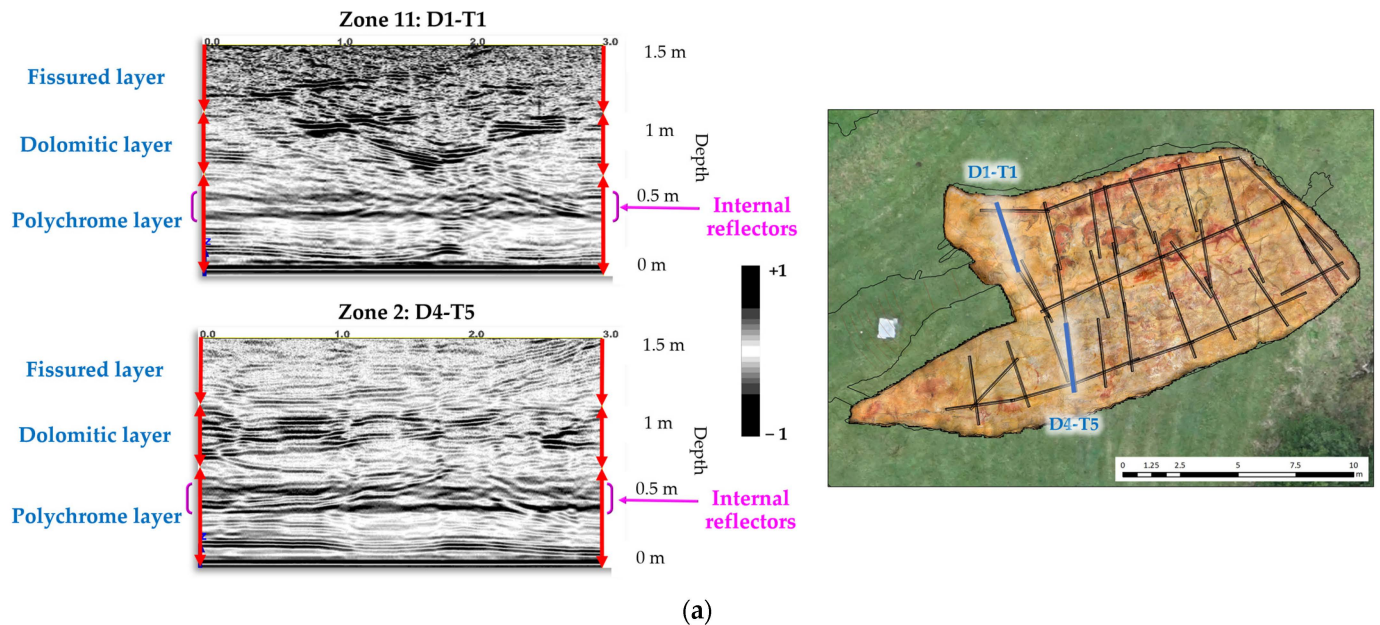


Figure 11. (a) Radar records with their stratigraphic interpretations (profiles D4-T5 and D1-T1, 900 MHz antenna) where the presence of internal reflectors in the Polychrome layer has been indicated. (b) Photographs of the front of the Polychrome layer at the junction before the access stairs to the Polychrome Hall showing (using a white arrow) an area of the front of the Polychrome layer that coincides with the internal reflector detected in terms of depth and thickness from the basal surface.

4. Discussion

The water supply to the Polychrome Hall comes from direct infiltration of rainwater through the fractures. Knowing its regime is fundamental to the conservation of the cave. The availability of a detailed elevation model of the layer overlying the Polychrome Hall has made it possible to use hydrological tools to determine the size of the drainage basins,

watercourses, water accumulation zones, and potential sinkholes through which water enters the underlying layer.

Having an accurate model of the interior and exterior relief of the cave is of vital importance for several reasons. First, the exact location of the strata and the geological features within the overlying layer is essential to knowing the state of karstification of the cave and the causes of the deterioration of the rock art within it. However, it is also fundamental to guarantee the safety of the workers and visitors to the cave since it lets us know and mitigate geotechnical risks such as collapse or subsidence and to establish tracking methods in the areas that require it. In addition, the models make it possible to locate the results of future, present, and even past studies, making it possible to make long-term evolution and strategic decisions on conservation. Finally, in environmental terms, these models help with the evaluation of the impacts of human activity on the conservation of the cave, making it possible to propose effective environmental and preventive conservation mitigation measures.

The results of this study have confirmed the existing interconnection between the exterior and interior environments of the Polychrome overlying layer, mainly due to the existence of vertical fractures that run from the exterior surface to the ceiling, as is the case for the most significant central fracture. These vertical fractures interconnect different discontinuities (fractures, joints, detachments, and stratigraphic planes) that lead to the circulation of gases and the infiltration of water via fracturing and/or open joints, i.e., there are interconnections between the discontinuities in the quarry through which processes of infiltration and fluid circulation and exchange occur between the cavity (Polychrome Hall) and the outside.

Using antennas with 400 MHz and 900 MHz frequencies inside the Polychrome Hall let us map the main discontinuities and develop a detailed description of the internal stratigraphy in the geological environment near the basal surface where the prehistoric paintings are located. Disruptions within the Dolomitic layer are a clear sign of alterations or disintegration, decreasing the waterproofing effect, segregated from the Polychrome layer by slim intercalation of loamy-clay, diminishing the waterproofing effect at the juncture of these two strata. This amplifies droplet formation on the lower surface.

Thus, the GPR dataset has shown that the spatial arrangement of discontinuities in the layer overlying the Polychrome Hall is complex. For further analysis of the conclusions obtained in this study, it would be convenient to conduct a 3D GPR study, reducing the distance between the profiles of the ceiling either in certain areas or in its entirety. This would have a significant impact on the cohesion of data associated with the zonation of wetting in the lithological levels, the internal structure of the central fracture, filling/opening processes of discontinuities (fractures/joints), relationship of the fracturing of the Dolomitic layer with drip points and the network of basal microchannels, and condensation processes, among others.

5. Conclusions

The periodic control to which areas of the ceiling of the Polychrome Hall are subjected has made it possible to detect and record direct alterations in the paintings associated with the washing and erosion by the dissolution of its mineral parts. Scanning Electron Microscopy (SEM) shows detachments of particles of millimetric order that tell us about flaking, disintegration, disaggregation, or loss of cohesion. This loss of adhesion of the pigment to the support is associated with the physical–chemical features of water, which incorporates CO₂ and other nutrients from the soil [8] to the surface of the ceiling through the outer soil cover, partially dissolving the limestone rock [8].

In summary, one cause of the fall and loss of pigment is the partial and/or selective dissolution of the surface of the limestone support of the painting associated with the physical and chemical features of one of the most important agents of alteration [9] present in the Polychrome Hall: water.

A GPR survey lets us promote a study of the microenvironmental dynamics in relation to the processes involved in the CO₂ fluxes between the cave and the exterior.

Continuing with this analysis and focusing on other possible causes of the loss of pigment that could cause acceleration in the dragging and washing of paint, it is worth noting the presence, not constant or permanent, of more surface moisture as small laminar flows of water concentrated in the central part of the ceiling of the Polychrome Hall on both sides of the central fracture, about 70 cm in both north and south directions.

The combination of GPR and geomatics techniques carried out in the Altamira cave, both from the top and from inside the Polychrome Hall, have shown that the central fracture has a vertical development that begins on the surface (lapiés zone) near the Polychrome Hall ceiling, giving the central fracture an average dimension of about 7.5 m in depth, constituting a direct water access route.

It will be interesting, in the future, to evaluate the state of the overlying layer from the dolomitic level to the Polychrome level using a reliable and non-destructive solution based on a higher frequency GPR antenna in the range of 1 GHz–2 GHz. The objective will be a high-resolution 3D survey to determine the trajectory followed by water from the dolomitic layer to the Polychrome layer, allowing the calculation of thicknesses and identification of the existence of possible voids, zones of presence/absence of water, cracks, and fractures.

This conservation work has a priority objective that is crucial to maintaining the cave and the art it houses in the best possible condition. The valuable information obtained through these geophysical prospecting studies combined with geomatics techniques deepens our knowledge of the causes of deterioration, which are still active today, to establish lines of research that will help us reduce the risks of deterioration and reduce or slow down its impact on the art in the cave.

The study presented here enhances our understanding of the dynamics of the water that has accessed and continues to access the Polychrome Hall's ceiling. It, along with related research on water dynamics, enables the development of a conservation strategy focused on putting indirect measures into practice to proactively prevent damage by eliminating the risk of alteration through the avoidance of water's solvent effect on the rock art. Detailed knowledge of water pathways allows for indirect interventions to divert specific water flows responsible for carrying away small pigment particles due to occasional water drips.

However, due to the complexity of Altamira's conservation challenges, which are largely influenced by anthropogenic factors, there is no alternative conservation strategy but to maintain maximum internal microenvironmental stability, reducing material and energy exchange rates. Our efforts, through this study, are geared towards determining the speed of alteration processes and trying to slow them down.

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Publicación 3: Multisensory Analysis of the Moisture Course
of the Cave of Altamira (Spain): Implications for Its
Conservation

Article

A Multisensory Analysis of the Moisture Course of the Cave of Altamira (Spain): Implications for Its Conservation

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Abstract: This paper addresses the conservation problems of the cave of Altamira, a UNESCO World Heritage Site in Santillana del Mar, Cantabria, Spain, due to the effects of moisture and water inside the cave. The study focuses on the description of methods for estimating the trajectory and zones of humidity from the external environment to its eventual dripping on valuable cave paintings. To achieve this objective, several multisensor remote sensing techniques, both aerial and terrestrial, such as 3D laser scanning, a 2D ground penetrating radar, photogrammetry with unmanned aerial vehicles, and high-resolution terrestrial techniques are employed. These tools allow a detailed spatial analysis of the moisture and water in the cave. The paper highlights the importance of the dolomitic layer in the cave and how it influences the preservation of the ceiling, which varies according to its position, whether it is sealed with calcium carbonate, actively dripping, or not dripping. In addition, the crucial role of the central fracture and the areas of direct water infiltration in this process is examined. This research aids in understanding and conserving the site. It offers a novel approach to water-induced deterioration in rock art for professionals and researchers.

Keywords: data integration; mapping; karst system; rock discontinuities; cultural heritage; rock art; preventive conservation; geomatics; ground penetrating radar; cultural management



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1. Introduction

The conservation of rock art caves is a critical part of preserving cultural heritage, offering insights into ancient civilizations. In the global realm of cultural studies, this endeavor intersects with geophysics, geomatics, and remote sensing technologies. Geophysics methods such as Electrical Resistivity Tomography (ERT) using a pole-dipole array, coupled with local rainfall analysis, discern underground water storage zones like recharge areas, aiding in cave environment monitoring non-invasively in France's Lascaux Cave complex [1]. Ground Penetrating Radar (GPR) has been used to preserve painted caves [2] and their conservation condition [3,4]. Geomatics tools like GIS and photogrammetry support the creation of detailed maps and 3D models, as seen in Australia's Murujuga rock art [5,6], helping in conservation planning. Additionally, remote sensing techniques, including satellite imagery and drones, provide expansive views, helping monitor sites like Bhimbetka Rock Shelters in India [7,8], enabling distant assessment and safeguarding against environmental degradation or human impact.

The cave of Altamira is a masterpiece of universal art, an exceptional testimony of a vanished cultural tradition, landscape, and a technological ensemble that illustrates, like

few others, a significant period in the history of mankind. For this reason, it was inscribed on the UNESCO World Heritage List in 1985.

It is in Santillana del Mar (Cantabria), which is in the North of the Iberian Peninsula (Figure 1) and has an irregular shape of about 290 m, where galleries open, including the famous Polychrome Hall, where its well-known bison were drawn [9,10].

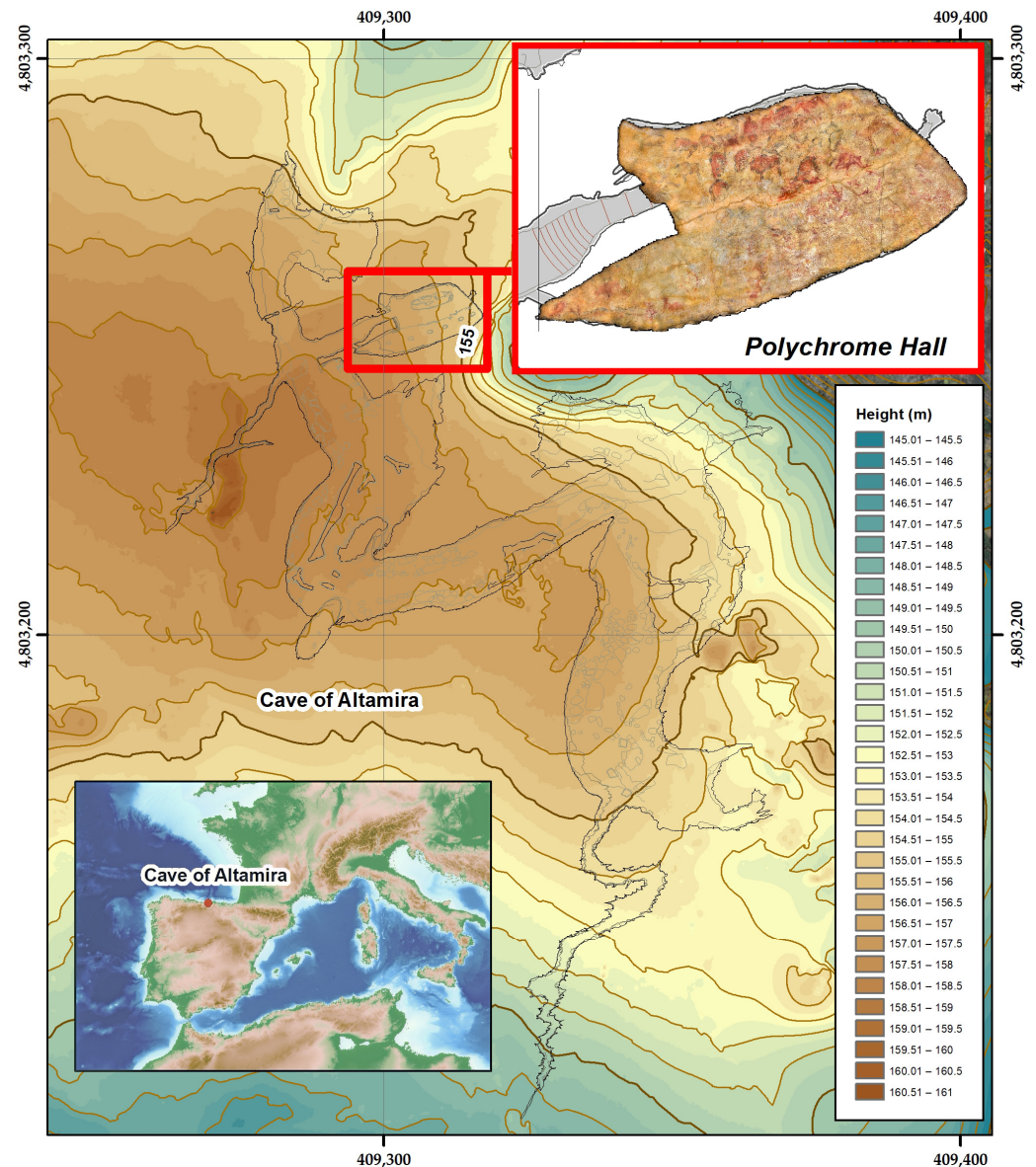


Figure 1. Location and map of the surroundings of cave of Altamira where the outline of the cavity is projected onto the surface (shown by a black line). It is also shown highlighting the orthoimage of the ceiling of the Polychrome Hall where the cave paintings are located.

Many of its paintings show substantial conservation due both to the low rate of water infiltration generated by the geological tabular structure of the cave and its stable microclimatic conditions due to its natural closure [11], which took place 13,000 years ago.

1.1. The Cave of Altamira Geographic Setting

1.1.1. Climatic Context

The climatic environment at the cave of the Altamira site is defined by a Cfb climate according to the Köppen classification, which is classified as oceanic or Atlantic and is characterized by being temperate and humid with no dry season and mild summers. Exten-

sive measurements of microclimatic parameters, including temperature and precipitation, have been made outside the cave. These studies have provided a better understanding of the environmental conditions affecting the cave, using instruments such as rain gauges and sonic anemometers to measure precipitation and wind speed and tests to evaluate the thermal effect of the exterior door. The external temperature mainly determines the temperature distribution inside the cave through the surrounding rock mass, and its behavior shows marked seasonal variations, with the warmest months being July and August and the coldest months being December, January, and February.

The recent average outdoor temperature stands at 14.6 °C, with an average range of 8 °C. Monthly temperatures follow a pseudo-sinusoidal pattern, with summer (July–August) being the warmest and winter (December–January–February) the coldest. The relative humidity is consistently high, ranging between 80% and 90% throughout the year, with fluctuations between 30% and near 100%. Typically, summer months exhibit higher specific humidity, while winter months hit the lowest annual levels. The annual accumulated precipitation is around 1300 mm, typical for a rainy region, mainly falling in autumn/winter [12].

Regarding CO₂ concentration in external air—a significant gas affecting cave preservation—it fluctuates monthly, averaging between 400 and 500 ppm without a distinct pattern, unlike inside the cave [13]. Gaseous exchange within the cave, focusing on CO₂ and radon variation, shows seasonal behaviors influenced by thermal gradients between indoor and outdoor environments, alongside moisture saturation in the surrounding rock's cracks and fissures. This exchange is more active in summer and less so in winter, with transitional periods in spring and fall. External humidity remains high, 80% to 90%, throughout the year, while precipitation, about 1300 mm annually, concentrates mainly in autumn and winter, shaping the meteorological conditions that affect Cave of Altamira's behavior and conservation.

1.1.2. Geology of the Cave

The cave of Altamira exhibits several lithological units in its interior, identified and mapped according to the terminology of [14]. Comparatively, many levels have been recognized on the exterior, which is evident in the interior, along with external alteration patterns, providing clues to identify these patterns at greater distances from the entrance. Detailed geologic mapping of the surrounding area has allowed us to characterize the hydrologic conditions and geologic geometry, both at the surface and in the subsurface next to the cave. These studies reveal a complex stratigraphy, highlighting formations such as the Ojo Negro, San Esteban, and Altamira, where the latter is important to delimit units of cavity development and the strata that host the prehistoric paintings.

In detail, the Ojo Negro formation comprises Lower Cenomanian dolomitized calcarenites [15], being considered the basal unit. The San Esteban Formation, 26 m thick, consists of three identifiable units, while the Altamira Formation, dated to the middle-upper Cenomanian [16], hosts the Altamira karst complex, being fundamental to define the cavities and strata where the prehistoric paintings have been made [17]. The Cave of Altamira is developed in this formation. Several layers have been identified, such as the Polychromes and the Brown, with particular paintings and geological features, letting us understand their formation and relationship with the cave paintings.

However, the structural geology and geomorphology of the cave of Altamira show a limestone hill with a slight slope close to a horizontal monocline. The area exhibits stratigraphic units affected by subvertical faults with slight movements distributed in different directions. In addition, a connection between the dolines and the fault network is seen, with sinkholes aligned parallel to the fault planes, suggesting the influence of the faults on the current karst activity. Landslides are also common in the area, particularly in areas near the dolines, evidencing erosion phenomena and soil and rock displacements.

1.1.3. Previous Microclimatic Monitoring Investigations Conducted in the Cave

The monitoring studies of microclimatic conditions carried out in the Cave of Altamira have provided detailed knowledge of the environmental conditions inside the cave and how they impact the preservation of the cave paintings [18–22]. Specifically, continuous monitoring of various microenvironmental parameters has been conducted, such as temperature at different heights, the temperature of the rock substrate, air relative humidity, the concentration of CO₂ and ²²²Rn in the indoor air, atmospheric pressure, and wind speed inside the cave.

The results have enabled the identification of preservation variables, both from the natural dynamics of the cave and anthropogenic factors that occasionally contribute material and energy, inducing changes in the cave's natural physicochemical and biological conditions. Among these variables, the concentrations of CO₂, and to a lesser extent ²²²Rn, inside the cave are relevant. The cavity's connection with the outside in the gaseous phase shows its highest magnitude during summer, favoring material flow between the exterior and the interior of the cave. But during the winter period (November to May), there is an almost complete cessation of interconnection with the exterior in the gaseous phase, helping to concentrate these gases.

Another significant factor inducing deterioration processes in the cave paintings is undoubtedly the infiltration of water entering the cave through major fractures and fissures. Additionally, water vapor condensation decisively contributes to increasing relative humidity and triggers microcorrosion processes of the rock supporting the paintings.

The microclimatic monitoring studies conducted in the Cave of Altamira have provided detailed insight into the environmental conditions inside the cave and their impact on the conservation of the cave paintings. They have identified the primary sources of moisture in the cave, which is essential for implementing preventive conservation measures to reduce the effects of all these deterioration factors involved in the natural dynamics of the cave and its paintings.

1.1.4. History of Previous Interventions

The history of interventions in the Cave of Altamira during the 20th century reveals significant changes that have affected its conservation. These actions, although they did not include direct restoration of the paintings, harmed the natural environment of the cave and its rock art [23–25]. Notable among these alterations were the installation of an entrance door, the construction of artificial walls, the filling with cement of the crack in the ceiling of the Polychrome Hall, and the addition of an artificially illuminated central corridor to facilitate public access.

The scientific community became concerned about the condition of the paintings in the 1970s, especially the discoloration observed in some representations. The increase in the number of visitors drastically affected the environmental conditions, causing a decrease in relative humidity and an increase in temperature and carbon dioxide in the cave. This led to the closure of Altamira in 1977, and it was later reopened with a visitor regime limited to 8500 visitors per year. However, subsequent research showed that even this limited number of visitors generated conservation problems in the limestone rocks and cave paintings.

After the temporary closure in 2002 due to the detection of cyanobacteria linked to artificial lighting, a more in-depth analysis of the state of conservation was undertaken. Studies by the CSIC showed that the changes made over the years had transformed the natural ecosystem of the cave, allowing the proliferation of bacteria and processes of dissolution of the rocks. In addition, the human presence associated with the emission of CO₂ and condensation processes accelerated the deterioration of the limestone rock and the paintings. These facts emphasize the need to base conservation actions on scientific knowledge to reduce the negative impact of tourism on cultural heritage.

1.2. Previous Studies

Such is the fragility of this cave that, geologically, it is, so to speak, at the end of its life, as many studies have shown. An important network of fissures, fractures, and displacements from the top of the cave to the cave ceilings themselves affects its stability and determines important changes in the circulation of infiltrating water, which generates processes of concretion, microcorrosion, dissolution, and the dragging of paint. Water infiltration with the condensation water and CO₂ concentrations are the main problems for the conservation of the paintings. To address this problem, an intervention was carried out to try to reverse the infiltration of rainwater through the network of fissures and fractures in the cave. This intervention made in the decade of the 1920s consisted of filling the central fracture and other fractures with hydraulic mortar on the ceiling of the Polychrome Hall and with cement on the outer surface of the lapiés [26].

Besides this, anthropic factors continue to be the main threat to its conservation. The many internal and external changes this cave was subjected to after its discovery generated a radical change in its environmental dynamics and made it possible for a lot of nutrients to enter by infiltrating the water, something that led to the proliferation of bacterial and fungal colonies.

The most worrying factors within the conservation of caves have to do with deterioration processes related to water, geology, biodeterioration, and human presence [26–28]. To understand their dynamics and reduce the alterations they generate, it is important to develop effective conservation strategies aimed at controlling harmful agents such as temperature, humidity, and CO₂.

CO₂, along with water, plays an important role in the dissolution and entrainment processes of the supporting rock (Figure 2). We are concerned with various deterioration processes, including microcorrosion, adhesion loss, cracking, washing, and loss of support. These processes have been in motion since the cave's inception and continue to this day. It is important to emphasize that these deterioration processes start from the moment the Altamira art was crafted.

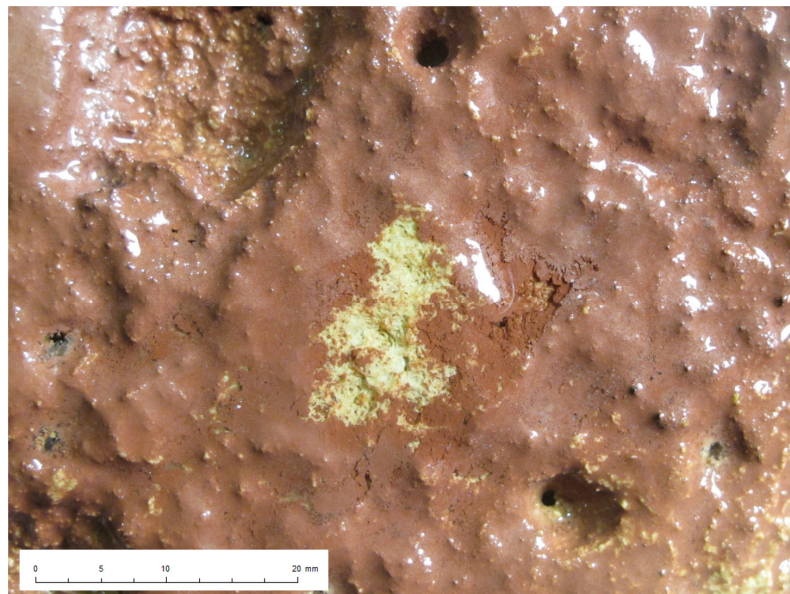


Figure 2. Image showing the microcorrosion of the supporting rock and the craquele of the pigment. Note that white areas are produced by light glints so no information is available.

Knowing and studying the underlying dynamics of these processes associated with paint loss from washing in active drip areas is essential to design strategies to control each agent of alteration and the interactions between them.

The only guarantee of long-term preservation must be through the control of these agents of deterioration, humidity, temperature, and CO₂. Future conservation measures have to consider all these factors in an unstable preservation environment. In this sense, these studies are focused on integrating data that allow the creation of a first approximation of the hydrogeological model [29–32] of the Polychrome Hall overlying layer.

These models are a mathematical and conceptual representation of a groundwater system used to understand, simulate, and predict aquifer behavior [33–35]. These models are essential for groundwater resource management, as they allow for characterizing the aquifer, simulating groundwater flows, assessing water quality, evaluating environmental impacts, and planning long-term water resource management. A hydrogeological model is an essential tool in the management and conservation of groundwater and groundwater resources, as it allows understanding and predicting the behavior of aquifers and making informed decisions on their use and management [36–39].

Losing adhesion of the pigment to the support is related to the physical and chemical features of the water, which incorporates CO₂ and other nutrients from the soil [24] to the surface of the roof through the outer soil cover, causing the partial dissolution of the limestone rock and giving rise to the formation of small interconnected depressions of millimetric or centimetric size that, like a hydrographic network, act as a vehicle for transporting both the paint itself and carbonates, salts, clays, small fragments of quartz and dolomite, as well as other products, dragging them to the different drip points [40].

In the framework of our ongoing GPR geophysical investigations in the cave of Altamira [41,42], using time-domain radar data processing, moisture zones and discontinuities (fractures, fissures, detachments, stratification planes, joints, voids) were mapped in the overlying layer of the Polychrome Hall. This mapped set of moisture zones and discontinuities configure the connecting pathways of matter and energy exchange between the exterior surface and the interior of the Polychrome Hall. These pathways contribute to the dripping and exterior-interior gaseous exchange processes of the Polychrome Hall. Furthermore, the results revealed that the internal rock structure of the overlying layer of the Polychrome Hall is complex with zoned internal singularities.

To understand the hydrogeologic model of the Polychrome Hall, it is necessary to integrate three key elements to understand the potential flow of moisture.

- **Surface Model:** obtained by drone photogrammetry to generate a 2 cm ground sample distance (GSD) model of ground elevation. This model is analyzed to obtain the sinks. A sinkhole in hydrology refers to a geologic or structural feature that acts as a drainage point for water flow in a hydrologic system. Sinks play an essential role in the water cycle by letting surface water flow into the subsurface.
- **Overlying thickness model:** The digital processing of GPR data is generally based on the amplitude values of the signal for interpretation. Time domain radar data thus consist of back-scattered signals from the subsurface and the signals can be defined as plots of time versus amplitude of the reflected electromagnetic pulses. In addition, the transformation of GPR data into its instantaneous magnitude, phase, and frequency information is an alternative way of processing GPR data. The Hilbert transform is used to express the relationship between the magnitude and phase of a signal or between its real and imaginary parts. This transform reconstructs the phase of a signal from its amplitude. A comprehensive mathematical description of the attributes of GPR data can be found in [43–47]. The Hilbert transform can be successfully applied to complex subsurface rock structures to enhance the reflection and absorption contrast of the electromagnetic wave in a geological medium. As a result, GPR attributes can often uncover or highlight features or patterns that are not evident in standard amplitude data [48–51].
- **Polychrome ceiling model:** In 2014, a photogrammetric campaign was conducted to document the ceiling of the Polychrome Hall. This effort aimed to achieve a sub-millimeter resolution level, distinct from the laser scanning process [52]. High-resolution digital elevation models (DEMs) with 200 microns GSD were generated

for the cave's ceiling. By integrating hydrological data, this approach allowed us to simulate capillary pathways and identify critical mass points where water eventually drips to the cave floor. Moreover, the modeling process could consider various factors, such as the geological properties of the ceiling material and its permeability.

The model was used to calculate the drip points and possible water courses based on the existing fractures. Knowing the water leak points is important because they are the end of the water flow path and the place where small particles, fungi, bacteria, and paint carried by the water could fall to the ground.

Once the three models have been integrated, it is possible to interpret them together and make sections of them to understand the course of the water flow. The paper deals with how to determine the main moisture/water courses in the Polychrome overlying layer, as well as its particularities due to the karstification of the ceiling (fractures, voids, calcification, condensation, etc.). In this study, the use of Hilbert transform attributes in GPR interpretation aims to increase the knowledge of the internal geometry of the karst rock mass overlying the Polychrome Hall and thus characterize the electromagnetic response of the presence of moisture and water zones in its overlying carbonate rocks.

2. Materials and Methods

The formation of caves arises from the complex interplay of chemical reactions, geological phenomena, tectonic forces, and atmospheric influences on limestone rock, gradually dissolving it. This paper shows an innovative approach that employs five remote sensing techniques to comprehensively analyze various facets of cave systems. The proposed method incorporates the characterization of the exterior surface of the cave, the cave, Polychrome ceiling, and the overlying layer. By integrating these five remote sensing techniques, a holistic understanding of the cave environment is achieved, enabling researchers to track the details of the karst system. This multifaceted approach goes beyond conventional cave exploration by providing a nuanced perspective on the exterior morphology, interior dynamics, artistic features on the cave ceiling, and the overall health of the overlying layer. This method gives researchers the means to anticipate ceiling drips, an important part of preserving caves and their cultural or geological significance. The union of these remote sensing techniques stands as a promising avenue for advancing our understanding of cave systems and putting proactive measures into practice for their conservation [53], as shown in Figure 3.

2.1. General Workflow Diagram

Integrating data into the model initiates with the establishment of a reference frame, a task accomplished using the accuracy of the Global Navigation Satellite System (GNSS) [54], a globally spanning satellite network technology [55]. Back in 2013, the TOPCON Hyper II receivers [56] were used to create a geodetic reference system, aligning with the European Terrestrial Reference System 1989 (ETRS89). The assessment of observed phase changes, executed with Topcon Tools software [57], resulted in a reference frame boasting an average accuracy of 1.7 cm when determining the coordinates of exterior cave vertices.

The significance of maintaining a highly precise cartographic model of the cave manifests when projecting knowledge-based models that rely on georeferenced parameters, encompassing aspects such as microbiological, climatic, hydrochemical, geomorphological, and geophysical data [58].

Once the reference frame was established, a surface model was obtained by drone photogrammetry to generate a 2 cm (GSD) model of ground elevation. To reach this resolution, a flight plan was made to obtain measurements throughout the entire cave's overlying layer (40 Ha). Over 4800 pictures were taken, 52 Ground Control Points (GCP) were measured with RTK-GNSS to reference the flight, and another 40 points were measured for quality control. The mean error of the control points was 1.76 cm [41].

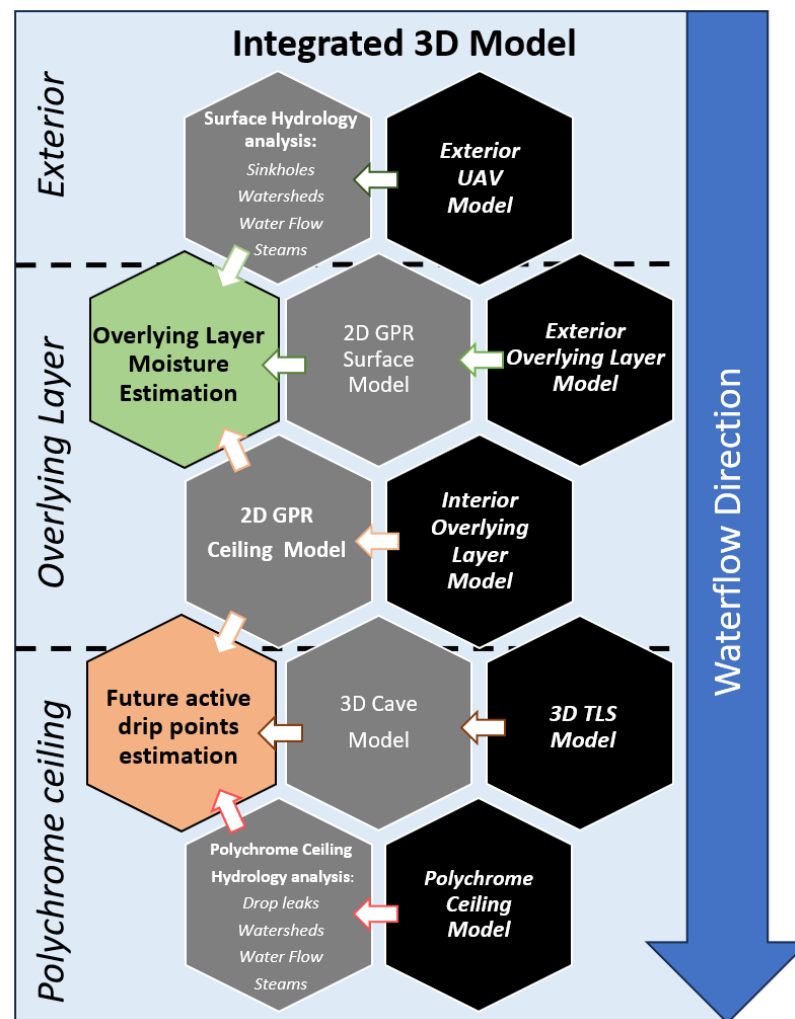


Figure 3. General workflow scheme followed in this study (adapted from [41,42]). The black hexagons indicate the integrated models, the gray hexagons the analysis performed on the models and the colored hexagons the analysis performed from the previous ones.

Earlier in 2014, a photogrammetry campaign was conducted to document the Polychrome Hall ceiling [52], complementing the laser scanning process and achieving sub-millimeter resolution documentation. The Hasselblad H4 D-200 MS camera, capable of capturing true R-G-B color, was chosen given its suitability for both geometric accuracy and color analysis. Equipped with HC 3.5/35 and HC 4/28 lenses, this camera captured frames at a resolution of 8176×6132 pixels. A minimum resolution of 16 pixels/mm² was set, with an illumination system comprising two 4800 Kelvin-degree LED flat screens, each providing an illuminance of 980 lux and covered with a Rosco Cinegel 3000 Tough Rolux plastic diffuser.

The photogrammetric support involved the detection of homologous points extracted from the 3D laser scanner's point clouds. Eighty evenly distributed points were strategically placed throughout the hall, with half serving as control points for model validation. These images were collectively adjusted, leading to the generation of a high-density point cloud containing about 11 billion points. This massive dataset was filtered and generalized to produce another point cloud containing around 3.5 billion points. From this refined dataset, a high-resolution 3D digital model of the ceiling was generated, boasting about 200 million polygons. This model was used to create a 6 Gigapixel orthoimage and a simplified version with 4 million polygons, which facilitated seamless integration.

Once the geometric models are available, hydrology calculations are performed since they play a critical role in understanding the dynamics of water movement across the overlying layer and Polychrome ceiling surface. The paper explores the methodologies and results of a hydrological analysis performed to model water flow in two very different scenarios. The top of the Polychrome Hall is located above the maximum level of influence of possible lateral contributions of water infiltrating into the karst from topographically higher areas so that the water supply is produced by direct infiltration of rainwater through the fractures and hair cracks [27,28]. It is at the uppermost region of the overlying layer, within the initial centimeter, where the water moves on the surface, where the drains through which the water can enter are located. The objective is to find the sinks through which water can potentially enter the overlying layer towards the Polychrome Hall.

Secondly, the overlying layer, where the thickness of the bedrock does not exceed nine meters, with the thickness of the superficial soil cover varying between 10 and 30 cm. The most superficial rock layer shows some brecciation and dissolution effects, with accumulations of clays and other minerals (dolomite particles). There is a high degree of decompression, both in the Polychrome Layer itself and in the overlying brown, wedge, and orange layers. Another factor modifying the structural characteristics of the bedrock is the sealing performed in the decade of the 20–30 s of the last century with Portland cement of the surface fractures of the ceiling of Polychrome, which presumably were the direct route of rainwater percolation.

After the overlying layer, already on the Polychrome ceiling, the displacement of water through it is modeled due to surface tension, which is an essentially capillary phenomenon that manifests itself thanks to the physical and chemical properties of water and the inherent porosity of the limestone rock; this process, characteristic in karstic environments, plays an important role in the redistribution of water through the Polychrome ceiling and in the formation of calcifications and geological structures such as stalactites and stalagmites.

2.2. Hydrology of the Polychrome Overlying Layer

From the 3D model obtained by UAV, a hydrological analysis is performed in QGIS [59] with the key objective of elucidating the sources and destinations of water within the area. Multiple analytical functions have been applied to help with an accurate representation of the dynamics of water flow over this terrain [60].

The stream ordering method employed in this study is rooted in the Strahler method [61]. This method assigns numerical values to segments of a raster, effectively representing branches in a linear network. The numerical order assigned to these segments is instrumental in classifying different types of streams based on their tributary counts. The increase in stream order occurs when streams of the same order intersect. Consequently, the intersection of two first-order links creates a second-order link, while the intersection of two second-order links results in a third-order link, and so on. However, it is worth noting that the intersection of links with differing orders does not affect the order; instead, it retains the order of the higher-ranked link.

The “Basin” function delineates drainage basins by identifying ridge lines that separate them. This process is vital in understanding the spatial distribution of watersheds within the study area [62]. Utilizing an input flow direction raster, the analysis effectively identifies connected cells belonging to the same drainage basin. The “Flow Distance” analysis calculates the horizontal or vertical component of downslope distance, following the flow paths to the cells that converge into stream cells. This method allows for the computation of minimum, weighted mean, or maximum flow distances in the case of multiple flow paths.

Sinks are typically low-lying areas or depressions in the landscape where water can collect, forming temporary or even permanent water bodies. They are important in our hydrological analyses because they are the places where the groundwater is recharged.

2.3. GPR of the Overlying Layer

GPR is commonly used in the investigation of the internal structure of rock masses (blocks and discontinuities in the rock matrix) and in the mapping and characterization of fractures and faults, which are generally defined as mechanically discontinuous, anisotropic, and heterogeneous environments [63–71]. A particular use of GPR allows the efficient characterization of discontinuities in a karst system. GPR has proven to be the most successful technique for high-resolution imaging of karst features compared to other non-invasive techniques [72–77]. Furthermore, GPR attribute analysis can provide more information from radar records, as GPR attributes are indicative of significant changes in the lithologies and physical properties of geological media [78–82]. GPR is a non-destructive electromagnetic method that provides continuous, high-resolution information on the internal structure of rock masses and their physical properties in both vertical and lateral directions. The GPR technique is based on the propagation of short electromagnetic pulses ($t \leq 1$ ns) in the study medium. The reflection of these pulses is produced when there are sharp changes in the medium's electromagnetic properties: magnetic permittivity, electrical conductivity, and dielectric permittivity. In GPR records, an electromagnetic pulse is defined by the velocity, frequency domain, and amplitude of the wave. These GPR signal features are, therefore, strongly influenced by the medium's electromagnetic properties (magnetic permittivity, electrical conductivity, and dielectric permittivity) of the medium and their contrasts with each other [83,84]. In low-loss media, the dielectric permittivity (ϵ_r) can be approximately calculated by the equation:

$$\epsilon_r = \left(\frac{ct}{2h} \right)^2 \quad (1)$$

where h is the depth of the layer, t is the two-way travel time (elapsed time) in the GPR profile, and c is the velocity of light (0.299 m/ns). Mean velocities (v) are calculated from [83,84]:

$$v = \frac{c}{\sqrt{\epsilon_r}} \quad (2)$$

The reflection amplitudes at the two-material interface can be estimated using the reflection coefficient (R). The reflection amplitudes and intensities of GPR signals are proportional to the contrasts in dielectric permittivities at reflector boundaries and are dependent on the reflection coefficients. Since most GPR studies are carried out in non-magnetic media (low-loss media), the approximate expressions for the electromagnetic impedance (Z) and reflection coefficient (R) for two media are given by [58,59]:

$$Z_1 = \frac{1}{\sqrt{\epsilon_{r1}}}; \quad Z_2 = \frac{1}{\sqrt{\epsilon_{r2}}}; \quad R = \frac{\sqrt{\epsilon_{r1}} - \sqrt{\epsilon_{r2}}}{\sqrt{\epsilon_{r1}} + \sqrt{\epsilon_{r2}}} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (3)$$

where ϵ_{r1} is the dielectric permittivity of the upper layer and ϵ_{r2} is the dielectric permittivity of the lower layer; Z_1 is the electromagnetic impedance of the upper layer, and Z_2 is the electromagnetic impedance of the lower layer.

