Journal of Maritime Archaeology
https://doi.org/10.1007/s11457-023-09382-3

RESEARCH ARTICLE

# The Application of Photogrammetric and Topographic Techniques to Investigate Submerged Caves: A Case Study of Georeferenced Point Installation at the Font of Ses Aiguades Cave (Alcúdia, Mallorca)

**Manuel J. Fumás Soldevilla[1] · Pablo Cantuel González[2] · Francesc Gràcia Lladó[3] · John Kendall[4] · Florian Huber Wilhelm[5] · Antonio Jesús Talavera Montes[6] · Miguel Ángel Perelló Estelrich[7] · Pablo Fraile Fraile[6]**

Accepted: 16 October 2023


**Abstract**
In recent decades geoarchaeological techniques have increasingly been used to document archaeological remains in terrestrial and underwater sites. However, the archaeological record in submerged caves lacks systematic documentation techniques, due to difficulties of the environment and time limitations. These methodological constraints may result in incomplete documentation of an archaeological site and its artifacts. In the present work, we aim to combine geoarchaeological techniques, photogrammetry, topography, and manual surveying to geolocate archaeological remains dated to the Roman period of Mallorca (30 BCE [Before Common Era] and 70 Common Era (CE), in one of the most important submerged sites in Europe, the Font of Ses Aiguades cave in Alcúdia (Mallorca). An innovative methodological protocol based on non-intrusive surveying was applied to improve the historical, topographical, and archaeological knowledge of the cave. Here we propose a fast, rigorous, and economic documentation protocol for the generation of a georeferenced database of submerged archaeological remains. We also demonstrate the superior cost/benefit balance of generating a georeferenced photogrammetric three-dimensional model of a site versus manually calculating the geopositions of underwater archaeological artifacts. This study also corroborates the efficacy and accuracy of photogrammetry versus manual measurement.

**Keywords** Underwater archaeological survey · Font de ses Aiguades (Mallorca) · Photogrammetry · Bathymetry · GPS technology

## Introduction

As the field of marine archeology developed, terrestrial archaeological techniques were adapted to study underwater archaeological sites, allowing for the collection of the maximum amount of contextual information of underwater sites, and allowing for their later interpretation (León 2003; Ogloblin Ramirez et al. 2021; Shahack-Gross 2017). However,

Extended author information available on the last page of the article

Published online: 29 November 2023

only recently are these techniques being applied to the exploration of archaeological sites in submerged caves. This kind of investigation is relatively uncommon due to the high level of specialized knowledge and certification required in diving, gas, and decompression techniques (Huber 2009; Campbell 2017).

Hundreds of methodological manuals for surveying and excavation of terrestrial archaeological projects have been produced (e.g. Renfrew and Bahn 1993; Carandini 1997; Domindo et al. 2007; Bahn and Renfrew 2008). With the advent of marine archaeology the production of such manuals for underwater archaeological investigations have also been developed (eg. Maarleveld, Guérin, and Egger 2001; Bowens 2009). However, excavation and exploration techniques for archaeological remains in submerged caves are lacking standardization. Archaeological work in submerged caves is usually limited to describing the geographical and historical context of the studied site and the results of archaeological project without prioritizing excavation techniques (Campbell 2018). Gaps remain in this developing field concerning technical issues such as how georeferencing of an archaeological site in a flooded cave can be best achieved, and what is the most comprehensive topographic method to maximize success rate while saving time and reducing costs. The answer does not appear in any manual or book specialized in the subject (Campbell 2018). In this study we propose a methodology to address those concerns.

For three decades, the problems of geolocation and topography of terrestrial caves have found technical solutions in the aerial environment with the appearance of LIDAR (*Light Detection And Ranging)* systems *(*Moyes and Montgomery 2016) and laser scanners (Chase et al. 2017). These technical solutions, which today allow the creation of digital clones of caves, have left submerged caves aside due to the disadvantages that the aquatic environment presents. This conspicuous omission of submerged caves has limited developments in the field of geopositioning of submerged archaeological artifacts (Vallicrosa et al. 2020; Fumás 2022a).

In submerged caves, previous work has focused on documenting and describing archaeological remains. However, there is a lack of information on the methods used to geolocate the spatial distribution of submerged cave sites and their materials (Huber 2009; García, 2014; Arroyo-Cabrales et al. 2015; Rissolo et al. 2015; Campbell 2017; Barba-Meinecke 2020; Barba-Meinecke, Pizá Chavez y Quetz León 2022; Fumás 2022a, 2022b) The majority of published articles are based on previous topographies carried out by cave divers using a basic calculation method produced by applying measurements of the submerged polygonal galleries in relation to a guide line. Thus, significant errors are common, especially when these galleries reach hundreds or thousands of meters (García 2014; Fumás 2023).

