Digital Analysis of Rock Art in Santa Olaya Canyon: Integrating Cultural Landscape and UAV Technologies for Conservation

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Abstract

This research work presents the digital documentation of rock art found on a rock face in the Santa Olaya Canyon, in the municipality of Burgos, Tamaulipas. Unlike rock art found in caves, these open-air expressions are actively integrated with the natural and cultural landscape, functioning as symbolic markers of the territory. Through controlled flights with a DJI Mavic Air 2 drone and 3D photoreconstruction techniques, a difficult-to-access vertical surface of a rock face with rock paintings was recorded with high precision. The methodology employed responds to the need for conservation and study of these sites, which lack institutional protection mechanisms from the INAH (National Institute of Archaeology and History) or, as in this case, conservation and cultural research studies. It also contextualizes the value of rock art in Tamaulipas, particularly in the Sierra de San Carlos, where some of the most significant collections in northeastern Mexico are found and where evidence of theft and vandalism of portions of some of them has been found. The application of non-invasive digital technologies is positioned as an effective tool for the documentation, analysis, and dissemination of archaeological heritage, especially in remote and limited-access regions. The generated orthomosaic and point clouds provide the opportunity to create a digital legacy of the area.

1. Introduction

Outdoor rock art, unlike that found in caves, can be considered part of the landscape because their location directly interacts with the natural environment, integrating them into the spatial, visual, and cultural configuration of the territory (Bradley, 1997). These types of sites integrate elements of the natural and cultural landscape, such as topography, light, vegetation, and climatic elements, suggesting an intentional relationship between the representations and the surrounding space (Chippindale and Nash, 2004). Vigliani (2015) states that rock art interacts with its surrounding landscape as a cultural manifestation, implying that the paintings are not only art but also territorial or symbolic markers that reflect the worldview of human groups in relation to their environment.

Outdoor rock art is studied as a relational phenomenon that links the materiality of rocks with the cultural landscape. These types of manifestations are found in the Sierra de San Carlos, with the most abundant and diverse being those found in various locations in the Santa Olaya Canyon, in the municipality of Burgos. These are located in rock shelters and have been interpreted as nodes in a significant landscape, where the choice of location responds to social, ritual, or ecological criteria. This aligns with archaeological perspectives that view rock art as a practice inscribed in space, not merely as isolated representations (Radillo, 2008). Despite the manifest importance of the sites in the Santa Olaya Canyon, referred to in various journalistic sources, it is the work of Tobias and Morrison (2018) that truly contextualizes the lost tribes of Tamaulipas.

The INAH has not been able to establish adequate mechanisms for their protection and preservation, making them available for public observation. And even worse, the isolation and difficult accessibility facilitate vandalism and the removal of parts of the walls with cave paintings.

Therefore, the archaeological site was documented using digital technologies, a technique that has gained relevance in recent years, especially for the conservation, analysis, and dissemination of cultural heritage.

This contribution seeks to:

1. Integrate Culture and landscape, highlighting outdoor rock arts and symbolic markers in the territory of San Carlos and San Nicolás, Tamaulipas.
2. Integrate UAV (Unmanned Aerial Vehicle) technologies for innovative documentation and data creation for 3D reconstruction of rock arts in an accurate and not invasive way.
3. Creates a manner to do digital preservation by creating a high-resolution digital archive through the orthomosaics and 3D models, which allow long term study and conservation of details.
4. Conservation is also heritage advocacy which emphasizes the importance of protecting the current unprotected rock art sites in Tamaulipas, urging the institutional attention.

1.1 Background

Rock art in mountainous contexts with bodies of water has been the subject of study in different regions of the world, given that these landscapes often have symbolic and functional connotations for prehistoric communities (Whitley, 2001). In Mexico, similar studies have been conducted in areas such as the Sierra de San Francisco (Baja California) and the Balsas River basin (Vega et al., 2021), where archaeological analysis has been combined with digital recording techniques for their conservation (Murray et al., 2016).