This reflection coefficient equation implies that the greater the contrast between the two media, the higher the percentage of incident energy that will be reflected at the boundary/discontinuity of the reflector. For the case where the moisture/water content in a medium is significant, this moisture/water content becomes an influential factor for the values of the dielectric permittivities of geological materials since the dielectric permittivity of water (81) is much higher than that of any other geological material (3–40). According to expression (3), high-amplitude radar reflections are also generated at the interfaces of water-affected (wetter) areas in the subsurface with respect to any surrounding geological material of lower velocity. Therefore, radar reflections of higher amplitude will primarily occur within the same geological formation or at the interfaces of two geological materials whose electromagnetic properties differ considerably [83,84].

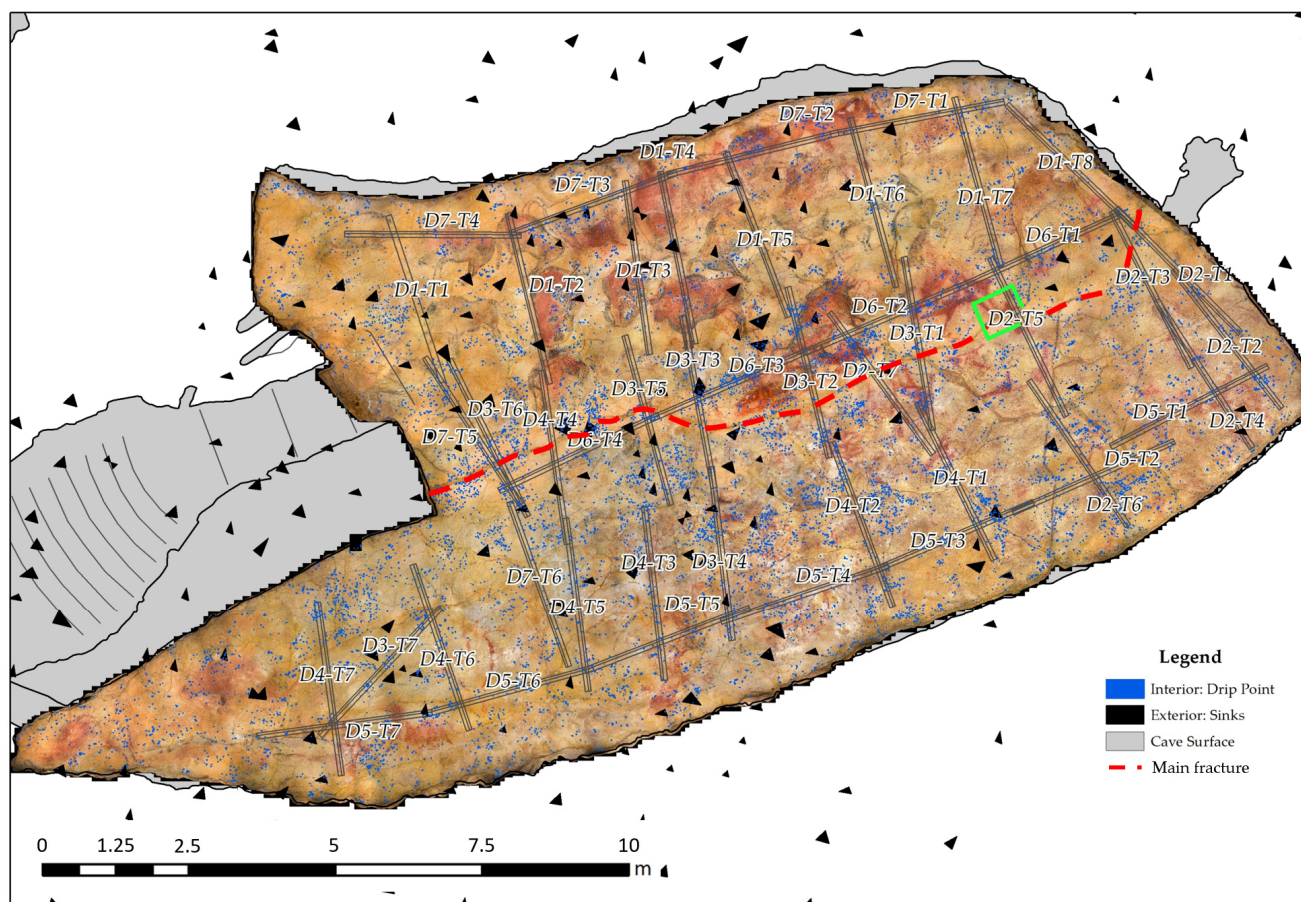
The GPR reflection data were collected using a commercial time domain pulse system, SIR-3000 (Geophysical Survey Systems, Inc., GSSI, Nashua, NH, USA). Due to the importance of the cave paintings in the Polychrome Hall for the cave of Altamira as a complex, it was considered necessary to study in more detail the first meters of its overlying rock from ceiling basal surface. For this purpose, two nominal center frequency antennas of 400 MHz and 900 MHz were used and selected for this study due to their penetration depth capability and wave resolution. The GPR antennas were fitted with odometer wheel (encoder) in order to calculate trace interval distance. For this study, 48 profiles were projected near the ceiling of the Polychrome Hall with each of the 400 MHz and 900 MHz antennas; in total, 96 GPR reflection profiles were recorded. The GPR profile layouts were transverse and parallel to the central fracture, which is sealed with mortar. (Figure 4b), considering the uneven relief of the ceiling and the displacement conditions in the Polychrome Hall. GPR data were collected with the antennas air-coupled to the ceiling of the Polychrome Hall to ensure that no contact occurred between the antennas and the ceiling. This was achieved by placing the antennas on a 3 m long traveling device. The GPR profiles were georeferenced using laser scanning.

Their layouts were transverse and parallel to the central longitudinal fracture (Figure 4a), taking into account the irregular relief of the ceiling and the displacement conditions of its interior. GPR data were collected with the antennas air-coupled to the ceiling of the Polychrome Hall in order to ensure that no contact occurred between the antennas and the ceiling. This was achieved by placing the antennas on a 3 m long traveling device. The GPR profiles were georeferenced using laser scanning.

The average velocity of the GPR wave was determined by the hyperbola fitting method on a set of hyperbolas recorded in different reflection profiles, obtaining an average velocity value of 10.9 cm/ns. The dielectric permittivity (ϵ) was calculated to be 7.5, according to the following Equation (2) [83,84]. This value was applied for calculation of the processed depths in the investigated site of overlaying layer of Polychrome Hall.

A post-acquisition processing procedure was applied to the raw data sets using RADAN 7.6 software (Geophysical Survey Systems, Inc., GSSI, Nashua, NH, USA). The first step was a 1D processing consisting of DC shift and zero-time correction (time-zero adjustment). After this, the 2D processing was applied to the reflection profiles according to these steps: (i) background removal; (ii) bandpass filters; (iii) linear amplitude gains; (iv) a time-to-depth conversion performed based on calculated velocity average of 11.06 cm/ns for the overlying rock layer.

Next, we use the Hilbert transform technique to decompose electromagnetic pulses into their attributes, such as instantaneous magnitude, phase, and frequency. The instantaneous magnitude display is useful for indicating the raw energy reflected by an interface or layer. Therefore, it highlights the changes in lithology and porosity, the presence of interstitial fluids, and the identification of thin layers. Instantaneous phase information can be more affected by significant changes in dielectric permittivity than by amplitudes (e.g., the presence of moisture/water); therefore, it is easily affected by electromagnetic impedance contrast. Thus, the instantaneous phase information allows the continuity of the reflectors to be followed and does not depend on the amplitude. Therefore, the instantaneous phase information improves the visualization of the discontinuities present in the radar records in areas of greater or lesser attenuation of the electromagnetic signal. The instantaneous frequency shows how the terrain filters the radar signal. The instantaneous frequency identifies areas with high attenuation, allowing areas with significant lithological and interstitial fluid changes to be located. This attribute also allows the identification of very thin horizontal discontinuities, such as bedding planes.



(a)



(b)

Figure 4. (a) Overlap of exterior sinks, interior drip points, position of the central fracture and position of the GPR profiles projected on the ceiling of the Polychrome Hall that were carried out with the 400 MHz and 900 MHz antennas. The green rectangle shows the position of (b) Image with detail of the central fracture sealed with mortar framed in green in (a).

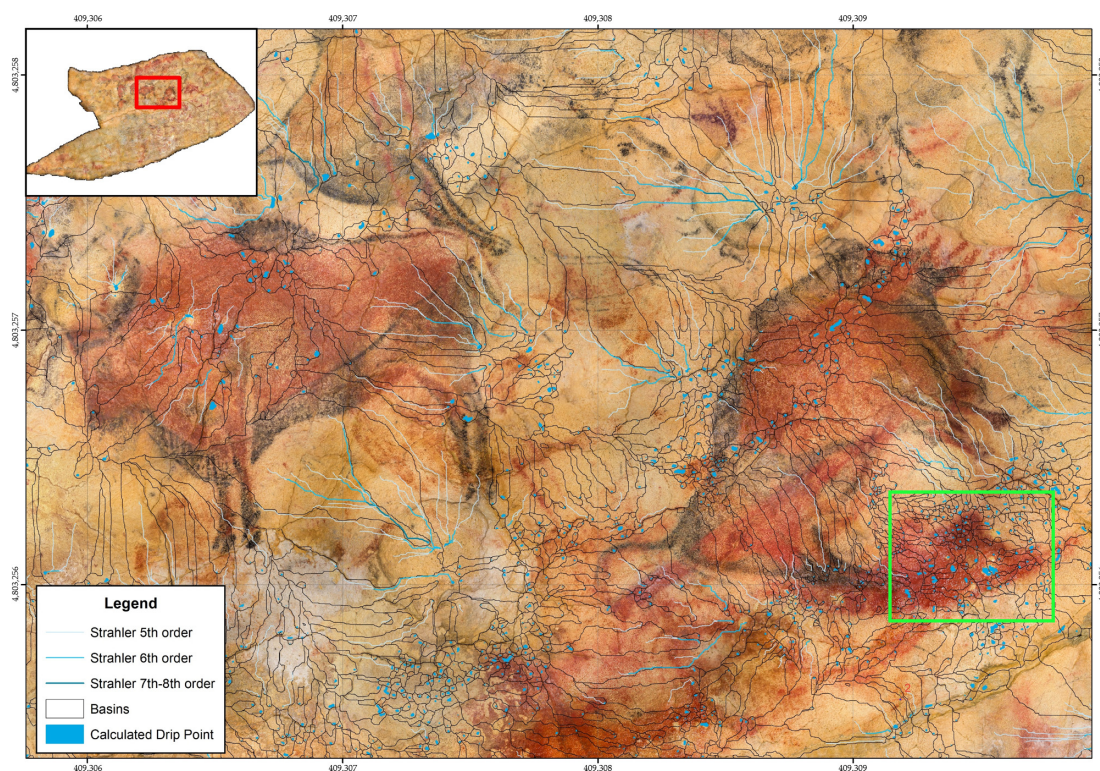
2.4. Polychrome Ceiling Hydrology

In the interior of the cave, the modeling of water movement within the ceiling, where water moves primarily due to the influence of surface tension, presents a challenging scenario. This phenomenon occurs as water infiltrates through the porous and fractured ceiling material, guided by capillary forces and the cohesive properties of water molecules [85–87]. To accurately model this process, GIS technologies play an essential role.

The identification of the precise locations where water droplets will ultimately fall to the cave floor (Figure 5) has significant implications for cave conservation. Understanding the flow paths and points of ingress is important for predicting potential damage and degradation of rock paintings.

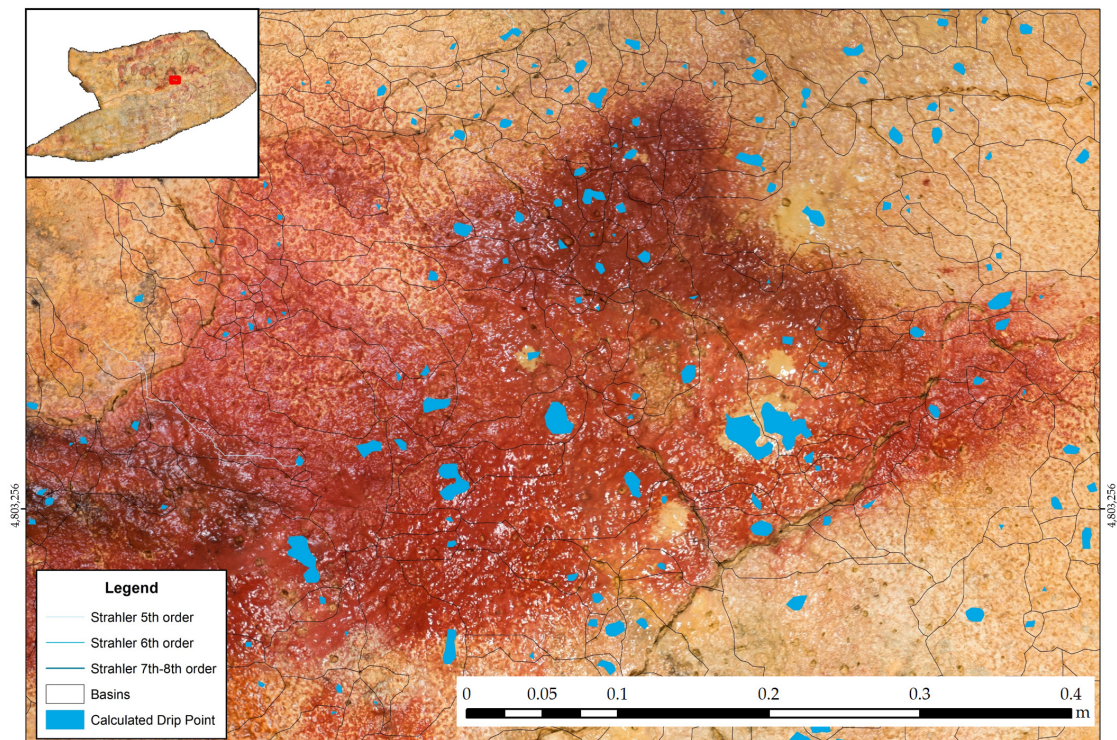
The workflow includes the same calculations as in Section 2.2, stream order analysis, basin delineation, and flow distance accumulation, but it now includes the calculation of the drip points. The identification of drip points is a key aspect of the analysis. Drip points are specific locations within the cave ceiling where accumulated water, driven by surface tension and capillary action, reaches a critical saturation point and eventually drips down to the cave floor. These drip points represent important features to map and understand, as they can have profound implications for rock art deterioration, cave formations, water quality, and ecological dynamics. (Figure 6).

By simulating water movement and saturation levels within the cave's ceiling, GIS can assist in predicting the precise areas where dripping occurs. Identifying these drip points is vital not only for geological and hydrological research but also for conservation efforts. It allows for the monitoring of potential erosion or the growth of calcifications, stalactites, and stalagmites, as well as the study of how water chemistry and nutrients are transported to the cave floor, influencing the unique ecosystems that often exist within caves.



(a)

Figure 5. Cont.



(b)

Figure 5. (a) Location of the ALT-1 active drip zone at the hind legs of the great bison figure (marked in a green rectangle). (b) Image with detail of the hind leg area of the great bison showing active drip points (indicated with blue polygons) and streams (indicated with blue lines). The thicker the blue lines (streams) the higher the hierarchy in the ALT-1 active drip zone.

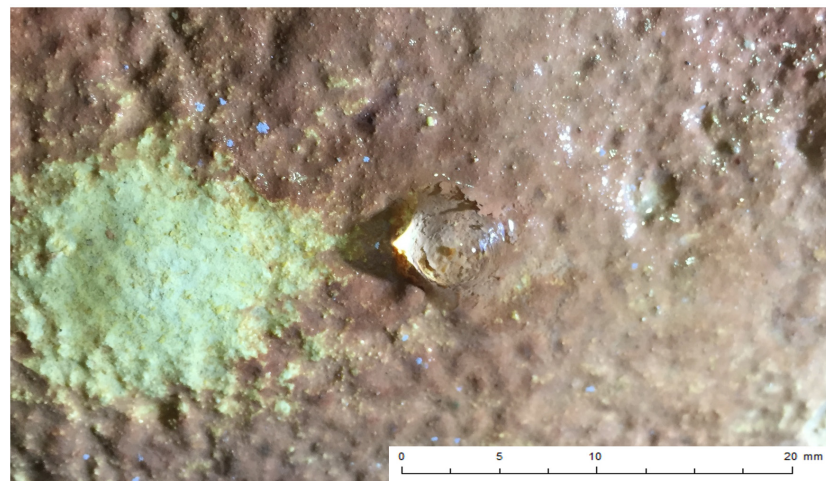


Figure 6. Detailed image of a sheet of water on Polychrome ceiling showing the surface tension of the water.

3. Results

3.1. Results of the Hydrology of the Polychrome Overlying Layer

The study of the deterioration processes that, due to infiltration water, are directly associated with fractures or diaphragms in a cave such as Altamira requires the use of techniques such as the following. The initial step involves a comprehensive geological assessment of the fractured overlying layer, accurately mapping potential sinks, streams, and basins. By utilizing QGIS [59] software, a high-resolution photogrammetric flight

with a pixel size as fine as 2 cm has been used to make the calculations. This detailed imagery enables the calculation of sinks, streams, and contribution basins, providing a precise understanding of the surface area each basin encompasses (Figure 7).

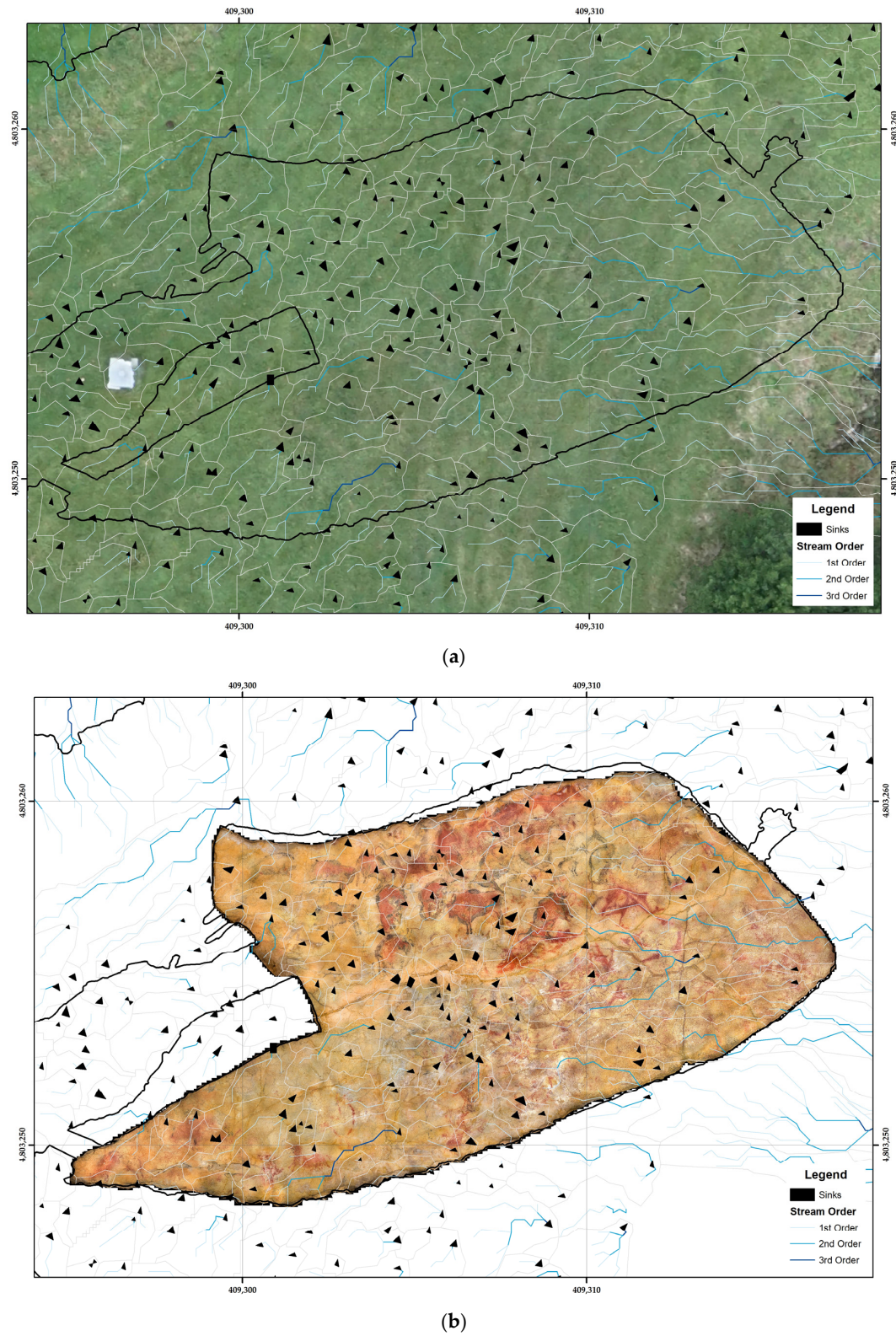


Figure 7. (a) Basins, sinks and classified streams according to the Strahler method [61] in the overlying layer of the Polychrome Hall; (b) Superimposition of the above results on the orthoimage of the Polychrome ceiling.

Following the geospatial assessment, the obtained data are superimposed with the orthoimage of the Polychrome Hall (Figure 7b). This overlay allows for a nuanced examination, identifying sinks that correlate with surfaces affected by pigment migration and wash-out processes, distinguishing currently active sinks, and projecting potential future active sinks. This approach, combined with the systematic monitoring and follow-up to which we subject the affected areas with active dripping points of the Polychromes ceiling, puts us in a position to intuit the behavior of the water, pre-dictating and consequently anticipating possible damage to the paintwork.

The application of GIS and photogrammetric technology not only offers a comprehensive view of the cave overlying layer but also provides a powerful tool for ongoing conservation efforts [88–92]. The curators obtain valuable information on the possible fractures and fissures directly involved with the processes of paint wash-out located within each of the documented basins.

3.2. Results of the GPR Overlying Layer: Attributes

GPR instantaneous attributes have been applied as a robust and intuitive tool to complement and enhance the information obtained from karst structure with standard processing and interpretation of GPR reflection profiles recorded using the 400 MHz and 900 MHz antennas (Figure 8). The use of instantaneous magnitude, phase, and frequency attributes has facilitated the characterization of the main moisture/water zones within the overlying layer of the Polychrome Hall. The instantaneous magnitude attribute display is useful to show the raw energy reflected by an area, interface, or layer. The karst structure of the overlying layer has a significant moisture/water content, being an influential factor for the dielectric permittivity values of its carbonate rocks since the dielectric permittivity of water (81) is much higher than that of any other geological material (3–40). According to expression (3), high-amplitude radar reflections are also generated at the interfaces of water-affected (wetter) subsurface areas with respect to the surrounding carbonate rocks of lower dielectric permittivity (drier). As shown in Figure 8a, the highest amplitude radar reflections recorded have occurred within the same carbonate layer or at interfaces with considerably contrasting electromagnetic properties due to the presence of moisture/water zones. This instantaneous magnitude attribute has enabled the detection of preferential moisture/water flows or pathways at the time of GPR data acquisition. It also provides a better indication of their boundary characteristics and dimensions (Figure 8b). The instantaneous phase information has allowed us to improve the visualization of the discontinuities detected in the Polychrome Hall's overlying layer detected in the radar records. This attribute is most strongly affected by significant changes in dielectric permittivity due to the presence of moisture/water in this karst structure. These changes involve electromagnetic impedance contrast. The instantaneous phase attribute has been used to follow the continuity of the reflectors/discontinuities recorded in areas of the overlying layer where attenuation of the electromagnetic signal occurs (Figure 8c). The instantaneous frequency attribute shows how the radar signal is being filtered out by the carbonate rocks in the overlying layer of the Polychrome Hall (Figure 8d). The instantaneous frequency attribute shows the existence of zones with a smaller decrease in the high-frequency spectrum in relation to changes in the dielectric permittivity values of the carbonate rocks due to the presence of fluids in the discontinuities (fractures, joints, pores, detachments). This presence of moisture/water zones in the discontinuities of carbonate rocks is marked by significantly lower instantaneous frequencies than in the dry zones of the surrounding carbonate rocks. This is a useful feature for determining their contour shapes and morphological sizes.

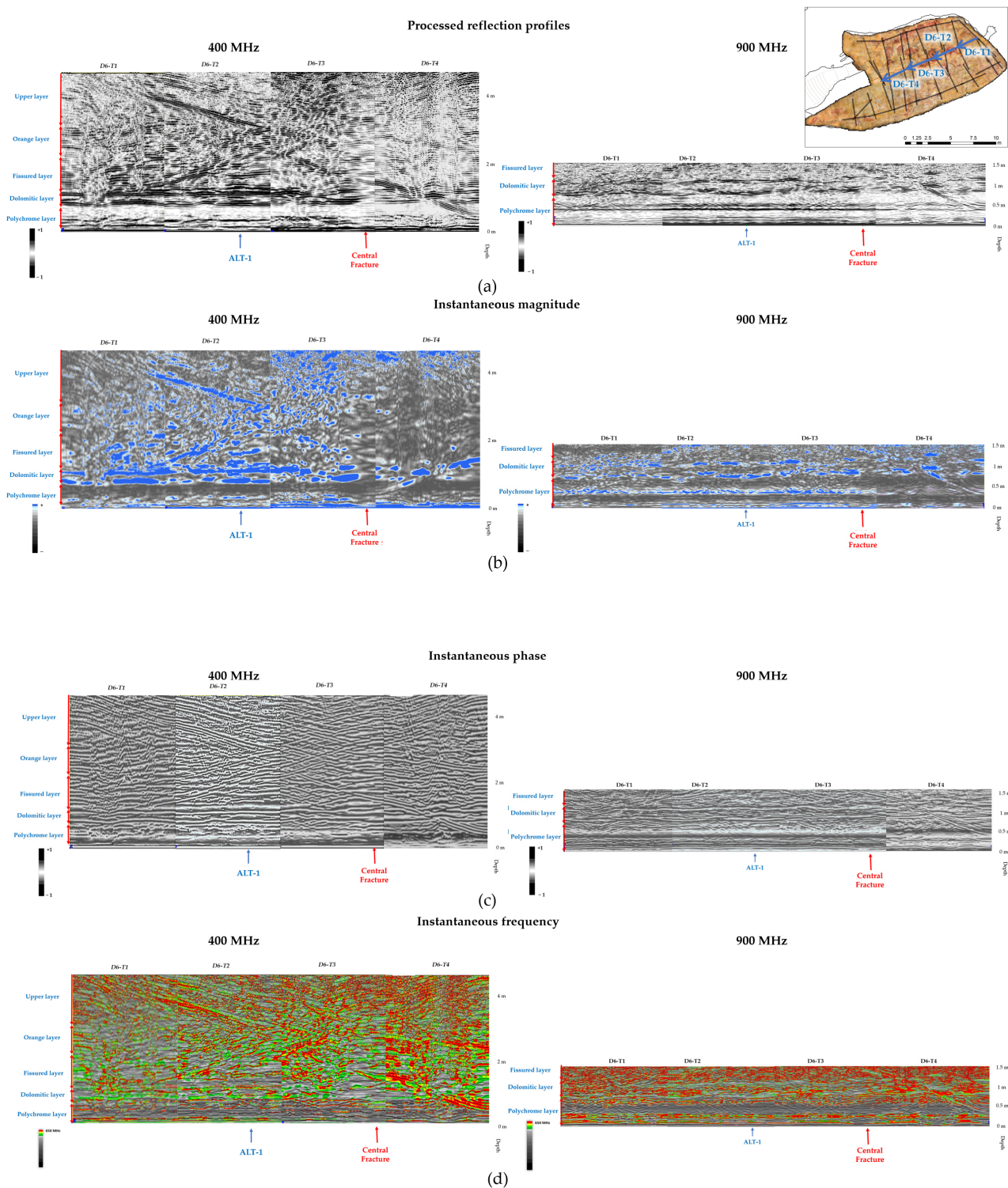


Figure 8. Example of GPR attributes from Hilbert transform on reflection profiles D6-T1, D6-T2, D6-T3 and D6-T4 recorded with the 400 MHz and 900 MHz antennas air-coupled to the ceiling of the Polychrome Hall. (a) Processed reflection profiles, and after the application of the following attributes: (b) instantaneous magnitude; (c) instantaneous phase; (d) instantaneous frequency. The active drip zone ALT-1 (indicated by the blue arrow) and the central fracture (indicated by the red arrow) are shown. The correlation of these reflection profiles with the stratigraphic layers of the Polychrome Hall overlying layer is also shown (the thicknesses of each recorded layer are indicated by red vertical arrows).

With the previous information, we can conclude

- The vertical fractures condition important water access routes to the innermost parts of the cap, causing pockets or accumulations of relevant moisture in the contact zone between the end of the dolomitic layer and the beginning of the Polychromes layer. This accumulation of moisture in the contact of both layers will generate, as the preferential disintegration of the dolomitic layer is taking place, the percolation of water towards the areas closer to the surface of the Ceiling, generating, therefore, a greater risk for the conservation of the painting by activating new processes of dragging and migration of the painting.
- Vertical fractures, often associated with diagonal planes (detachments), exhibit inclined cleavage surfaces that generate cavities in the rock, forming a porous topology. These cavities, resulting from the intricate interplay between fractures and detachments, serve as potential hydrogeological interconnection pathways, fostering subsurface water flow and enabling seepage and moisture transfer along these lines of weakness. This hydrogeological phenomenon, akin to the “communicating vessels” principle, underscores the structures’ role in helping with water migration through limestone, thus influencing subsurface dynamics. In the alterations seen in Altamira [18], the Polychrome Hall’s ceiling shows a film of discontinuous, irregularly distributed, and sometimes carbonated clays between the limestone substrate and the painting. These clays, subjected to internal tensions from moisture variations, lead to the loss of pigment adhesion and detachment from the support. Concurrently, environmental humidity contributes to carbonate dissolution, promoting mineral decomposition reactions on the limestone surface [93]. Ultimately, losing pigment adhesion is linked to the water’s physical-chemical features, incorporating CO₂ and nutrients from the soil [24]. This water reaches the ceiling’s surface through the outer soil cover, causing partial limestone dissolution and forming interconnected depressions. Functioning like a hydrographic network, these depressions transport paint, carbonates, salts, clays, quartz fragments, and dolomite, among other products, to various drip points [40].
- Observations from radargrams indicate that in the southern zone, neighboring the central fracture, moisture presence is notably less pronounced, aligning with the depicted radar imagery. The detected moisture appears to originate from surrounding areas associated with the take-off planes of the northern zone, with the central fracture acting as the distinguishing boundary between these zones. Furthermore, upon surface-level analysis of photogrammetric images in ALT1, particularly at locations with pigment fall, an evident water flow trajectory has been identified. This flow is observed to transport pigment through a network of cracks and fissures that notably align with the general dip of the Ceiling, indicating a directional correlation between the fissures and the flow pattern. This indicates that the greater moisture that influences the southern zone near the central fracture and near the entrance is due to the action or precedence of the northern part near the central fracture but not directly from the south. This tells us of a clear north and south zonation and that the moisture input comes almost exclusively from the central rift to the north. In the south, maybe the lack of moisture is not a sign that the area is better preserved or less affected by internal fractures, but rather that these are sealed, clogged, and have a plugging effect for this moisture, and that the moisture that is recorded comes from other adjacent areas. This is also reflected in the surface of the ceiling because, in the southern zone, there are fewer dripping points and more speleothems, carbonations, or concretions, which indicate that in the past, this zone was active and that these internal fractures percolated moisture or water, which washed paint, but that now this no longer occurs or at least does not occur as significantly as in the northernmost zone.
- Focusing on other possible causes associated with the loss of pigment that could be accelerating the processes of dragging and washing of paint, it is worth mentioning the presence, not constant or permanent, of more surface humidity that as small laminar flows of water are concentrated in the central part of the ceiling of the Polychrome

Hall, on both sides of the large fracture sealed with mortar, at about 70 cm in both north and south directions (for example, the control zone ALT1_1 has a distance of 68 cm in the north direction regarding the large central fracture).

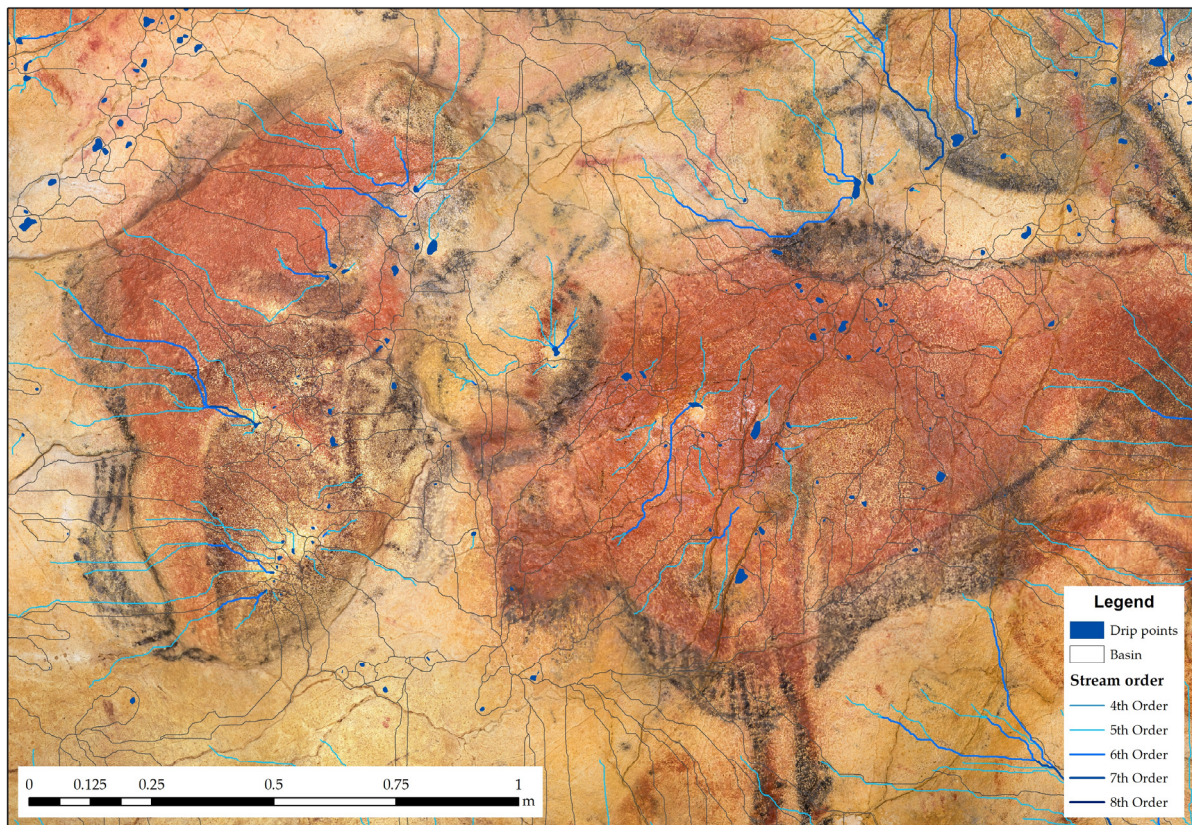
- Recent geophysical prospecting studies [41,42] carried out in the cave of Altamira, both from the overlying layer and from inside the Polychrome Hall, have shown that the large central fracture has a vertical development that, from a depth of 1.4 m in relation to the outer overlying layer, penetrates to the ceiling of the Polychrome Hall itself. In addition, the study concludes that the mortar filler applied by injection from the interior over this large fracture penetrates between 21 cm and 30 cm deep. At certain points, this filling is changed/deteriorated, generating a partial percolation of the water flows; however, at the best-preserved points, this filling is acting as a “plug”, diverting the water flows to adjacent areas.

3.3. Hydrology of Polychrome Ceiling

Using a detailed 3D model with a GSD better than 200 microns, hydrographic calculations have been executed to unveil critical geological features. The focus has been on determining contribution basins, streams, and dripping points, providing an understanding of water flow within the studied environment. The calculated basins serve as a pivotal metric, offering insights into the amount and activity of cracks. Concurrently, channels are mapped to discern the trajectory of water flow, including the directionality of potential pigment entrainment. This high-resolution model has enabled the examination of the hydrographic network, contributing to a comprehensive understanding of the geological dynamics.

To ensure the accuracy and reliability of the hydrographic calculations, a rigorous validation process has been implemented. The results have been systematically contrasted with real-world observations in the field or through orthoimage (Figure 9), creating a verification that includes dripping points in washed areas. This verification step is essential in confirming the fidelity of the 3D model's predictions for aligning virtual representations with real geological features.

The significance of these hydrographic calculations extends beyond mere visualization, offering valuable information about the water distribution and pathways (Figure 10). Dripping points, which pinpoint areas where water ultimately reaches the ground, are important indicators of the hydrological behavior of the environment. This detailed analysis not only furthers our understanding of active cracks and water channels but also sheds light on the specific locales where water interacts with the cave floor, informing broader insights into the geological processes at play in the studied area.