## The Importance of Topographic Georeferencing in Archaeological Prospection

Georeferencing in underwater archaeology documents the location of a certain site in space in a univocal way—that is, it provides a unique location defined by a series of points with known coordinates, in both a reference system and in a cartographic projection. The importance of georeferencing applied to the study of submerged cavities ranges from obtaining basic data about their spatial context (e.g., local or global), to the comparison of cartographies or spatial data of different ages, to providing additional physical safety regarding the site of the underwater field campaign (Davila and Camacho 2012).

In general terms, topographic survey is understood as the set of techniques and methodologies capable of documenting spatial and geometric information of the terrain to obtain its graphic representation considering a pre-established tolerance. In other words, topographic survey results in the passage from the physical reality of the terrain to paper or map. It provides essential geometric information to understand and contextualize the remains found in the site (Pachas 2009). The applied methods and instruments provide us with the tolerance or maximum permissible error. The field methodology and the instrumentation directly affect the economic viability of the archaeological project. Certain procedures can make the expedition economically unfeasible (Fernández Gómez 2008).

Photogrammetry is accepted as one of the most dependable, fast, and rigorous documentation techniques, especially when combined with topographic surface methods (Yamafune 2016; Moya and Muñoz 2017; Nocerino et al. 2018; Abdelaziz and Elsayed 2019). The combination of these techniques can be used to produce a georeferenced digital model of a site and its archaeological or paleontological finds (Green and Gainsford 2003; Huber 2014; Balletti et al. 2015; Fumás 2023).

In the case of Font de ses Aiguades cave, the biggest problem in the use of photogrammetry stemmed from reconstructing three-dimensional coordinates of the captured terrain by photographs and geometric analogy (Quirós 2014). Photogrammetry was limited by low visibility conditions in the work area caused by halocline and percolation which made it impossible to take pictures, and posed a serious risk to the safety of the human dive team.

(Domínguez et al. 2013; Zhukovsky et al. 2013; Balletti et al. 2015; Yamafune 2016).

For photogrammetric work it is necessary to obtain the coordinates of datum points to insert the geolocation of photographs in a specific reference system. Then, this information must be verified (Fraser and Edmundson 2000; Bitelli et al. 2017). Nevertheless economic, logistical, and conceptual difficulties of work in submerged archaeological caves restricts the use of photogrammetry for the documentation of archaeological remains. Thus, the aim of this work is to introduce a cost-effective manual method to obtain georeferenced points of archaeological artifacts without using a three-dimensional georeferenced model.

## Research Aims and Approach

The need to extract the maximum information from the site, without removing land or extracting artifacts, respecting the basic principles of UNESCO regarding the conservation of underwater archaeological sites (Maarleveld et al. 2013) and the National Plan for the Protection of Underwater Heritage (Ministerio de Cultura 2009; Paper 2009), was one of the most important aspects of this project.

This project was designed to maximize dive time, reduce unnecessary costs, obtain archaeological data, and collect data comparable with other topographic methods such as cave mapping or manual trigonometric measurements (Kister 2017).

The objective was to obtain a 3D georeferenced model of the site. Reference points of the site and each of its ceramic pieces were collected for five reasons: (1) To validate that our novel photogrammetric surveying method can be extrapolated for use in other submerged cave sites, (2) to relocate artifacts allowing us to observe possible looting, (3) to increase safety for diving members of the expedition, (4) to document the geography of the site at regional and global scales, and (5) to use manual measurement as an alternative method to the use of photogrammetry to calculate the spatial geoposition of archaeological remains (McCarthy and Benjamin 2014; Chibunichev et al. 2018).

## Study Area

This study is part of the research carried out in the Font of Ses Aiguades cave, within the Underwater Archaeological Research in the Caves of Mallorca (IASCM) project 0337SET2019ARQ.242–19 Alcúdia (Fumás 2021). IASCM aimed to improve surveying archaeological techniques for the study of submerged caves and complement the archaeological study of the anthropogenic use of Mallorcan cavities (Ramis and Santandreu 2011). The Font of Ses Aiguades cave (UTM X: 501,021,46, Y: 4,413,637,02 (ETRS89, UTM 31)) is in the north-east of Mallorca, in the bay of Alcudia, near the islet of Alcanada (Gràcia et al. 2001). The cave is accessible through a well that is approximately six meters above sea level, and is located on a gentle slope from the sea to the interior that continues towards the Puig de Sa Madona 169 m (m) above sea level (Fig. 1).

Since Roman times, the bay of Alcudia was frequented by navigators, as evidenced by the various Roman wrecks. The well entrance is located barely a hundred meters from the seashore. The site was identified a few kilometers from the ancient city of Pollentia, which together with Palma, was a center of diffusion of the Romanization of the island (Hodges 2000; Munar and Sastre 2010).

