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Bridging Photogrammetry and GIS Through Workflow Automation: A Scalable Approach for Spatially-Linked 3D Data in Underwater Cultural Heritage

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Abstract

Efficient photogrammetric data processing and seamless integration with Geographic Information Systems (GIS) are crucial for large-scale digital heritage and scientific research. By leveraging pre-documented processes and AI-generated scripts, CINDAQ developed an automated photogrammetry workflow designed to enhance efficiency while ensuring consistent data quality. This system not only streamlines image-to-model processing but also integrates directly with a GIS-based Single Source of Truth (SSOT), enabling real-time spatial data updates and improved metadata management. By automating model generation, linking photogrammetric datasets to spatial layers, and enforcing standardized metadata structures, we have significantly reduced processing time and enhanced data accessibility for researchers. Additionally, the system lowers the technical barriers to entry, allowing non-specialists to engage with photogrammetry tools, thereby democratizing access to 3D modeling and spatial analysis. By simplifying workflows and reducing manual effort, this approach enables large-scale model production, increasing scientific collaboration and accelerating discoveries. The findings highlight a scalable, reproducible strategy for bridging photogrammetry and GIS, ultimately providing a structured, efficient, and inclusive digital archive for subterranean and underwater research, which can be replicated to other study areas.

1. Introduction

1.1 Background

Mexico’s Yucatan Peninsula is a karstic region with extensive submerged cave networks (Bauer-Gottwein et al., 2011) accessible through natural sinkholes called cenotes. They contain significant biological (Álvarez and Iliffe, 2008), cultural, archaeological and paleontological materials, including animal bones, human remains, Maya artifacts, and ancient ochre mines (Chatters et al., 2014; Barba-Meinecke et al., 2020; MacDonald et al. 2020).

Figure 1. Objects and features to be documented include (1) Human and (2) faunal remains, (3) artifacts (CINDAQ)

CINDAQ has spent over two decades exploring these underwater caves and documenting these sites of interest using scientific diving and geospatial technologies to support research and preservation (Fortin et al., 2021a). Semi-automated topographical surveys, wall measurements, and detailed hand-drawn maps provide a backbone to tie information into space - including but not limited to diver observations, collected media, and photogrammetric models. Efficient photogrammetric data processing and seamless Geographic Information Systems (GIS) integration are essential for large-scale digital heritage projects. Streamlining these processes not only accelerates model production but also enhances scientific usability, enabling researchers to navigate the archive of spatial data and identify meaningful patterns across datasets.

1.2 Problem statement: manual, technically challenging and difficult-to-scale processes

Given the extent of Mexico’s submerged cave systems, which span thousands of kilometers, documenting features of interest is a long-term endeavor involving multiple contributors over years or decades. Ensuring consistency in both quality and formatting is essential to allow scientific analysis of materials documented by different individuals across time and space.

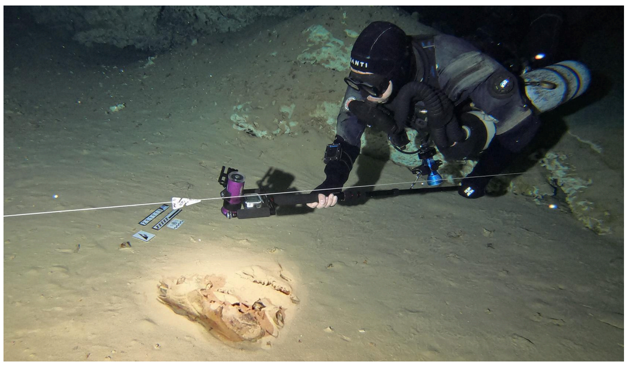

Figure 2. Documenting features in underwater caves (CINDAQ)

Moreover, data collection takes place in highly challenging conditions: several hours of underwater travel are often required to access target sites within complex, labyrinthic tunnel

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networks with no natural light and no direct access to the surface. These environments present unique hazards, including ceiling percolation and silty floors, and significantly limit the number of individuals capable of performing in-field documentation. Importantly, these cave diving contributors are rarely trained photogrammetry specialists.

Providing cave divers with the required technical skills for photogrammetry training can pose logistical difficulties. Additionally, if the documentation workflow is perceived as overly complex or repetitive, it may impact motivation, thereby reducing productivity and compromising data quality.