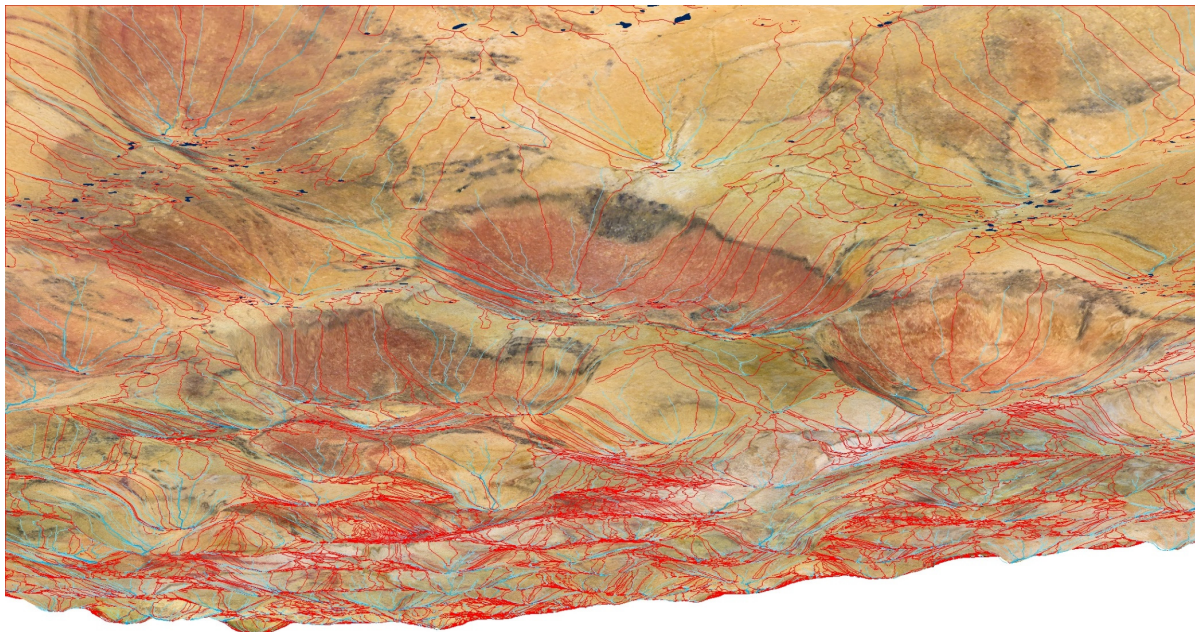


(a)

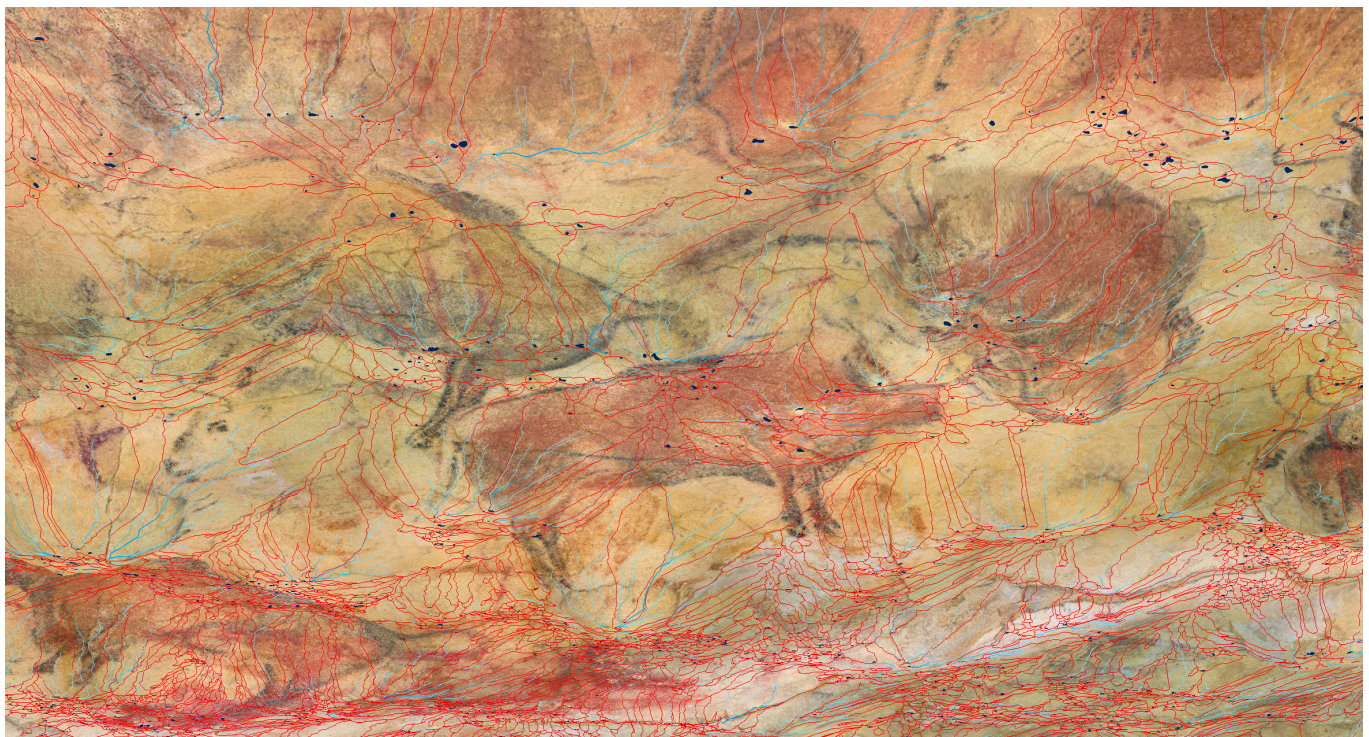


(b)

Figure 9. (a) Superimposition of basin, streams, drip points on orthoimage to check washed calculated points with real ones; (b) drip point located in the hump area or central part of the bison.



(a)



(b)

Figure 10. (a) General view of the 3D model of basins in Polychrome Hall ceiling showing the basins, streams and drip points; (b) Detail view of the model shown in Figure 9.

4. Discussion

In our investigation, centered on data integration, geomatics, GPR, and the conservation of caves, the past studies and working hypotheses emphasize the critical importance of comprehensive considerations. Data integration stands out as an indispensable factor, providing a foundational framework for a more holistic understanding of the subject [94]. Historically, research efforts have often neglected the amalgamation of diverse datasets,

opting instead for isolated fragments that may inadequately capture the complexity of the phenomenon under investigation.

The significance of outdoor hydrology, particularly its profound impact on various environmental and geological variables, is paramount. A nuanced understanding of outdoor hydrology is essential to ensure the precision and reliability of research outcomes. Similarly, the overlying layer assumes an important role in geological and environmental investigations, influencing moisture distribution, corrosion or microcorrosion processes, and the habitat suitability for diverse organisms. As our discussion unfolds, these interrelated elements will be carefully examined to shed light on their collective contribution to the broader scientific understanding of the cave conservation challenges [95].

Focusing on the specific case of the Polychrome Hall, this study reveals a predominant susceptibility to humidity-related deterioration processes. The sources of moisture stemming from rainwater infiltration or condensation processes have multifaceted repercussions, notably encompassing stone support corrosion and carbonate precipitation. Specifically, when addressing support corrosion, it is essential to clarify that it pertains to limestone corrosion induced by condensation water directly and indirectly by CO₂ concentration, which triggers water acidification (whether in the form of water sheets or droplets), thus inciting the corrosion process. When discussing carbonate precipitation, the reference is to infiltration water laden with calcium carbonate that precipitates onto the ceiling surface, instigating distinctive alterations such as glazes. Additionally, humidity contributes to pigment migration due to infiltration water entrainment, banding and diffusion halo formation, and the proliferation of microorganisms.

The consistently damp condition of the hall ceiling, characterized by water percolation, seepage, and intermittent dripping, is closely associated with specific geological features, such as fractures from the surface penetrating vertically to almost the ceilings of the cave and hairline cracks and cracking. Despite seasonal variations, the relative humidity remains saturated throughout the year, influenced by both dripping and condensation processes.

The primary objective of the conservation efforts undertaken at the cave of Altamira is to mitigate the deterioration resulting from processes related to water infiltration. Our interest is focused on understanding and reconstructing the trajectories of dripping water on its way to the drip points, causing the transport of clay deposits or pigments seen in various areas. By doing so, we establish a direct link between water penetrating the surface through fracture planes and its journey from the innermost zones of the mountain range, eventually incorporating it into the surface of the ceiling, which acts as one of the many water “catchment basins”. Along its path, this water has the potential to carry away clay or pigment particles adhered to the ceiling’s surface.

This research has practical implications for conservation. The placement of georeferenced soil cores makes it possible to precisely locate the drips involved in pigment carry-over; observing the provenance of that water from its source, thanks to the examination of pigment particles linked to these drips, we can identify their sources and correlate them with basin studies, providing insights into patterns and frequencies of occurrences. The analysis conducted provides a comprehensive understanding of these events, linking them to external climatic factors and other indirect phenomena. This information is important for effective conservation and preservation strategies aimed at safeguarding the cave of Altamira. Indirect factors like the interaction of CO₂ with the environment can influence the site’s conservation, potentially helping to form pigment and limestone rock deposits. This CO₂-driven process might acidify water, detaching rock particles from the cave’s ceiling. This detachment could compromise the integrity of ancient rock paintings if limestone particles adhere to the pigments. Monitoring these indirect factors becomes imperative, given their potential impact on the long-term preservation of this significant archaeological site and cultural heritage.

The evaluation of the state of the overlying layer from the dolomitic level to the Polychrome level using a reliable and non-destructive solution based on the use of a high-frequency GPR. The objective will be the high-resolution survey to know in detail the

trajectory followed by the water from the dolomitic layer to the Polychrome level, allowing the calculation of thicknesses, the existence of possible voids, zones of presence/absence of water, cracks, and fractures. This study, applied in a systematic way, allows us to know the difference in behavior and movement of the water in the ceiling of Polychromes.

The standard GPR interpretation method successfully identifies discontinuities in the overlying Polychrome Hall layer; however, it may not be effective in recognizing areas of moisture/water prone to seepage or waterways (Figure 11a). Therefore, the use of the Hilbert transform to the obtained radar signal to extract attributes has improved the identification of the inherent properties of the geological materials of the overlying Polychrome Hall layer, as the instantaneous magnitude attribute to identify areas of moisture/water potential for seepage or waterways (Figure 11b).

As shown in Figure 11, the presence of these moisture zones is mainly related to two lateral sources (Figure 11a): one on the south side clearly associated with the large central fracture (dashed red line), and another on the north side from a fracture of similar length to the central one, which even begins at a higher level (almost one meter from the surface). This vertical fracture reaches almost the surface of the ceiling of the Polychrome Hall at the great bison's belly and hind legs, which are located in the active drip zone ALT1 (Figure 5). This moisture zone clearly comes from higher elevations. In addition, it is related to a central fracture (indicated by the red dashed line) and to the seepage of water flowing down the northwest-southeast dip (Figure 11b). This is corroborated by analyzing the photogrammetry images of the ceiling surface taken in the active drip zone ALT1. In this active drip zone ALT1 with pigment fall, water flowing is observed, which carries pigments through a series of fractures and fissures that seem to run in favor of the ceiling dip. Likewise, the moisture sources described above are also the same for the belly area of the great bison.

Furthermore, this quantitative transformation of the obtained GPR data ensures the objectivity of the attribute results, which serves as a valuable input to the multisensor analysis for better interpretation. Additionally, this attribute analysis contributes to a better understanding of the gas exchange and drip processes in this karst system. Planning 3D GPR studies on isoattribute surfaces can help monitor the pathways of matter exchange flows and their spatial and temporal variations in karstic formations containing caves with rock art. Since 3D GPR monitoring is mainly based on the relationships between GPR signals, there are discontinuities and moisture in the internal structure of each karst system.

The preservation of rock art in caves such as Altamira shows an unstable conservation environment and presents important remains, with the most worrying factors being water, geology, biodegradation, and human presence. Understanding the dynamics of these factors and reducing the alterations they generate requires the development of effective conservation strategies. These strategies should aim to control deterioration agents such as temperature, moisture, and CO₂.

CO₂, combined with water, plays a pivotal role in the dissolution and entrainment processes of the supporting rock [95–98]. Microcorrosion, loss of adhesion, cracking, washing, and loss of support are alarming processes. Although these processes have been occurring since the formation of these caves, they remain active today [99–102].

In the case of the cave of Altamira, these processes associated with washing away and loss of support are particularly concerning as they result in the loss of paint. Understanding the underlying dynamics of these processes, which are associated with the loss of pigment fixation to the support and its migration and washing towards the dripping points, is important. This knowledge is essential for designing strategies to control each alteration agent and the interactions between them. The findings from this study can inform the development of such strategies, contributing to the preservation of these invaluable heritage assets.

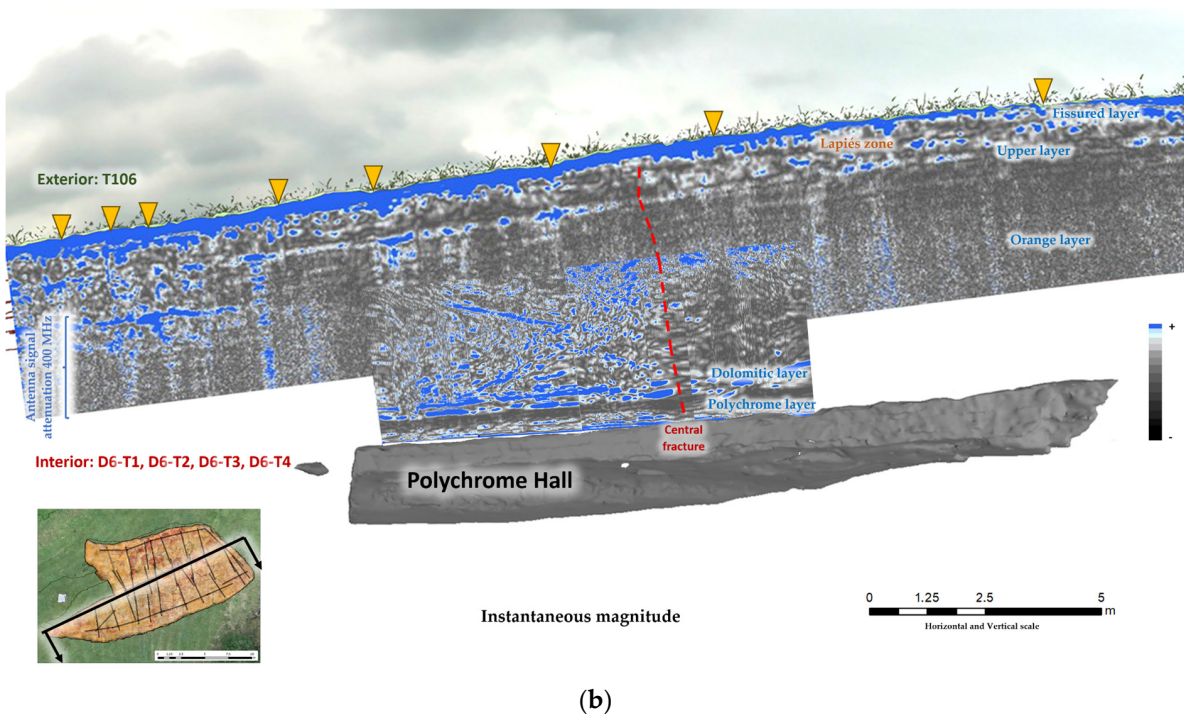
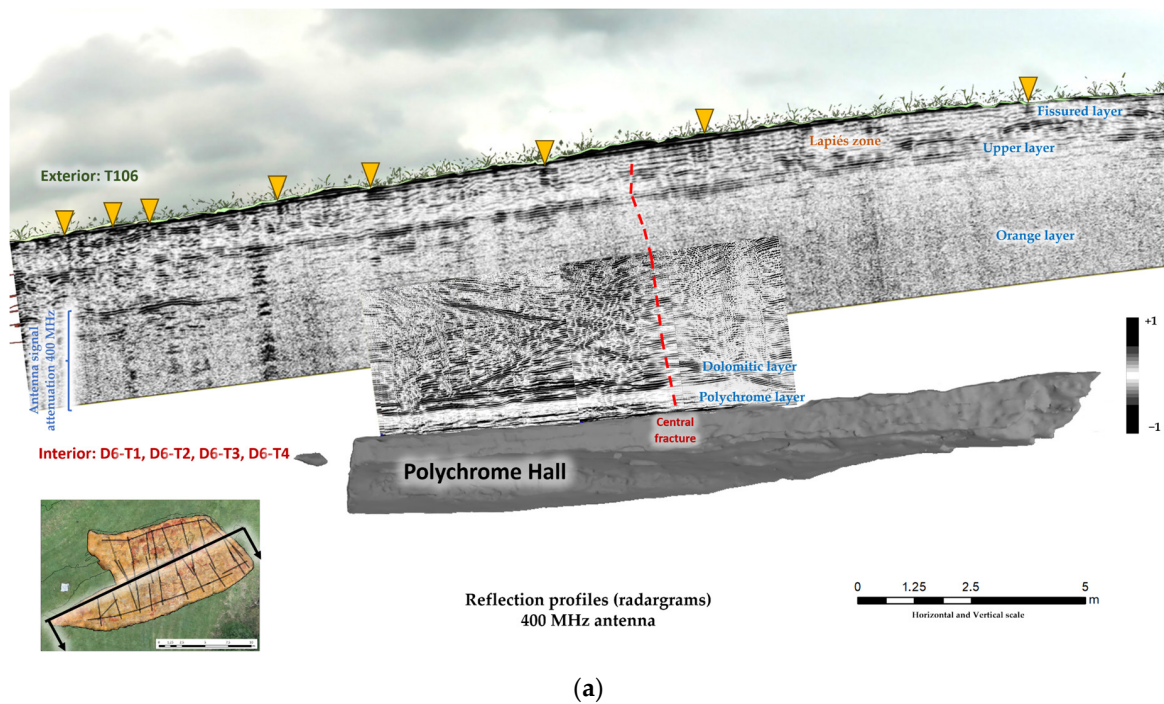


Figure 11. (a) Cross section showing the main vertical discontinuities in the overlying Polychrome Hall layer obtained by precise georeferencing of the inner reflection profiles D6-T1, D6-T2, D6-T3 and D6-T4 and the outer reflection profile T106; (b) Cross section with the instantaneous magnitude attribute derived from these reflection profiles shows the main areas of moisture/water infiltration or water pathways in the overlying Polychrome Hall layer. The central fracture can be seen to run from the lapiés zone (fissured layer) to the basal surface of the Polychrome layer (indicated by the red dashed line). The surface sinks coinciding with or close to the layout of these reflection profiles have been plotted (indicated by ochre triangles). Also shown are the signal attenuation zone with the 400 MHz antenna and the correlation of the reflection profiles with the stratigraphic units of the overlying layer of the Polychrome Hall.

Recent geophysical prospecting studies conducted in the cave of Altamira [41,42], encompassing both the exterior and interior of the Polychrome Hall, have revealed noteworthy insights (Figure 11). Specifically, the investigation indicates that the prominent central fracture, highlighted in red within the imagery, extends vertically from a depth of 1.4 m relative to the exterior surface, penetrating up to the ceiling of the Polychrome Hall itself. A mortar filler applied through injection in the 1920s reaches depths between 21 and 30 cm within this substantial fracture, acting as an important “plug” that diverts water flows away from the crack to adjacent areas. This diversion is of paramount significance as the infiltration water, originally entering through the central fracture, is redirected in its final centimeters to collateral zones. This redirection leads to irreparable consequences for certain paintings near the crack, as it introduces an additional volume of water, resulting in the emergence of new dripping points associated with this infiltration water (Figure 5).

The dip and pronounced fissuring responsible for the separation of the Polychrome stratum from its immediate overlying stratum [103] contribute to the percolation of a greater water volume toward the north side from the central fracture. Additionally, it is noteworthy that the southern zone, characterized by a higher prevalence of speleothems in the upper layers above the dolomitic layer, creates a sealing effect preventing water access on the southern side. This inhibits the conduction of infiltration water in the upper strata to areas situated north of the substantial fracture.

5. Conclusions

Applying an integrated model in this hydrographic study has shed light on the water/moisture pathways within a karst system and their subsequent impact on the Polychrome ceiling, a critical part of rock art conservation.

Our study revealed that the vertical cracks or discontinuities associated with the joint system of the rock mass forming the Polychrome Hall’s ceiling play a significant role in the activation of deterioration processes of paints and supporting rock. These discontinuities divide the rock’s interior, constituting the Polychrome’s overlying layer into vertical “blocks”, helping with the flow of water and gases and enabling communication between the horizontal stratigraphic planes of different limestone layers.

Furthermore, vertical discontinuities extend from near the surface to the Polychrome layer, contributing materials/substances from the quarry’s higher levels. This finding can significantly aid in the conservation efforts of such invaluable rock art.

The exterior UAV model helped with a comprehensive analysis of water flow patterns, contributing to a more accurate depiction of the hydrological network.

The GPR data offered valuable insights into the composition and features of the overlying layers above the karst system, aiding in understanding the geological context and potential vulnerabilities contributing to water infiltration.

GPR mapping successfully identified discontinuities within the geological formations, critical for delineating potential pathways for water movement and assessing the risk of water pooling or moisture storage. Mapping these discontinuities enhances our understanding of the dynamics between surface water and the karst system.

By correlating GPR data with observed cave conditions, we could link specific water flow patterns to the activation of microcorrosion processes that induce the partial dissolution of the limestone rock. This connection provides a clearer understanding of the mechanisms responsible for the degradation of cave structures, with implications for preserving valuable cultural and geological features such as rock art.

The study underscores the environmental impact of water movement within the karst system on the preservation of rock art. The dissolution processes of the rock, partly induced by the infiltration water, directly threaten the integrity of the paint as it is located on the limestone itself.

The findings from this study can inform the development of conservation strategies aimed at mitigating the adverse effects of water on cave structures and rock art. These can

include indirect interventions to avoid the pigment entrainment processes generated by the water film on the ceiling surface.

It is possible to consider specific risk mitigation measures based on the research findings. These measures include restricting access to the cave during periods of high water accumulation in the ceiling since visits generate excess CO₂ incorporated into the water. Therefore, access is discouraged at certain times. We have proposed setting specific times of permanence in the cave and in the Polychrome Hall, such as 120 min from October to April and 80 min from May to September, maintaining internal climatic conditions within limits established through the analysis of historical data.

Expanding the knowledge of the dynamics of water access by studying the geophysical survey at different times of the year and relating it to external rainfall periods has been suggested. We also suggest relating the moisture data to the influence of CO₂ and external humidity on the cap, which acts as an impermeable layer for the degassing of the cave. In addition, determining the relative moisture in the GPR records and correlating it with external rainfall to better understand the climatology in the overlying layer has been proposed.

To expand knowledge about the preferred water pathways, three-dimensional GPR monitoring is recommended for each season of the year over periods of several years. This would provide important information on water pathways both outside and inside the Polychrome overlying layer. In addition, GPR zonation and classification of the Polychrome overlying layer is proposed to identify the number and typology of discontinuities present, which would be fundamental to understanding the structure and behavior of the rock formation.

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Publicación 4: Remote Sensing and Environmental
Monitoring Analysis of Pigment Migrations in Cave of
Altamira's Prehistoric Paintings

Article

Remote Sensing and Environmental Monitoring Analysis of Pigment Migrations in Cave of Altamira's Prehistoric Paintings

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Abstract: The conservation of Cultural Heritage in cave environments, especially those hosting cave art, requires comprehensive conservation strategies to mitigate degradation risks derived from climatic influences and human activities. This study, focused on the Polychrome Hall of the Cave of Altamira, highlights the importance of integrating remote sensing methodologies to carry out effective conservation actions. By coupling a georeferenced Ground Penetrating Radar (GPR) with a 1.6 GHz central-frequency antenna along with photogrammetry, we conducted non-invasive and high-resolution 3D studies to map preferential moisture pathways from the surface of the ceiling to the first 50 cm internally of the limestone structure. In parallel, we monitored the dynamics of surface water on the Ceiling and its correlation with pigment and other substance migrations. By standardizing our methodology, we aim to increase knowledge about the dynamics of infiltration water, which will enhance our understanding of the deterioration processes affecting cave paintings related to infiltration water. This will enable us to improve conservation strategies, suggesting possible indirect measures to reverse active deterioration processes. Integrating remote sensing techniques with geospatial analysis will aid in the validation and calibration of collected data, allowing for stronger interpretations of subsurface structures and conditions. All of this puts us in a position to contribute to the development of effective conservation methodologies, reduce alteration risks, and promote sustainable development practices, thus emphasizing the importance of remote sensing in safeguarding Cultural Heritage.

Keywords: cultural heritage; remote sensing methodologies; deterioration; cave environments; rock art; Ground Penetrating Radar; photogrammetry; moisture mapping; preventive conservation; geospatial analysis



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1. Introduction

The Cave of Altamira stands as a masterpiece of universal art, offering exceptional insight into a vanished cultural tradition, landscape, and technological heritage that illuminates a crucial period in human history. Recognized for its significance, the cave was designated as a UNESCO World Heritage Site in 1985. Situated within the Iberian Peninsula, specifically in the autonomous community of Cantabria, between the municipalities of Santillana del Mar and Reocín, The Cave of Altamira extends a length of 290 m (Figure 1). It holds a distinguished status as one of the most significant repositories of prehistoric art, with remarkable examples of Palaeolithic paintings dating back thousands of years. Particularly noteworthy are the depictions of signs and animals adorning the ceiling of the

Polychrome Hall, offering invaluable insights into the beliefs and lifestyles of prehistoric hunter–gatherer societies.

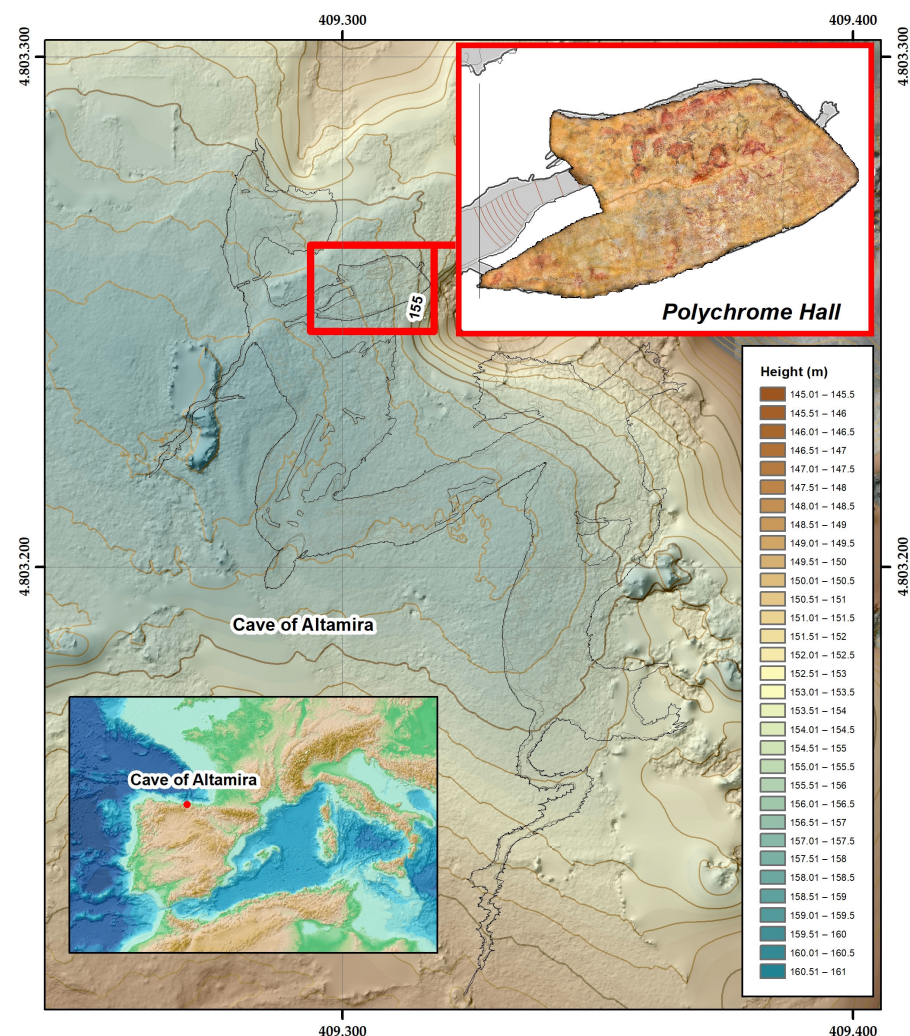


Figure 1. Location map of the Cave of Altamira: projection of the Cave of Altamira on the topographic surface, showing the Polychrome Hall and the orthoimage of its Ceiling.

After the discovery of the Cave of Altamira in 1868, it underwent countless transformations, some aimed at preparing the cave for public visits and others to try to solve the serious stability problems affecting the cave ceilings. In parallel, to prevent water infiltration problems in the Polychrome Hall, a series of more or less fortunate interventions were carried out, among which was the injection of cement mortar over the central fracture that crosses the Ceiling from west to east, which caused significant changes in the water courses that had access through this large fracture, affecting the conservation of the paintings in areas near it [1]. So, these and many other transformations affected and still affect the Cave of Altamira today. Its preservation, within an unstable conservation environment, is a major challenge for the cave's conservators and managers.

The main active deterioration factors in Altamira are directly related both to its internal microclimate and to its anthropic activities [2–6]. The criteria used for the management and conservation of the Cave of Altamira have led to the application of a series of measures and protocols aimed at protecting the cave, its paintings, and its environment [1,7]. Its preservation requires the implementation of global strategies that address the deterioration problems generated in its cave art due to the complex interaction between surrounding waters and the characteristics of the air in the cave (humidity, temperature, and CO₂) [8].

The variable action of these parameters produces alterations such as microcorrosion, dissolution, migration, and finally, detachment of the pigments constituting the cave art. In addition to this, the Cave of Altamira is a senile karst complex characterized by the presence of an important network of discontinuities (fissures, fractures, joints, detachments, stratification planes, and voids) from the upper part of the cave to its ceilings [9–11]. These structural elements affect the cave's stability and condition significant changes in the infiltration water circulation, generating relevant alterations on the paintings such as flaking, washing/erosion, and carbonate concretions [12].

GPR is widely used in investigations of geological media, such as surveys of geological contact, groundwater, the detection of voids, fractures, and seepage, and even non-destructive testing of stone quality in quarries [13–16]. Discontinuities in a rock medium (fractures, joints, voids, and bedding planes) represent electromagnetically active contacts/interfaces for GPR, where part of the radar pulse energy is reflected back to the surface, producing a radar record as a reflection profile (radargram) [17–19]. GPR is used to efficiently characterize discontinuities in a karst system [20]. Compared to other non-invasive techniques, GPR has been the most successful technique for high-resolution imaging of karst elements [21–25]. Additionally, GPR attribute analysis can provide further information from radar data [26–30]. In this context, the integration of Ground Penetrating Radar (GPR) and photogrammetry has emerged as an indispensable tool to preserve rock art, offering non-invasive and high-resolution techniques to map and monitor cave environments. This integration presents a promising approach, allowing detailed 3D surveys and geospatial analysis crucial to understanding the factors influencing the degradation of Cultural Heritage, enabling the implementation of measures for its preservation [24,31–39]. In the GPR campaigns carried out in 2017 and 2018 in the Cave of Altamira, antennas with central frequencies of 100 MHz, 400 MHz, and 900 MHz were used, and through the integration of Global Navigation Satellite System (GNSS) data, a 3D Terrestrial Laser Scanner (3D TLS), and Unmanned Aerial Vehicle (UAV) photogrammetry, it was possible to map moisture zones and discontinuities in the overlying layer located internally right above the surface of the Polychrome Hall ceiling (Ceiling). This mapped set of moisture zones and discontinuities determined the main water infiltration pathways and related them to dripping points on the Polychrome Hall ceiling. In parallel, this study allowed for defining the main connection pathways for material and energy exchange between the outer surface and the inside of the Polychrome Hall. Additionally, the importance of the Dolomitic Layer and Polychrome Layer interface in the conservation status of the Ceiling was determined [35–37].

In 2023, a very high-resolution 1.6 GHz antenna was used to further study the internal structure of the Ceiling. This choice of a high-frequency antenna (>1 GHz) was intended to improve the resolution in detecting internal reflectors and changes/disruptions within the Polychrome Layer as close to the Dolomitic Layer as can be achieved, providing a reliable and non-invasive approach.

The proposed objective of the GPR technique is the high-resolution mapping of the water flow path in the Polychrome Layer from the Dolomitic Layer. The GPR data have allowed the estimation of discontinuities and moisture zones in the first 50 cm depth from the surface of the Ceiling. In this study, we refer to a control area ALT1 in the center of the Ceiling (Figure 2a). The ALT points depicted on the map represent sensitive areas where either pigment migration and carry-over processes or areas with bacterial growth have been detected. These locations undergo high-resolution microphotogrammetric monitoring to assess their evolution objectively. The control area under study is located on a large red clavicle placed near the legs of one of the large polychrome bison (Figure 2b). Claviforms are abstract signs dating from the Upper Palaeolithic period characterized by their elongated shape with a central bulge, although their precise meaning remains unclear; they are commonly in many caves, especially in the Cantabrian region, suggesting a cultural interaction between regional populations during that era.

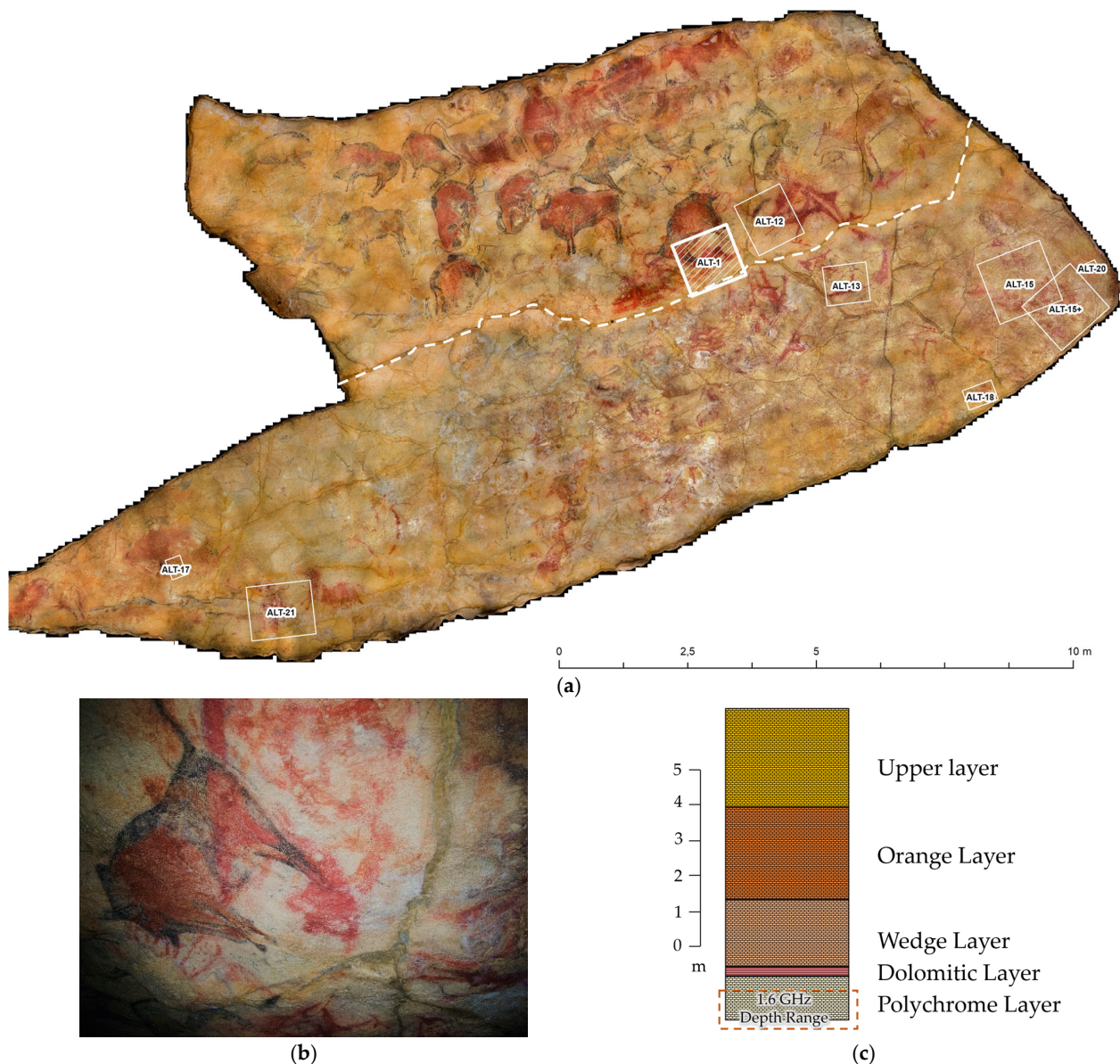


Figure 2. (a) Location of control area ALT1 in Polychrome Hall ceiling. The dashed white line indicates the position of the central fracture. (b) Picture of the general view of ALT1 study area. (c) Schematic stratigraphy of the Polychrome Hall ceiling according to [9–11], showing the depth range reached with the 1.6 GHz antenna in Polychrome Layer.

The stratigraphy (Figure 2c) of the Polychrome Hall ceiling has been detailed in previous work [9–11]. The orange layer, characterized by ochre and orange-colored limestone slabs with intercalated layers of loams and clays, is situated between the fissured layer and the upper level. The fissured layer comprises tableted limestone benches showing distinct morphologies resulting from dissolution processes. Additionally, the dolomitic layer, distinguished by a high degree of dolomitization and ochre coloration transitioning to brown upon alteration, is separated from the Polychrome layer by a fine clayey loam intercalation. These clarifications aim to enhance the reader’s understanding of the stratigraphic composition. The geological layers directly influencing the processes affecting the ALT1 control area are the Polychrome Layer and the Dolomitic Layer [35–37]. The Polychrome Layer, a 60–70 cm thick limestone layer, holds particular significance as Palaeolithic paintings were executed on its basal surface, using load-bearing structures and hydroplastic deformation morphology. The Dolomitic Layer, with a thickness ranging from 10–25 cm, exhibits located

disintegration processes. The Dolomitic Layer overlies the Polychrome Layer and acts as a protective barrier, providing a degree of impermeability due to its thin intercalation of marls and clays in contact with the Polychrome Layer. Therefore, the Dolomitic Layer safeguards against water infiltration at the Ceiling surface. These two layers provide crucial insights concerning the site.

The results obtained in the Polychrome Layer using the 1.6 GHz antenna and its 3D data integration have allowed:

- Obtaining a higher-resolution response in the first centimeters of depth from the surface of the Ceiling, where the mentioned red claviform sign is located. This has been complemented with earlier 2D records obtained with the central antenna of 900 MHz frequency.
- Mapping the spatial configuration of moisture flows present in the study area directly involved in the Polychrome Layer. For this purpose, preferential moisture pathways have been mapped, as well as monitoring of the surface water dynamics, and the main dripping points associated with the migration and detachment processes of pigment.

On the basis of these considerations, the main objective of this study is to provide valuable information that contributes to proposing reliable solutions to improve the conservation of the cave and its art.

Despite significant advances in remote sensing technologies, there are still problems when effectively applying these methodologies as basic tools for conservation in cave environments. Existing research on remote sensing has mainly focused on characterizing cave structures, with limited emphasis on correlating these findings with dynamics related to water infiltration and pigment migrations [40]. The existence of divergent hypotheses about the effectiveness of remote sensing in adopting specific conservation measures highlights the need for comprehensive and standardized methodologies [1]. Key publications in this field have highlighted the importance of remote sensing in obtaining useful basic information to implement measures aimed at safeguarding Cultural Heritage [41–44], emphasizing the need for interdisciplinary approaches that combine geophysical techniques with geospatial analysis. Controversies arise regarding the reliability and accuracy of remote sensing data, especially in complex cave environments where factors such as rock composition and moisture content vary significantly. As for moisture content, variations arise from different periods throughout the year, influenced by factors such as the access of infiltration water through fractures and fissures or changes in these water dynamics due to punctual variations in the order of moisture pockets or fillings, among others.

In this work, we show how remote sensing methodologies offer a valuable perspective, letting us understand the interaction between degradation agents (such as water/moisture) originating on the surface and, by infiltration, coming into contact with the paintings on the ceilings and walls of the Cave of Altamira. Taking advantage of the capabilities of remote sensing technologies, such as high-frequency GPR and photogrammetry, we aim to evaluate microclimatic environmental factors affecting the stability and integrity of the cave's ecosystem.

In our study of the Cave of Altamira, our aim was to understand the complex interplay between climatic variations and anthropogenic activities. While our primary focus centered on assessing damage related to moisture and pigment migration, we recognized the significant influence of human interventions on the environmental dynamics within the cave. Anthropogenic activities, such as applying cement mortar to seal fractures and constructing artificial walls, have changed the moisture circulation and microclimate, resulting in notable changes in the ecosystem of the cave.

Historical changes, including the installation of entrance doors and the construction of corridors with artificial lighting, have disrupted the natural state of the cave. These interventions over the past century have transformed the cave of Altamira from an oligotrophic environment to one significantly influenced by external factors related to anthropogenic action. Looking ahead, our research aims to dig deeper into these relationships to de-

velop more comprehensive conservation strategies for safeguarding this invaluable cultural heritage site.

The main conclusions of this study emphasize the importance of integrating remote sensing techniques into conservation practices to preserve Cultural Heritage sites such as the Cave of Altamira. Thanks to high-resolution three-dimensional studies and geospatial analysis, we have improved our understanding of the complex interaction between environmental factors and the degradation of prehistoric paintings. Our findings highlight the essential role of remote sensing in helping with preventive conservation strategies involving decision-making and, in parallel, contributing to the long-term sustainability of these invaluable cultural assets.

2. Materials and Methods

2.1. Study Site

The study focused on the control zone designated as ALT1 located in the central part of the Polychrome Hall ceiling (Figure 3a). This zone covers an area of 1.2 m² and is arranged around a large red claviform sign located under the hind legs of one of the large polychrome bison. The detail of the sign corresponding to our control area ALT1 affected by various processes of migration and pigment washing associated with drip spots is depicted in the images. In the left image (Figure 3b), the sign seems scarcely affected by migration processes and paint washing. However, the right image (Figure 3c) shows the same sign eighteen years later, exhibiting numerous drip spots that have occasionally washed away the paint. These images collectively illustrate the progression of pigment loss and degradation.