The cave, with a NE-SW direction, consists of a set of galleries (NE: gallery of the Moraguesi Typhlocirolana, N: Myotragus gallery and the small gallery) that converge with each other in the *Sala de les Àmfores*, the largest chamber of the cave. The cave has a total length of approximately 180 m; the majority of which is submerged. However, there are abundant air chambers throughout the cave (Gràcia et al. 2001). The submerged deposit is formed by landslide and archaeological artifacts dated between II BCE and modern times. The cone has a projected area of about 200 square meters with an approximate volume of 63.25 cubic meters from the top to 7.5 m deep. This cone starts from about 2 m underwater to 14 m deep in the aforementioned *Sala de les Àmfores* reaching the interior of the gallery of the *Moraguesi Typhlocirolana,* the richest archaeological area (Gràcia et al. 2001) (Fig. 2).

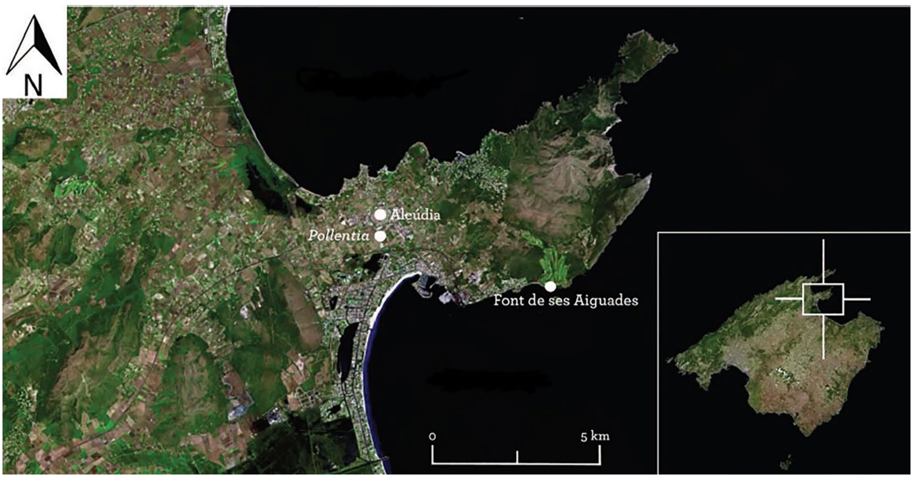


**Fig. 1** Geographical map with the location of the Font de Ses Aiguades cave. Adapted from Colom and Járrega 2020

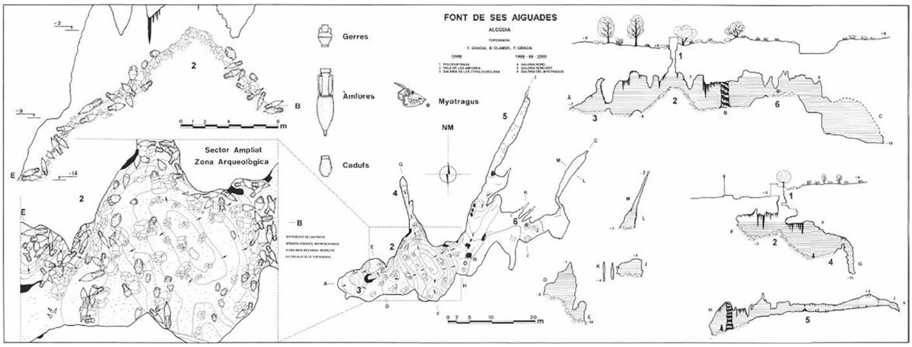


**Fig. 2** Topographic plan of the Font of Ses Aiguades cave (Gràcia et al. 2001)

## The Archaeological Site: the Font of Ses Aiguades Cave

The Font of Ses Aiguades is a cavity in which archaeological materials were indirectly deposited. The cave was not inhabited prior to its flooding. The cave was flooded at the end of the Pleistocene, while the first human arrival to the island is dated to the 3500 BCE (Ramis et al. 2002). The cave served as a water supply for the inhabitants of the island and for the navigators who anchored in the bay. The islet of Alcanada in front of the Font of Ses Aiguades cave, facilitated the recognition of the coast by sailors (Gómez 2018). During the Roman period, the cave had greater influx due to the proximity of Pollentia harbour (Giaime et al. 2017; Colom and Járrega 2020). Ses Aiguades served as a major water supply for the Mediterranean maritime network, its location and accessibility suggests it was an essential water point for sailors and merchants (Marlasca and López 2014).

At the end of the 1990s, the team of Group Nord Mallorca (GNM), part of the Balearic Federation of Speleology (FEB) directed by Dr. Francesc Gràcia, and the cave divers Bernat Clamor, Joan Josep Lagverne, Josep Vega, Antoni Merino, and Guillem Mulet, extracted a total of 189 pieces of pottery from the cave. There are parallels between the amphoras found in the cave and those that were transported in Mediterranean shipping. These amphoras originate from the pottery workshops of Hispania Tarragona, specifically in the area of pre-Roman Iberian Laietani settlements (Gràcia et al. 2001; Colom and Járrega 2020; Fumás 2023) (Fig. 3).