Rock paintings in Tamaulipas represent one of the most significant cultural manifestations of northeastern Mexico. Particularly in the municipalities of San Nicolás and San Carlos, important rock art sites have been identified that offer valuable information about the region's pre-Hispanic cultures.

1.2 Sierra de San Carlos: A Rock Art Center in Tamaulipas

The Sierra de San Carlos, located in the municipalities of San Nicolás, Burgos, Cruillas, Jiménez and San Carlos, is recognized for housing one of the largest concentrations of rock art in Tamaulipas. Research has identified more than 5,000 cave paintings, distributed across sites such as Cueva de los Caballos, La Noria, Las Colmenas, and El Carrizo. These depictions include anthropomorphic, zoomorphic, astronomical, and abstract figures, reflecting the daily activities, religious beliefs, and natural environment of the groups that inhabited the area.

Additionally, petroglyphs have been discovered in the region, such as the heron carvings in the Sierra Chiquita, which may date back more than 10,000 years, suggesting symbolic communication between pre-Hispanic groups.

Petroglyphs and heron sculptures have been discovered in the Sierra Chiquita, estimated to be more than 10,000 years old, in the region. This suggests that there is symbolic communication between pre-Hispanic groups that could be due to the existing rock formations of the Sierra Madre Oriental and its proximity to mountain areas where they explored, such as the Sierra de San Nicolás, and where it is believed that undocumented rock art still exists. Future research in this regard reveals an imminent possibility for the use of aerial photogrammetry to help reveal new findings that expand the network of rock knowledge in the State of Tamaulipas.

All these sites are highly valuable for understanding the artistic expressions of the pre-Hispanic groups in the region, as well as for studying their social practices, their beliefs and their relationship with the environment, among other essential manifestations of the culture of identity in northeastern Mexico.

It is of utmost importance to know the cultural identity of Tamaulipas, that the artistic manifestations that the first settlers had in these cave paintings are preserved and studied. However, many of these sites are inaccessible and are located in the mountains so precautions should be taken and visited with local guides and take the necessary precautions but also preserve and avoid looting.

1.3 Remote sensing analysis of rock art is currently documented:

High-quality images obtained with drones such as the Mavic 2, whose characteristics are detailed in Table 1, could have limitations could be the performance of the camera when distinguishing pigment losses or the lighting conditions at the edges of the rock. These challenges could be part of the new methodologies that would indicate the timing of sample collections, or the use of lamps attached to drones.

DJI Mavic 2 Pro drone was also used by Grzegorz Baran September 15, 2019 — The idea behind this tool is quite simple: anything without paint is considered an areal density standard. Pattee (2016) applied photogrammetric and laser scanning recording methods for the study of a castle ruined. His study primary goal was to inventory a digital preservation data. Although, both methods generated interactive 3D models by combining still images he concludes that photogrammetry and precise laser measurements (laser scanning), can enhance by combined into a single model.

In the present case, the wall is located in a difficult-to-access river canyon, with an inclination of over 70 degrees and a length of approximately 40 meters. The remote location and geometry of the site precluded the use of scaffolding, so an aerial methodology was chosen. With the digital documentation of the cave paintings in the Santa Olaya Canyon, as a way to contribute to their preservation and support the INAH in the procedures that lead to establishing appropriate mechanisms to activate an appreciation process.

This activity contributes to the following project goals:

1.4 Influence Goals

To encourage more residents to appreciate their heritage and share their knowledge, finding in it an alternative to improve their well-being and their economy.

To design, in an academic and socially participatory manner, a circuit for the appreciation of rock art, with the support of the INAH (National Institute of Natural History), so that it can carry out the procedures and actions for its regulatory protection, enabling adequate mechanisms to activate the circuit under the responsibility of ejidatarios (communal landowners) and government authorities.

1.5 Research Goals

To produce a scientific-artistic visual catalog in digital media of the natural and anthropogenic landscapes in Santa Olaya Canyon. This, along with its characterization and mapping, is the basis for protecting the iconic Cerro del Diente as a Natural Monument in Tamaulipas.