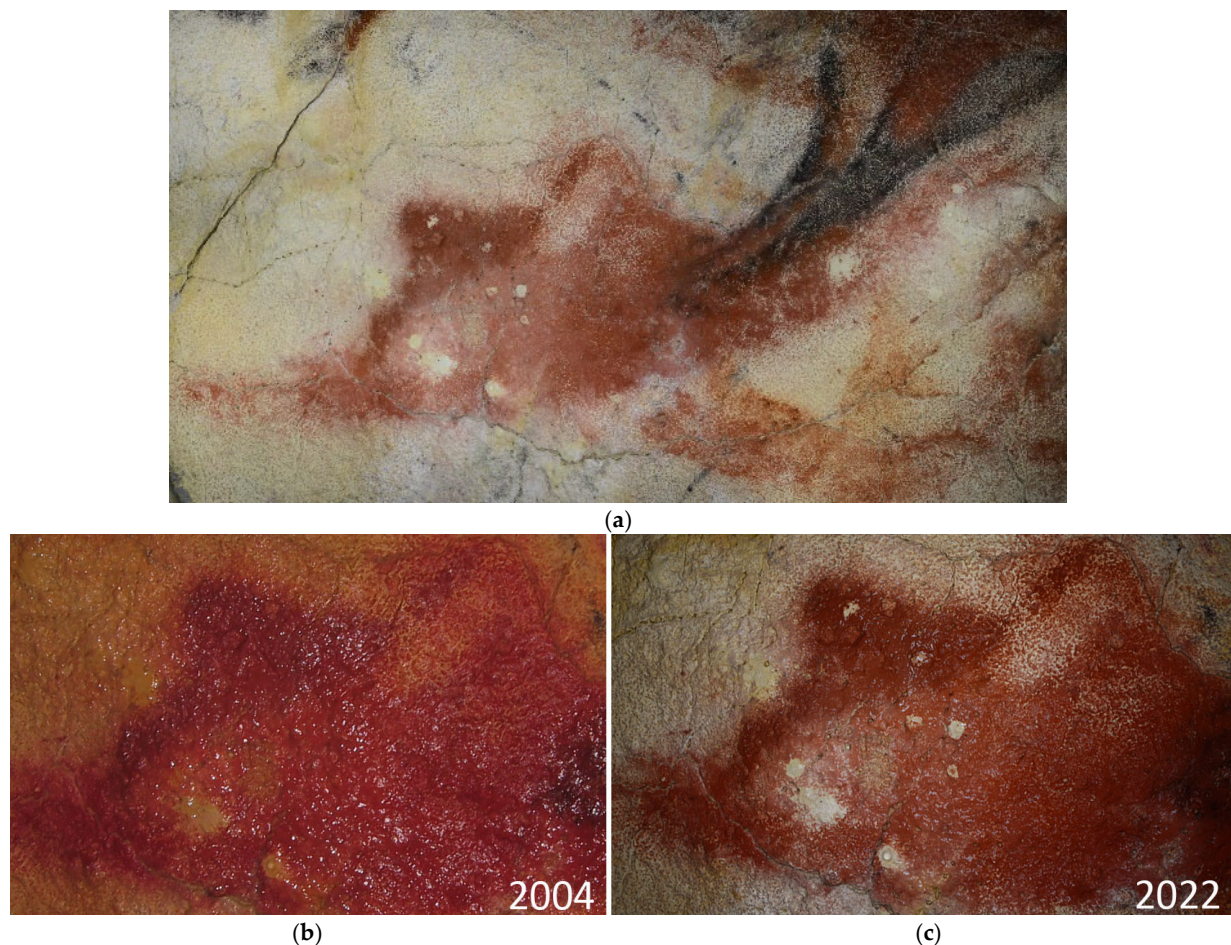


Figure 3. (a) Control zone ALT1 and comparative pictures between (b) 2004 and (c) 2022 where migration and pigment dragging and pigment loss processes associated with drip points occur.

In recent years, ALT1 has been affected by multiple infiltrating water drips that have caused dragging of pigment, leading to migration processes and, ultimately, the deterioration of the painting. This research poses significant challenges aimed at improving the conservation of this area and, by extension, other areas of the Ceiling affected by these same deterioration processes associated with water infiltration and consequent pigment dragging [45].

2.2. General Workflow Diagram

Integrating data into the model (Figure 4) begins with establishing a reference frame using the precision of the Global Navigation Satellite System (GNSS) [46,47]. At first, in 2013, Topcon Hyper II receivers [48] were used to establish a geodetic reference system aligned with the European Terrestrial Reference System 1989 (ETRS89). Evaluating observed phase changes, aided by Topcon Tools 8.2 software [49], yielded a reference frame with an average accuracy of 1.7 cm for determining the coordinates of exterior cave vertices by using the method described in [50].

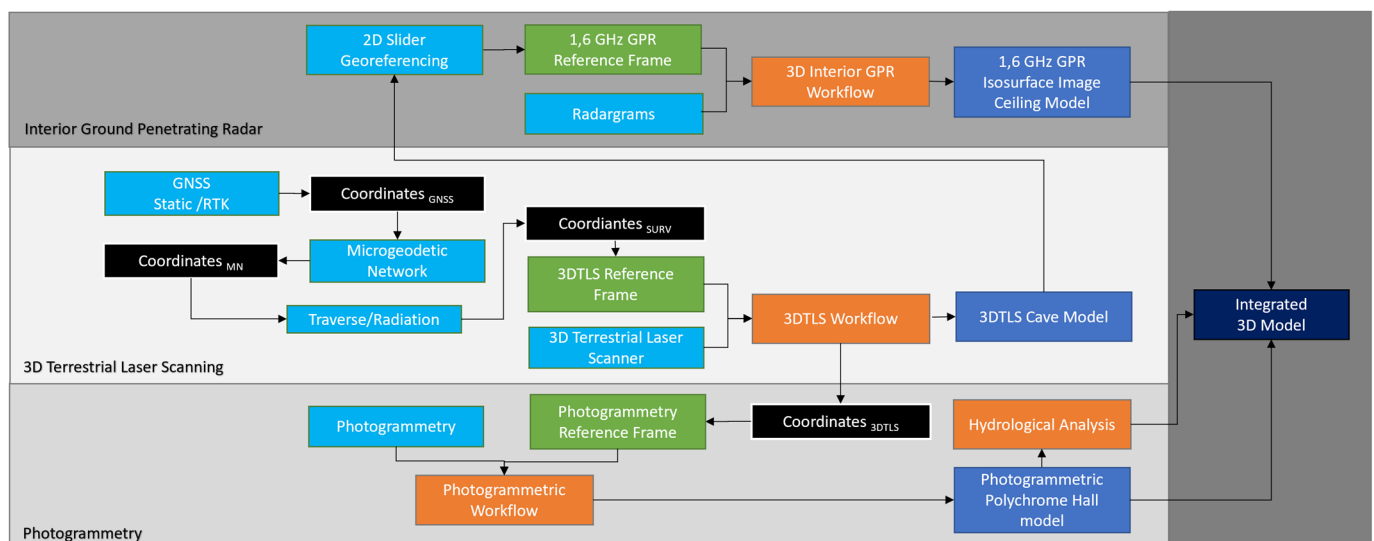


Figure 4. General workflow scheme followed in this study.

To ensure an accurate cartographic model of the cave, precise 3D TLS methods were employed [42]. The process began from a closed traverse adjusted and compensated through the cave using a Topcon GPT-7503 (Topcon Corporation, Tokyo, Japan) total station [51]. Sixteen traverse stations were established, covering a total length of 430 m, with an angular closure error of 0.0218 g and a linear closure error of $X = -0.001$ m, $Y = -0.005$ m, $Z = 0$. A total of 66 checkerboards, distributed throughout the cave, served as reference points for the 3D TLS, ensuring precise georeferencing of scans. The field campaign, conducted in December 2013, used a Faro Focus X-130 (Faro Technologies Inc., Lake Mary, FL, USA) [52], requiring 300 scans. Calibrated spheres were employed as tie points, while traverse checkerboards served as references, achieving an adjustment accuracy of 2.7 mm for 95% of the points [53]. In a previous photogrammetry campaign conducted in 2014, the Polychrome Hall Ceiling was documented using a Hasselblad H4 D-200 MS (Gothenburg, Sweden) camera, achieving a minimum resolution of 16 pixels/mm². The photogrammetric process involved detecting homologous points extracted from the 3D TLS point clouds, strategically placing eighty evenly distributed points throughout the hall, with half serving as control points for model validation. These images were collectively adjusted to generate a high-density point cloud containing approximately 11 billion points, which was then filtered and generalized to produce another point cloud containing around 3.5 billion points. From this refined dataset, a high-resolution 3D digital model of the Ceiling was generated, comprising approximately 200 million polygons. This model facilitated

the creation of a 6 Gigapixel orthoimage and a simplified version with 4 million polygons, enabling accurate integration. Utilizing the geometric models, hydrology calculations were conducted to comprehend the dynamics of water movement across the overlying layer and Polychrome Ceiling surface, analyzing surface water flow patterns and identifying potential entry points for water infiltration towards the Polychrome Hall [35–37]. Finally, a dual-axis slider employing three 1.2 m sliders aimed to cover a 1 m² control area (ALT-1), with precise positioning achieved through scanning and 5 cm equidistance interval profiling.

2.3. Remote Sensing Methods

2.3.1. Photogrammetry of the Polychrome Ceiling

The documentation of horizontal surfaces associated with gravitational issues poses challenges due to complexity and inaccessibility, prompting the use of advanced remote sensing techniques [53,54]. In 2014, a photogrammetry campaign was conducted to document the Polychrome Hall ceiling [55], complementing laser scanning with a sub-millimeter resolution. The Hasselblad H4 D-200 MS camera, chosen for its R-G-B color capture and geometric accuracy, used HC 3.5/35 and HC 4/28 lenses, capturing frames at 8176 × 6132 pixels resolution. At least 16 pixels/mm² was maintained, with two 4800 Kelvin-degree LED screens providing 980 lux illumination, diffused with Rosco Cinegel 3000 Tough Rolux plastic.

Photogrammetric support involved homologous point detection from the 3DTLS point clouds. Eighty evenly distributed points, half serving as controls, were placed throughout the Hall. These images were collectively adjusted to generate a high-density point cloud of approximately 11 billion points. Subsequent filtering and generalization produced a refined point cloud with around 3.5 billion points. From this dataset, a high-resolution 3D digital model was generated, boasting approximately 200 million polygons. This model helped with the creation of a 6 Gigapixel orthoimage and a simplified 4 million polygon version, ensuring seamless integration for the study of rock art and the associated processes of alteration. Once the geometric models were available, hydrological calculations were carried out, as understanding the dynamics of water flow through the overlying layer and the ceiling surface of the Polychrome Hall plays a fundamental role in understanding the active alteration processes associated with the ceiling surface paintings.

The data collected in 2014 maintain their relevance and reliability for our analysis, even considering potential changes in the cave's condition. The photogrammetric campaign conducted in 2014 provided valuable insights into the cave's micro-morphological particularities, particularly regarding pigment conditions and surface alterations. While minor changes may have occurred since then related to microcorrosion processes of the supporting rock, these are at the micron level and are very subtle changes. These are unlikely to significantly affect the integrity of the data or the accuracy of our analysis. Additionally, ongoing monitoring efforts, including annual high-resolution photogrammetry of key zones like ALT1, ensure that any changes are captured and accounted for in our assessments. So, we affirm that the data from 2014 remain a robust foundation for our hydrological calculations and the understanding of alteration processes within the cave.

The aim of integrating the geometric models with hydrological analyses was to gain insights into how water interacts with the internal structure of the Ceiling over time, revealing patterns of erosion, disintegration, concretion, and moisture infiltration, potentially revealing patterns.

2.3.2. GPR of ALT1 Control Area

The GPR technique consists of the propagation of short electromagnetic pulses ($t \leq 1$ ns) in a medium. These pulses reflect when there are changes in the electromagnetic properties of the medium (magnetic permittivity, electrical conductivity, and dielectric permittivity). So, the characteristics of the GPR signal are strongly influenced by the electromagnetic properties of the medium and their contrasts with each other. The contributions of electrical conductivity and magnetic permeability to the recorded signal cannot be distinguished in typical GPR

studies using frequencies between 8 MHz and 2.5 GHz [56,57]. In low-loss media, the dielectric permittivity (ϵ_r) can be estimated by the equation [58,59]:

$$\epsilon_r = \left(\frac{ct}{2h} \right)^2 \quad (1)$$

where h is the depth of the layer, t is the two-way travel time (elapsed time) in the GPR profile, and c is the velocity of light (0.299 m/ns). The mean velocity (v) is derived from:

$$v = \frac{c}{\sqrt{\epsilon_r}} \quad (2)$$

The amplitude of a registered signal is a function of several factors: the amplitude of the transmitted signal, the geometrical dispersion (and thus the travel distance), the reflection coefficients between the interfaces (due to targets causing reflection and refraction of the signal), the signal scattering (due to small targets causing scattering), and the absorption of the medium.

The absorption of the medium is defined by the attenuation coefficient α . The attenuation coefficient is dependent on several factors (the angular frequency (ω), the electrical conductivity (σ), the dielectric permittivity (ϵ), and the magnetic permeability (μ)), as given in Equation (3) [60], with the average conductivity and the dielectric permittivity of the medium being key influences:

$$\alpha = \omega \sqrt{\mu \epsilon} \left(\frac{1}{2} \left(\sqrt{1 + \left(\frac{\sigma}{\omega \epsilon} \right)^2} - 1 \right) \right)^{\frac{1}{2}} \quad (3)$$

Since most of the GPR studies are carried out in non-magnetic media (low-loss media), in this, case Equation (3) simplifies to Equation (4) [61]:

$$\sigma \ll \omega \epsilon \rightarrow \alpha = \frac{\sigma}{2} \sqrt{\frac{\mu}{\epsilon}} \quad (4)$$

Equations (3) and (4) show the dependence on the dielectric parameters of the media that depend on their physical properties, with the water content being one of the important factors. This attenuation coefficient α represents the amplitude behavior during the propagation of the electromagnetic wave through the medium as a result of energy absorption.

The reflection amplitudes at the two-material interface can be estimated using the reflection coefficient (R). GPR signal reflection amplitudes and intensities are proportional to the contrasts of the dielectric permittivities at the reflector boundaries and depend on the reflection coefficients. In non-magnetic media (low-loss media), expressions for the approximate electromagnetic impedance (Z) and reflection coefficient (R) for two media are given by [59,60,62]:

$$Z_1 = \frac{1}{\sqrt{\epsilon_{r1}}}; \quad Z_2 = \frac{1}{\sqrt{\epsilon_{r2}}}; \quad R = \frac{\sqrt{\epsilon_{r1}} - \sqrt{\epsilon_{r2}}}{\sqrt{\epsilon_{r1}} + \sqrt{\epsilon_{r2}}} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (5)$$

where ϵ_{r1} is the dielectric permittivity of the upper layer and ϵ_{r2} is the dielectric permittivity of the lower layer; Z_1 is the electromagnetic impedance of the upper layer and Z_2 is the electromagnetic impedance of the lower layer.

This reflection coefficient equation implies that the greater the contrast between the two media, the higher the percentage of incident energy that will be reflected at the boundary/discontinuity of the reflector. If the moisture/water content in a medium is significant, this moisture/water content becomes an influential factor for the values of dielectric permittivities of materials/media, as the dielectric permittivity of water (81) is higher than that of any other geological material (3–40) [59,63].

Thus, a higher water content in the interior of the medium results in two effects on the amplitude of the electromagnetic wave:

- The effect of attenuation on the amplitude is a derivative of the attenuation coefficient. The amplitude of the wave propagating through the materials/media decreases drastically as a function of the degree of moisture. Consequently, the wave is attenuated and the wave incident on the targets within the medium generates a low-amplitude anomaly in the radar records, and in some cases, the anomalies may not even be visible [22,64–68].
- An additional effect on the amplitude is a function of the reflection coefficient. In the case of surface moisture in areas under dry material/medium, the contrast in dielectric permittivity between the wet and dry media is greater the higher the water content is, increasing the reflection coefficient. This means that the greater the contrast between the electromagnetic parameters of two materials/media that are in contact, the greater the percentage of incident energy that will be reflected at the boundary/discontinuity of the reflector. The strength (amplitude) of the reflected fields is proportional to the magnitude of the dielectric constant. Radar reflections of higher amplitude will occur mainly at interfaces within the same geological layer and at material/media interfaces that have significantly different electromagnetic properties. Thus, the anomaly due to the existence of moist areas has a higher amplitude in the reflection profile, as has been reported by different authors [20,37,60,68–74].

As shown in Figure 2c, the rock medium studied with the 1.6 GHz antenna has been limited to the limestone Polychrome Layer due to the depth of penetration achieved. The surface tension water and active drip points observed on the ceiling are evidence of internal moisture zones in this limestone layer. In the dry zones of the limestone, the relative dielectric permittivity is lower than in the moist zones [59,69]. The existence of water-affected (moister) zones within the dry limestone medium produces interfaces with different relative dielectric permittivities. In the dry zones, the relative dielectric permittivity is lower than in the water-affected (moister) zones. As a consequence, when the wave reaches these interfaces, part of the energy is reflected. According to expression (5), high-amplitude radar reflections are also generated at the interfaces of the water-affected (moister) and dry zones of the Polychrome Layer. It is relevant to notice that the existence of moisture in the interior of the limestone medium (Polychrome Layer) causes the limestone–water interface to have a higher dielectric contrast than the limestone–air interface and, consequently, a stronger reflection [69,70,75].

GPR signal penetration and detection resolution depend on the antenna frequency used. Higher-frequency antennas offer better detection resolution but also increase signal attenuation, which results in lower penetration into rocks [59]. The penetration depth at which the GPR technique can record discontinuities within a rock mass is strongly influenced by its electromagnetic parameters (dielectric permittivity, electrical conductivity, and magnetic permeability). Variations in the electromagnetic parameter values can indicate alterations in the rock and conductive minerals, porosity, joints, fractures, water content, and fillings within the discontinuities. In geological media, the attenuation factor increases as the conductivity of the medium increases. In addition, the propagation of electromagnetic waves in a rock mass is also affected by attenuation due to the degree of water saturation, water mineralization, distance, porosity variation, and the number of discontinuities [60,76–79]. The high-frequency antenna choice (>1 GHz) provides a higher resolution in detecting the dimensions and geometries of reflectors/elements in a medium, which may be associated with internal changes/discontinuities [58,80,81]. However, the penetration depth with these high-frequency antennas is lower than the 900 and 400 MHz central-frequency antennas used in earlier GPR campaigns. Due to the range in penetration depth of high-frequency antennas (>1 GHz), this survey was focused on the Polychrome Layer.

The comparison between antennas in GPR studies highlights a trade-off between resolution and penetration depth. The high-frequency antenna offers superior resolution,

capable of detecting features as small as 2 cm, but its penetration depth is limited to 0.4 m. However, the low-frequency antenna provides a lower resolution but can penetrate up to 4.5 m, making it more suitable for deeper subsurface investigations [56,58,82–86]. The choice of antenna is closely related to the resolution of a specific conservation problem as accurately as possible: the washing of paint, which is directly linked to water accumulated in the first centimeters from the basal surface of the Ceiling. This justifies the use of a higher-frequency antenna (higher resolution and lower penetration), as shown in Table 1. Additionally, addressing deeper accumulations indirectly requires an antenna with greater penetration. Ultimately, the objective is to respond to a conservation need, balancing the requirement for resolution against the need for depth penetration to ensure optimal results in subsurface imaging and detection applications [56,58,82–86].

Table 1. Comparison of parameters for the 400 MHz, 900 MHz, and 1.6 GHz antennas used on Polychrome Hall ceiling.

Frequency	1.6 GHz	900 MHz	400 MHz
Frequency Range	1.3–1.9 GHz	600–1200 MHz	250–600 MHz
Wavelength in Air (m)	~0.1875	~0.333	~0.75
Wavelength ($\epsilon = 7.5$) (m)	~0.0684	~0.1213	~0.2732
Minimum Resolution ($\epsilon = 7.5$) (m)	~0.0342	~0.0606	~0.1366
Estimated Maximum Depth ($\epsilon = 7.5$) N = 20 (m)	~1.1 m	~0.456 m	1.026 m
Estimated Maximum Depth ($\epsilon = 7.5$) N = 100 (m)	~0.4 m	~2.28 m	~5.13 m
Vertical and Horizontal Resolution	0.0342 m	0.0606 m	0.1366 m
Image Clarity (Entropy)	0.8–1.0	0.5–0.8	0.2–0.5
Signal Attenuation	High (50–70 dB)	Moderate (30–50 dB)	Low (20–30 dB)
Antenna Gain	High (20–30 dB)	Medium (10–20 dB)	Low (0–10 dB)
Antenna Beamwidth	15°	25–30°	45–50°
Signal-to-Noise Ratio (SNR)	15 dB	12 dB	10 dB

The digital processing of time-domain GPR data generally relies on the amplitude values of the signal for interpretation. Furthermore, the transformation of the GPR data into its instantaneous magnitude, phase, and frequency information requires additional processing of the GPR data. The Hilbert transform has been applied to complex rock masses to enhance the reflection and absorption contrasts of electromagnetic wave propagation. Thus, GPR attributes can reveal or highlight features or patterns that are not clear in standard amplitude data [86–88].

In this study, using Hilbert transform attributes in the interpretation of GPR data can help us to increase our knowledge of the internal structure of the Polychrome Layer by characterizing the electromagnetic response to the moisture zones within it.

2.3.3. GPR Data Acquisition

The high-resolution GPR survey was performed using an SIR 4000 system manufactured by Geophysical Survey Systems, Inc. (GSSI, Nashua, NH, USA). The GPR system was equipped with a 1.6 GHz central frequency antenna. The choice of a high-frequency antenna (>1 GHz) was intended to improve the resolution in detecting internal reflectors and changes/disruptions at a 50 cm depth in the Polychrome Hall ceiling. This antenna configuration provided depth penetration ranging from 0 cm to approximately 50–60 cm, depending on the medium and its electromagnetic properties, while maintaining a high-resolution capability [58,80].

Due to the presence of Palaeolithic paintings on the Ceiling, the GPR data were collected with the air-coupled antenna on the Polychrome Hall Ceiling to avoid any contact between the antenna and the Ceiling that could cause damage to the cave paintings. It had to be assumed that the antenna height would affect the data recording process. To reduce this effect and consider the minimum allowable distance to the rock paintings on the Ceiling, data acquisition was performed at a height depending on the 1.6 GHz

central-frequency antenna of 10 cm (Figure 5). This height ensured the maximum possible amount of energy transmitted to the rock mass and reduced the effects of coupling to the air to obtain accurate and high-quality GPR records [89,90]. This antenna configuration provided a penetration depth of up to approximately 50 cm into the Polychrome Layer, while maintaining a high-resolution capability [58,80,81].

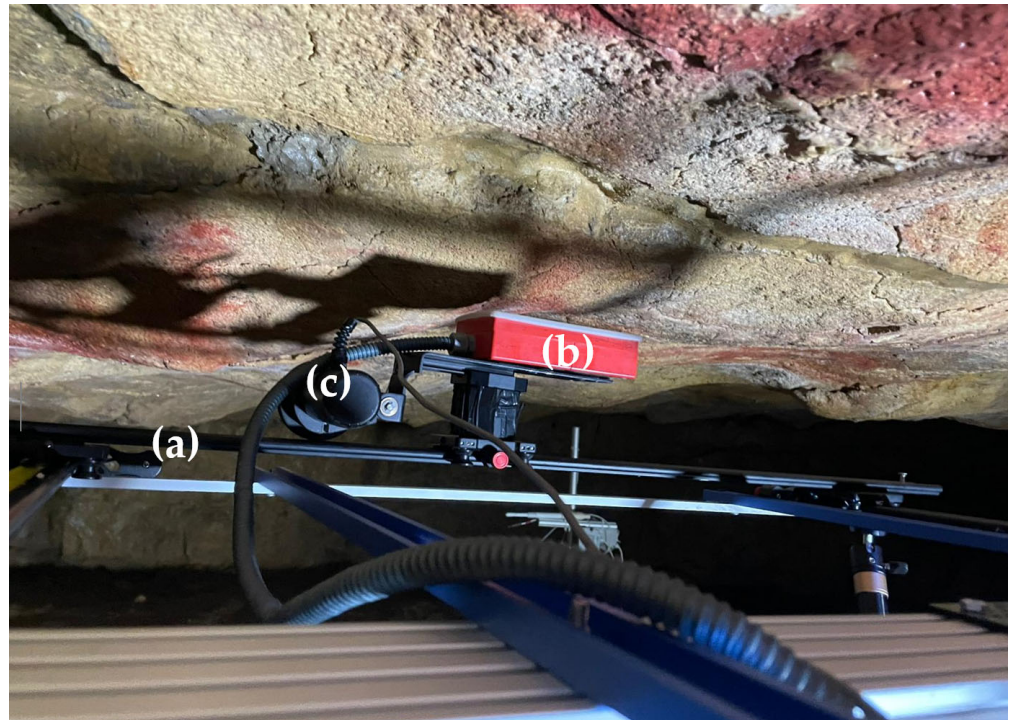


Figure 5. Photograph showing the device designed (a) in which the 1.6 GHz antenna was installed (b) with the odometer (c) maintaining a minimum distance in relation to the study area of the Polychrome Hall ceiling of 10 cm.

A 1 m-long slider was chosen due to operative limitations inside the cave, on which the 1.6 GHz antenna was placed, focusing on the Ceiling (Figure 5). An odometer wheel (encoder) was used to calculate trace-interval distance. Further, the reflection profiles were georeferenced through 3D scanning of the sliders where the antenna was fit.

The survey aimed to spatially map the internal distribution of moisture in ALT1 and its immediate surroundings. To achieve this, a 5 cm × 5 cm grid pattern was designed specifically for ALT1, including 23 longitudinal and 23 transverse profiles. These profiles were strategically laid out and numbered for the study's purposes, as illustrated in Figure 6. Additionally, a square grid measuring 1 × 1 m was established, using equidistant orthogonal 2D lines spaced every 5 cm. This grid was centered on the ALT1 control point, as depicted in Figure 5, with the 2D lines oriented transversally and parallel to the central fracture of the Polychrome Hall ceiling. This approach helped with comprehensive data collection and analysis of moisture distribution within the designated area.

2.3.4. GPR Data Processing

The GPR wave mean velocity was determined by the hyperbolic fitting method on a set of hyperbolas recorded in different reflection profiles, resulting in a mean velocity value of 0.111 m/ns. The dielectric permittivity (ϵ) was calculated to be 7.2, according to Equation (2). To calculate the processed depths in the investigated polychromatic layer, this value was applied. This mean velocity was also used in the Kirchhoff migration for the 2D processing of the GPR data.

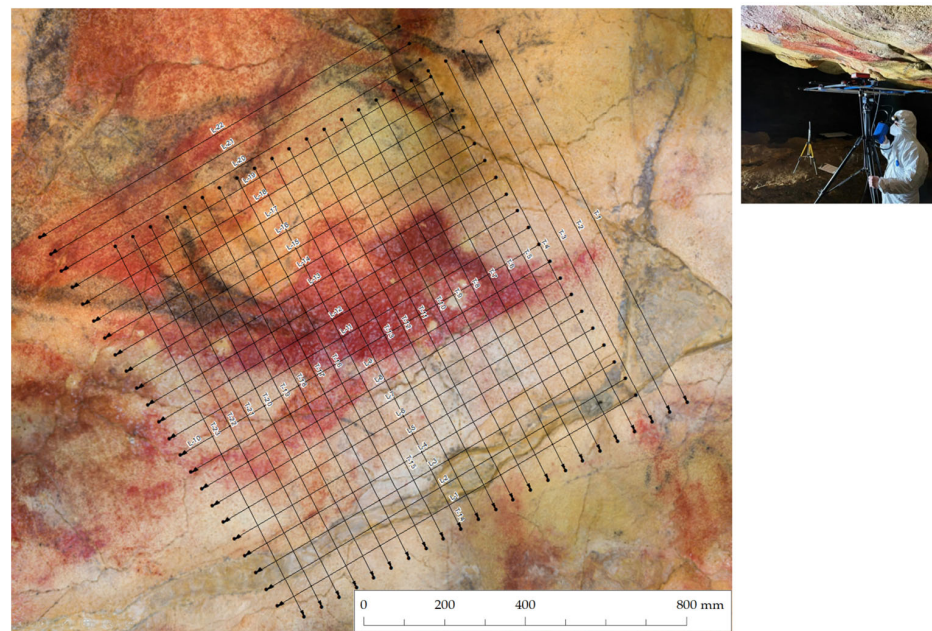


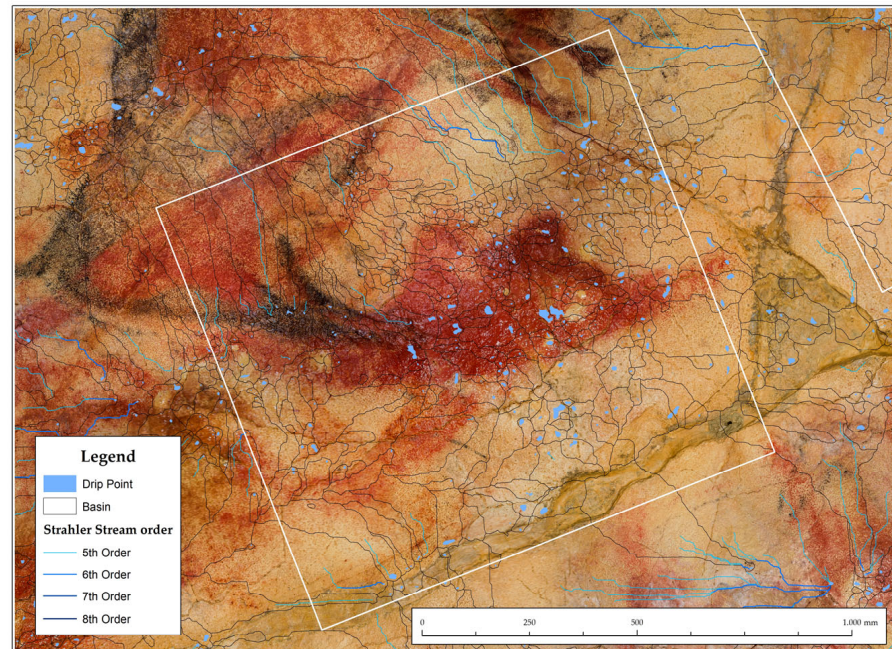
Figure 6. Detail of the control area ALT1, with layout of the longitudinal and transverse profiles made in ALT1 and image of the field configuration.

The raw field GPR dataset needs to have a post-acquisition processing procedure applied to it before generating amplitude maps and rendering 3D images with all reflection profiles on a grid. There are several techniques for post-acquisition processing of radar signals. In this study, a basic data-processing procedure and a Hilbert transform attribute (instantaneous magnitude) were applied to the raw dataset, using RADAN 7.6 software (Geophysical Survey Systems, Inc., GSSI, Nashua, NH, USA) [91]. The first step was 1D processing consisting of zero-time correction (time-zero adjustment). After this, the 2D processing was applied for the reflection profiles according to the following steps: (i) background removal filter; (ii) bandpass filter; (iii) linear amplitude gains; (v) Kirchhoff migration filter using the calculated average velocity (0.111 m/ns); (vi) a time-to-depth conversion performed based on a calculated velocity mean velocity of 0.111 m/ns for the limestone of the Polychrome Layer; (vii) Hilbert transform attribute: instantaneous magnitude. Next, each processed reflector profile was aligned within the grid to generate horizontal amplitude 3D maps and isosurface (isoattribute-surface) images that allowed us to pinpoint the presence of significant moisture/water zones. Several amplitude slice maps were created at different levels for mapping the subsurface up to depths of 36 cm. Amplitude depth-slice maps from the 3D model were used to identify moisture/water zones at a constant depth. Once the depth-slice maps had been generated, the highest amplitudes in all profiles within the grid were rendered in an isosurface image. This isosurface image was colored to show certain amplitude values (the highest ones) while others were made transparent in order to best represent only moisture/water zones and simplify locating moisture/water zones and their interpretation. This transparent visualization of the 3D GPR dataset was performed to reveal the main moisture/water zones in this studied volume of the Polychrome Layer.

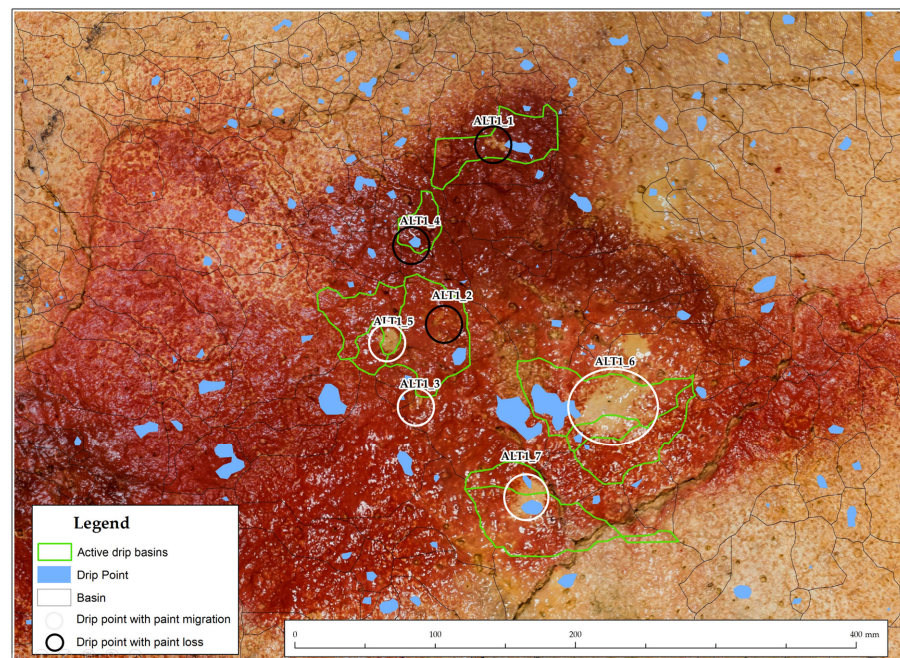
2.4. Polychrome Ceiling Hydrology

Modeling water movement within the cave's interior poses a significant challenge, particularly in the Polychrome Hall ceiling where water primarily moves under the influence of surface tension. This phenomenon occurs as water infiltrates through the porous and fractured limestone rock, guided by capillary forces and the cohesive properties of water molecules [92–94]. GIS technologies play an important role in accurately modeling this process. Identifying the drip points involved that induce processes of erosion, flaking,

disintegration, and washing by dissolution of some of the mineral parts, including the constituent pigments of the Altamira art (Figure 7), holds profound implications for cave conservation. Understanding the flow paths and points of ingress is essential for predicting the potential damage and degradation of rock paintings.



(a)



(b)

Figure 7. (a) Location of the ALT-1 active drip zone near the hind legs of the great bison figure. Drip points are indicated with blue polygons and streams with blue lines. The thicker the blue lines (streams), the higher the hierarchy in the ALT-1 active drip zone. (b) Active drip basins highlighted in green involved in the recorded pigment migrations in recent years. Black circles indicate areas of paint drop and loss and white circles indicate areas where pigment has been transported by the water film with no pigment fall recorded in recent years.

The workflow involves using a 3D high-resolution photogrammetric model to conduct a hydrological analysis [95] in QGIS [96], aimed at elucidating the sources and destinations of water within the area. Various analytical functions, including the Strahler method [97], are applied to accurately represent water flow dynamics over the Ceiling.

The Strahler method assigns numerical values to segments of a raster, reflecting branches in a linear network. It classifies streams based on their tributary counts, with an increase in stream order at intersections. The “Basin” function delineates drainage basins by identifying ridge lines that separate them, which is important for understanding spatial water distribution [98]. Using input flow direction raster data, the analysis identifies connected cells within the same basin. The “Flow Distance” analysis calculates horizontal or vertical downslope distances along flow paths to converging stream cells, helping with the computation of various flow distance metrics.

The workflow includes the addition of drip-point calculation, which concerns specific locations within the cave Ceiling where accumulated water reaches a critical saturation point and drips down and constitutes an important feature to map and understand. They can significantly affect rock art deterioration, cave formations, water quality, and ecological dynamics (Figure 8). By simulating water movement and saturation levels within the cave Ceiling, GIS aids in predicting the precise areas of dripping. Identifying these drip points is important for geological and hydrological research and conservation efforts. It allows for tracking potential erosion, calcification growth, and the transport of water chemistry and nutrients to the cave floor, influencing unique cave ecosystems. All this information allows the managers of the Cave of Altamira to make decisions to anticipate damage to reduce the deterioration of the cave and the paintings it houses.

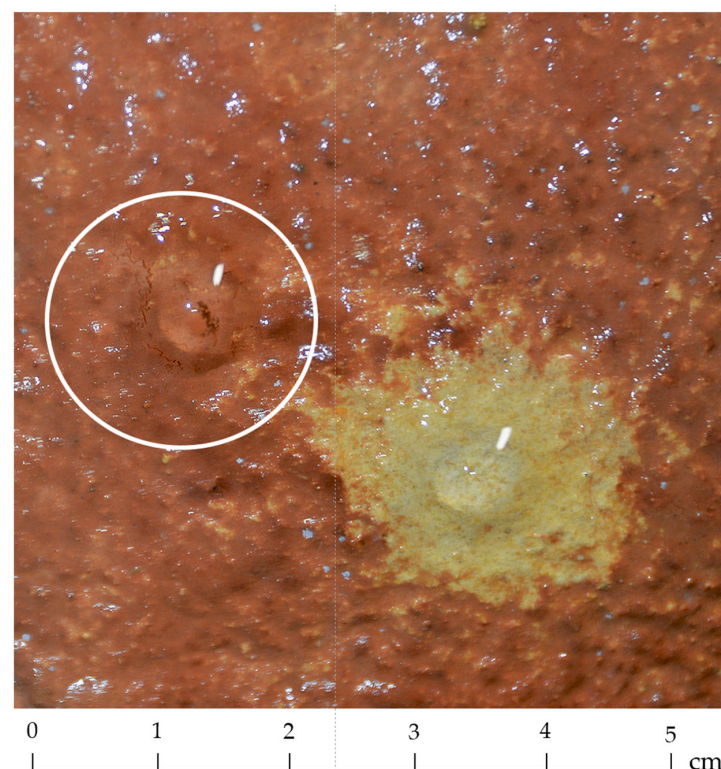


Figure 8. Image showing the limestone rock stripped of paint due to the process of dragging and dripping of water. The white circle highlights a new drip that has already caused the loss of pigment adhesion to the supporting rock.

3. Results

The results obtained with the 1.6 GHz antenna shown in Section 3.1 indicate the distribution of moisture in the internal part and for the first 36 cm from the surface of the

Polychrome Hall ceiling in the ALT1 control zone. Hydrographic calculations based on a three-dimensional model reveal the dynamics of water flow on the Ceiling, aiding in understanding the active fissures involved in pigment drag processes, as well as related drip points (Section 3.2). Six relevant moisture zones with varying elevations and characteristics are observed. These zones are linked to surface microchannels and the large central fracture mapped in previous campaigns (2017 and 2018) as shown in Section 3.3. Despite encountering some issues with data acquisition using the antenna, such as noise interferences and depth limitations, the results allow for the interpretation of water and moisture access dynamics to the Ceiling surface. This information lays the groundwork for applying conservation strategies to minimize deteriorations related to infiltration water on the Polychrome Hall ceiling of the Cave of Altamira.

3.1. Moisture Mapping in ALT1

In the ALT1 control zone, after processing GPR data, six high-moisture zones were detected, each with different characteristics (Figure 9b,c):

- Moisture Zone 1 is strongly associated with the geometry of the central fracture mapped in the 2017/2018 campaigns. This moisture accumulation is parallel to the central fracture and reaches a depth of 36 cm (Figure 9a). Moisture Zone 1 results from the moisture concentration in areas adjacent to the central fracture due to the dam effect generated by the injection of cement mortar applied over the entire development of this large fracture crossing the Ceiling from west to east (Figure 2a). The antenna information shows the existence of discontinuities in the mortar, indicating partial degradation, disintegration, or deterioration at certain points. Additionally, the antenna indicates that the depth of this injected filling from the early last century presents a variable thickness.
- Moisture Zone 2 is closely associated with drip points ALT1_1, ALT1_2, and ALT1_4 as shown in Figure 7b, between 3 cm and 5 cm deep. Its highest moisture concentration is at a depth of 3 cm.
- Moisture Zone 3 is between 2 cm and 12 cm deep. Its highest moisture concentration is at a depth of 2 cm.
- Moisture Zone 4 is associated with the vertical fractures mapped in the 2017/2018 campaigns and projected into the belly of the large bison associated with our ALT1 control zone. It ranges from 2 cm to 36 cm deep.
- Moisture Zone 5 is between 6 cm and 12 cm deep. Its highest moisture concentration is at a depth of 7 cm.
- Moisture Zone 6 is between 6 cm and 19 cm deep. Its highest moisture concentration is at a depth of 6–7 cm (Figure 9a).