The multi-site nature of the documentation effort, where relevant features are often isolated and located kilometers apart, further complicates efforts to spatially integrate the data. This fragmentation makes it difficult for analysts to gain a comprehensive overview of the dataset and to identify spatial relationships between documented objects.

Finally, photogrammetric datasets stored across disparate local systems are difficult to share and interpret. Without consistent data storage structures and a unified spatial framework, experts may struggle to access, navigate, and analyze the repository as a coherent whole.

1.3 Objectives: A user-friendly, consistent and scalable workflow linking photogrammetry and GIS

To address the challenges outlined above, we established a set of objectives that have guided the development of our workflow and its supporting tools over the past several years (Fortin et al., 2021b).

Our primary objective has been to ensure consistency across all photogrammetric models. This includes processing all datasets using standardized parameters and generating a uniform set of outputs, such as dense point clouds, textured mesh models, and orthomosaics in predefined formats. In parallel, we have prioritized the systematic preservation of metadata, including the date and time of image acquisition. This approach aims to safeguard data integrity and ensure that no dataset is overlooked or excluded from the central repository—in short, to make every model count.

A secondary objective, focused on field operators, has been to improve both the productivity and quality of model generation while minimizing the complexity, time, and cognitive load associated with the processing steps. By lowering technical barriers and streamlining workflows, we aim to democratize photogrammetric documentation, empowering non-specialists to produce reliable and scientifically valuable outputs.

Finally, usability is a cornerstone of the system’s design. Our goal has been to provide external experts, often unfamiliar with the cave environment or GIS platforms, with intuitive access to all relevant information. By making the data navigable and analyzable without requiring domain-specific knowledge, we aim to facilitate the identification of patterns and the development of new research questions across disciplines.

2. Methods

2.1 Process standardization

The development of CINDAQ’s automated photogrammetry workflow in 2024 was the result of a multi-year effort to standardize, document, and refine model generation. Before automation, the team established detailed procedural guidelines through an in-house wiki, ensuring methodological consistency (Carboni, 2016). By 2023, these steps were consolidated into a comprehensive workflow, including necessary steps and suggested parameters, covering image alignment, point cloud generation, noise filtering, mesh model generation, scaling, export to other viewing or analysis platforms, streamlining both training and execution.

The resulting step-by-step workflow has since been employed as both an online and offline tool for training. New contributors use it to acquire essential processing skills, while experienced team members reference it to verify parameters, refresh knowledge, ensure consistency, or troubleshoot processing issues. Beyond internal use, the documentation has also facilitated transparent communication with external research partners regarding CINDAQ’s modeling practices.

2.2 Data Management

In addition to workflow standardization, all data related to model production, including original imagery, processed outputs (such as point clouds, project files, and orthomosaics), and contextual materials (e.g., site videos and expert assessments), are organized following a consistent folder structure applied uniformly across all documented sites.

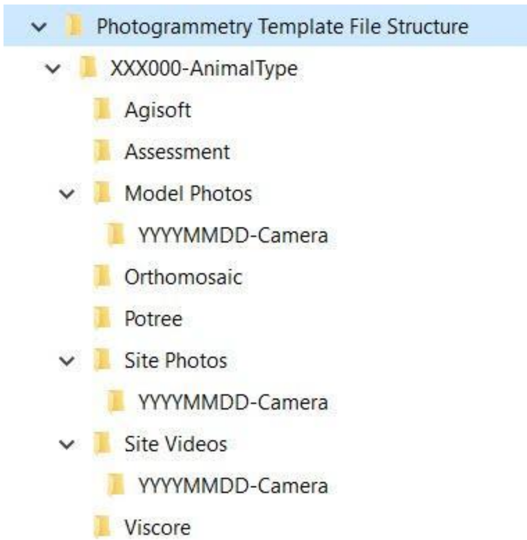

Figure 2. Standard photogrammetry folder template

While various organizational schemes could have been adopted, the critical element lies in enforcing uniformity: each dataset is stored in subfolders with standardized naming conventions, and all files are labeled using clear, descriptive nomenclature which, in the case of images used for processing, includes acquisition date and camera identifier. This structure not only facilitates intuitive navigation for both field personnel and researchers, but also supports robust data management by enabling automated scripts for monitoring, processing, and error detection.