Most of the recovered Roman amphorae were reused wine vessels, which are dated to approximately the second and first centuries BCE, (e.g., Dressel 2–4: Amphora 10, Amphora 21; Dressel bética 7–11: Amphora 24; and Dressel-1 italic type of the first century BCE with flat handles) (Gràcia et al. 2001; Gràcia 2015) (Fig. 3).

Many ceramic remains were extracted in the 1999 excavation campaign, but some remain buried and submerged inside the cave. A problem emerges while attempting to make a rigorous classification of them, as ceramics of several periods appear mixed, which complicates the historical contextualization of the site (Colom and Járrega 2018) (Fig. 3).

There remains a need to complement the database made by Gràcia (2001) (Fig. 4) by producing a scaled and oriented photogrammetric model that would allow for georeferencing the pieces already found in previous excavation campaigns, and to verify the existence of preserved ceramic remains, allowing for the contextualization of the site.

Fig. 3 Ceramics from the extraction campaign of 1999 are preserved in the Museum of Mallorca (Footage courtesy of the Swiss TV documentary SRF1)

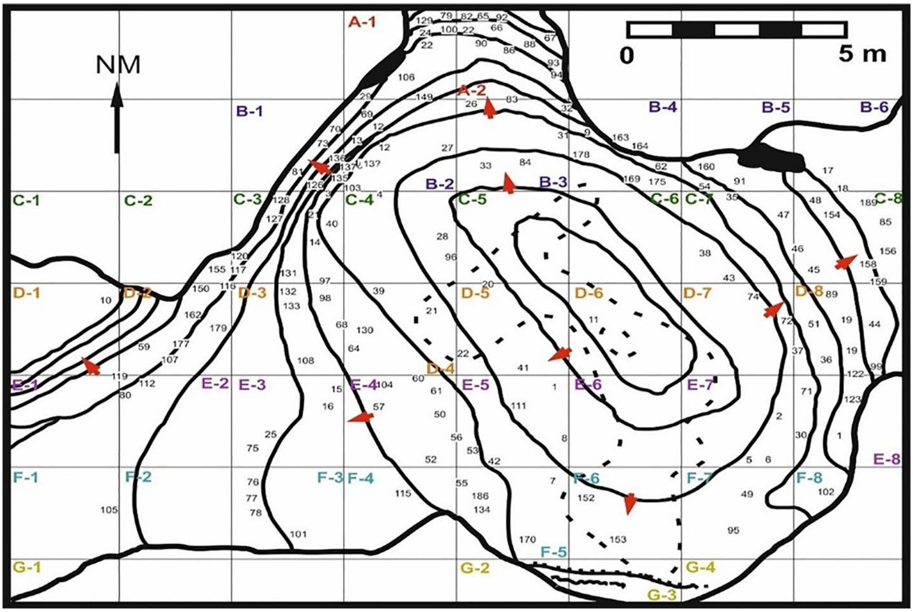


Fig. 4 Plan of the the Sala de les Àmfores (carried out in 1999) on a grid. The black lines indicate the bathymetry in meters while the red arrows indicate the orientation of the slope of the cone with the location of the extracted pieces (Modification A. Talavera) (Gràcia et al. 2001) (Color figure online)

## Materials and Methods

To obtain a georeferenced three-dimensional model, four different methods were applied following a specific workflow: preliminary underwater topography calculation, installation of an underwater datum point, underwater photogrammetry, and manual calculation and location of target ceramics.

### Preliminary Underwater Topography

The preliminary topographical recording of the cave was carried out in 1999 by the speleological research team Group Nord Mallorca (GNM), headed by Gràcia (2015) (Fig. 4) to produce a map with a basic presentation of the cave geometry. During this project some underwater sections were thoroughly explored by installing a guide line, numbered every 5 m. In other more complex or sensitive areas, such as the dejection cone in the *Sala de les Àmfores* and *the Myotragus Gallery*, buoys anchored along the guideline were used to record from a distance.

Following this preliminary work we produced an approximate location, depth, and typology of the ceramic collection (Fig. 4), as well as created a virtual survey grid to spatially connect the artifacts previously extracted and those remaining in situ. Respecting the topography recorded by Gràcia in 1999, we observed a mound where the considerable number of ceramic fragments increased as the depth increased. We designed a photogrammetric campaign to address the less-detailed areas recorded in the earlier project by georeferencing the submerged ceramic remains in situ, as well as combining classical terrestrial topography techniques, to obtain a georeferenced three-dimensional model of the site with a high level of detail to allow for analysis of each of the ceramics recorded.