2. Methodology

2.1 Site Description

Santa Olaya Canyon is located north of the San Carlos Mountains, a geographic discontinuity at the intersection of the Great Plains of North America and the Northern Gulf Coastal Plains (Figure 1). It lies between 400 and 450 meters above sea level within the municipality of Burgos, Tamaulipas. It is an isolated area accessible only by pickup truck, via a 16-km dirt road in the absence of rain. Despite this, some of the paintings show clear signs of vandalism.

Rock art is found on a wall approximately 5 m high, distributed over approximately 100 m of the cliff. The site known as "El Mural" is the rock shelter where the greatest concentration of rock art is located. It is composed of sedimentary rocks from the

Lower Cretaceous, while the canyon soils are highly erodible Leptosols that lack agricultural potential; however, conditions are conducive to the development of submontane and thorny scrub. The climate is extreme, with average temperatures of 28.5°C and diurnal variations of up to 13.6°C. It is warm and sub-humid, with rainfall reaching 600 mm per year, occurring mainly in summer.

2.1.1 Data Acquisition: Each of the 21 selected UVUs underwent detailed aerial data acquisition using the UAV platform specified in Table 1.

Table 1. Drone used to generate inventory data

Brand	DJI
Model	Mavic 2 Zoom
Features 	• 1/2,3″ CMOS with a RGB camera of 12 million effective pixels • Field of View (FOV): 83° (24 mm) and 78° (48 mm) • 35 mm Format Equivalent: 24– 48 mm • Aperture: f/3.8 (48 mm) • Shooting Distance: 0.5 m to

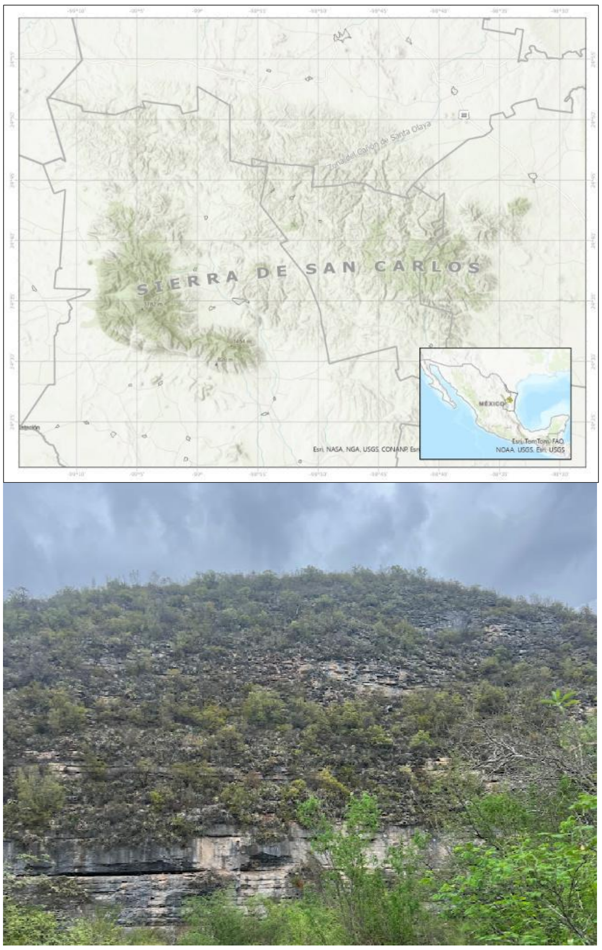


Figure 1. Above, the location of the Santa Olaya Canyon in the Sierra de San Carlos, Tamaulipas, and below, a view of the mountain range and in the lower section, the area where the river and the cave paintings are located.

Data collection protocols were recorded for each flight, incorporating the survey data (Table 2). Additionally, to ensure data replicability and facilitate future analysis, detailed records were kept of all operational parameters configured for each mission and the prevailing weather conditions (Tables 2-4). The extent of the surveyed area and the flight path of each UAV deployment were also documented (Figure 3).