Primary data storage is handled by a Network-Attached Storage (NAS) system configured with snapshot functionality, allowing for rapid recovery in the event of user error, data corruption, or malware incidents, including encrypting ransomware. To ensure long-term data integrity, the NAS is backed up to a cloud-based storage service, mirrored to an off-site emergency NAS, and archived to an offline array of disks.

2.3 Photogrammetry Workflow Automation

In order to develop an automated photogrammetry pipeline, we have leveraged our wiki-based workflow documentation as input for AI-assisted code generation. This process, which was greatly accelerated by using Large Language Models (LLM) to create the first coding drafts that were then edited by our team, produced a modular series of Python scripts, each responsible for automating a specific stage of the photogrammetry process.

Every step involving Agisoft Metashape — from project initialization and image alignment to dense point cloud generation and filtering (based on confidence metrics), mesh reconstruction, orthomosaic generation, and mesh decimation for online dissemination — was encapsulated into distinct Python functions using the Metashape API. These functions are compiled into a dedicated library, allowing reuse across future projects (Aicardi, 2020). Configuration parameters for each step are read from a TOML-based configuration file, with default values that can be manually adjusted. Each configuration file is stored alongside its corresponding model to ensure reproducibility and traceability.

Complementary libraries were developed to integrate with additional software in our photogrammetry ecosystem. These include functions for Sketchfab, used to publish decimated mesh models online, and Viscore, a point-based visual analytics tool developed at UC San Diego. These extensions automate post-processing and streamline the export of Metashape outputs into visualization and analysis environments.

The automation system, deployed on a high-performance workstation, has reduced total processing time by a factor of five, primarily by eliminating manual intervention and repetitive steps. This reduction in complexity lowers technical barriers, allowing non-specialists to contribute effectively to model generation and expanding access to photogrammetry-based documentation. The approach not only enhances productivity but also improves reproducibility and scalability, supporting long-term scientific research and heritage preservation efforts.

Importantly, the system preserves all original image data and allows users to manually reprocess models as needed. Each step of the pipeline can be selectively re-executed with updated parameters, and all parameter changes are systematically logged. For example, a user may choose to manually refine the dense point cloud after automatic processing using the default confidence-level filter values. In this case, the project can be reopened, the point cloud manually edited, the configuration file updated to bypass earlier processing steps (e.g., alignment, depth map and dense cloud generation), and the workflow resumed to produce new outputs based on the modified dataset.

2.4 Notes on Mesh Model and Point Clouds

The workflow includes the generation, storage, and publication of textured mesh models, which are shared via platforms such as Sketchfab for rapid reference and public engagement. These models, which can be decimated to reduce file size and improve handling, are accessible through free, user-friendly online visualization tools that require neither licensing nor advanced technical skills. Their smooth appearance makes them particularly effective for outreach and communication, facilitating broader public awareness (Bourke, 2013). Additionally, decimated mesh models serve as lightweight previews that allow researchers to assess potential areas of interest before engaging with the full-resolution datasets.

From a scientific standpoint, however, the primary analytical value lies in the high-resolution dense point clouds produced by the workflow. These datasets support digital twin generation and feed into visual analytics environments that enable precise segmentation, annotation, and measurement. Domain experts—such as archaeologists, paleontologists, and geologists—can interact with point data to isolate specific features, perform spatial analyses, take measurements, classify elements, or overlay contextual imagery. This functionality is primarily delivered through Viscore and Potree, with automated data export facilitated via dedicated scripts and standardized output formats. Thanks to the modular structure of the workflow, additional export formats and software integrations can be implemented as needed with minimal effort.

The pipeline supports both the scientific and outreach components by systematically generating, organizing, and storing dense point clouds for advanced analysis, alongside mesh models optimized for efficient online visualization.

2.5 Single-Source-of-Truth Approach to GIS Linking

Ensuring seamless integration between photogrammetric datasets and Geographic Information Systems (GIS) is essential for maintaining data consistency, enhancing accessibility, and ensuring long-term usability.

In earlier phases of the project, data storage was non-standardized and fragmented across multiple platforms. As a result, locating models associated with specific areas—and retrieving relevant information for each dataset—required substantial manual effort. The implementation of a standardized folder structure and centralized storage on a Network-Attached Storage (NAS) system, as described previously, represented a critical step toward resolving discrepancies and enabling reliable manual mapping of datasets within the GIS environment.