### Installation of an Absolute Underwater Datum Point

To obtain a high-resolution recording of the artifacts' context it was necessary to install a datum point with known coordinates in an accepted reference system within the underwater cave system. As mentioned above, Global Positioning System (GPS) technology or other geolocation methods cannot operate due to the lack of signal in confined environments (Huber 2009, 2014; Fumás 2022b). The field campaign aimed to collect georeferenced coordinates of a series of vertices surrounding the entrance to the cave to be used as fixed points for the subsequent calculation of the network of total vertices to the end point of the polygonal inside the cave (Fig. 5).

To do this, a Real Time Kinetic (RTK) survey was conducted using Differential Global Positioning Systems (DGPS) and a Leica model GS16 topographic total station with an angular precision of 1 s sexagesimal (1'') and an accuracy in the measurement of distances of 1 mm and 1.5 ppm (parts per million). Thus, it was possible to obtain the real-time positioning service and Global Navigation Satellite System (GNSS) differential, connecting with the National Geodesic Network of Reference of Permanent Stations (ERGNSS) provided by the National Geographic Institute (IGN) and through a VRS solution (Virtual Reference Stations). The precision of the GPS instrument is approximately 2 cm (cm).

A total of two datum points were was obtained: Absolute Datum Point 1 (ADP1) in a terrestrial environment, and Absolute Datum Point 2 (ADP2) of the underwater environment.

ADP1: The vertical entrance, which gives access to the cave, made it possible to measure the first point on the hook of a cabin beam. This point allows for the joining of

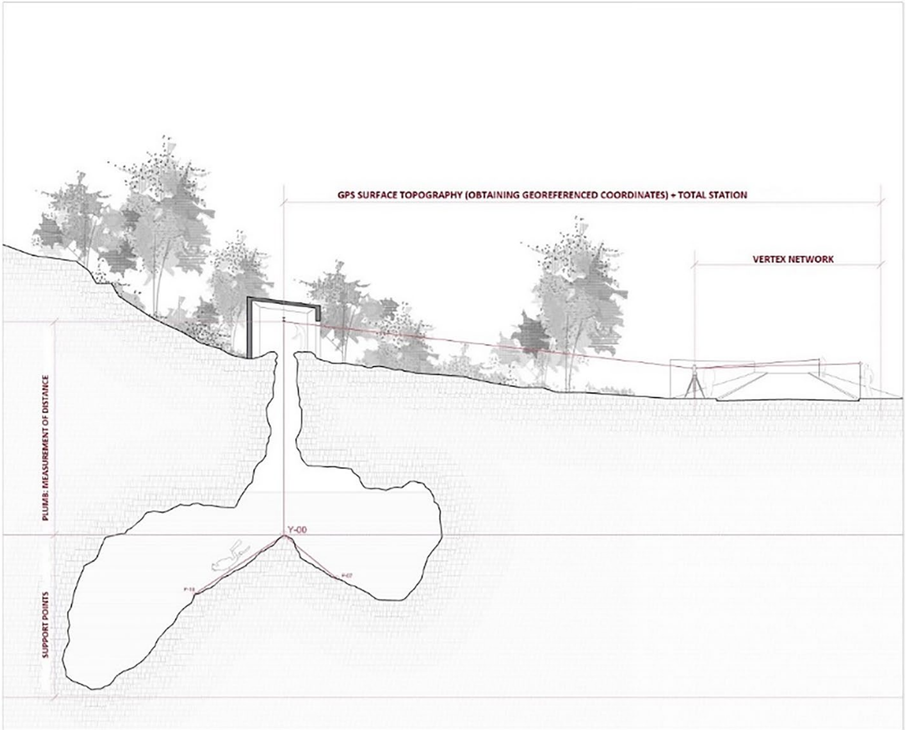


**Fig. 5** Schematic showing the topographic methodology used to obtain the control ADP1 corresponding to the upper vertex of the submerged archaeological cone of the Font de Ses Aiguades cave (ADP2) (Author: Pablo Cantuel)

the observations from the terrestrial area to the submerged archaeological site (Fig. 5). To obtain the georeferenced coordinates of the hook point, which indicates the entrance to the cave, a topographic network of vertices with GPS technology was measured from the outside. This terrestrial point was collected at UTM 31N, X: 514,132.708, Y: 4,409,979.195 (Fig. 6a).

ADP2: At the highest part of the well and 11.62 m (m) from the top of the submerged cone, a steel nail was installed to mark one point of the network in the confined and submerged space. To define that point, a plumb line was dropped from the hook of the cabin. Taking into account the theory of bounded planes (Navarro 2020), the point of the hook and the point at the top of the site have the same georeferenced coordinates, planimetrically speaking.

The third coordinate (Z), the distance between the apex of the submerged cone and the hook, was measured with a measuring tape. Then that distance was subtracted to the orthometric altitude of the hook point. This submerged point was collected at UTM 31N, X: 514,132.708, Y: 4,409,979.195, H: -2,332 (Fig. 5, 6b).