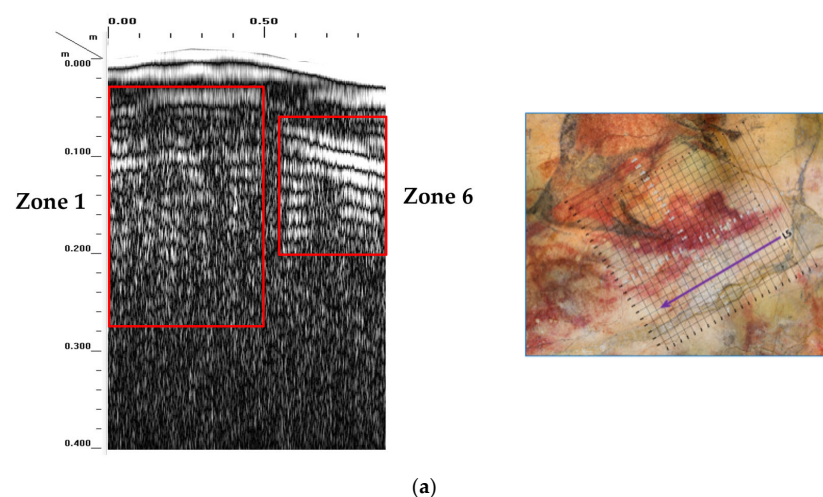


Figure 9. Cont.

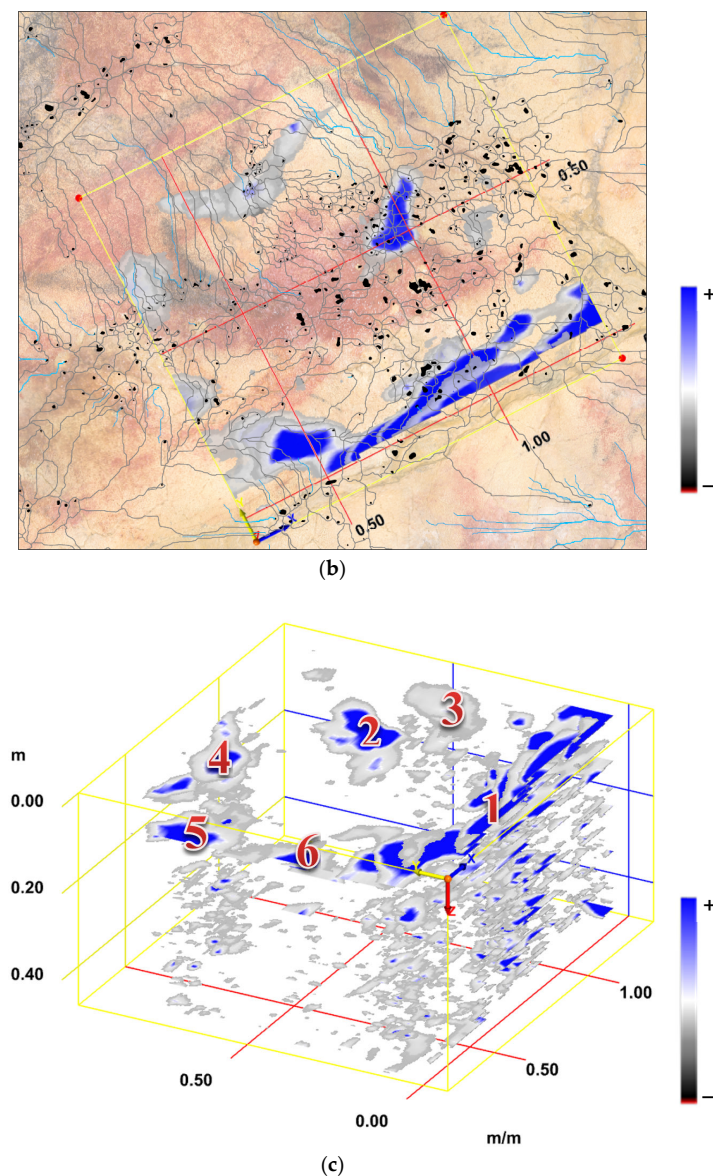


Figure 9. (a) Reflection profile L5 (greyscale amplitudes) showing high-amplitude and strong reflections due to water, interpreted as the presence of moisture within the Polychrome Layer (highlighted in red rectangles: zones 1 and 6). (b) Areas of water/moisture: Superimposition of the sections of the first 36 cm. In blue the areas with higher presence and in white the areas with lower presence. (c) The 6 areas of high moisture mapped in the 3D isosurface model in ALT1 (highlighted with red numbers).

These described moisture zones correlate with both the large fractures (mapped in the 2017 and 2018 campaigns) that develop vertically from the first meters of the overlying layer towards the Ceiling surface and the small fissures or fractures observed on the surface, acting as small moisture inputs (Figure 10). All of this ultimately combines in the different surface microchannels leading to the respective drip points.

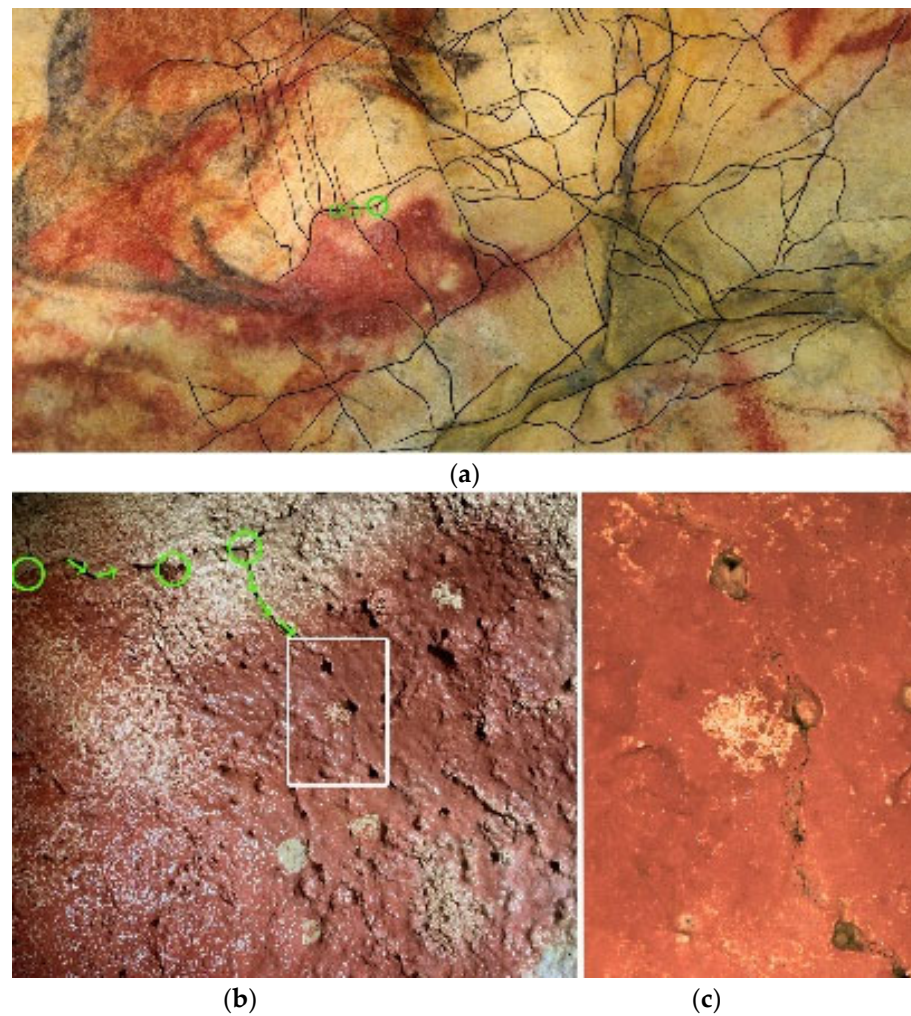


Figure 10. (a) General view of the main surface fissures and fractures in the ALT-1 control area. (b) View of some of the small fissures or fractures that act as small contributions of moisture affecting, as highlighted in the box, the drip point ALT1_4. (c) Detail view of ALT1_4 control area.

3.2. Hydrology of the Polychrome Ceiling

Hydrographic calculations have been carried out using a detailed 3D model with a ground sampling distance (GSD) of less than 200 microns to reveal critical geological characteristics. The main objective is to identify the contribution basins, streams, and drip points, providing information on the dynamics of water flow in the studied environment. The obtained basins constitute an important metric that allows an understanding of the extent and activity of the fissures. In parallel, channels are accurately mapped to discern the trajectory of water flow, including possible pathways for pigment drag and other potential deposits such as clays or limestone particles, in some cases related to microcorrosion processes induced by another significant alteration agent present in caves such as CO₂ [99–102]. This high-resolution model helps to thoroughly examine the hydrographic network, contributing to a global understanding of the existing hydrogeological dynamics on the Polychrome Hall ceiling (Figure 11).

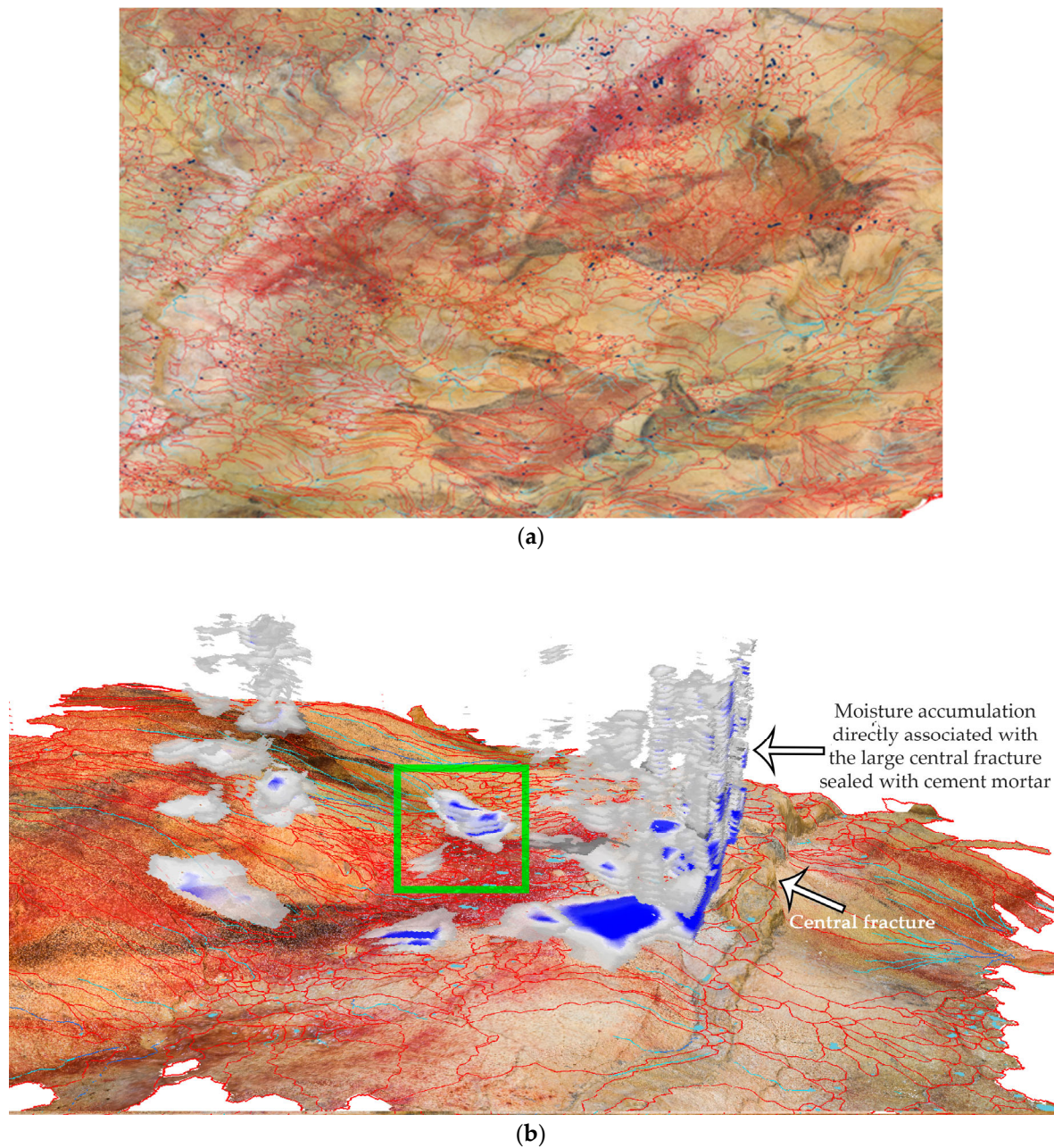


Figure 11. (a) Representation of hydrographic basins and active drip points over a wide surface of the Polychrome Hall ceiling. (b) 3D view showing the moisture distribution within the large central fracture and the control zone ALT1. It showcases the surface-level features like basins, streams, and drip points on the Ceiling area, with varying shades showing the degree of moisture accumulation. Lighter colors mean lower moisture accumulation, while blue indicates the highest accumulation of moisture. The green box highlights the internal moisture close to the Ceiling surface that is directly involved in the processes of paint carry-over, migration, and loss in the ALT1 control area.

To ensure the accuracy and validity of hydrographic calculations, a rigorous validation process has been executed. The results are compared with real field observations or through orthoimages, thus verifying the accuracy of the calculated drip points. This verification step is essential to affirm the fidelity of the 3D model predictions, aligning virtual representations with real geological features. In this verification process, information obtained through the so-called “witnesses” located on the floor of the Polychrome Hall is also important (Figure 12). These witnesses, covering an area of 1×1 m, are made of rigid material formed

from two thin aluminum sheets joined to a solid polyethylene core and lined with a 100% synthetic fabric made of high-density polyethylene fibers, which are lightweight, durable, breathable, and resistant to water, abrasion, and bacterial penetration. The witnesses are georeferenced, allowing the documentation of any dripping from a specific area of the Ceiling surface. Their information, combined with the aforementioned hydrological study, determines the origin of clay, limestone, and pigment drag deposits. This valuable information is transferred to a series of tables that inform us of the dynamics and periodicity of these events [103].



Figure 12. Location of the different witnesses located on the floor of the Polychrome Hall. Witness covering a series of drips located on the hump and head of one of the large polychrome bison.

The importance of these hydrographic calculations goes beyond mere visualization as they provide valuable information about water distribution and pathways in the inner part of the Ceiling (see Figure 11). Drip points, indicating areas where water ultimately precipitates, are important indicators of the hydrological behavior of the environment. This detailed analysis not only improves the understanding of water access through active fissures and water channels but also sheds light on specific areas where water interacts with the cave floor, offering broader insight into the geological processes at play in the studied area.

3.3. The Central Fracture

The presence of a higher degree of superficial moisture, which is concentrated in the central part of the Polychrome Hall ceiling in the form of small laminar water flows on both sides of the large fracture sealed with cement, critically influences some of the pigment drag and washing processes involved in our ALT1 control zone (Figure 13). Geophysical prospecting studies conducted in the Cave of Altamira in recent years have revealed that the large central fracture has vertical development that, from a depth of 1.4 m relative to the exterior surface, penetrates, reaching the actual surface of the Polychrome Hall ceiling. On the other hand, the aforementioned injection with cement mortar acts partially as a ‘plug’, diverting water flows towards adjacent areas, precisely where our ALT1 control zone is located (Figure 11b).

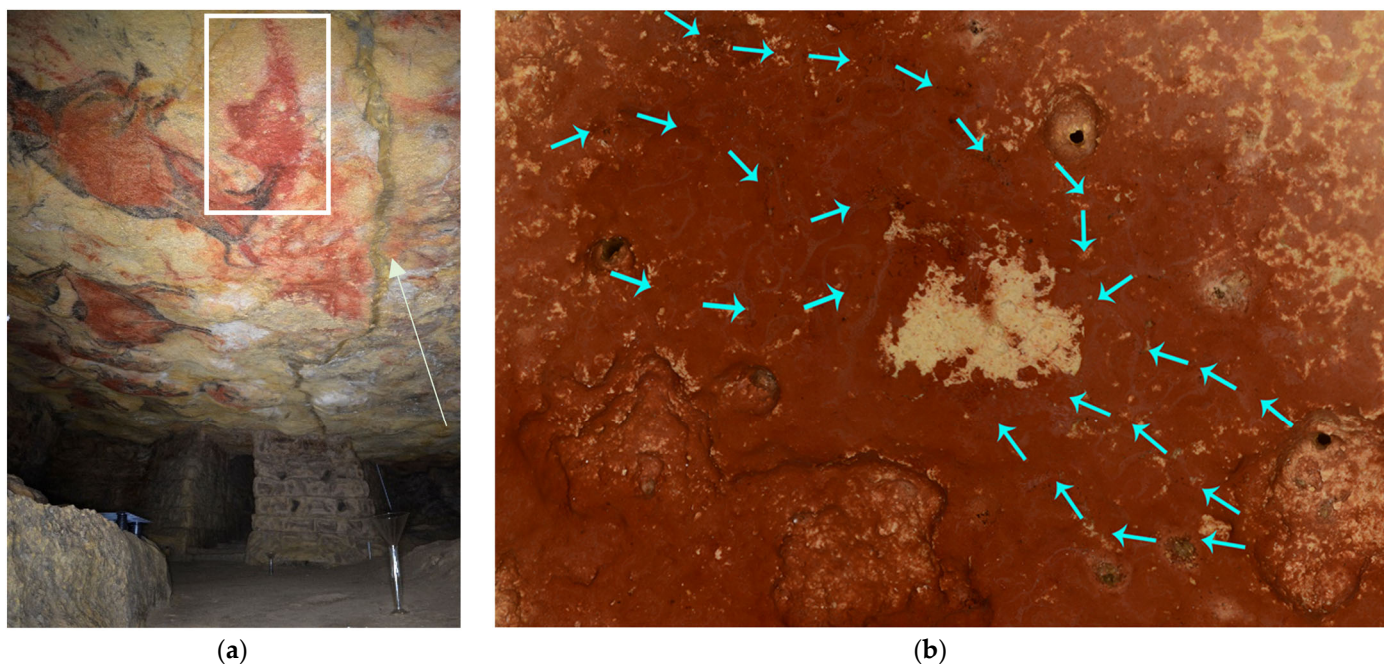


Figure 13. (a) Large central fracture sealed with cement mortar (indicated by the white arrow) and location of the nearby claviform signal (white box). (b) Drip point ALT1_1 and its associated main water inputs (blue arrows indicate the location and orientation of the marked water flows).

3.4. Limitations and Challenges

The problems regarding data acquisition are derived, among other issues, from the difficulty in locating the areas of interest, as they are situated on the Ceiling, which obviously does not allow any contact of our antennas with its surface. On the other hand, the Ceiling surface is bathed in a thin but constant layer of water, which also conditions data collection. Additionally, there are significant conservation constraints related to both the length of stay and the use of materials inside the Polychrome Hall [1].

Noise interferences and signal attenuation have limited the depth penetration of data acquisition beyond the first 50 cm, making subsurface characterization difficult. The combined use of different antennas and the application of a novel methodology by using antennas from the exterior surface in combination with those applied from the interior of the Polychrome Hall has allowed us, after correlating all the data, to obtain more extensive and more precise information on internal fractures and the moisture involved.

The results reveal complex relationships between the distribution of moisture and its associated fractures and fissures and highlight how certain environmental factors decisively influence the conservation of this type of Cultural Heritage site.

4. Discussion

The results of our study shed light on the complex dynamics of moisture distribution in the Polychrome Hall of the Cave of Altamira. Thanks to the integration of high-resolution GPR data with previous campaigns and geospatial analysis, we have been able to better understand the underlying processes related to the dynamics of infiltrating water affecting the conservation of this Cultural Heritage.

The geophysical prospecting campaign with the 1.6 GHz antenna in the ALT1 control zone and up to the first 50 cm depth allowed us to conclude that the highest amount of internal moisture is found between 10 and 20 cm from the surface, with the least moisture load found at greater depths of above 30 cm. Additionally, the presence of this moisture is mainly related to two lateral contributions, one on the southern side, clearly associated with the large central fracture, and another on the northern side coming from a large fracture

of similar development to the central one that even begins at a higher elevation and, discontinuously, reaches almost the same depth as the central one (Figures 10 and 11b).

The greatest water percolation is located towards the northern side, taking as a reference the large central fracture that crosses the Ceiling from west to east. This direction of moisture flow could be explained by:

- a) The dip of the strata of the Altamira karst itself.
- b) The greater percolation of moisture in the western area of the studied quadrant is due to the sealing with cement mortar applied over this large fracture.

4.1. Interpretation of Results in Light of Previous Studies

Our observations are based on studies carried out in the Cave of Altamira, particularly those using GPR technology with variable frequencies. The use of a 1.6 GHz antenna allowed for improved resolution in detecting wet areas and structural characteristics in the upper layers of the cave Ceiling. A comparison with previous campaigns using lower frequencies helped to better understand subsurface conditions and temporal changes.

4.2. Implications for Conservation Strategies

The identification of different moisture zones, areas, and channels and the origin of deposits detached from the Ceiling, especially those of pigment and limestone and dolomite particles, provides important information as they speak of the activation of a series of deterioration processes associated with microclimatic variations. The correlation between moisture distribution and active drip points underscores the need to adopt proactive conservation measures to mitigate the potential damage caused to rock art by the access and circulation of this infiltrating water on the Ceiling surface.

4.3. Broad Context and Future Research Directions

Our results contribute to the broader discourse on the conservation of Cultural Heritage in cave environments, highlighting the importance of integrating remote sensing methodologies for effective conservation. Future research directions may include:

- Further studying moisture dynamics and its correlation with seasonal variations to refine conservation strategies.
- Continuous monitoring of structural stability to assess long-term changes and the effectiveness of possible conservation interventions.

Considering these lines of research would advance our understanding of the complex interactions that shape the preservation of such valuable Cultural Heritage, which in turn would help implement new and more effective preventive conservation strategies. Establishing sustainable practices based on knowledge of these active deterioration processes will enable the activation of new control and monitoring protocols. Ultimately, this will put us in a better position to understand the processes involved in the deterioration of rock art, allowing us to anticipate damage and foresee deterioration in top-tier Heritage Sites such as the Cave of Altamira.

5. Conclusions

Our study represents a significant advancement in understanding the deterioration factors involved in the conservation of art in the Cave of Altamira, especially in the Polychrome Hall. Leveraging advanced remote sensing techniques, particularly high-frequency Ground-Penetrating Radar (GPR), along with geospatial analysis, we have achieved a comprehensive characterization of moisture distribution, and the constraints affecting the structural stability of the Ceiling have been better understood.

The data obtained provide relevant insights into the factors influencing the degradation and conservation of the cave's prehistoric paintings, elucidating the complex interaction between climatic influences, anthropogenic activities, and geological characteristics. By delineating moisture zones and identifying detachment areas, we have established a

foundation for implementing new preventive conservation strategies aimed at mitigating risks and proposing measures to safeguard this invaluable Cultural Heritage.

This study underscores the importance of interdisciplinary collaboration among professionals from different fields to address the multiple challenges posed by the conservation of this type of Heritage. By integrating research for conservation purposes, we can develop holistic approaches focused on the long-term sustainability of these heritage sites.

The research has allowed us to determine the trajectory of water movement in the first 50 cm from the ceiling surface, enabling the identification of the main internal structural discontinuities involved in water access to areas where cave art is distributed. This study was repeated at different times of the year, allowing observations of variations in water behavior and movement within the ALT1 control zone located in the center of the Polychrome Hall ceiling.

Looking ahead, our work lays the groundwork for exciting avenues of research, such as continuous monitoring of the environmental dynamics involved in rock support and pigment detachment processes, the refinement of conservation strategies, and the exploration of innovative technologies for the non-invasive characterization of cave environments [104]. Additionally, our findings underscore the need for ongoing commitment to local communities and stakeholders to ensure effective management and protection of Cultural Heritage resources.

The conservation of the Cave of Altamira faces significant challenges, especially regarding deterioration processes related to its geological stability and the infiltration of water. To mitigate these threats posed by active deterioration processes, it is essential to develop effective conservation strategies that improve our understanding of the current conservation status of the cave.

The integration of geomatics remote sensing technologies, such as 3DTLS, UAVs, and GPR, has helped to rapidly, accurately, reliably, and non-invasively document complex elements such as fracture systems involved in the main access routes for water infiltration into the cave. We have correlated these fractures with several hydrographic basins dividing the surface of the Polychrome Hall ceiling, water streams, and drip points, inducing erosion, scaling, disaggregation, and dissolution processes affecting mineral components, including the pigments constituting Altamira art. With this knowledge, Cave of Altamira managers will be able to make proactive conservation decisions to prevent damage and reduce the risk of cave and painting deterioration [105].

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Publicación 5: Tracking Moisture Dynamics in a Karst Rock
Formation Combining Multi-Frequency 3D GPR Data: A
Strategy for Protecting the Polychrome Hall Paintings in
Altamira Cave

Article

Tracking Moisture Dynamics in a Karst Rock Formation Combining Multi-Frequency 3D GPR Data: A Strategy for Protecting the Polychrome Hall Paintings in Altamira Cave

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Abstract: This study addresses the features of the internal structure of the geological layers adjacent to the Polychrome Hall ceiling of the Cave of Altamira (Spain) and their link to the distribution of moisture and geological discontinuities mainly as fractures, joints, bedding planes and detachments, using 3D Ground Penetrating Radar (GPR) mapping. In this research, 3D GPR data were collected with 300 MHz, 800 MHz and 1.6 GHz center frequency antennas. The data recorded with these three frequency antennas were combined to further our understanding of the layout of geological discontinuities and how they link to the moisture or water inputs that infiltrate and reach the ceiling surface where the rock art of the Polychrome Hall is located. The same $1 \times 1 \text{ m}^2$ area was adopted for 3D data acquisition with the three antennas, obtaining 3D isosurface (isoattribute-surface) images of internal distribution of moisture and structural features of the Polychrome Hall ceiling. The results derived from this study reveal significant insights into the overlying karst strata of Polychrome Hall, particularly the interface between the Polychrome Layer and the underlying Dolomitic Layer. The results show moisture patterns associated with geological features such as fractures, joints, detachments of strata and microcatchments, elucidating the mechanisms driving capillary rise and water infiltration coming from higher altitudes. The study primarily identifies areas of increased moisture content, correlating with earlier observations and enhancing our understanding of water infiltration patterns. This underscores the utility of 3D GPR as an essential tool for informing and putting conservation measures into practice. By delineating subsurface structures and moisture dynamics, this research contributes to a deeper analysis of the deterioration processes directly associated with the infiltration water both in this ceiling and in the rest of the Cave of Altamira, providing information to determine its future geological and hydrogeological evolution.

Keywords: moisture mapping; Ground Penetrating Radar; 3D modeling; preventive conservation; capillary rise; stratigraphic interpretation; rock art; geomatics



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1. Introduction

The Cave of Altamira, located in Santillana del Mar in the autonomous community of Cantabria in Northern Spain, is a relevant site for human Cultural Heritage, renowned for its prehistoric rock art dating back thousands of years. The cave extends about 290 m and broadens at key locations, most notably the Polychrome Hall, which houses its distinguished paintings and engravings dating from more than 35,000 years ago to 14,000 years ago, including the group of polychrome bison on the Polychrome Hall ceiling (Figure 1).

Altamira holds historical significance as the first cave where Paleolithic rock art was discovered. Its significant archaeological deposits and globally recognized artworks culminated in its designation as a UNESCO World Heritage Site in 1985.

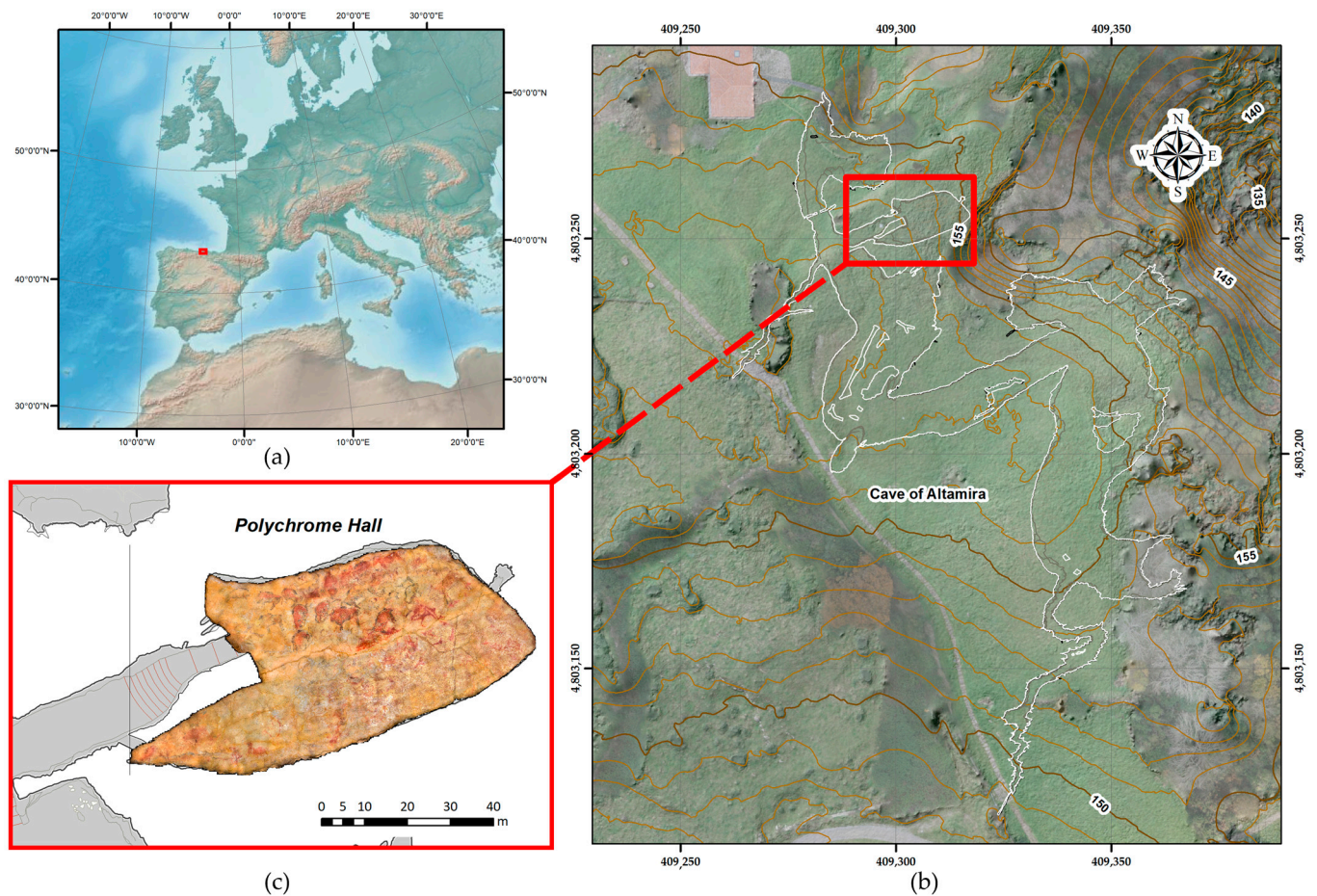


Figure 1. (a) Location map of the Cave of Altamira (b) Projection of the Cave of Altamira on the orthoimage, indicating in a red frame the position of (c) the Polychrome Hall with the rock art orthoimage overlayed.

Over millennia, the cave has served as a recurring site for hunter-gatherer societies, clear in the many representations of animal figures and signs, among other things scattered throughout its halls and galleries a testament to a prolonged artistic creation process. Despite its historical significance, the cave's conservation faces challenges, particularly concerning the conservation of its ancient rock art on the Polychrome Hall ceiling.

The Cave of Altamira is framed within the regional structure of a large syncline called Santillana-San Román, with a NE–SW orientation. The Cave of Altamira began its development in the Pliocene and forms part of the upper zone of a karstic complex. The Altamira Formation is a carbonate series of Cenomanian age (Middle–Upper Cretaceous). The structure and lithology of the Cretaceous calcareous section where the cave is located (Altamira Formation), the reduced strata thickness, with thin marl intercalations, the sub-horizontal stratification and its high degree of fracturing mean that gravitational subsidence is one of the most outstanding morphological features. In its present state, the Cave of Altamira can be classified as a senile cave in a phase of dismantling by collapse, with a low development of lithochemical reconstruction processes [1,2]. In particular, the layers that form the overlying strata of the Polychrome Hall, from the ceiling to the ground surface, are as follows [3]:

- Polychrome Layer, consisting of 0.70–0.8 m of whitish-colored limestones. The base of the Polychrome Layer is the ceiling of the Polychrome Hall where the polychrome bison paintings are located.
- Dolomitic Layer, made up of 0.10–0.25 m of highly dolomitized limestone. This Dolomitic Layer is separated from the Polychrome Layer by a loamy-clay intercalation.
- The Fissured Layer, consisting of a 1.3 m package of fissured and karstified limestone.
- Orange Layer, made up of 0.8 m of orange-colored micritic limestones.
- Upper Layer, where 2 m of yellowish limestones and calcarenites with a 0.2 m marly intercalation can be recognized.

The overlying layer, where the bedrock thickness does not exceed nine meters, exhibits signs of brecciation and dissolution, with accumulations of clays and minerals, such as dolomite particles. There is significant decompression both within the Polychrome Layer and in the overlying Dolomitic, Fissured Orange and Upper layers. The structural characteristics of the bedrock have also been altered by the sealing of surface fractures in the Polychrome Layer with Portland cement in the 1920s and 1930s, which likely blocked the direct pathways for rainwater infiltration [4]. In the Polychrome ceiling, water movement is influenced by surface tension, a capillary phenomenon resulting from the physical and chemical properties of water and the inherent porosity of the calcareous rock. This process, characteristic of karstic environments, is crucial in redistributing water through the Polychrome ceiling and contributing to the formation of calcifications and geological structures.

Leading publications in this field [5] underline the importance of collecting key data through remote sensing [6–9] for the safeguarding of Cultural Heritage, with the aim of integrating geospatial analysis with geophysical techniques. The non-invasive feature and high resolutions of geophysical methods allow accurate mapping of discontinuities in geological complexes [10–14]. The use of geophysical methods provides information on the geological environment, helping to improve the results obtained with geological research methods for the study of the internal structure of karst systems [15–20]. Nowadays, Ground Penetrating Radar (GPR) has become the most widely used geophysical tool to pinpoint and locate discontinuities within the rock mass of the karst system, such as fractures, joints, voids, bedding planes and detachments and moisture zones [21–31]. These features make the GPR technique suitable for the study of karst formations with prehistoric art [32–35].

Several GPR campaigns have been conducted with different frequency antennas in 2017, 2018 and 2022, as shown in Figure 2b–e and Table 1, to characterize the real conservation problems affecting the Ceiling, primarily related to the fractures associated with varying depths of water infiltration, which impact the preservation of the rock art [36–39]. These challenges require a deeper understanding of the geological and hydrological processes affecting the cave's stability and rock art preservation. Building on the GPR results of previous campaigns conducted at the Cave of Altamira, a GPR campaign was carried out in April 2023, with the aim of furthering our understanding of the geological and hydrological dynamics within the cave. In this campaign, antennas of different frequencies (Table 1) were used to map the moisture distribution and identify structural features in the rock formations on the ceiling of the Polychrome Hall that support the cave paintings, particularly focusing on the control area designated as ALT1. The aim of this study was to investigate the interaction between moisture infiltration, geological structures, and the preservation of rock art in ALT1. These efforts have yielded significant insights into the spatial distribution of moisture and its correlation with geological features like fissures and microchannels.

In the 2023 campaign, which focused on the multisensory analysis of the moisture course [38], the ALT1 control zone was studied. This ALT1 control zone is located in the center of the ceiling of the Polychrome Hall (Figure 3a). In this control zone there is a prominent Upper Palaeolithic abstract sign: a large red claviform near the hind legs of one of the large polychrome bison.

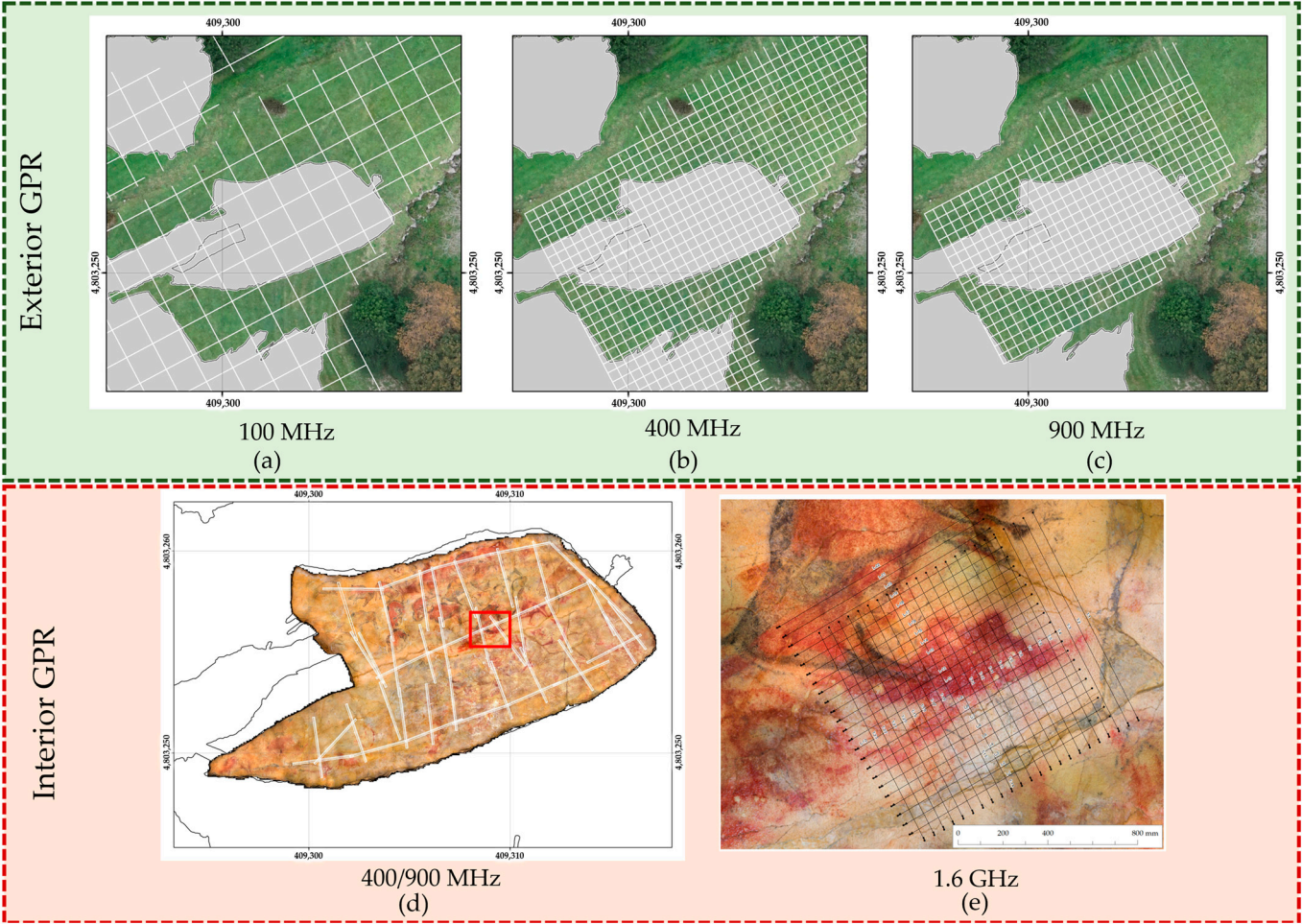


Figure 2. Overview of previous GPR studies conducted in the Altamira Cave and Polychrome Hall ceiling: (a) 100 MHz exterior grid 3 × 3 m, (b) 400 MHz exterior grid 1 × 1 m, (c) 900 MHz exterior grid 1 × 1 m, (d) 400 and 900 MHz interior reflection profiles (indicated with white lines), and location of area around ALT1 (indicated with a red square), (e) 1.6 GHz interior grid 5 × 5 cm in 2022.