Table 2. Geolocation and temporal data for the UGA 3 survey.

Site	https://maps.app.goo.gl/6cF7ujKTnrXgsjDy6
Date	October 9th, 2023
Hour	10:30 am

Table 3. Flight mission configuration

Flight parameters	Size and Measure
Altitude	1-6 m
Area	100 m2
Number of images	127
Overlap	75% (lateral and frontal)

Table 4. Weather conditions during the drone flight mission

Temperature	14 °C
Wind speed	6 km/h
Wind direction	NNW
Probability of precipitation	0%
Cloud cover	80%

2.2 Survey information

Figure 2 illustrates a structured, multi-stage protocol for spatial data acquisition and processing using UAVs for the canyon inventory. This methodology describes the sequential steps required to obtain raw aerial data and generate accurate 3D models of the rock face containing the rock paintings.

Prior to takeoff, extensive mission planning was conducted, including the definition of the flight parameters detailed in Table 3. The adjustment was performed as an open network, without external control information, relying solely on onboard GNSS/IMU data for initial positioning. The sensor 1/2.3 CMOS is a standard small sensor, and flights were done to flight very close to the wall to maintain the high Ground Sample Distance. This planning ensured optimal data quality and coverage, tailored to the specific characteristics of the target canyon. Furthermore, considerations regarding airspace regulations, potential obstacles, and battery management were crucial during pre-flight preparations. During flight operation, the UAV autonomously or semi-autonomously executes the defined flight plan, capturing a series of overlapping aerial images. During the flight, the UAV's status, including battery levels, GPS signal, and altitude, is continuously monitored to ensure mission success and data integrity.