The combination of terrestrial topographic techniques and plumb line measurements enables us to obtain an identifiable point with known and georeferenced coordinates within the confined and submerged space. For recording we chose the ETS89 coordinate

Fig. 6 Images of topographic measurement collection. a) Method of collection of exterior points using total station model Leica TS16. b) Method of collecting underwater measurements from the hook to the top of the submerged cone by means of a plumb line

system and for the cartographic projection the UTM31 spindle corresponding to the Balearic Islands.

## Photogrammetry

Photogrammetry of the Font of Ses Aiguades cave was performed with a Canon EOS 77D camera (camera with 24MP APS-C sensor) with Easydive housing, and Sigma brand 10–18 mm (mm) fisheye lens (Fig. 7a, d). The APS-C sensor had a crop factor of 1.6 relative to a full-frame camera, so the 10-mm lens was equivalent to a full-frame 16-mm. Artificial light was necessary for conducting the photogrammetry within the darkness of the cave. A pair of Easydive Revolution 15,000 video lights (15,000 lumens, 160º beam angle and 5200 K color temperature) and a pair of Inon Z330 strobe lights were used to illuminate the cave.

Agisoft Metashape Professional software was used to produce photogrammetry maps. The coordinates of the pixels were transformed to coordinates in millimeters referring to a Cartesian system. Once the internal orientation was obtained, the relative orientation was carried out, which allowed us to produce geometrically related images with a common coverage (by coplanarity of homologous points) in photographs. In addition, Agisoft Metashape Professional was used to create an orthoimage in the XY plane. Lastly, we used ArcGIS software to overlay the model with contour lines and a north–south grid.

Once the photogrammetry model was generated, it was necessary to perform the absolute orientation and connect the underwater points with the national datum point. To carry out this process it was necessary to know the coordinates of a series of support points in both systems (local system and global system) and with them to apply a transformation of coordinates. These points had to be obtained underwater with coordinates referring to the chosen coordinate system (Quirós 2014) (Table 02). In our case, the ETRS-89 coordinate system and the UTM cartographic projection for use 31 were chosen, because it is a global reference system and the official system for the Spanish territory, that is, the most widespread in the national territory.

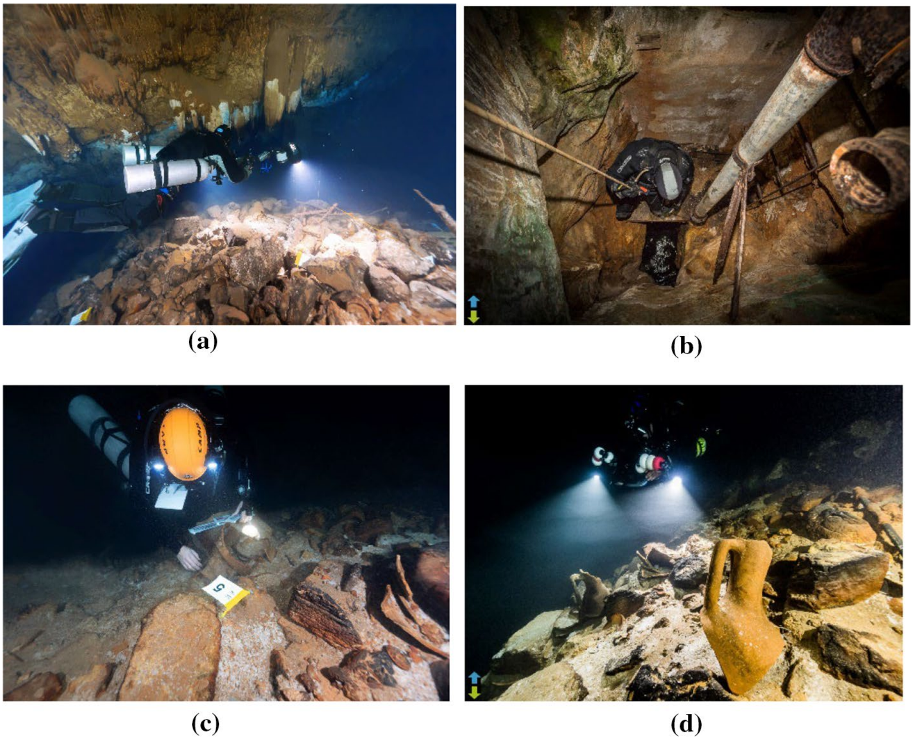


**Fig. 7** **a** The cusp of the submerged dejection cone (Photo M.A. Perelló) **b** Archaeologist Manel Fumás descending through the vertical access to the cave (Photo F. Huber) **c** Underwater labeling of artifacts (Photo. M.A. Perelló) **d** Submerged amphorae on the sides of the depositional cone (Photo F. Huber)

The Agisoft Metashape Professional software offered us the X, Y, Z coordinates in the image system for each point where each of the archaeological artifacts was located, but the three datum points should be georeferenced in the model.