Building upon this foundation, the next phase toward a unified, semi-automated geospatial platform involved creating and maintaining a central index of all available models. This index should function not only as a reference overview, but more importantly, as a framework to associate photogrammetric datasets and their related files with their corresponding metadata.

To accomplish this, CINDAQ adopted a Single Source of Truth (SSOT) methodology to centralize metadata and link records across NAS directories, Dropbox, Sketchfab, and GIS layers. This SSOT is currently implemented as a structured Google Sheet, synchronized with GIS platforms through a bidirectional update system. The SSOT captures key metadata including model creation dates, diver observations, expert assessments, and spatial coordinates.

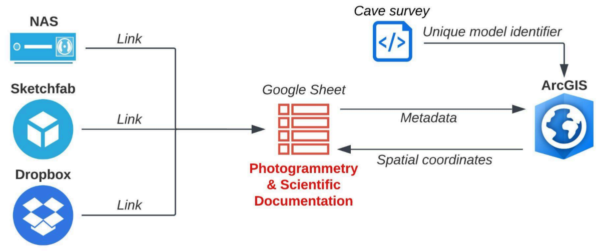

Figure 3. Linking the SSOT with data storage, survey & GIS

After fieldwork, cave divers download the collected data to the standard folders, enter basic information into the SSOT and locate the models on their survey using standard keywords and Unique Identifiers (UIDs). A series of in-house Python scripts—executed automatically via a job scheduler—searches the NAS for corresponding datasets and populates the SSOT with direct links to both local and online file repositories. A second set of tools, implemented as ArcGIS Pro geoprocessing models relying on additional custom Python functions, extracts GPS coordinates and depth from cave survey data, writes them into the SSOT, and finally transforms it into GIS feature layers published to the organization's online platform, thus making each model discoverable alongside all associated metadata.

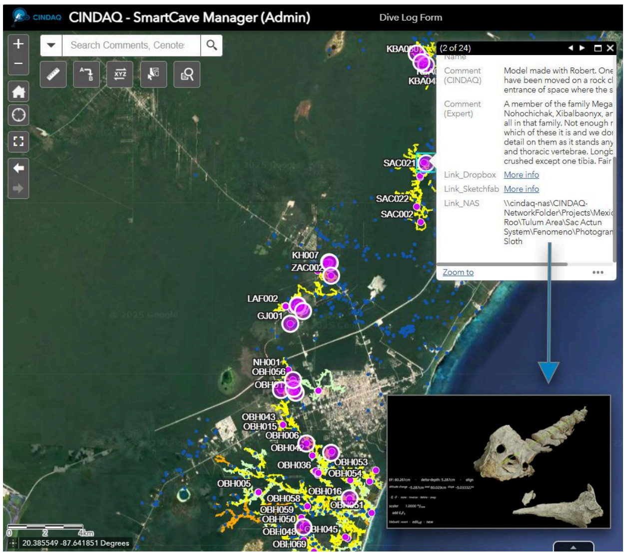

Figure 4. Visualization of available photogrammetric datasets with links to related files and metadata

In addition to improving data integration, this system has exposed inconsistencies within legacy records, enabling a continuous refinement process. By visualizing data gaps and misalignments, researchers can identify and resolve missing or erroneous entries, leading to higher data quality. This feedback loop resulted in a 40% increase in the number of models spatially linked within the CINDAQ database in 2 months, and a 100% increase in 8 months, from 103 to 206 georeferenced objects. The modular architecture of the system also supports future scalability, enabling migration to alternative SSOT frameworks, such as SQL-based databases or native GIS feature layers.

3. Results

3.1 Productivity

The introduction of a compact photogrammetry setup in August 2020 (Fortin et al., 2021a) significantly improved data collection capabilities in the field, enabling more efficient and frequent documentation of submerged sites. However, the most substantial gains in model processing efficiency were observed after the implementation of an automated workflow on November 17, 2024. Between August 2020 and the automation date, an average of 0.143 models per day were processed. Following automation, this rate increased to 0.205 models per day, representing a 43.7% improvement.