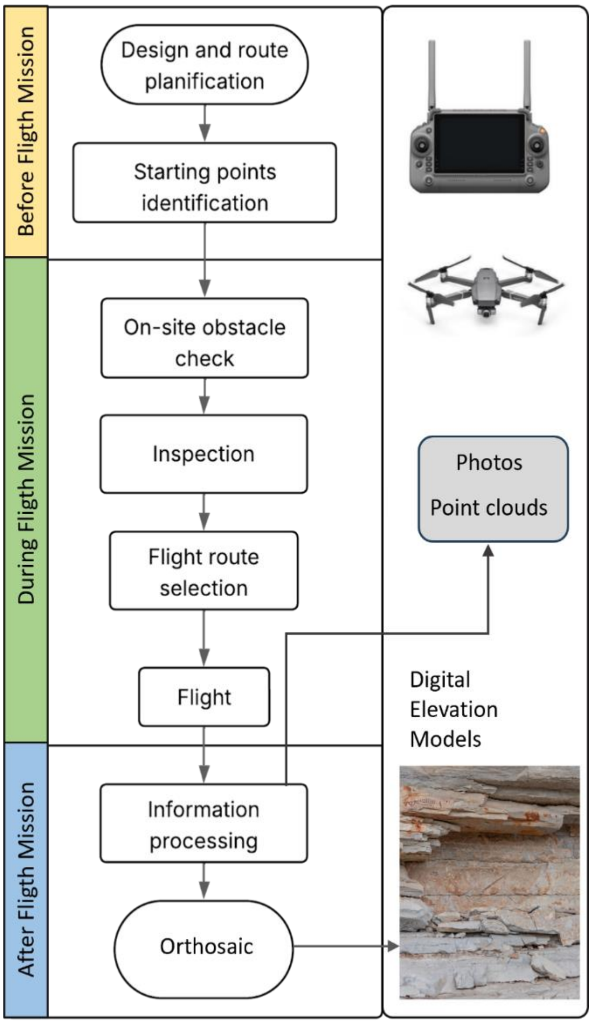


Figure 2. Methodological framework of the flight mission and data processing

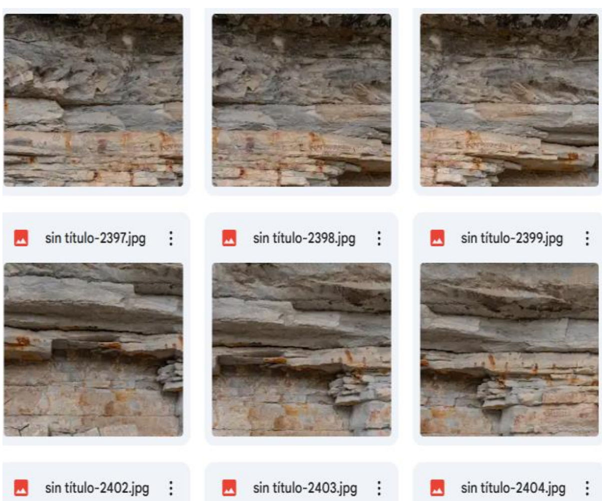


Figure 3. Wall of petroglyphs with the extraction.

2.3 Internal Accuracy and Bundle Adjustment

Because no external control information was used, the tuning was made as an open network based on the GNSS/IMU metadata on board the UAV. The final 3D models ensured their reliability and internal consistency by evaluating the Mean Root of Square (RMS) reprojection error which was calculated at 1 ± 0.2 pixels.

To ensure metric accuracy, the photogrammetric process included a scaling and validation phase based on physical field measurements using a steel tape measure (Figure 4). Distances between identifiable natural features (e.g., specific rock formations) were measured manually on-site. These known dimensions were then used as scale constraints within the processing software (Metashape) to refine the model's scale and correct for potential linear distortions.

Figure 4. Steel tape measure used for physical field measurements.

By maintaining a high image overlap (typically >80%) and a consistent Ground Sample Distance (GSD) across short-range flight paths, the subpixel accuracy of the mooring point match was preserved. This approach allowed for a relatively stable reconstruction of the canyon wall geometry, providing sufficient accuracy for the qualitative and spatial inventory of the cave paintings.

2.4 Three-dimensional UAV-based data processing

2.4.1 Point cloud generation: The generation of dense point clouds was conducted by applying photogrammetry techniques (Remondino et al., 2011). The computational power employed for the processing, as well as the exemplified results for the cave, are displayed in Table 5.

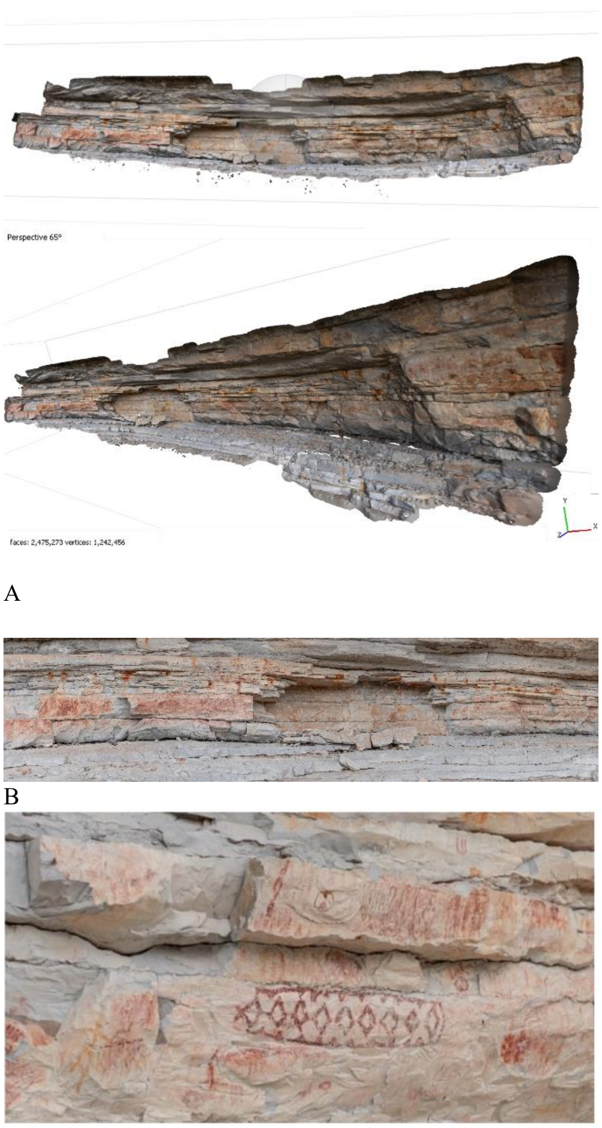
Point cloud processing and characteristics	
Processor	AMD Ryzen Threadripper 1950X 16-Core, 3.40 GHz
Memory (RAM)	16 GB
Number of points	15,310,913
Processing time	35 minutes
Bands	RGB