### Manual Measurement and Trigonometric Registration of Ceramics

Manual measurements and trigonometric calculations were also used to locate specific archaeological remains ($n=10$) (identified with numbered labels, Fig. 7c). A flexometer, compass, and waterproof notebook were used to measure and record the artifacts. To make the calculations, the hypotenuse (Fig. 8, side C) was measured from ADP2 or Point Zero (Fig. 8 P.0) located at the apex of the submerged cone to the archaeological remains called Point X (Fig. 8, P.X). Finally, the depth of the water was calculated using a diving manometer (Fig. 8, side A).

## Results

The result obtained from this complex technical methodology was a complete scaled and oriented three-dimensional model, in which each of the ceramic remains inside the cave can be located, measured, and studied (Fig. 9).

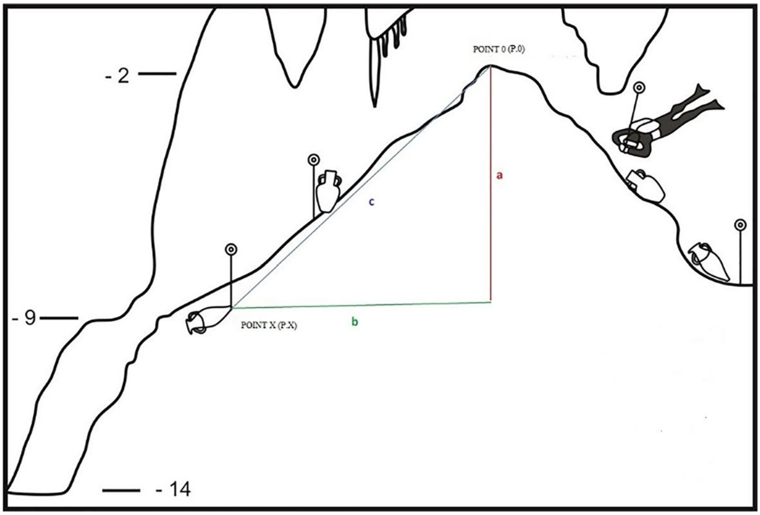


**Fig. 8** Schematic diagram of manual measurements taken to calculate position of archaeological materials. Measurements calculated with the equation: $\mathbf{b} = \sqrt{\mathbf{c}^2 - \mathbf{a}^2} = \mathbf{DH}_{\mathbf{A}}^{\mathbf{B}}$ (Author; Antonio J. Talavera)

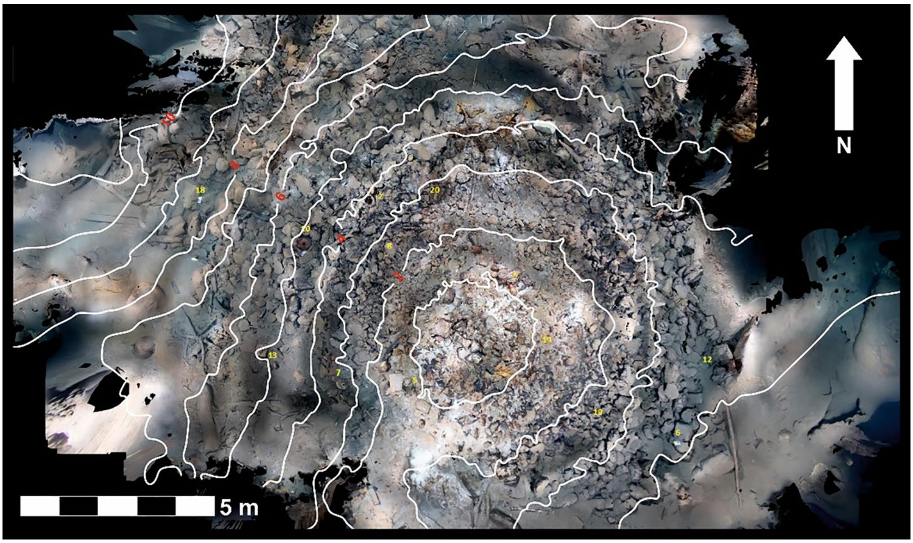


**Fig. 9** Photogrammetric model of the study area, in which the contour lines are indicated in meters, with scale and orientation. Numbers in yellow indicate the position of the registered and georeferenced archaeological remains (Author; John Kendall)

## GPS Data

The standard geopositioning of the photogrammetric model was obtained by giving a value of 0.00 to the coordinate of the vertex of the submerged mountain (Fig. 8, Point 0), which generated a series of local coordinates that, in turn, were used to calculate the geopositioning (X, Y, Z) of the ceramic pieces documented with respect to Point 0. After obtaining these primary local coordinates, we introduced the terrestrial topographic coordinate, obtained by differential GPS of the vertical of the well (X, Y, Z), in the ETRS89 and UTM31 systems, recalculating the model and providing the final real coordinates of the geopositioning of each of the pieces documented with tags during the dive (Table 1).