	Before automation	After automation
Duration (days)	2145	205
Number of models	232	42
Models/day	0.108	0.205

Table 1. Automation-induced productivity gain

These results indicate that the automated system streamlined processing steps, reduced manual intervention, and enhanced overall scalability. In combination with standardized procedures, the workflow automation has led to a measurable increase in productivity while maintaining data quality and consistency.

3.2 Democratizing access to 3D modeling

Beyond improving processing efficiency, automation has also led to a more equitable distribution of workload among contributors. To assess this shift, we calculated the number of models processed by each team member and derived two statistical indicators: the standard deviation and the coefficient of variation (CV), both expressed as a percentage of total contributions. These metrics reflect the dispersion of individual contributions relative to the group average. The standard deviation measures the absolute spread of contributions, while the coefficient of variation (CV) expresses that spread relative to the average, offering a normalized measure of balance across the team.

Before automation (from August 2020 to November 2024), the standard deviation was 16.35%, and the CV reached 114.44%, indicating a highly uneven distribution of labor. After automation, the standard deviation dropped to 13.53%, and the CV decreased to 67.66%, reflecting a more balanced and sustainable workload. This larger drop in CV shows that although some variation remains, contributors are now participating more evenly relative to the group average—indicating improved team engagement and better distribution of effort.

This shift not only reduces the risk of bottlenecks and contributor fatigue but also makes the photogrammetry workflow more scalable, resilient, and accessible to a wider team. The improved workload balance ensures that no single contributor is disproportionately responsible for model production, supporting the long-term sustainability of the documentation process. In other words, the workflow has become not only more efficient but also more inclusive.

3.3 Enhancing interpretability and facilitating data-driven discoveries

The optimization of both data collection methods and processing workflows, combined with the integration of photogrammetric models into GIS visualization platforms, is already yielding scientific benefits. Researchers can now examine a greater number of spatially referenced models, enabling the identification of emerging patterns in archaeological, geological, and paleontological datasets.

The compact photogrammetry setup developed by the CINDAQ team (Fortin et al, 2021a)—which is lightweight, suitable for use in confined or difficult-to-access areas, and does not impede divers' ability to navigate the cave—has played a key role in expanding documentation coverage. Crucially, the assurance that multiple models can be processed efficiently using the automated workflow has encouraged the documentation of sites that might otherwise have been overlooked. This is particularly evident in locations where scattered, fragmented bone material is present across broad areas. These smaller sites would typically have been noted during the survey, but 3D documentation was often deemed unjustified, as the expected scientific return did not outweigh the perceived effort and complexity of data collection and processing.

A compelling example is site GJ001 in Quintana Roo, Mexico. The site, located along a single tunnel accessible only through multiple restrictions—unsuitable for bulky traditional photogrammetry equipment—was found to contain at least 18 discrete bone clusters. Most consisted of one or two bones or fragments. Owing to the streamlined data collection and processing approach, all 18 clusters were documented and subsequently reviewed by a paleontologist. The expert identified remains from several species, including sloths, peccaries, horses, and a dog, many showing evidence of chewing or fractures consistent with tooth marks (see Figure 5). These findings supported the interpretation of the site as a likely carnivore den. Following this discovery, six additional paleontological sites exhibiting similar bone distributions and damage patterns were subsequently identified as potential locations of comparable predatory behavior.

Figure 5. A 17-cm-long scapula showing teeth marks in a presumed carnivore’s den - example of a discovery stemming from the streamlining of the photogrammetry process

The increased productivity enabled by automation has also contributed to the documentation of at least twelve underwater cave sites containing horse remains. These findings have significant implications for public outreach, challenging the widespread misconception that horses were not present in the region prior to European contact. From a scientific perspective, they also provide new data to reassess species distribution patterns in Late Pleistocene and early Holocene Mexico.

The combination of detailed process documentation, field-adapted image acquisition methods, and automated workflows has not only scaled up the production of photogrammetric datasets, but also ensured they are consistently delivered to researchers. By integrating these outputs into a centralized Single Source of Truth (SSOT), organizing them within a structured data repository, and visualizing them through an intuitive GIS platform, the system also scales up the interpretative process—enabling new hypotheses and insights to emerge. The identification of predator dens and the reassessment of horse presence in the region are examples of discoveries that have benefited from this systematized approach.