Table 5. Wall art point cloud data and processing information.

3. Results

An orthomosaic was digitized to understand the complexity of the rock structure. With a point cloud of over 4.38 million, the rocks can be visualized using a drone. However, short-range photogrammetry will be necessary to detect the details of the petroglyphs, into the range of characteristics and ecological conditions present within the broader spectrum of UGAs in San Nicolás.

The point cloud obtained with the DJI Mavic Air 2 drone allowed for precise capture of the rock surface, revealing complex details of the rock art in Santa Olaya Canyon. In just 42 minutes, a set of 4.3 million points was generated, reflecting the ability of low-cost drones to perform detailed mapping in relatively short periods of time. The resolution obtained with the point cloud was 0.2 cm / pixel sufficient to identify patterns and details of the rock paintings, suggesting that 3D photoreconstruction technology is suitable for documenting this type of cultural heritage in hard-to reach areas.



A

B

C

Figure 5. Details of the rock art digitization. A) Point cloud of the middle portion, B) Angled view showing the roughness of the rock face, and C) a frontal photograph.

The use of the drone allowed for efficient coverage of the rock face, overcoming the limitations of traditional techniques, such as terrestrial photography or manual measurements, which often lack the precision necessary for proper digital preservation.

Despite being a low-cost drone, the results obtained demonstrate the feasibility of using accessible technologies for recording and preserving archaeological heritage, especially in remote sites without institutional protection, such as the cave paintings in Tamaulipas.

The high point cloud density (4.3 million) provided a detailed and scalable model of the rock face, facilitating future research on the evolution and cultural context of the cave paintings, as well as their long-term conservation.

The results obtained with the drone also indicate that, by integrating photoreconstruction technologies, a three-dimensional digital archive can be generated that is accessible to researchers and authorities, which is essential for preserving archaeological sites without direct intervention that could alter the physical space.

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With the methodological approach of digital photoreconstruction of archaeological areas exposed in the mountains and with relatively difficult access, it is shown that low-cost UAVs represent a digital and non-invasive tool to document, conserve and disseminate rock art in this type of regions, as is the case of the Sierras de San Carlos and San Nicolás in Tamaulipas. Mexico.

4. Conclusions

Low-cost multirotor drones represent a versatile, accessible and efficient tool for the documentation of digital rock art material in the Santa Olaya Canyon, in San Carlos, Tamaulipas. This study provides accurate and well-detailed records that were documented in a short period of time, but that will have great implications for preserving the details, which unfortunately are increasingly vulnerable, due to the lack of interest of the authorities, the access that the tourist population has to the rocks and the lack of an institutional strategy to preserve the cultural heritage of this heritage.

It is important to point out that remote sensing technologies, especially low-cost photogrammetry, open up new possibilities for preserving the details of the cultural heritage of mountainous areas that are difficult to access in Mexico. Through the generation of point clouds and three-dimensional and photoreconstructed models, it is possible to create a digital legacy that can contribute to the non-invasive conservation of cave paintings, ensuring that details of the oldest cave history in the region can be preserved, ensuring that the physical integrity of the pieces is not compromised and facilitating long-term study and dissemination.

On the other hand, this methodology, in addition to being innovative, is effective and will allow it to be replicable and scalable. Offering a valuable tool for researchers and authorities in the conservation of archaeological heritage, especially in those areas that are difficult to access and without institutional protection.

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