Table 1. Frequency antennas used on the exterior and interior of the Polychrome Hall ceiling of the Cave of Altamira in the different GPR campaigns.

Campaign Year	Cave Exterior Antenna Frequencies	Polychrome Hall Ceiling (Inside the Cave) Antenna Frequencies
2017–2018	900–400–100 MHz	900–400 MHz
2022		1.6 GHz
2023		300–800–1.6 GHz

In the broader scientific landscape, it is well-established that multiple factors drive moisture infiltration into cave environments and impact the preservation of rock art. While some studies emphasize the direct correlation between fissures and moisture ingress, others highlight the role of complex hydrological networks in transporting moisture over vast distances within cave systems, and a third factor considers the impact of condensation water on both water distribution and conservation within these environments.

In the case of Altamira, the three factors are evident: the karst and its dip influence the water supply, the vertical or subvertical fractures provide a direct water supply and condensation water contributes to moisture zones within the cave system.

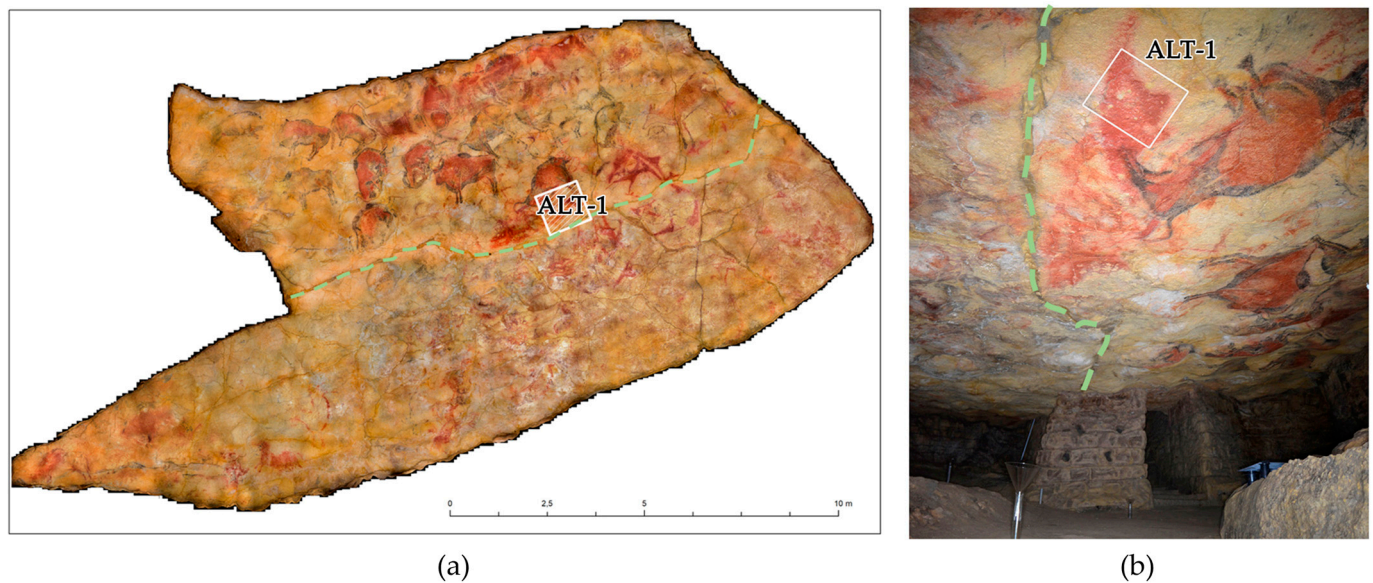


Figure 3. (a) The location of the control area ALT1 on the ceiling of the Polychrome Hall. The dashed light-green line marks the path of the central fracture that runs across the ceiling from west to east. (b) A photograph showing a general view of the ALT1 study area, with the same dashed light-green line indicating the central crack, which has been sealed with cement.

This research aims to follow up on previous studies by carrying out a rigorous and detailed analysis of the internal geological structures present in overlaying strata between the outer covering and the cave's ceilings. By using Ground Penetrating Radar (GPR) technique at different frequencies, 300 MHz, 800 MHz and 1.6 GHz as shown in Table 1, we aim to offer the tools to obtain relevant information through non-invasive techniques, highly respectful of the Cave, providing access to internal morphology and detail of relevant areas for conservation concerns. The comparison of antennas used in GPR surveys reveals a balance between resolution and penetration depth (Table 2). The high-frequency 1.6 GHz antenna delivers excellent resolution, able to detect features as small as 2 cm, but it is limited to a penetration depth of approximately 0.4 to 0.5 m [40,41]. On the other hand, the 800 MHz and 300 MHz antennas, while offering lower resolution, can penetrate up to 4 m, making them more suitable for deeper subsurface investigations. This flexibility allows these frequencies to meet conservation objectives by balancing the need for high resolution with the requirement for deeper geological penetration, ensuring effective subsurface imaging and sensing for preservation efforts [42–47].

Table 2. Comparison of the parameters for the 1.6 GHz, 800 MHz and 300 MHz antennas utilized on the ceiling of the Polychrome Hall during the 2023 survey campaign.

Frequency	1.6 GHz	800 MHz	300 MHz
Frequency Range	1.3–1.9 GHz	0.5–1.0 GHz	0.2–0.4 GHz
Wavelength in Air (m)	~0.1875	~0.375	~1.0
Wavelength (m) ($\epsilon = 7.5$)	~0.0684	~0.136	~0.364
Minimum Resolution (m) ($\epsilon = 7.5$)	~0.0342	~0.068	~0.182
Estimated Maximum Depth (m) ($\epsilon = 7.5$) N = 20	~1.1 m	~2.2 m	~6.0 m
Estimated Maximum Depth (m) ($\epsilon = 7.5$) N = 100	~0.4 m	~0.8 m	~2.0 m
Vertical and Horizontal Resolution	0.0342 m	0.068 m	0.182 m
Image Clarity (Entropy)	0.8–1.0	0.6–0.8	0.4–0.6
Signal Attenuation	High (50–70 dB)	Moderate (30–50 dB)	Low (10–30 dB)
Antenna Gain	High (20–30 dB)	Moderate (15–25 dB)	Low (10–20 dB)
Antenna Beamwidth	15°	30°	45°
Signal-to-Noise Ratio (SNR)	15 dB	10 dB	5 dB

Through analysis and interpretation of GPR data, this study endeavors to provide valuable insights into Altamira geological evolution, structural stability and ongoing conservation challenges. By digging into the processes of deterioration affecting the cave structural stability and indirectly affecting conservation issues related to water infiltration, this research opens the door to implementing preventive measures that guarantee the preservation and sustainability of this Cultural Heritage site, thus, offering a better understanding of some of the most relevant aspects for the conservation of the art of Altamira.

Despite these efforts, there remains a need to further elucidate the geological complexities within the Altamira Cave, particularly focusing on areas like ALT1, which are critical for understanding the interaction between moisture infiltration, geological structures and the preservation of rock art. This study builds on the foundations laid by earlier research campaigns to comprehensively analyze the geological and hydrological dynamics of the Polychrome ceiling in Altamira Cave, offering valuable insights for conservation efforts. This non-invasive geophysical test aims to monitor, by means of 3D mapping, the network of discontinuities (fractures, joints, bedding planes, detachments) and moisture areas present in the overlying layer around the ALT1 control area, from the Upper Layer to the basal surface (Polychrome Layer) of the ceiling of the Polychrome Hall. These factors affect the cave's stability and induce significant changes in the circulation of infiltration water, generating processes of concretion, microcorrosion, dissolution and dragging of paint [48]. This 3D mapping can also provide information on the role played by the water dynamics associated with the monitored section of the central crack (Figure 3), located about 70 cm from our ALT1 control area.

2. Materials and Methods

2.1. Study Area and Design

In the Polychrome Hall, curators have monitored different conservation-sensitive areas. Among these areas is our designated zone, ALT1, in the center of the Polychrome Hall and closely associated with prehistoric paintings, including a prominent sign known as the "claviform" where one of the large polychrome bison is arranged (Figure 4).

The choice of the ALT1 control area within the Polychrome Hall was informed by earlier research indicating microchannels, fractures, and other geological anomalies that could affect the preservation of the paintings. These anomalies facilitated water infiltration, allowing moisture to access the control area through internal fractures.

The study design incorporated campaigns conducted during different seasons or periods of the year to capture temporal variations and assess the long-term dynamics of water infiltration processes associated with the main internal cracks, fractures and fissures within the Polychrome Hall. This seasonal approach helped with the monitoring of changes in moisture distribution, fracture patterns and other geological parameters over time, providing valuable insights into the underlying processes shaping the cave environment and its impact on rock art preservation.

Through the systematic collection of data using Ground Penetrating Radar (GPR) techniques and advanced data processing methods, the study has allowed us to determine the main internal fractures of the ceiling in the ALT1 control area directly involved with the access of seepage water leading to migrations and pigment washing. In addition, this study has helped us to understand in greater detail the internal geological structure directly involved in the stability processes of the rock mass. This interdisciplinary approach aimed to provide a comprehensive understanding of the complex interplay between geological processes, environmental factors and the preservation of this globally significant cave and its rock art.

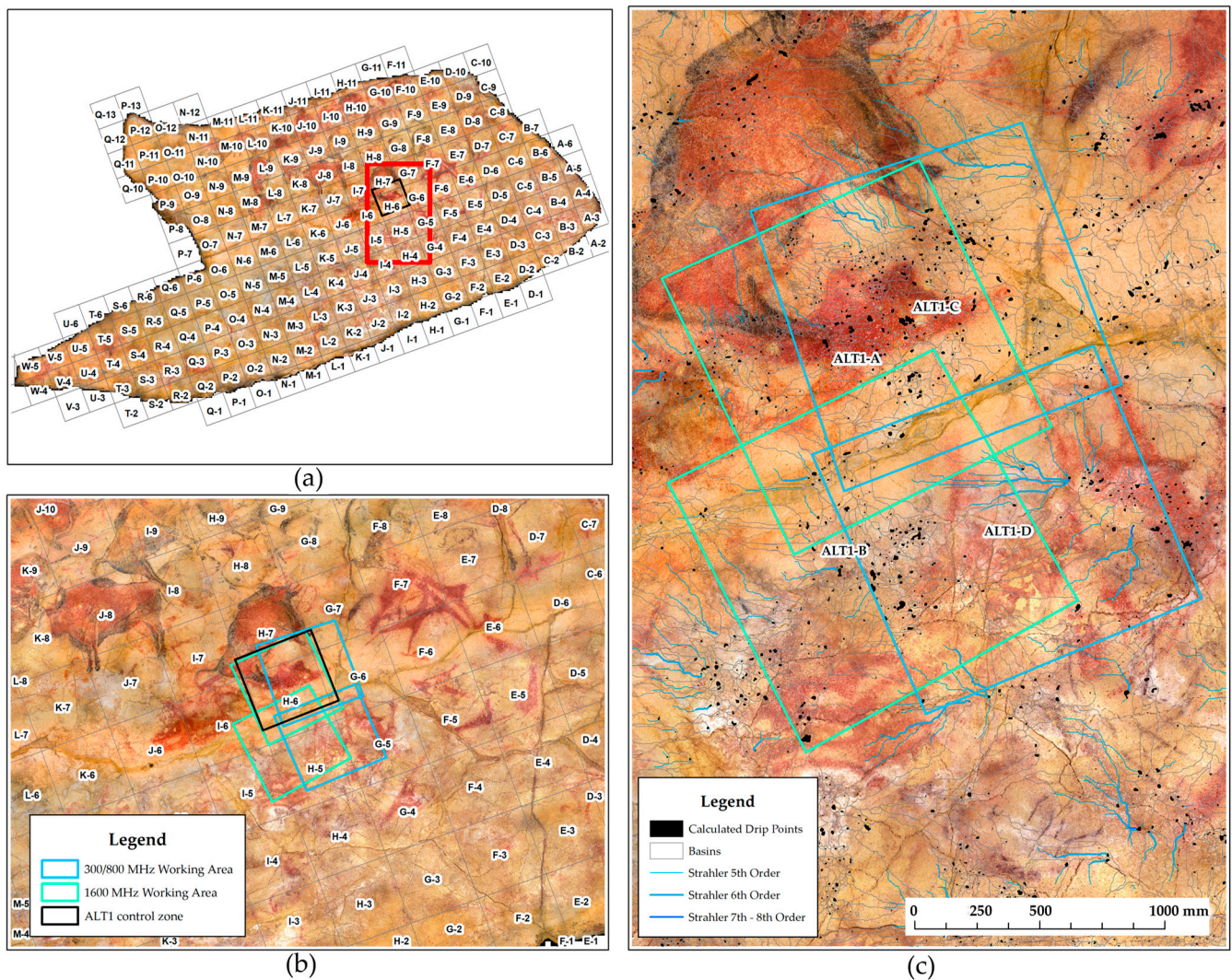


Figure 4. (a) Orthoimage of the Polychrome ceiling with the sectorisation grid and the location of the control area ALT1. (b) View of the ALT1 control area together with the sectorisation grids and the working areas for the 300/800 MHz and 1.6 GHz antennas and (c) overlapping of the working areas for 300/800 MHz and 1.6 GHz antennas with basins, streams and drip points.

2.2. General Workflow Diagram

The data integration process (Figure 5) began with the establishment of a precise reference frame using the Topcon Hyper II [49] (Topcon Corporation, Tokyo, Japan) Global Navigation Satellite System (GNSS) [50,51], which ensured accurate alignment to the European Terrestrial Reference System 1989 (ETRS89). A closed traverse was then carried out using a Topcon GPT-7503 total station (Topcon Corporation, Tokyo, Japan) [52], with 16 stations set out over a distance of 430 m. Checkerboard markers distributed throughout the cave were used for radiation measurements to ensure accurate georeferencing. A 3D model of the cave was then constructed using 3D terrestrial laser scanning (3DTLS) with a Faro Focus X-130 scanner (Faro Technologies Inc., Lake Mary, USA) [53]. This required 300 individual scans and achieved a 95% point adjustment accuracy of 2.7 mm, providing the necessary reference for the photogrammetry process [54,55].

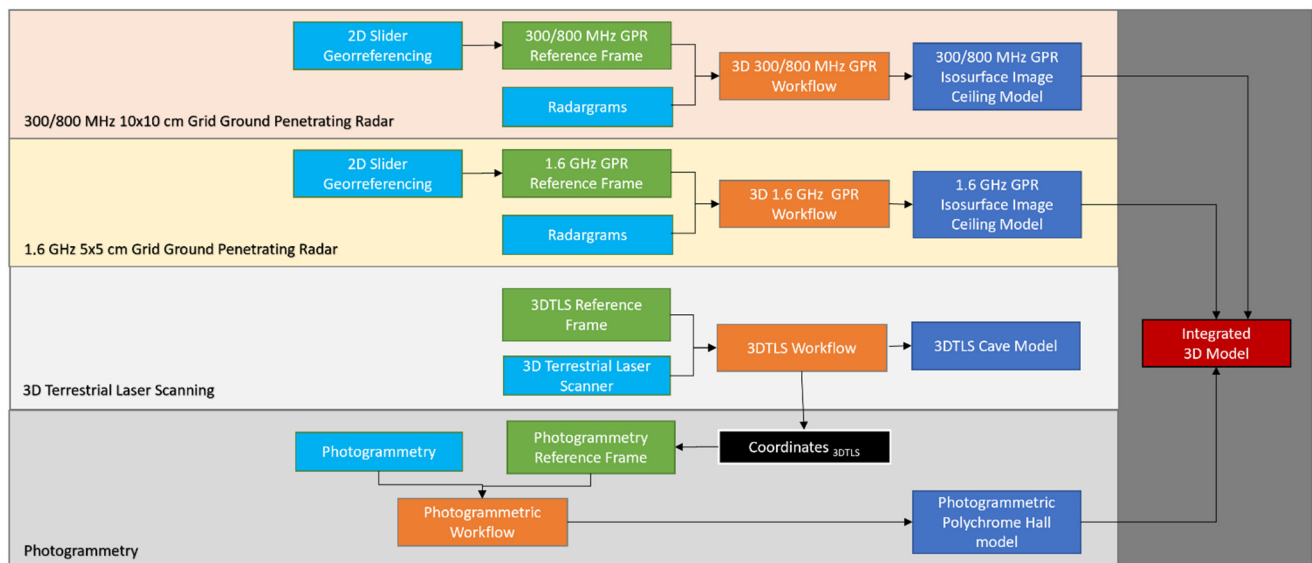


Figure 5. General workflow.

In a previous photogrammetry campaign conducted in 2014 [56], the ceiling of the Polychrome Hall was captured using a Hasselblad H4 D-200 MS camera (Gothenburg, Sweden), achieving a minimum resolution of 16 pixels per mm². These images were processed to create a high-density point cloud, which was later refined into a high-resolution 3D digital model of the ceiling. This model enabled the generation of a gigapixel orthoimage and a simplified polygonal model, both of which played an essential role in hydrological calculations to assess water flow patterns and identify possible water infiltration points towards the Polychrome Hall [36–39].

In February 2022, a dual-axis slider system made with three 1.2 m sliders designed to cover a 1 m² control area (ALT1) was used in a campaign aimed at estimating the distribution of moisture and discontinuities within the first few centimeters of the support rock where the polychrome paintings are located. A GPR antenna with a central frequency of 1.6 GHz was used to collect 2D radargrams on a 5 × 5 cm orthogonal profile grid, enabling the generation of 3D models, including 3D horizontal slices. The result offered valuable insights into the subsurface conditions that impact the preservation of the paintings.

Building on these findings, a more complete study was conducted in April 2023 using both single and dual-frequency GPR antennas (300/800 MHz and 1.6 GHz). This campaign aimed to further investigate the influence of the central fracture on moisture distribution. The data collection involved adjacent profile grids on either side of the central fracture, with grid dimensions varying according to the frequency used. The slider system ensured precise and consistent data collection during this campaign as well. This study deepened our understanding of the internal structure of the rock mass and its impact on the stability and preservation of the cave's rock art.

2.3. GPR of ALT1 Control Area

2.3.1. GPR Data Acquisition

Ground Penetrating Radar (GPR) was employed as the primary geophysical technique to investigate the subsurface structure and moisture distribution within the Polychrome Hall ALT1 control area. GPR offers a non-invasive and high-resolution method for imaging subsurface features by emitting electromagnetic pulses into the ground and recording the reflections from geological interfaces and moisture content variations.

The GPR surveys were conducted using equipment capable of capturing detailed subsurface images with high spatial resolution, using an SIR 4000 system manufactured by Geophysical Survey Systems, Inc. (GSSI, Nashua, NH, USA). Two GPR antennas (one of them dual) were used to cover a broad range of frequencies and penetration depths,

allowing for comprehensive subsurface characterization with three different resolutions (Table 2):

- 1.6 GHz antenna: This high-frequency antenna was used to capture fine details of the near-surface layers of the ceiling and detect subtle variations in moisture content and geological structures. Its short wavelength provided high-resolution images suitable for mapping fractures, microchannels and other shallow features within the rock formations.
- 300/800 MHz dual-frequency antenna: The dual-frequency antenna provided versatility, enabling deeper penetration into the subsurface while maintaining reasonable resolution. The lower frequency (300 MHz) facilitated imaging of deeper geological interfaces and moisture distributions, documenting moisture zones associated with fractures closer to the surface of the Polychrome ceiling. The higher frequency (800 MHz) offered enhanced resolution for detailed characterization of shallower layer features (discontinuities and moistures) located close to the rock paintings.

Due to the presence of delicate cave paintings on the ceiling of the Polychrome Hall, the GPR data collection was performed using a bow-tie antenna to avoid any physical contact with the artwork, thereby minimizing the risk of damage. The height at which the antenna was positioned had to be carefully managed as it affected the quality of the data. To mitigate this effect and maintain the required minimum ceiling clearance, the data acquisition heights were adjusted according to the antenna frequency. For the dual frequency 300/800 MHz antenna, the height was set to 20 cm (Figure 6a), and for the 1.6 GHz antenna, it was lowered to 10 cm (Figure 6b). However, the irregularities of the ceiling, characterized by pronounced protrusions, caused the distances to fluctuate. In some areas, the antenna was positioned as close as 10 cm, while in other areas the distance was greater, requiring continuous verification to ensure safe clearance. These antenna heights optimized energy transfer into the rock mass and reduced air coupling effects, which was critical to obtaining high quality GPR data [57,58]. The setup allowed penetration depths of up to 50 cm with the 1.6 GHz antenna, 2.8 m with the 800 MHz antenna and 4.3 m with the 300 MHz antenna, while maintaining high-resolution imaging capabilities [40,44,59]. The GPR surveys were conducted using a dual-axis slider system equipped with three 1.2 m sliders, designed to cover a 1 m² control area (Figure 6). This system ensured controlled movement and consistent data collection along predefined trajectories. During data acquisition, consistent survey parameters such as antenna orientation and odometry were maintained. The slider position was 3D scanned to accurate georeferencing and spatial registration of the data.

During data collection, the GPR system operated in continuous-wave mode, emitting electromagnetic pulses into the subsurface at regular intervals along the survey lines. Simultaneously, the system recorded the amplitude and travel time of reflected signals, capturing detailed information about subsurface features, interfaces and moisture content variations.

To ensure comprehensive coverage and reduce data gaps, the GPR profiles were spaced closely, with overlapping regions between adjacent lines. A 300/800 MHz antenna was used on the slider with a 10 × 10 cm equidistance grid (Figure 7a), while a 1.6 GHz antenna was employed with a 5 × 5 cm equidistance grid (Figure 7b). This setup facilitated precise mapping of internal fractures and potential water infiltration points, crucial for understanding rock mass stability and preserving the cave's rock art.

To enhance data quality and reduce noise interference, consistent antenna positioning, orientation and scan speed were maintained throughout data acquisition. These measures were crucial in achieving high-resolution subsurface profiles and 3D models.

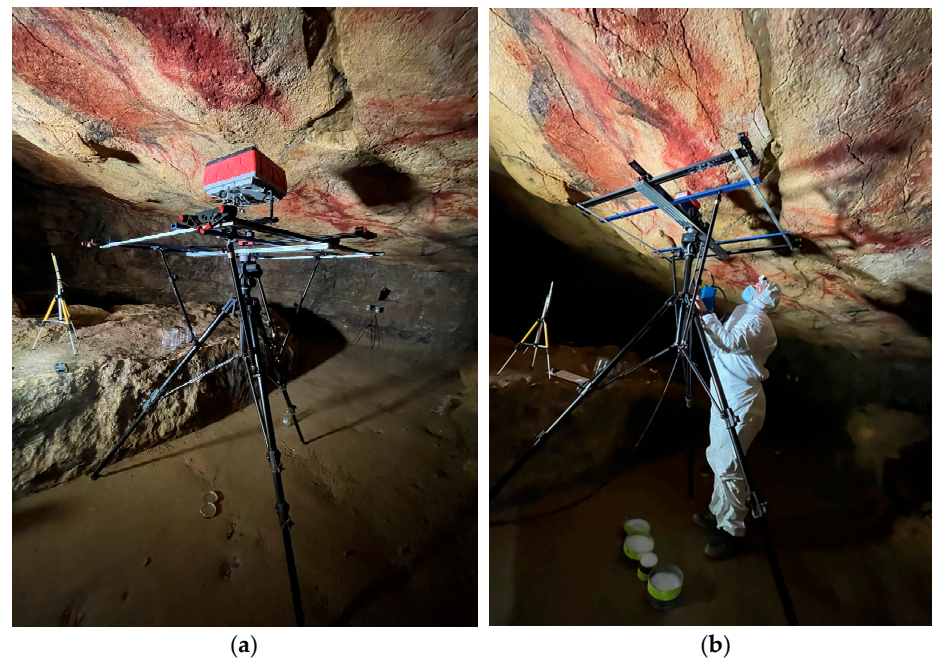


Figure 6. Photographs showing the GPR data collection set-ups in control area ALT1. (a) with the 300–800 MHz dual-frequency antenna and (b) with the 1.6 GHz antenna.

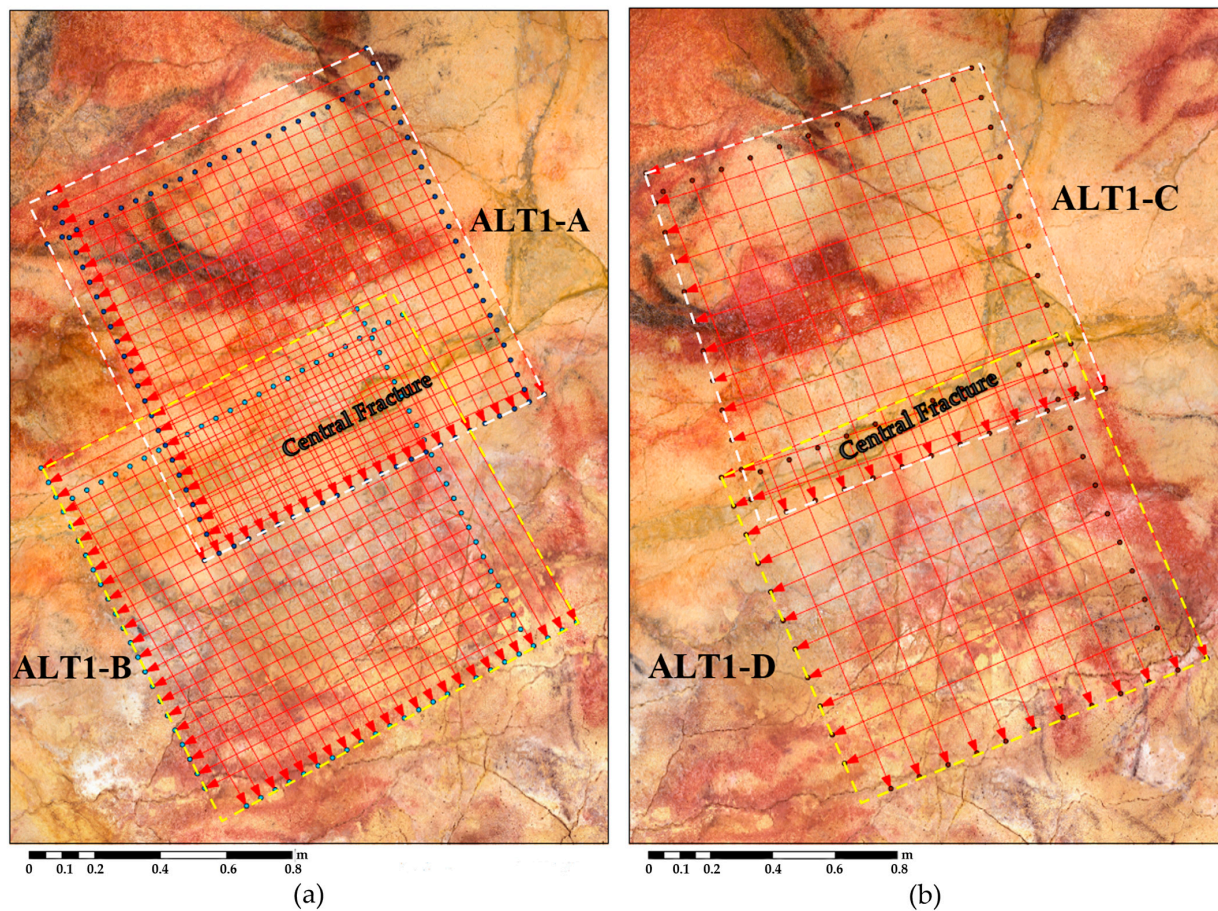


Figure 7. (a) Location of the two grids with an equidistance of 5 cm of the profiles using the 1.6 GHz antenna in the study areas ALT1-A (in white dashed square) and ALT1-B (in yellow dashed square). (b) Location of the two 10 cm × 10 cm grids using the 300/800 MHz dual frequency antenna in the study areas ALT1-C (in white dashed square) and ALT1-D (in yellow dashed square).

2.3.2. Data Processing

The processing of the GPR field data has followed the processing steps for A-scan, B-scan and C-scan of the GPR signal that were performed in the previous campaigns [37,38]. The use of the Hilbert transform (instantaneous amplitude) attribute in the interpretation of GPR data allows for increased understanding of the internal structure of the Polychrome Layer by characterizing the electromagnetic response to moisture zones within the layer over time. In addition, articles [37,38] describe the various factors, including discontinuities, that influence the amplitude of the electromagnetic wave. Furthermore, these considerations of how the instantaneous amplitude can be equivalent to the moisture content distribution and what other factors can also cause changes in amplitude have been based on contributions from several authors [12,31,46,47,60–71].

The average GPR wave velocity was determined using the hyperbolic fitting method on a series of hyperbolas recorded across different reflection profiles for the three-frequency antennas. This resulted in a mean velocity of 0.111 m/ns. The dielectric permittivity (ϵ) was calculated to be 7.2, following the low-loss media equation described in [60,62,72]. This velocity was then used for time-to-depth conversion and Kirchhoff migration during the 2D processing of the GPR data.

The raw GPR data obtained from the three different antennas underwent post-acquisition processing before amplitude maps were created and 3D images were generated from the reflection profiles. Basic processing steps were applied to the raw data, followed by a Hilbert transform attribute (instantaneous magnitude) using RADAN 7.6 software (Geophysical Survey Systems, Inc., GSSI, Nashua, NH, USA) [73]. Initially, 1D processing was performed, starting with zero-time correction. Then, 2D processing was applied to the reflection profiles, which included the following: (i) background removal; (ii) bandpass filtering; (iii) application of linear amplitude gains; (iv) Kirchhoff migration with the calculated mean velocity (0.111 m/ns); (v) time-to-depth conversion using the same mean velocity and (vi) Hilbert transform attribute for instantaneous magnitude. Once processed, each reflector profile was aligned within the grid to generate horizontal 3D amplitude maps and isosurface images that helped to identify significant moisture/water zones. Amplitude slice maps were created at different depths, revealing subsurface moisture/water features to depths of 50 cm with the 1.6 GHz antenna, 2.8 m with the 800 MHz antenna and 4.3 m with the 300 MHz antenna. These depth-slice maps allowed for the identification of moisture-rich areas at fixed depths. After generating the depth maps, the highest amplitude values from all profiles were plotted on an isosurface image. This image was color-coded to emphasize the highest amplitudes, while lower values were rendered transparent, simplifying the visualization and interpretation of the main moisture/water zones in the surveyed ceiling strata.

Data quality assessment procedures, such as visual inspection of refraction profiles, signal-to-noise ratio analysis and comparisons with ancillary data (e.g., surface topography and geological surveys) were used to identify and correlate contact layers in the GPR data according to geological stratigraphy [60,62,74].

3. Results

The interpretation of GPR data has revealed significant findings that contribute to our understanding of the Polychrome Hall ceiling geological structure and hydrological processes involved in the conservation of painting. In addition, complimentary datasets, such as basins, streams, drip points, cracks and fractures (Figure 8), were integrated with the results of the GPR data to help with a comprehensive interpretation and analysis. This interdisciplinary approach enabled the identification of subsurface structures, moisture dynamics and geological features relevant to the study objectives. Thus, the interpretation of the GPR results involved the qualitative and quantitative analysis of subsurface images, identification of geological interfaces and characterization of moisture content variations.

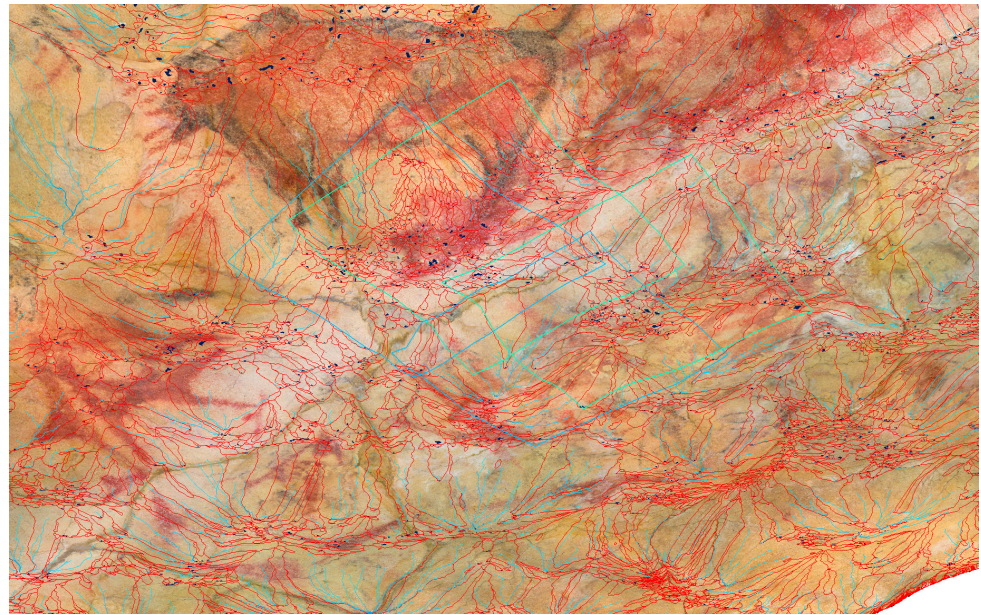


Figure 8. 3D model including basins (in red), streams (in light blue), drip points (in black) and the working areas (green boxes) for 1.6 GHz and 300/800 MHz antennas.

3.1. Detection of Subsurface Features

The GPR survey conducted in the Polychrome Hall enabled the detection and characterization of various subsurface features crucial for understanding the ceiling geological and hydrological dynamics (Figure 9). The interpretation of GPR data revealed diverse features, including fractures, geological interfaces, sedimentary layers and moisture related to discontinuities directly related to the supply of moisture or infiltration water to the uppermost layers of the Polychrome ceiling.

Fractures and fissures were prominently identified throughout the surveyed, taking into account their orientations, lengths and degrees of connectivity area at different depth penetration ranges according to the frequency antennas used (Figure 9b–e). These features reflect the complex tectonic history and structural framework of the cave system. The distribution and density of fractures not only provide insights into the mechanical properties of the rock mass but also indicate potential pathways for fluid migration and small dragged deposits of the type of clay particles, quartz, limestone, etc. within the subsurface environment, considering their dip and involvement in moisture-related discontinuities in the study area.

Moreover, the GPR data facilitated the mapping of geological interfaces, such as bedding planes, joints and contacts between different lithological units (Figure 9b–d). These interfaces play a significant role in delineating the geological stratigraphic architecture of the cave and can influence overlying layer flow patterns and the distribution of moisture within the subsurface layers.

Sedimentary layers, including limestone deposits, were discerned from the GPR data, allowing for the characterization of the depositional history and lithological heterogeneity within the cave. The identification of sedimentary sequences provides valuable information for reconstructing past environmental conditions and interpreting the geological evolution of the cave system.

Furthermore, the GPR survey facilitated the detection of moisture-related zones, such as areas of high moisture content, water infiltration zones and points of active dripping. These zones are indicative of localized hydrological processes, including percolation, condensation and capillary rise, which influence the distribution of moisture on the surface of the Polychrome ceiling. Understanding the spatial variability of moisture dynamics is crucial for assessing the preservation of rock art and geological formations.

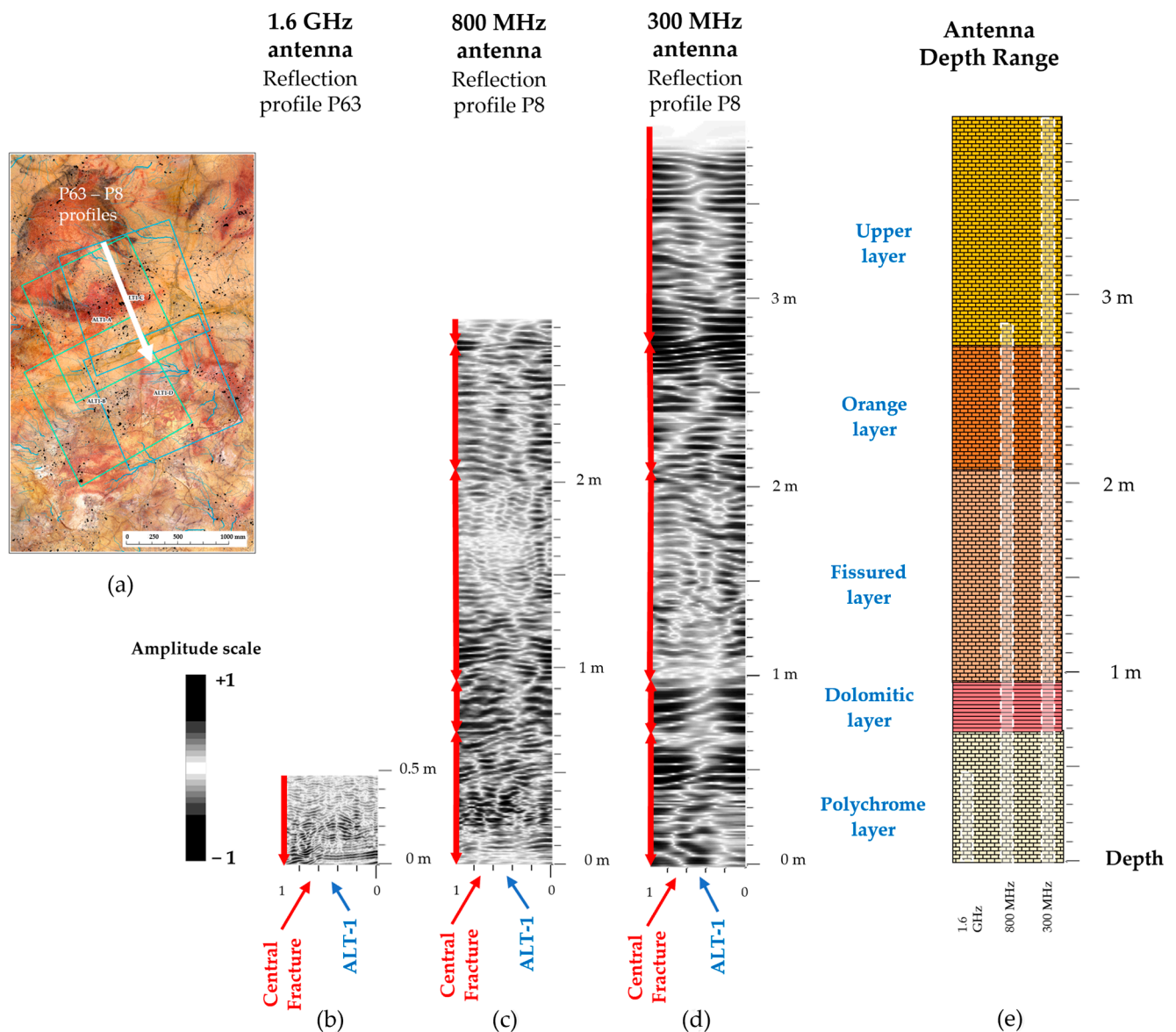


Figure 9. GPR reflection profiles processed in the ALT1 control area showing the main subsurface features (discontinuities), in particular the central fracture, with their stratigraphic correlations of the overlying layers of the ceiling for each frequency antenna used: (a) Location of P63 and P8 profiles which spatially coincide, (b) reflection profile P63 antenna 1.6 GHz; (c) reflection profile P8 antenna 800 MHz; (d) reflection profile P8 antenna 300 MHz; (e) schematic stratigraphy of the Polychrome Hall ceiling according to [2,3], showing the depth range reached with the 1.6 GHz, 800 MHz and 300 MHz frequency antennas.

3.2. Characterization of Moisture Dynamics

The GPR data analysis enabled a comprehensive characterization of moisture dynamics within the studied area of the Polychrome Hall ceiling, shedding light on the spatial distribution, temporal variability and hydrological processes governing moisture movement within this specific part of the cave environment.

The area of moisture directly implicated with the pigment drip points at ALT1 and recorded by the 1.6 GHz antenna in February 2022 was at a depth of 3 cm from the Ceiling surface. The survey carried out on 26 April 2023, with the same antenna, and for the same control area, relates a series of moisture zones at a depth of 9 cm from the Ceiling surface, with the one described above from the February 2022 campaign (Figure 10). This being a first approximation, and considering the need to obtain new data for different

periods, we propose that there is a dynamic in terms of water infiltration that, through the fractures, fissures and internal stratification planes, percolates to the surface of the Ceiling. We consider that the internal moisture zones mapped in our ALT1 control area on 17 February 2022 has had an impact, from April of the same year, on the washing of pigment in the drip points within the ALT1 control area, as well as causing the migration of paint in other associated drip points. In addition, the moisture zone recorded in April 2023 at a depth of 9 cm and above was directly involved in the paint washing processes at the same drip points and possibly others in April 2024.