However, the greatest strength of the system lies perhaps in its capacity to combine an increasing repository of geolocated photogrammetric models with additional spatial data layers, and to study their interrelationships through GIS-based analysis.

An illustrative case involves a presumed prehistoric ochre mine. Leveraging the photogrammetry setup and workflow described above, twelve models were created to document patches of broken speleothems whose distribution could not be readily explained by surrounding cave formations or gravitational collapse alone. In a second phase, diver comments about charcoal sightings were collated into a georeferenced feature layer. A custom Python script was used to compute the distance between each charcoal observation and the nearest marker of possible anthropogenic activity (e.g., conchoidal fractures or cairns), generating a heatmap of proximity. By linking the photogrammetry models to cave survey data via the SSOT framework, and overlaying this data with the color-coded charcoal layer, a pattern began to emerge, suggesting a potential path of human movement through the cave associated with prehistoric activity.

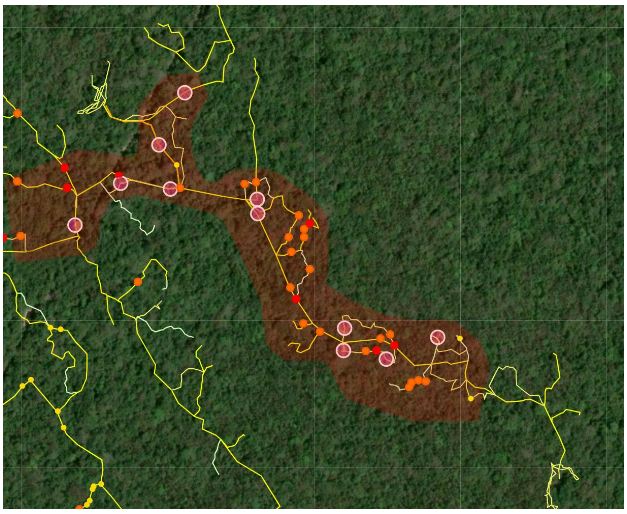

Figure 6. Overlaying photogrammetric models of broken speleothems with charcoal sightings to highlight possible paths

While this analysis does not yet constitute a definitive answer, the system allows us to connect and present data in such a way that new questions can be asked.

Overlaying models with other survey data like cave topography, divers’ observations or aerial imagery with embedded geographic metadata, scientists can correlate findings more effectively, identifying site clusters, geological formations, or previously unnoticed relationships. This integration enhances interpretability and facilitates data-driven discoveries, demonstrating the combined powers of streamlined photogrammetry workflows and GIS-linked photogrammetry for large-scale research initiatives.

4. Discussion & Conclusion

The development and implementation of CINDAQ's automation tools and GIS integration system has aimed to address several key challenges: synchronizing heterogeneous data sources, enabling non-specialist working in the very demanding underwater cave environment to participate effectively, maintaining consistency across hundreds of models, and ensuring that collection, processing, and analysis workflows are as seamless as possible.

Our experience highlights the value of combining standardization, process documentation, automation, and data integration. Together, these elements foster reproducibility, lower technical barriers, and facilitate new scientific insights. By aligning photogrammetry outputs with spatial and contextual metadata within a GIS-linked Single Source of Truth (SSOT), we not only streamline internal workflows, but also enable external experts to interpret models more effectively, ask new questions, and generate hypotheses grounded in spatial patterns.

As our system grows, we now see several avenues for future development. First, integrating remote sensing layers—such as water level, salinity, and flow—into the GIS environment will help contextualize photogrammetric data. Second, transitioning from a spreadsheet-based SSOT to more robust SQL databases will improve scalability and allow for new querying possibilities and for better user access control. Third, remaining manual steps, such as duplicating and populating folder templates, as well as parts of the manual data entry process into the SSOT, should be automated to further reduce overhead. Finally, embedding 3D visualization directly within GIS platforms will eliminate reliance on external viewers, closing the loop between data and interpretation.

While primarily developed in the context of underwater cultural heritage, the modular architecture of this system makes it applicable to other domains including terrestrial archaeology, geomorphology, and paleoecology. Ultimately, the system demonstrates how detailed process definition, standardization, targeted automation and thoughtful integration with GIS systems can enable structured, inclusive, and scalable digital documentation, supporting public outreach, scientific research and long-term preservation of information.

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