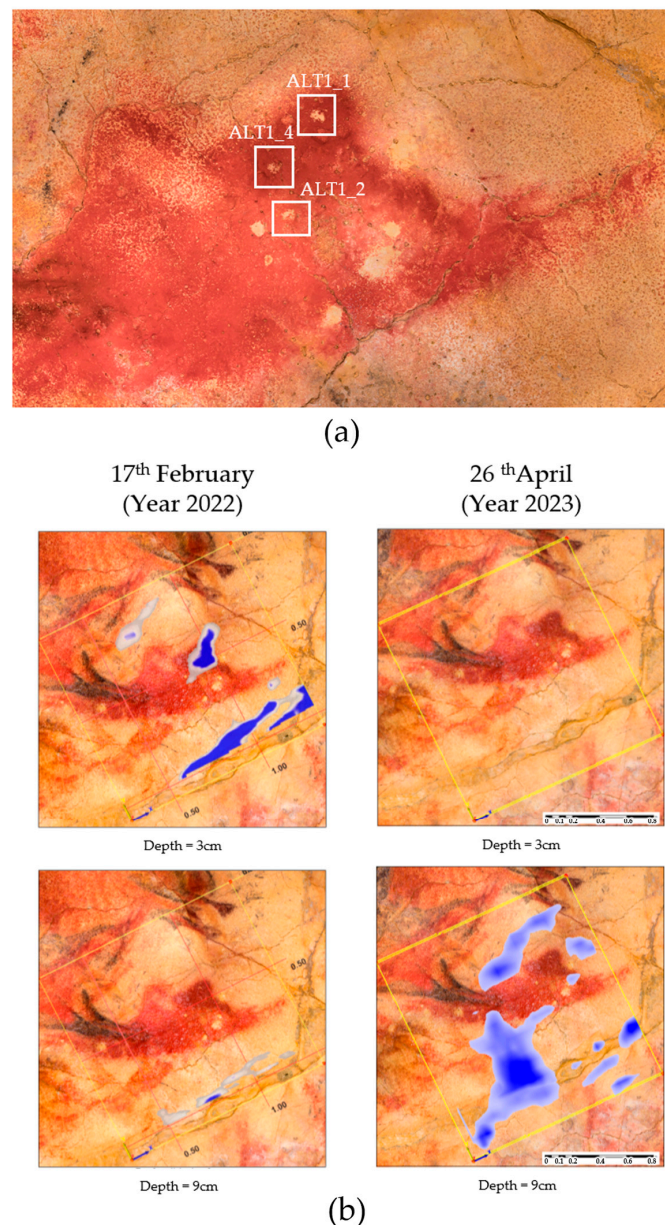


Figure 10. (a) location of the drip points ALT1_1, ALT1_2 and ALT1_4 involved in migration and pigment loss within the control area ALT1. (b) Evolution of the internal moisture zones detected by the 1.6 GHz antenna directly involved in the above mentioned dropping points.

In addition, it is likely that the moisture zone recorded in April 2023 at a depth of 9 cm and above is responsible for some of the pigment loss associated with the drip points located in ALT 1 that were recorded in April 2024. Further data collection over different time periods is needed to refine these observations and better understand the dynamics of moisture affecting the cave rock art.

Furthermore, the GPR analysis provided insights into the temporal variability of moisture content within ALT1 control area, including how this influences the degradation processes of the paint. By conducting repeated surveys at different time intervals, changes in moisture depths over time can be monitored. This approach allows for the identification of seasonal fluctuations, short-term hydrological events and long-term trends in moisture infiltration and redistribution. Understanding the temporal dynamics of moisture infiltration is important for assessing the vulnerability on the preservation of the paintings and its relation to the degradation processes that lead to microcorrosion of the supporting rock and, consequently, to the loss of adhesion of the pigment that generates the migration and washing away of the pigment. It also reveals internal changes, such as the reservoir effect of moisture, where saturation in one area can lead to water access in other internal areas, akin to a communicating vessels effect.

Additionally, the GPR survey facilitated the characterization of moisture retention zones and storage reservoirs within the subsurface environment. By identifying areas with high moisture content and delineating their spatial extent, the survey highlighted regions where water accumulates and persists over time. These moisture retention zones play a critical role in sustaining cave ecosystems, supporting microbial communities and influencing the growth of speleothems and other calcite deposits, while also inducing microcorrosion processes in combination with the accumulation or concentrations of CO₂, largely originating from the outside vegetation near the cave [75].

The GPR data offered valuable insights into how moisture dynamics interact with the cave's rock art features. By correlating moisture anomalies with the distribution of paintings, the survey highlighted potential impacts of moisture infiltration on the conservation of the existing art in this control area. Understanding these interactions is crucial for developing conservation strategies aimed at preserving the cave art, particularly on the ceiling of the Polychrome Hall, where moisture infiltration poses a significant risk to its preservation (Figure 11).



Figure 11. South area of the ceiling of the Polychrome Hall affected by carbonate concretions produced by the access of seepage water through the fracture zones.

3.3. Mapping of Geological Interfaces

The GPR survey provided detailed mapping of geological interfaces within the Polychrome Hall, offering insights into the subsurface structure and stratigraphy of the cave system.

One of the primary outcomes of the GPR analysis was the delineation of stratigraphic boundaries present in this area of interest and their correlation with the geological layers of the cave. By analyzing the reflections from subsurface interfaces, the survey identified distinct layers corresponding to different lithological units, such as limestone and dolomite. These stratigraphic boundaries are crucial for understanding the geological history of the cave, including depositional processes, sedimentary sequences and tectonic events that have shaped the landscape over time.

Furthermore, the GPR data revealed the presence of structural features such as fractures, faults and joints that intersect the geological layers within the cave. These structural discontinuities play a significant role in controlling the flow of water, gases and nutrients through the subsurface environment.

Moreover, the mapping of geological interfaces enabled the identification of karst features such as dissolution cavities, conduits and void spaces within the limestone bedrock. These karst features are critical components of the cave hydrological system, serving as conduits for groundwater flow and reservoirs for water storage. By delineating the spatial extent of karst features, the GPR survey contributed to the understanding of overlying layer flow patterns, recharge mechanisms and hydrological connectivity within the cave network.

Additionally, the GPR data facilitated the characterization of sedimentary deposits and alluvial fill within the overlying layer. By mapping the distribution and geometry of sedimentary layers, the survey enhanced our understanding of overlying layer sedimentology, including sediment transport mechanisms, depositional environments and paleoenvironmental reconstructions.

3.4. Correlation with Previous Studies

Comparing the findings of the current GPR survey with earlier studies conducted in the Polychrome Hall ceiling provided valuable insights into the temporal and spatial variability of subsurface features and moisture dynamics within the overlying layer system. The GPR survey results were compared with data obtained from earlier studies, revealing both consistencies and discrepancies between the findings. This comparative analysis shed light on the dynamic nature of the cave environment and the limitations of individual survey techniques.

One notable part of the correlation analysis was the confirmation of previously identified geological interfaces and structural features within the cave. The GPR data corroborated the existence of stratigraphic boundaries, fractures and karst features reported in earlier studies, showing the reliability and reproducibility of the survey methodology. This consistency in the identification of subsurface features across different studies enhances confidence in the interpretation of cave hydrogeology and geological processes.

However, discrepancies between the current GPR results and earlier findings were also seen, particularly regarding the spatial distribution and intensity of moisture dynamics within the cave. While earlier studies may have provided qualitative descriptions or localized measurements of moisture content, the GPR survey offered a more comprehensive and quantitative assessment of subsurface moisture patterns. Discrepancies in moisture dynamics between the current study and earlier investigations may arise from differences in survey resolution, data interpretation techniques or temporal variations in environmental conditions, water distribution and internal moisture.

The correlation analysis highlighted the importance of temporal monitoring and multi-methodological approaches in overlying layer research. By integrating data from multiple surveys conducted over different time periods and using diverse techniques, researchers can gain a more holistic understanding of the dynamics of the moisture bathing the ceilings of the Cave, especially the Polychrome Ceiling, and improve the accuracy of

environmental assessments. To further corroborate the data, future studies could enhance the analysis by correlating external precipitation processes with the time factor and their internal accumulation through fracture lines.

As for the specific moisture dynamics seen within the ALT1 area, direct correlation was made with the points of pigment dripping (Figure 10a) recorded by the 1.6 GHz antenna in February 2022. This moisture, previously at a depth of between 3 and 5 cm, is documented months later at a greater depth some 9 cm above its previous position. This observation indicates a significant shift in moisture distribution over time, with implications to preserve cave art. The analysis suggests that moisture present in February 2022 contributed to the washing of pigment dripping points in April, May and June 2022, and the current moisture depths, documented in April 2023, are slightly higher and have affected the pigment close to the drip points associated with our control area ALT1, as well as other control areas separated by a few centimeters from it (ALT12) in April 2024. This reflection underscores the dynamic nature of moisture infiltration and its potential effects on the conservation of cave art over successive years (Figure 12).

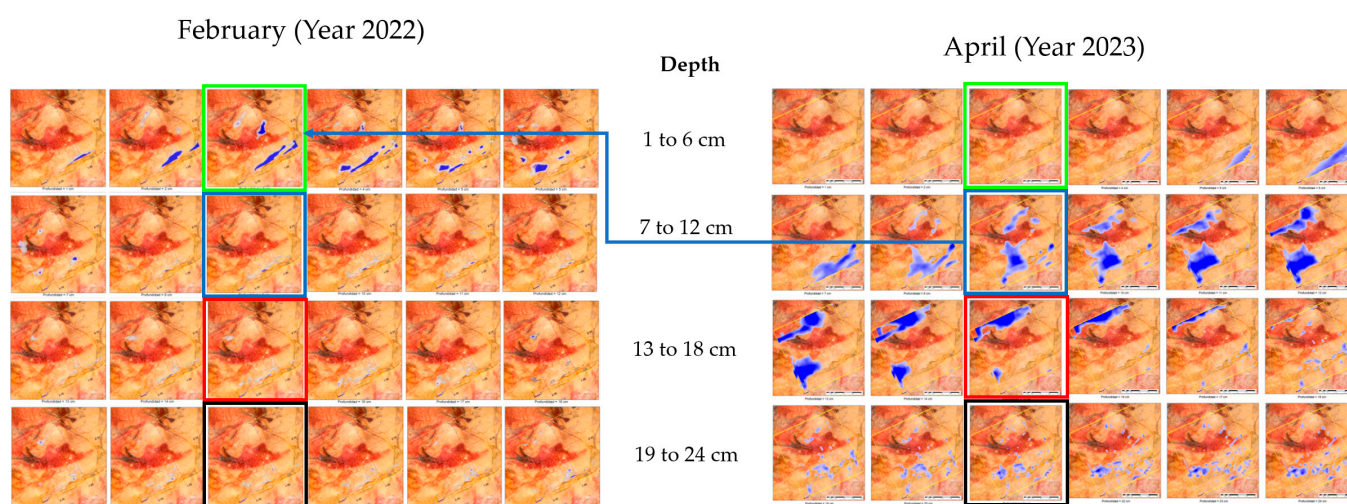


Figure 12. Evolution of moisture in the ALT1 control area. The highlighted boxes indicate significant changes in moisture depths relative to depth. In February 2022, higher moisture zones were observed at lower depths, while in April 2023, lower moisture zones were recorded at lower depths. The moisture recorded between April and June, which was involved in paint drips, has already reached the surface of the Ceiling; therefore, it was not detected by the 1.6 GHz antenna on 26 April 2023. The blue arrow connects the moisture moisture zones that, year after year, are associated with pigment dragging drips in ALT1.

3.5. Antennas Comparison

The comparison between different antennas operating at frequencies of 1.6 GHz, 800 MHz and 300 MHz provided valuable insights into the subsurface features of the Polychrome Hall within the Cave of Altamira. Each antenna frequency offered unique advantages and limitations, contributing to a comprehensive understanding of the geological and hydrological dynamics within the cave environment.

1.6 GHz Antenna: This antenna showed superior resolution, allowing for detailed imaging of shallow subsurface features with high precision. This antenna frequency proved effective in delineating fine-scale geological structures and moisture anomalies within the ALT 1 control area of Polychrome ceiling. By capturing subtle variations in moisture content and stratigraphic boundaries, the 1.6 GHz antenna helped with the identification of preferential flow pathways and moisture retention zones critical for understanding hydrological processes affecting the conservation of the art on the ceiling of the Polychrome Hall.

800 MHz Antenna: The 800 MHz antenna offered a balance between resolution and depth penetration, providing intermediate-level imaging of subsurface features within

the Polychrome Hall. This antenna frequency captured broader geological features and moisture patterns compared to the 1.6 GHz antenna, enabling the visualization of both shallow and moderately deep subsurface layers. While lacking the resolution of the higher-frequency antenna, the 800 MHz antenna provided valuable information on the spatial distribution of moisture and geological structures at a more extensive scale.

300 MHz Antenna: The 300 MHz antenna excelled in depth penetration, allowing for imaging of deeper subsurface layers and geological structures within the cave. While sacrificing resolution compared to the higher-frequency antennas, the 300 MHz antenna provided valuable insights into the stratigraphy and hydrogeological dynamics of the cave environment at greater depths. This antenna frequency was effective in mapping large-scale geological features and identifying potential subsurface water reservoirs or flow channels critical for understanding long-term moisture dynamics within the cave.

Integrating data from all three antennas provided a comprehensive view of the subsurface environment within the Polychrome Hall, complementing each other's strengths and compensating for individual limitations. The 1.6 GHz antenna was critical for understanding the dynamics of water flow and its direct impact on paint in the ALT1 control area, revealing the relationship between moisture and surface fissures and fractures. Meanwhile, the 800 MHz and 300 MHz antennas provided valuable insights into deeper subsurface structures. Specifically, the 800 MHz antenna helped correlate the detailed information from the 1.6 GHz antenna with larger fractures and structural features, while the 300 MHz antenna elucidated how these deeper fractures relate to external water entrance. By combining data across these frequencies, we developed a nuanced understanding of the geological and hydrological processes affecting the cave environment, which informs more effective conservation strategies and management decisions.

3.6. Integration with Other Data Sources

Integrating GPR data with other data sources is critical for a comprehensive understanding of the processes affecting the conservation of the art in the cave, especially the one on the ceiling of the Polychrome Hall. Ground truth measurements and field observations, collected during geological surveys and hydrological monitoring campaigns, serve as essential reference points.

In this sense, the observations made by [48] conclude that the ceiling surface of the Polychrome Hall is characterized by a discontinuous and irregular clay film, occasionally carbonated, situated between the limestone substrate and the paint layer. Internal stresses within these clays, induced by moisture variations (wetting/drying cycles), lead to the loss of adhesion of the pigment to the clay layer, and consequently, to the substrate. Concurrently, environmental humidity contributes to carbonate dissolution, as the accumulation of water films on the limestone surface promotes mineral decomposition reactions [76].

The adhesion loss of the pigment to the substrate is further linked to the physico-chemical properties of the infiltrating water, which, through the soil cover, incorporates CO₂ and other nutrients from the soil [3]. This process partially dissolves the limestone, resulting in the formation of small, interconnected depressions on the ceiling, resembling a hydrographic network. These depressions act as conduits for transporting not only the paint but also carbonates, salts, clays, quartz fragments, dolomite and other materials, dragging them towards various drip points [77].

The interpretations derived on the one hand from the GPR data which inform us of the important relationship in the inner part of the Ceiling of the fracture lines with the accumulations of moisture (Figure 13). The samples of sediments and pigment dragged from the drip points (Figure 14), corroborate the hypotheses outlined in the previous paragraph.

Visual inspection with a binocular magnifier, along with Scanning Electron Microscope (SEM) and X-ray diffraction analysis of pigment samples and other water-transported deposits at the drip points in ALT1, reveals millimeter-scale particle detachment indicative of flaking, disintegration or loss of cohesion. Additionally, SEM analysis has identified particles with low iron content and high concentrations of magnesium, calcium and oxygen,

likely corresponding to dolomite-type minerals associated with the Dolomitic Layer above the Polychrome Layer. The Dolomitic Layer is affected by a network of discontinuities extending from its roof to its walls, compromising the waterproofing of the thin loamy-clay intercalation separating it from the Polychrome Layer. These discontinuities help with the movement of water and moisture from the upper layers to the Polychrome Layer, aggravating the pigment detachment and rock degradation observed in the Hall.

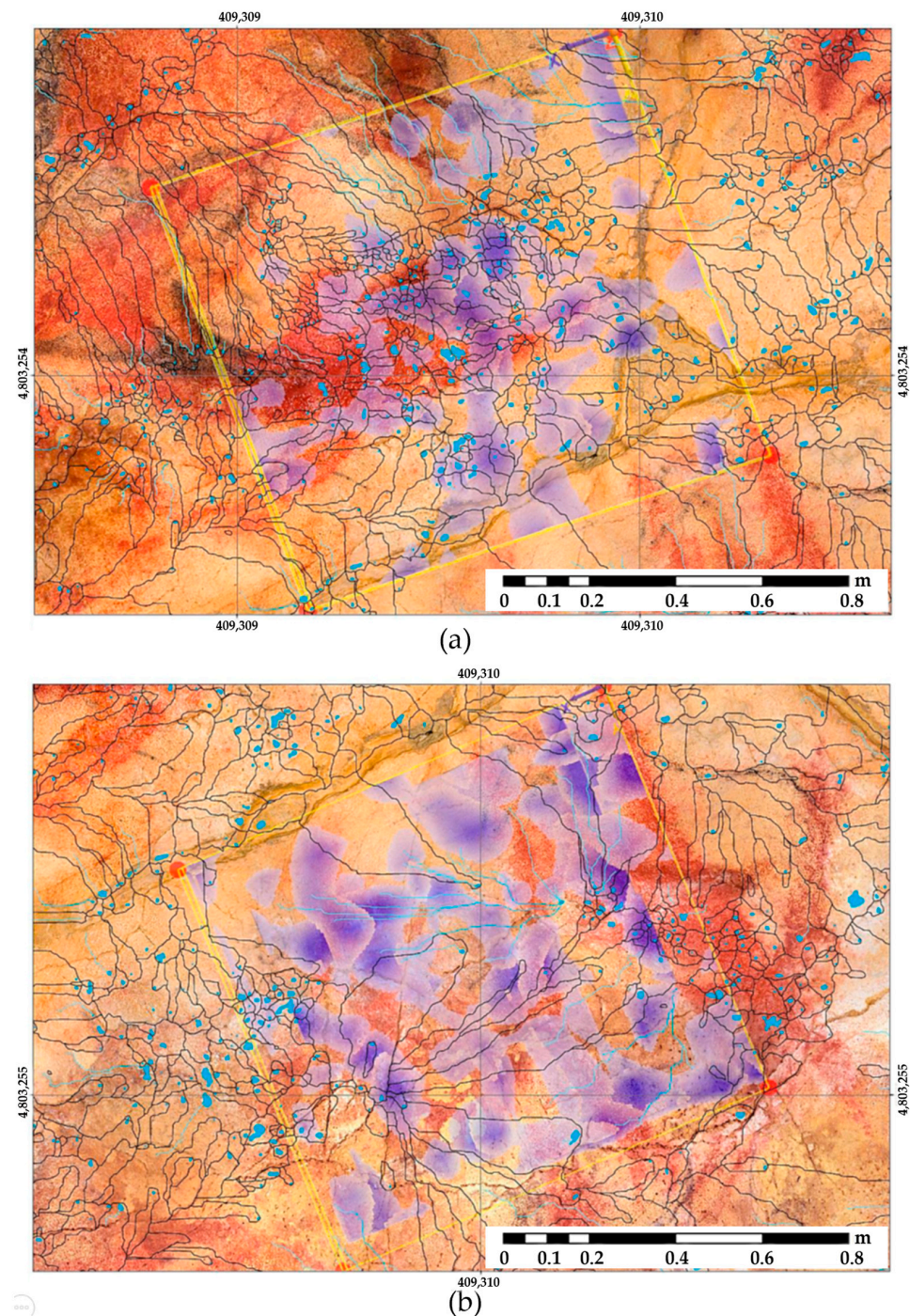


Figure 13. Overlying of the 3D horizontal sections framing the Dolomitic Layer in the 70 cm to 100 cm depth interval in the ALT1-C zone, captured using a 1.6 GHz GPR antenna. The figure shows multiple zones of irregularly distributed moisture, projected on the ceiling surface of the Polychrome Hall with the micro-basins and with the active drip points (water/moisture zones in shades of purple; active drip points in blue) for zones (a) ALT1-C and (b) ALT1-D.

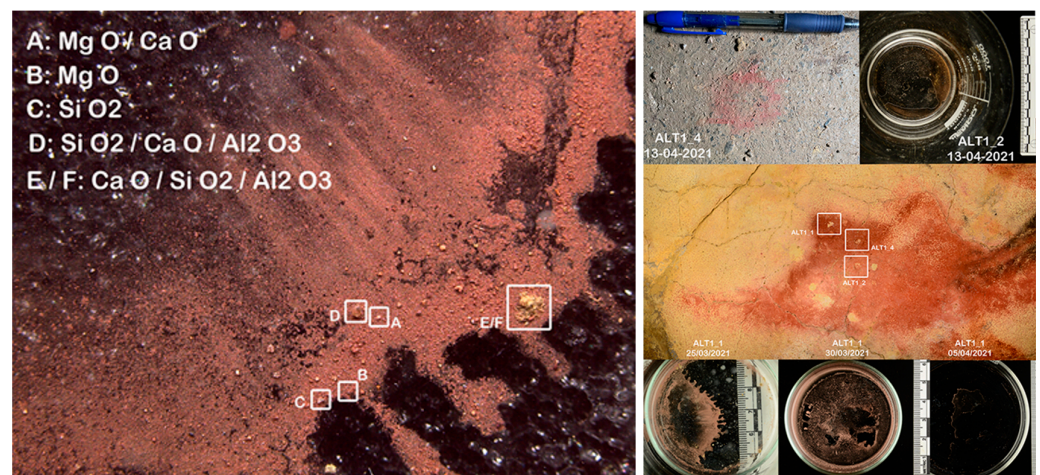


Figure 14. Pigment particles and other mineral deposits carried away by the drip water and collected in the containers located on the ground perpendicular to the drip points. SEM analysis of the detached particles indicates the existence of microcorrosion processes of the supporting rock associated with the presence of infiltration water, condensation and CO₂ concentration.

Moreover, the integration of GPR data with high-resolution surface models, basin, streams, drop points and orthoimagery enables the spatial context of subsurface features to be visualized and analyzed within the broader landscape context. Georeferenced GPR profiles overlaid on topographic maps or DEMs provide valuable insights into the relationships between surface morphology, hydrological pathways and subsurface structures, facilitating the identification of geological controls on ceiling evolution.

Furthermore, the integration of GPR data with hydrological models enables the assessment of long-term trends and predictive modeling of groundwater flow dynamics. This complex system of discontinuities represents the main pathways of fluid exchange with the interior of the Polychrome Hall (Figure 15), as well as with the seepage from the active drip points on the basal surface of the Polychrome Layer in the ALT1 control area (Figure 10a).

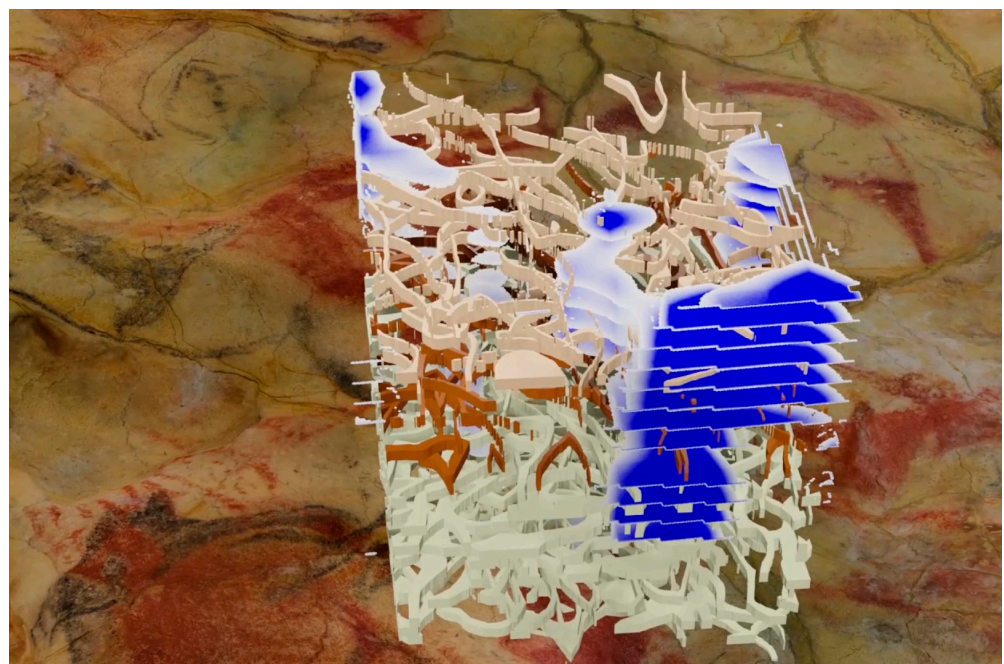


Figure 15. Perspective view of the discontinuities revealing zones of higher moisture, represented by a blue to white gradient, across the different strata of the Polychrome ceiling. Data were collected

using three GPR antennas: a 1.6 GHz antenna for the upper 50 cm, an 800 MHz antenna for depths up to 1.2 m, and a 300 MHz antenna for depths up to 4.9 m. This complex network of discontinuities highlights the primary pathways for fluid exchange within the interior of the Polychrome Hall, as well as seepage from the active drip points located on the basal surface of the Polychrome Layer in the ALT1 control area.

4. Discussion

The findings in this study provide valuable insights into the subsurface features of the Polychrome Hall within the Altamira Cave, as revealed by GPR surveys.

The different geophysical prospecting campaigns (February 2022 and April 2023) on the surface of the ceiling in the ALT1 control area indicate that the presence of moisture of infiltration water is mainly related to two lateral contributions, one on the south side, clearly associated with the large central fracture, and the other on the north side from a fracture similar in development to the central one, which even begins at a higher level (barely one meter above the surface) and which, in a discontinuous manner, practically reaches the surface of the Polychrome Hall. Another fracture on the north side has a similar development to the central one, beginning at a higher level (barely one meter from the surface) and discontinuously reaching the ceiling surface, vertically aligned with the belly and hind legs of the bison located near the claviform sign in our control area ALT1 (Figure 16).

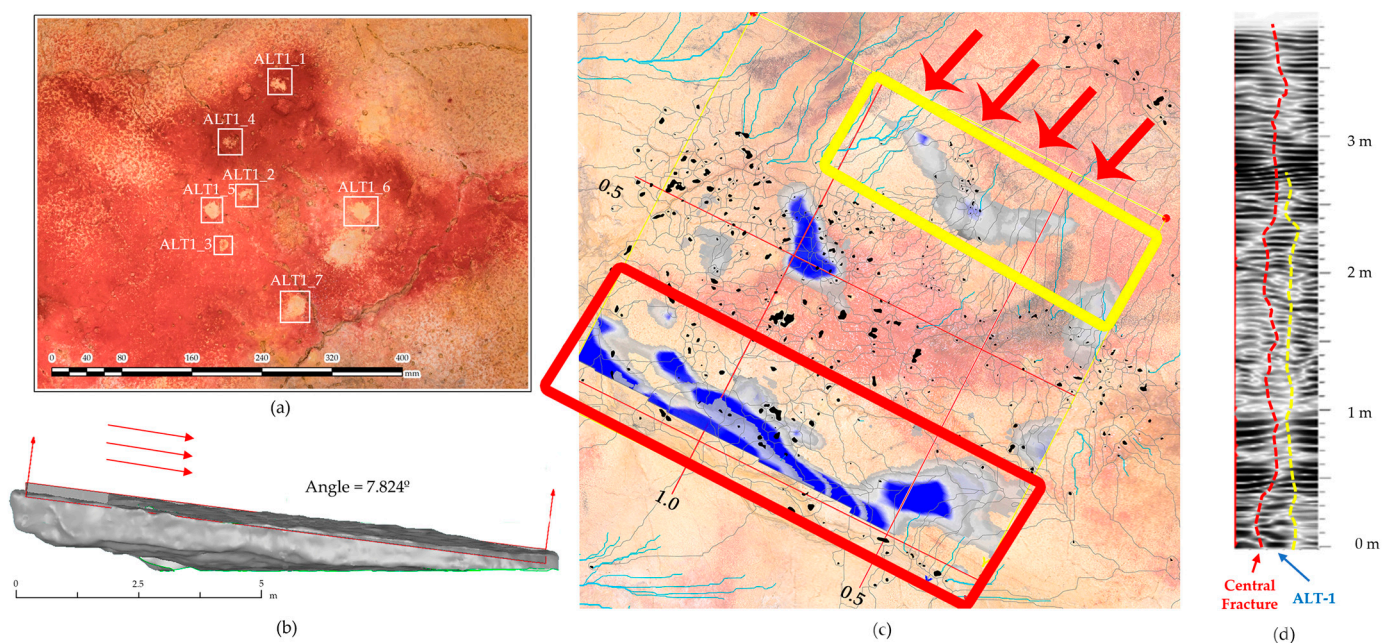


Figure 16. (a) Location of the drip points within the control area ALT1. (b) Mean dip of the Polychrome Hall calculated from the 3D model (c) Moistures associated with two large vertically developing fractures in the Polychrome ceiling. The red box shows the moistures associated with the large central fracture, the yellow box shows the moisture zones coming from the fracture located in the polychrome bison. The red arrows as well as the degree of dip of the ceiling show the relationship of this with the moistures associated with the dripping points with migration and loss of pigment from ALT1. (d) Reflection profile P8 obtained with the 300 MHz antenna. The dashed red line indicates the fracture (central fracture) associated with the moisture shown in red, and the dashed yellow line corresponds to the fracture associated with the moisture marked in yellow in (c).

The greatest percolation of water is towards the north side of the large central rift, in a west-to-east direction. This direction of moisture flow is explained by the dip of the strata. The moisture that percolates through the central fracture flows toward the fracture from

the beginning (west) to the bottom of the Polychrome Hall (east). Additionally, the greater percolation of moisture in the western area of the quadrant studied (Figure 7), on both sides of the central crack, compared to the east, is because the cement mortar that seals the large central crack is in a worse state of conservation in this area.

First, the detection of subsurface features, including fractures, fissures and moisture accumulations, offers important clues regarding the geological and hydrological dynamics within the cave system. Fractures and fissures may show structural weaknesses in the limestone bedrock, which could influence the infiltration and circulation of groundwater. The observed moisture accumulations are probably associated with localized percolation of water through fractures and with hydrological interactions between overlying rock layers. These findings support previous studies highlighting the significance of geological discontinuities and hydrological pathways in controlling the distribution of moisture within karstic systems [78,79].

Second, the characterization of moisture dynamics provides valuable information on the spatial distribution and temporal variability of moisture content within the Polychrome Hall. The identification of distinct moisture zones and their association with geological features, such as fractures and microchannels, suggests complex moisture transport processes influenced by both structural controls and external hydrological inputs. These findings contribute to our understanding of ceiling hydrology and underscore the importance of considering both intrinsic and extrinsic factors in modeling moisture dynamics within karst landscapes [80,81].

Third, the mapping of geological interfaces, including the contact between the Polychrome Layer and underlying dolomitic formations, provides valuable insights into the stratigraphic architecture and depositional history of the cave deposits. The observed irregularities and discontinuities in the Dolomitic Layer suggest complex geological histories characterized by tectonic activity, sedimentary deposition, and diagenetic processes as other complementary studies such as Scanning Electron Microscopy analysis (SEM) shows. These findings align with earlier studies on ceiling stratigraphy, highlighting the utility of GPR as a non-invasive tool for subsurface imaging and geological mapping in karst environments [82,83].

The detection of subsurface features using GPR represents a significant advancement in understanding the geological and hydrological dynamics of the Cave of Altamira Polychrome Hall ceiling. The identification of fractures and fissures not only provides insights into the structural integrity of the cave but also offers clues about the pathways through which water may infiltrate and circulate within the subsurface environment. These findings follow existing research on karst hydrogeology, which emphasizes the role of geological discontinuities in controlling groundwater flow and cave formation [84]. Further investigations into the spatial distribution and temporal evolution of subsurface features using advanced geophysical techniques could yield valuable insights into the dynamic nature of karst landscapes and their response to environmental change.

The variations seen in moisture zones between different depths and locations underscore the heterogeneous nature of moisture distribution within the cave environment, highlighting the need for comprehensive hydrological modeling approaches that account for both intrinsic and extrinsic factors [85,86]. Future research efforts could focus on integrating GPR data with hydrological models to improve predictions of cave moisture dynamics under different climatic scenarios and land use conditions.

The mapping of geological interfaces, particularly the contact between the Polychrome Layer and underlying dolomitic formations, offers valuable insights into the cave's stratigraphic architecture and paleoenvironmental history. The identification of irregularities and discontinuities in the Dolomitic Layer suggests complex geological processes that have shaped the cave over geological timescales. These findings contribute to our understanding of cave formation mechanisms and provide a basis for reconstructing past environmental conditions [48,87]. The mechanisms of geological formation of the cave and the stratigraphic relationship with the Dolomitic Layer are significant areas of ongoing discussion.

The influence of this Dolomitic Layer on the conservation of the art on the ceiling is still to be fully explored, as it exerts a protective effect due to its lower permeability regarding the water located at higher depths. The aforementioned erosive processes cause its partial disintegration, increasing water access to the surface of the ceiling and escalating the risks of migration, disintegration and occasional washing away of the paintings. Future studies could use interdisciplinary approaches, combining GPR with sedimentological, geochemical and chronological analyses to unravel the intricate geological histories preserved within cave deposits.

5. Conclusions

This comprehensive study conducted in the Polychrome Hall of the Altamira Cave system has not only shed light on the complex subsurface features but has also highlighted the significance of employing advanced GPR techniques in cave research. By digging into the intricate geological and hydrological dynamics, this study has provided invaluable insights into the intricate karst landscape and cave ecosystem.

The detection and characterization of subsurface features such as fractures and geological interfaces offer a deeper understanding of the ceiling structural complexity and hydrological connectivity. These findings not only contribute to the scientific understanding of karst landscapes but also hold practical implications for cave management and conservation efforts.

The mapping of moisture dynamics within the cave system is noteworthy, as it provides essential information for managing cave microclimates, understanding speleothem formation processes and preserving cave ecosystems.

The interdisciplinary nature of this study underscores the importance of collaboration between managers of the cave addressing the challenges faced by karst landscapes. By integrating scientific research with conservation efforts and policymaking, we can work towards sustainable cave management practices that ensure the long-term preservation of these unique ecosystems.

This being a first approximation and considering the need to obtain new data for different periods, it can be affirmed, based on the studies conducted, that there is a dynamic of water infiltration which, through fractures, fissures and internal stratification planes, percolates down to the surface of the ceiling. The internal moisture zones mapped in our control area ALT1 on 17 February 2022 affected the washing of pigment from some drip points in this zone by April of the same year, as well as provoking the migration of paint in other associated drip points. The moisture recorded in April 2023 at a depth of 9 cm and above is expected to directly contribute to paint wash-off at the same drip points, and possibly others, by April 2024.

This leads us to a clear reflection: within barely nine months, the moisture level involved in pigment carry-over at our ALT1 drip points will be located a few centimeters from the ceiling surface, initiating new processes of paint carry-over and destruction a month and a half later. This specific pattern highlights a seasonal dynamic in the processes of water infiltration percolation, which directly affects the conservation of the paint. If this pattern is confirmed, it would open the door to determining or suggesting conservation actions at certain critical times of the year. These actions could address the access of water that generates the washing and migration of pigment, potentially reversing the ongoing deterioration.

While this study has provided valuable insights into the subsurface characteristics and moisture dynamics of the Polychrome Hall in Altamira Cave, future research is essential to improve conservation efforts. Long-term monitoring of moisture infiltration and moisture zones using advanced GPR techniques alongside non-invasive methods such as high-resolution photogrammetry will help to track seasonal variations that affect pigment preservation. Extending the study beyond the ALT1 control area will provide a broader understanding of hydrological dynamics and identify additional areas at risk. The development of predictive models based on observed water infiltration patterns can guide

timely conservation measures. In addition, collaboration with conservation experts will be essential to translate research findings into actionable strategies. Finally, investigating the potential impacts of climate change on cave ecosystems will be important to anticipate shifts in water infiltration that may exacerbate paint deterioration, to refine our understanding and improve conservation strategies for Cave of Altamira.

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Data Availability Statement: The research data supporting this publication are not publicly available. The data were collected by GIM Geomatics as part of research and conservation studies of the Cave. These data are kept in the Museo Nacional y Centro de Investigación de Altamira. A video showing the results of this study is available in: <https://youtu.be/dv82eE-r-iA>, accessed on 18 October 2024.

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Publicación 6: 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

Article

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].

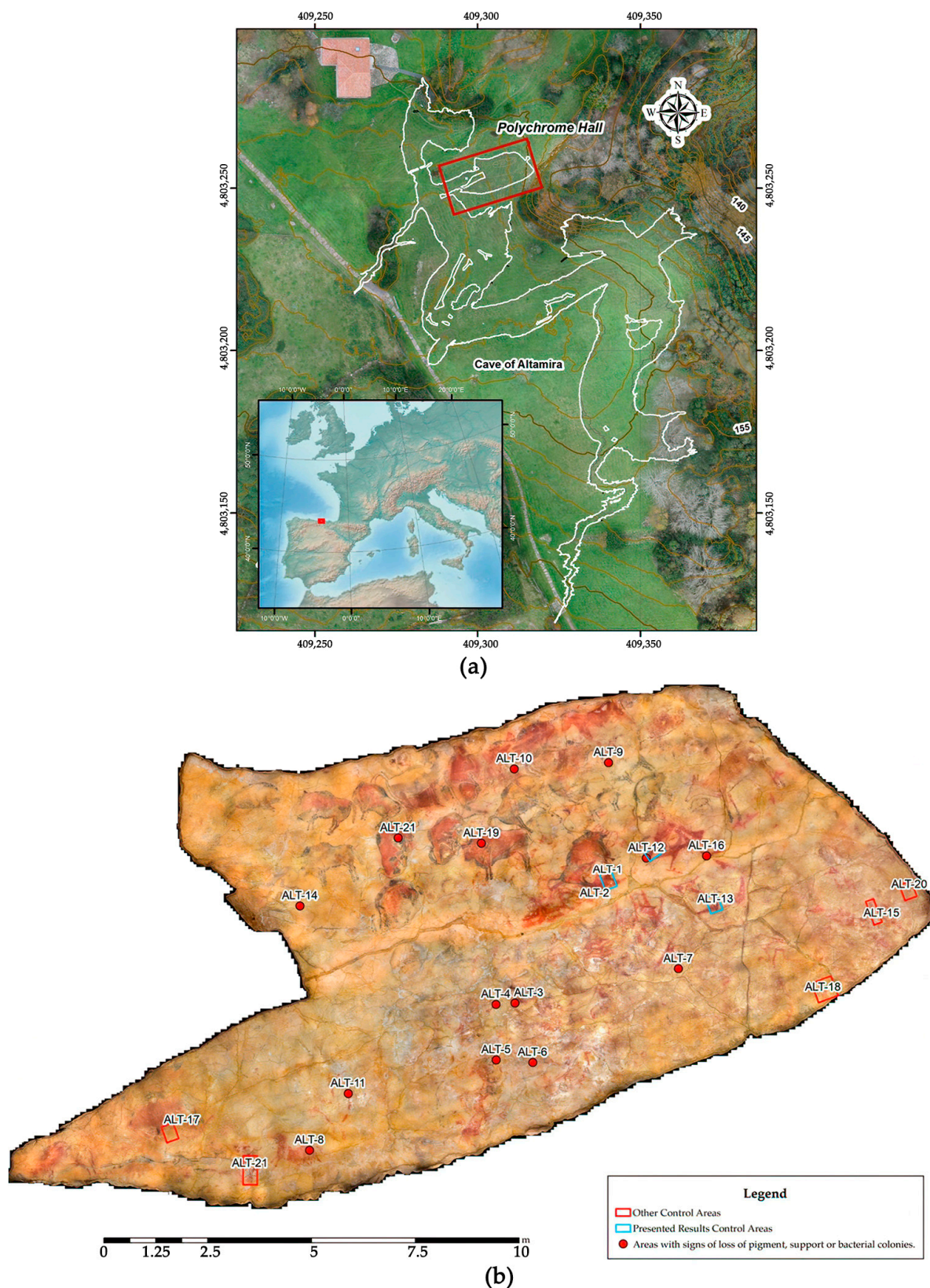


Figure 1. (a) Location map of the Cave of Altamira with the Projection of the Cave on the orthoimage, indicating in a red frame the position of (b) the Polychrome Hall with the key areas of interest for conservation efforts, including the zones most affected by active deterioration processes.

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 diachases 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.

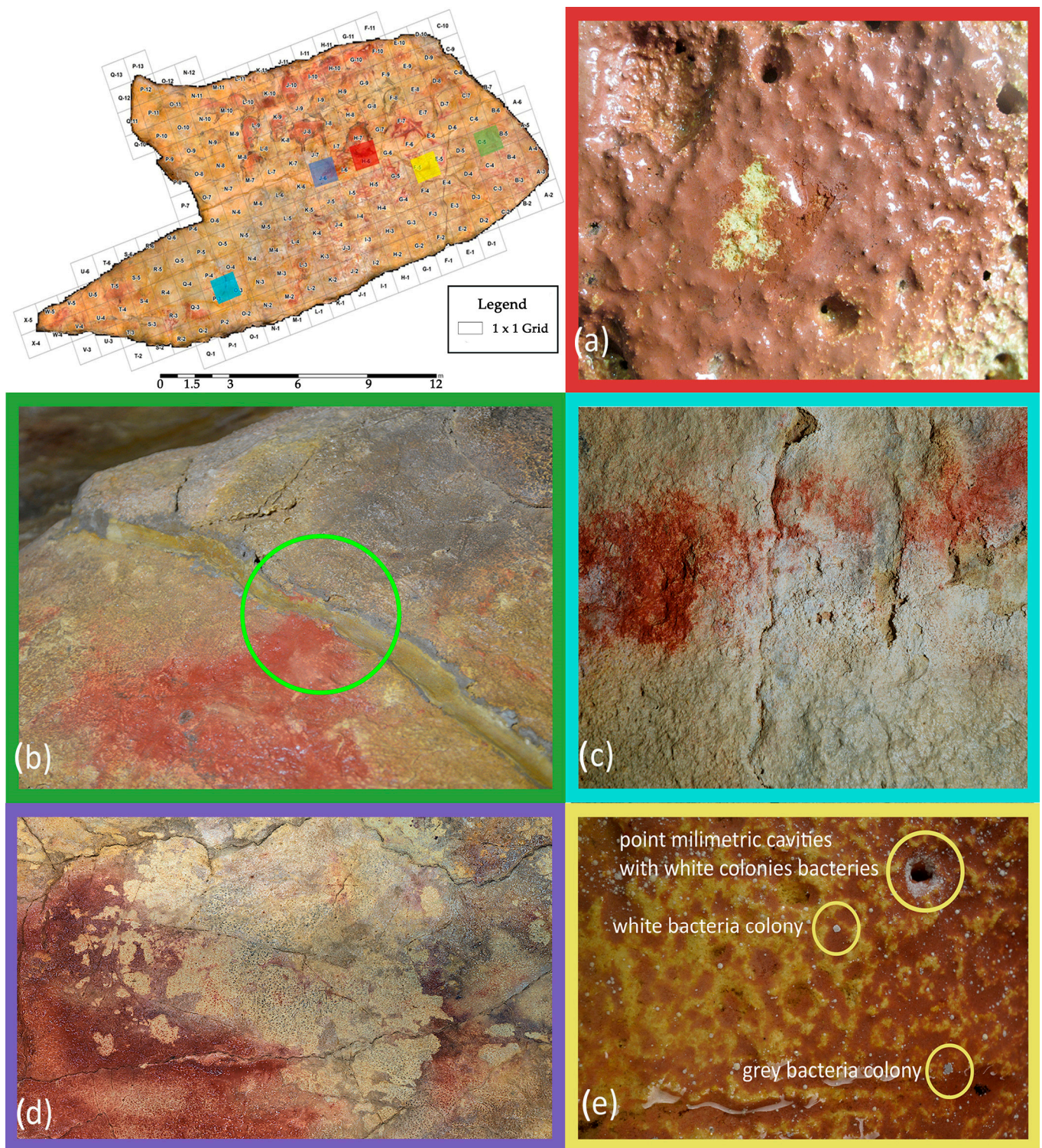


Figure 2. Main alterations associated with active deterioration processes on the surface of the Polychrome ceiling (a) Corrosion and dissolution of the limestone substrate (red box), (b) erosion and pigment transport by seepage water (green box), (c) encrustation, carbonate precipitation (light blue 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 CO₂ 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 CO₂ and radon, is strongly seasonal, following these temperature-driven airflow patterns. CO₂ 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 CO₂ 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 m², 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 CO₂ 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.

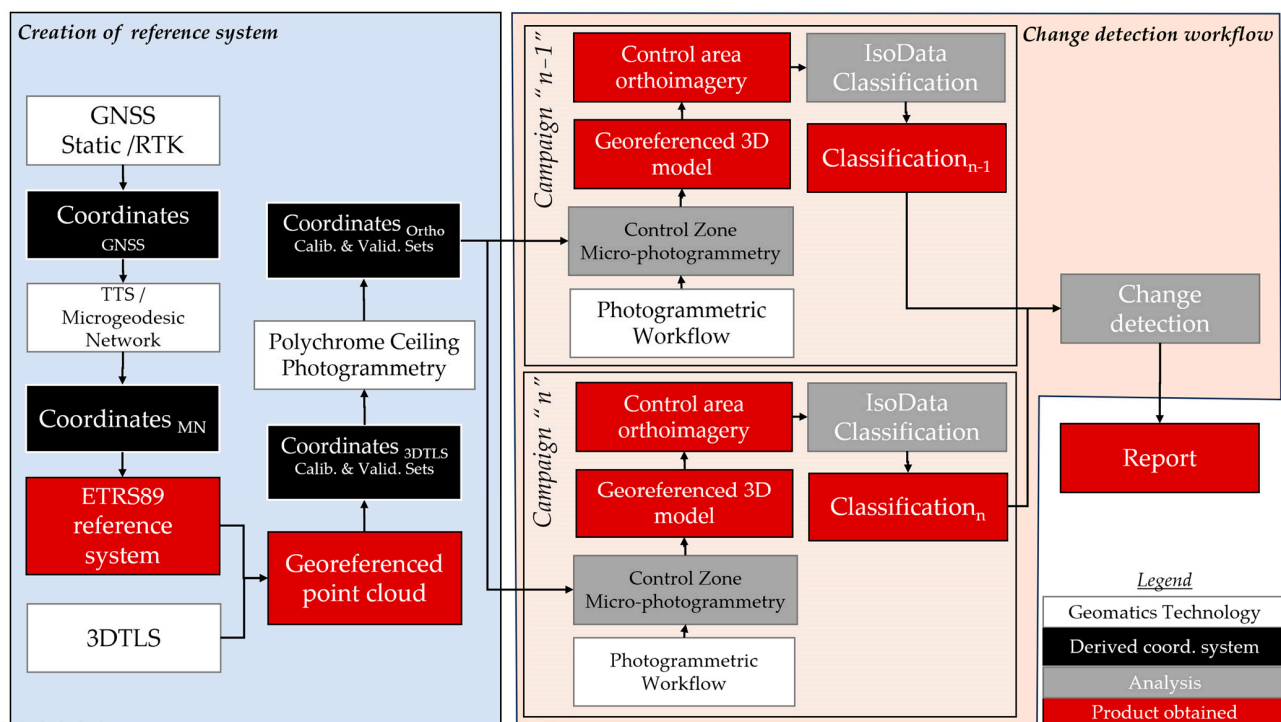


Figure 3. General workflow diagram.

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 $45\text{--}135^{\circ}$ 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 m², 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.

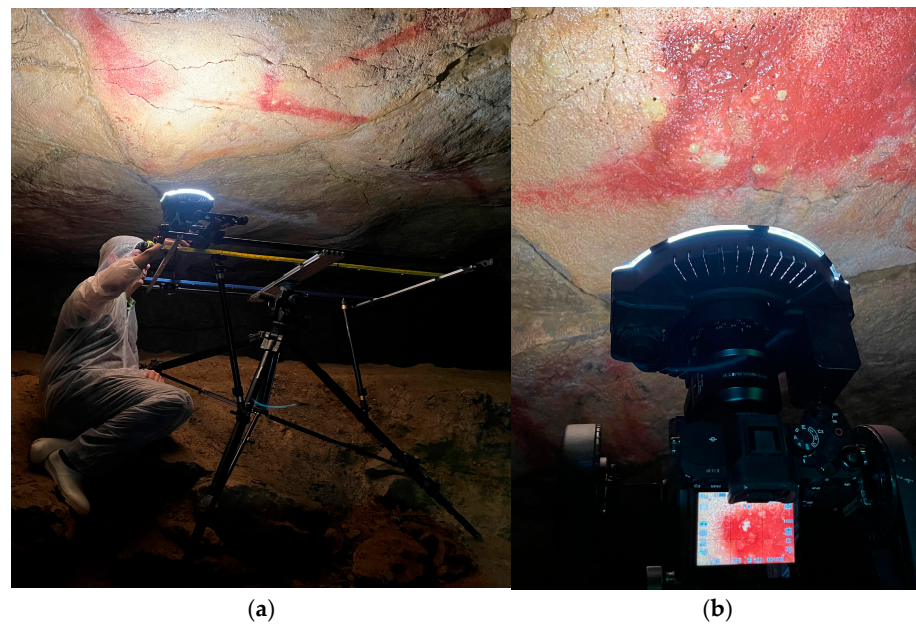


Figure 4. (a) Double-axis slider during image acquisition of ALT13 control zone. (b) Sony A7R Mark II camera with a 90 mm lens and cross-polarizing light.

- **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.

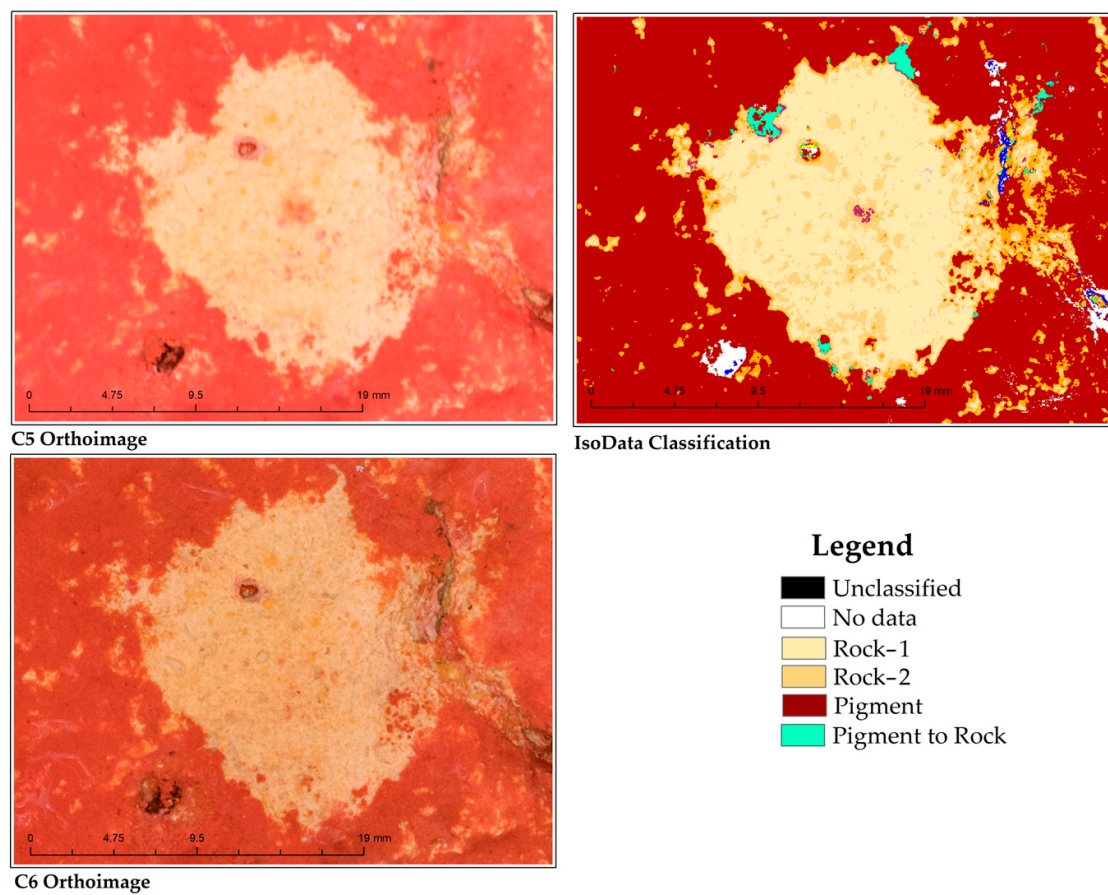


Figure 5. Orthoimage for campaigns 5 and 6 and the IsoData classification with the class pigment to rock represented in blue.

- **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.

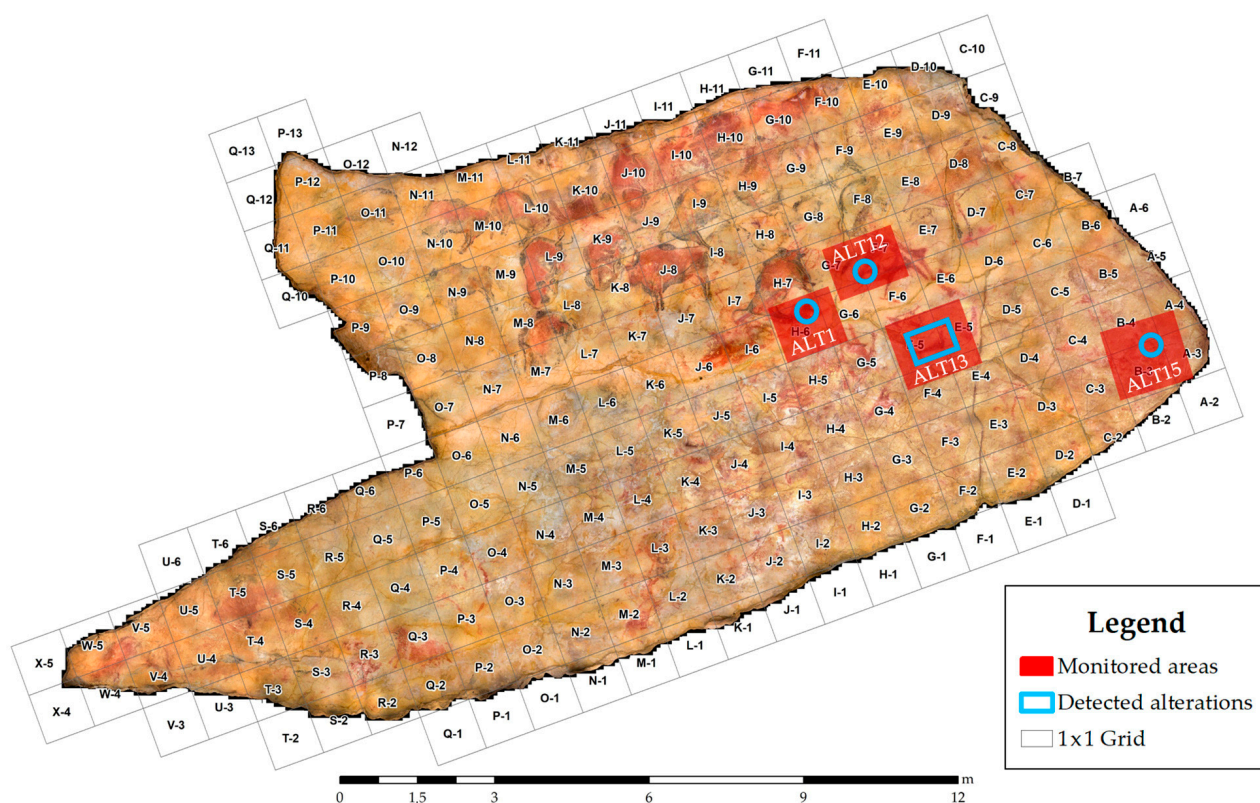


Figure 6. Control areas with their designation and the conservation hotspots or critical areas that we monitor and control more exhaustively.

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.

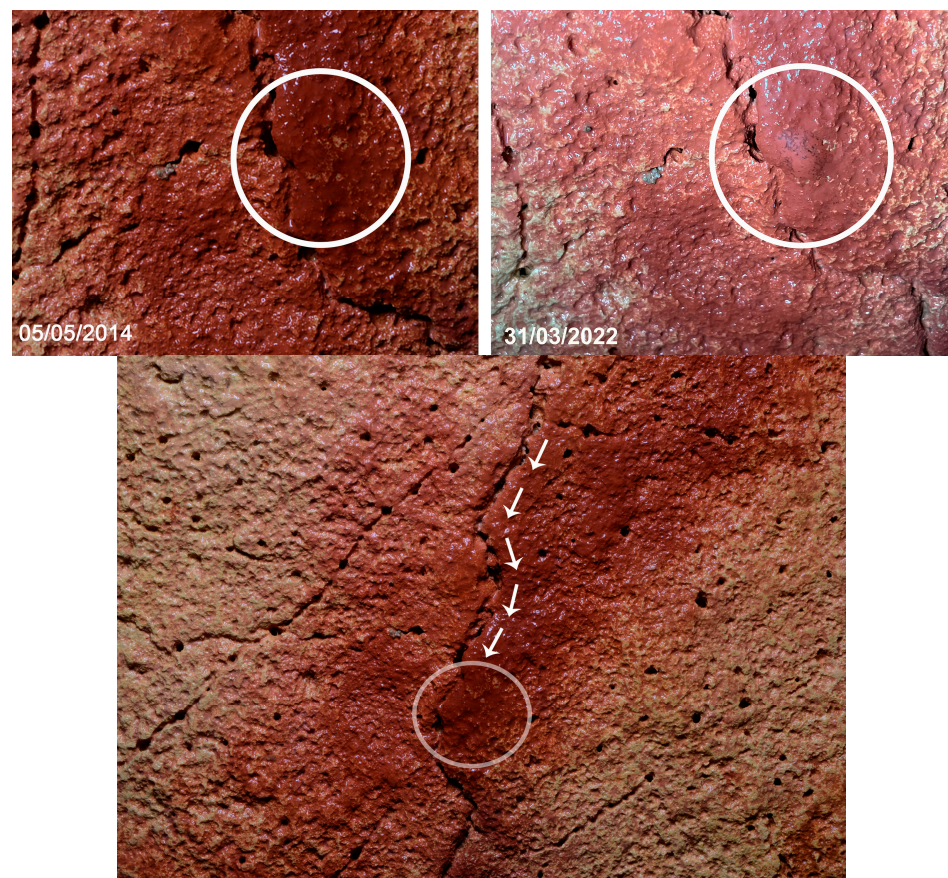


Figure 7. Comparison of the drip point with paint drop corresponding to ALT12 (years 2014–2022) and proposed water flow with pigment carry-over to the drip point. The white circles indicate the drop point with pigment drag. The arrows show the path of the water and its drag of pigment to the drop point.

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 cm² 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.

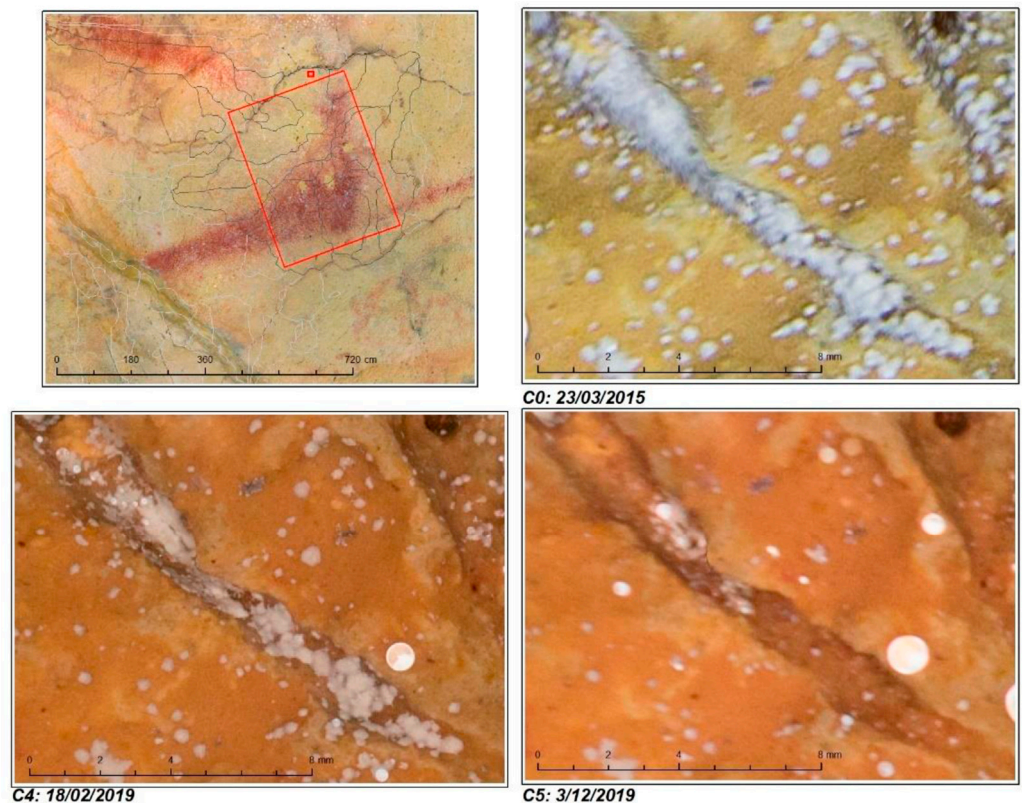


Figure 9. Changes in white bacterial colonies at one of the monitoring points within the ALT13 control zone. It shows a significant reduction in the number and size of bacteria colonies from 2019. The large red rectangle in the first figure indicates the control area location and the small rectangle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

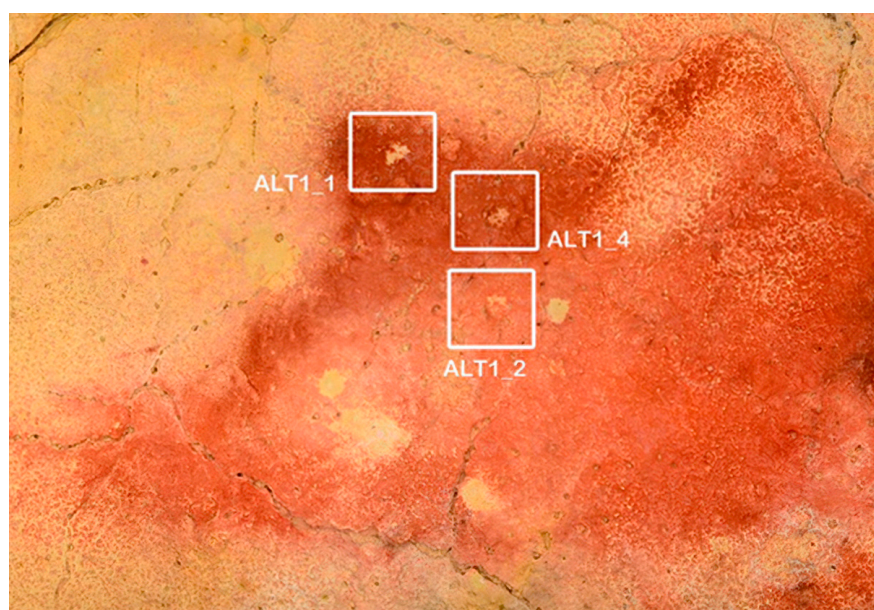


Figure 11. Control area ALT1 showing the three active drip points where carry-over and pigment loss associated with water dripping has been documented.

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).

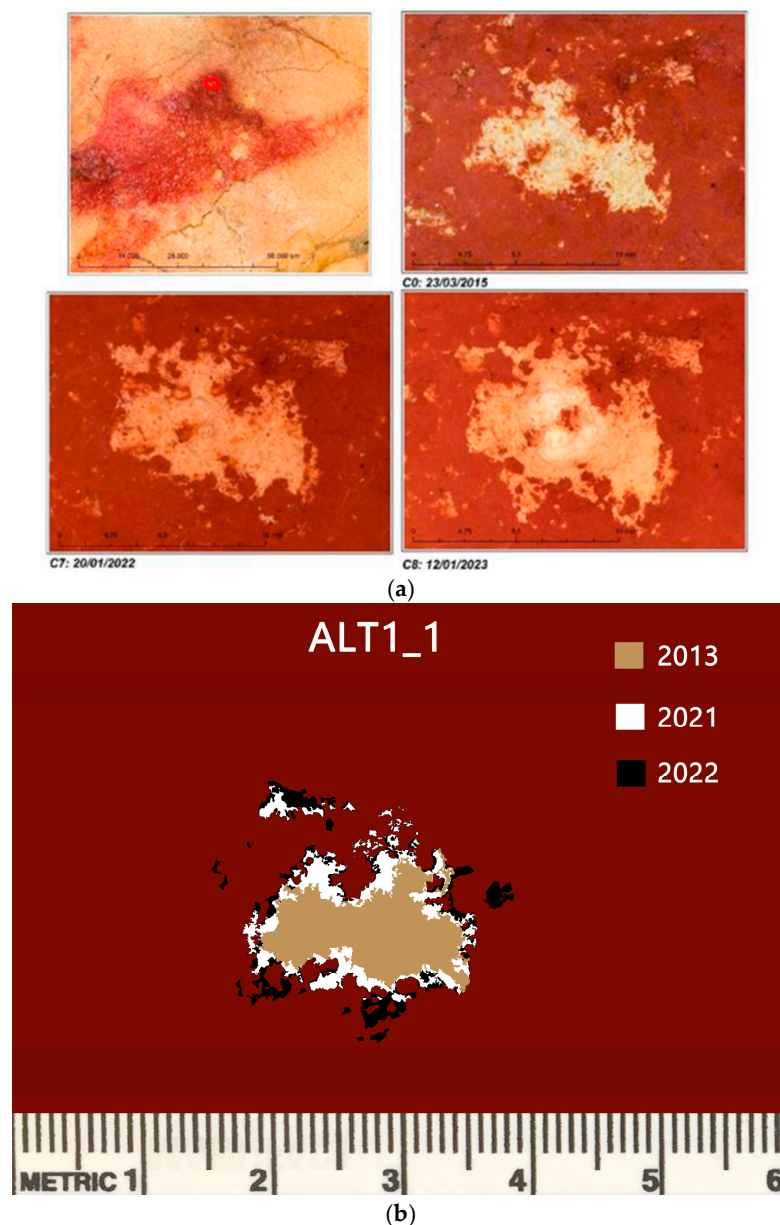


Figure 12. (a) Evolution of the surface area of the lagoon corresponding to drip point ALT1_1 from 2015 to 2023. (b) The image below shows the damage map and comparisons in relation to the years 2013, 2021, and 2022.

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.

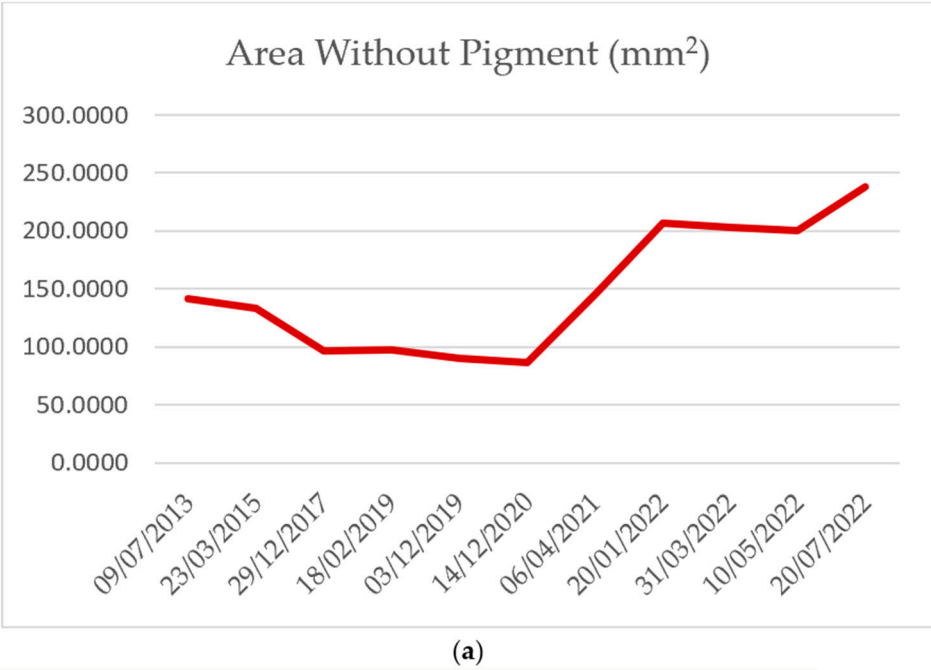
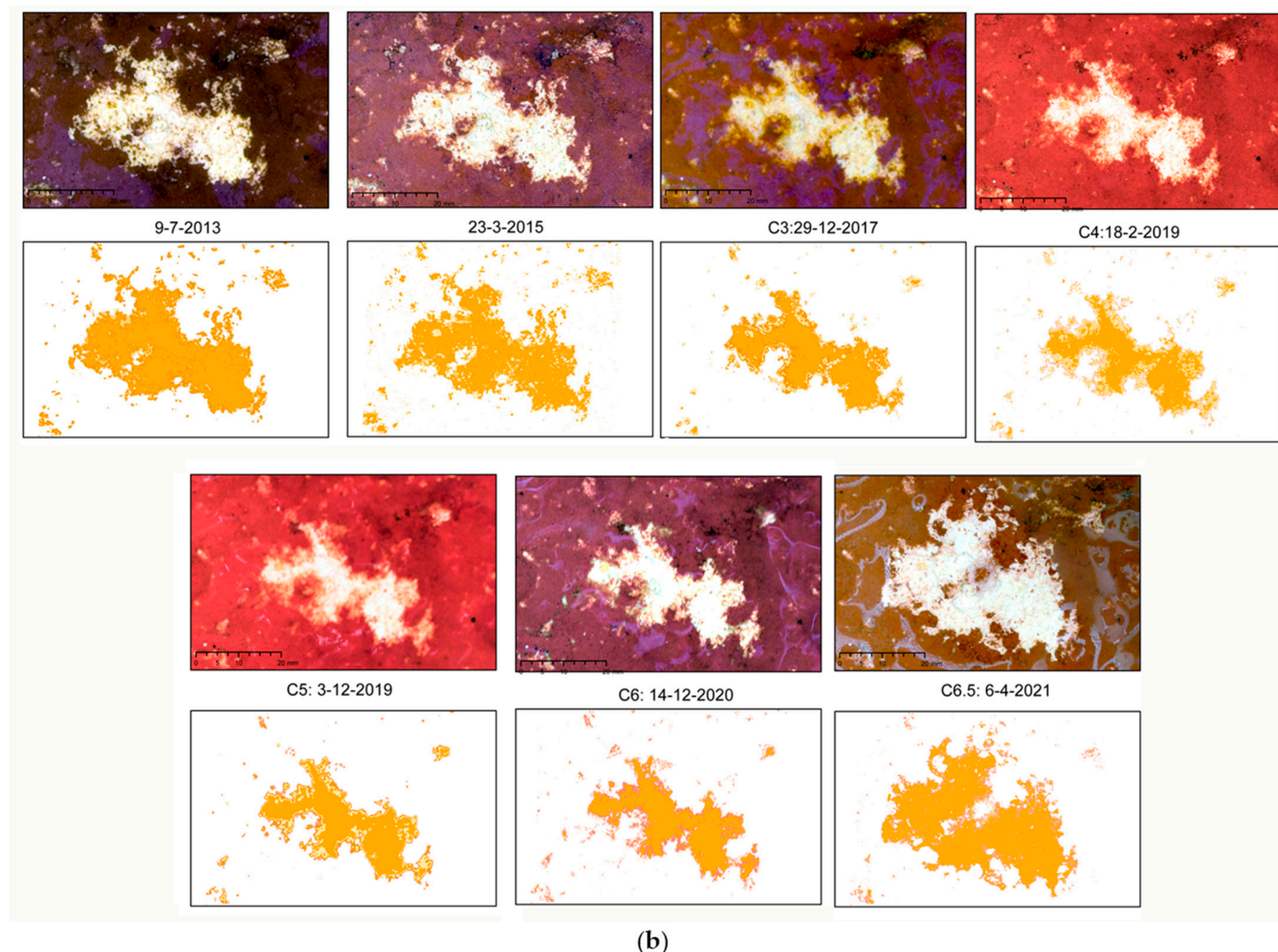


Figure 14. Cont.



(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	N° 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.

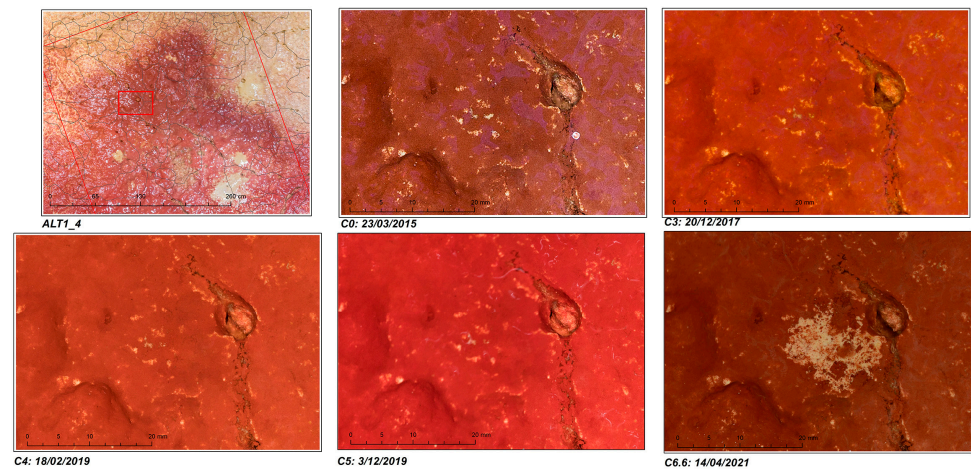


Figure 15. ALT1_4. The figure highlights the water flows involved in pigment transport and destruction. The large red rectangle in the first figure indicates the control area location and the small rectangle the location of the detail images.

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).

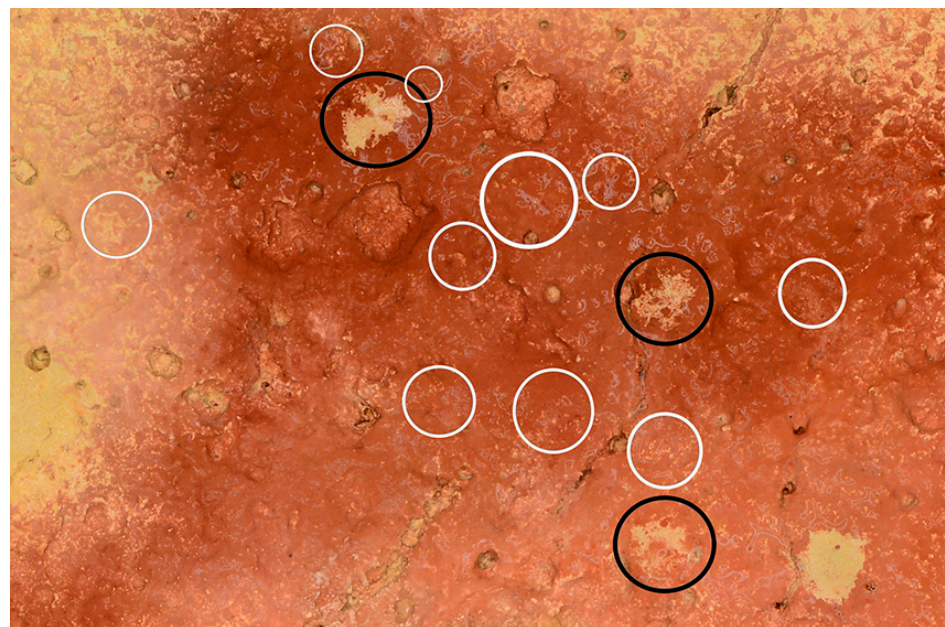


Figure 16. The analysis of ALT1_2 and ALT1_4 subzones. White circles in the figure indicate nearby areas showing preliminary signs of pigment detachment, similar to patterns observed in ALT1_1, ALT1_2, and ALT1_4, which are marked by black circles.

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 CO₂ 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 CO₂ 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 CO₂ concentrations. The CO₂-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 CO₂, 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.

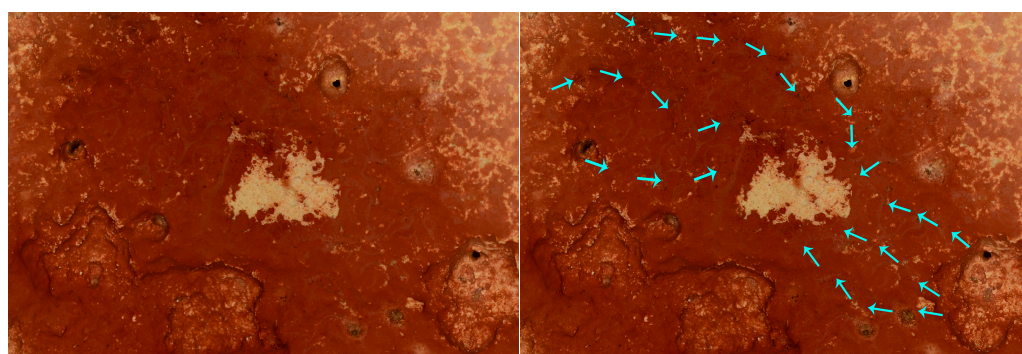


Figure 17. Migration of paint moving through small interconnected depressions and cracks within the Ceiling surface in control area ALT1. The arrows show the path of the water and its drag of pigment to the drop point. This complex process of deterioration, involving multiple environmental and biological [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).

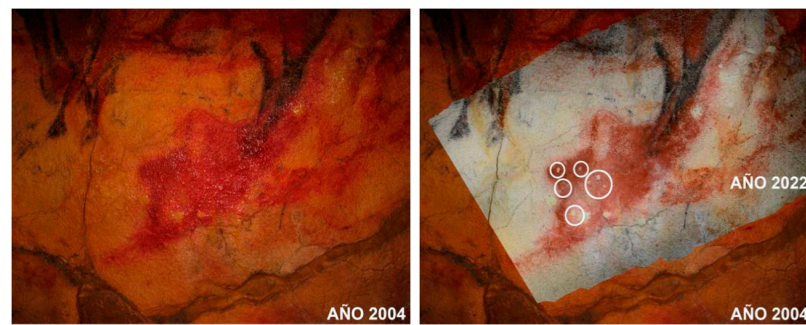


Figure 18. Comparative analysis of the red sign in ALT1 between 2004 and 2022, highlighting with white circles the significant variations related to pigment loss. The word *Año* in picture means year.

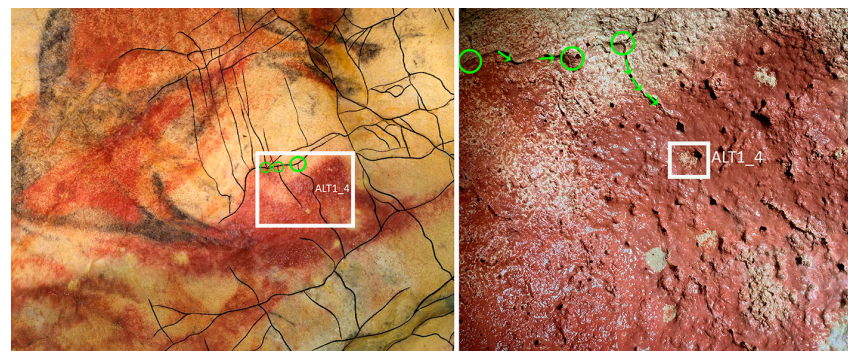


Figure 19. In the drip zone with migration of pigment ALT1_4, it has been determined which are the water flows (marked by the green arrows) that, associated with the fracture lines of the roof, generate the dragging and washing of the paint. The green circles indicate possible water circulation areas 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 CO₂ fluxes between the cave and the external environment. Understanding these dynamics is essential for developing strategies to manage CO₂ 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 CO₂ concentrations and carbonate dissolution. Previous studies, such as the work [39], have shown that certain bacterial colonies can capture CO₂ 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 CO₂.

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.

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