Table 1 lists the georeferenced coordinates and the precisions of the points that make up the network of vertices, allowing us to obtain the coordinates of the point in the submerged deposit (ADP2), here referred to as Point 0 (Fig. 8, P.0.).

## Photogrammetry

A 3D photogrammetric model was produced by recording the orientation and scale of the submerged deposit. For this, twenty labels were used to serve as photogrammetric targets to mark the most important areas of the site for later viewing.

Additionally, the photogrammetric software allowed us to plot the different contour lines, in this case the measured depth in meters, based on the data entered for Point 0. In doing so, we increased knowledge about the reservoir as a whole and it allowed us to compare our manual measurement of Z (depth) with the H obtained by the program and contrasted with the manual measurement calculations (Fig. 9 and Table 2).

## Manual Measurement

Using the Pythagorean theorem ($\boldsymbol{b} = \sqrt{\boldsymbol{c}^2 - \boldsymbol{a}^2} = \boldsymbol{DH_A^B}$), we were able to calculate the length of side B, meaning the horizontal distance between A and B ($\boldsymbol{DH_A^B}$)(Fig. 8).

The sine ( $\boldsymbol{X_B} = \boldsymbol{X_A} + \boldsymbol{DH_A^B} * \sin \boldsymbol{\sigma_A^B}$) and cosine theorem ($\boldsymbol{y_B} = \boldsymbol{y_A} + \boldsymbol{DH_A^B} * \cos \boldsymbol{\sigma_A^B}$) were used to transform the polar coordinates into Cartesian coordinates (*X* and *Y*). A total of ten pottery sherds were identified and used as control points. Finally, the *Z* coordinate was calculated by subtracting the difference between the artifact or Point *X* (P.X) and ADP2 or Point 0 (P.0) ($\boldsymbol{Z_B} = \boldsymbol{Z_A} + \boldsymbol{\Delta Z_A^B}$) (see Fig. 8 for locations of P.X numbered in yellow) (Table 3).

**Table 1** Table with the coordinates and precisions o/the /ive points taken with GPS equipment plus a point taken with total topographic station, as well as the zero point at the top o/the site (Author; Pablo Cantuel)

| Base coordinates (ETRS 89, UTM 31) | | | | | Precisions | | Methodology |
|---|---|---|---|---|---|---|---|
| I.D.POINTS | *X* (m) | *Y* (m) | *H* (m) | *Px* (m) | *Py* (m) | *Ph* (m) | |
| 1000 | 514,138,919 | 4,409,968,721 | 7,02 | 0,004 | 0,007 | 0,004 | GPS |
| 1001 | 514,151,708 | 4,409,967,604 | 7,605 | 0,008 | 0,008 | 0,009 | GPS |
| 1002 | 514,144,201 | 4,409,961,155 | 6,96 | 0,011 | 0,005 | 0,005 | GPS |
| 1003 | 514,148,074 | 4,409,975,772 | 7,854 | 0,002 | 0,002 | 0,012 | GPS |
| 1004 | 514,132,132 | 4,409,954,699 | 6,122 | 0,007 | 0,014 | 0,014 | GPS |
| 5000 | 514,132,708 | 4,409,979,195 | 9,288 | 0,021 | 0,022 | 0,027 | CLASSIC |
| POINT 0 | 514,132,708 | 4,409,979,195 | -2,332 | 0,021 | 0,022 | 0,077 | CLASSIC |

**Table 2** Table with the /inal local and global coordinates obtained by the photogrammetric program Agiso/t Metashape Pro/essional (Author; Pablo Cantuel)

| | *X* | *Y* | *Z* | *X*(m) | *Y*(m) | *H*(m) |
|---|---|---|---|---|---|---|
| Reference | 0,000 | 0,000 | 0,000 | 514,132,708 | 4,409,979,195 | 0,338 |
| Item 0 | – 0,560 | 0,315 | – 2,676 | 514,132,148 | 4,409,979,510 | – 2,338 |
| Item 2 | – 2,480 | 2,897 | – 5,957 | 514,130,228 | 4,409,982,092 | – 5,619 |
| Item 5 | – 1,394 | – 1,102 | – 3,738 | 514,131,314 | 4,409,978,093 | – 3,400 |
| Item 6 | 5,678 | – 2,149 | – 5,640 | 514,138,386 | 4,409,977,046 | – 5,302 |
| Item 7 | – 2,632 | – 1,549 | – 5,249 | 514,130,076 | 4,409,977,646 | – 4,911 |
| Item 8 | – 2,369 | 1,037 | – 4,877 | 514,130,339 | 4,409,980,232 | – 4,539 |
| Item 9 | 1,205 | 1,490 | – 3,207 | 514,133,913 | 4,409,980,685 | – 2,869 |
| Item 10 | – 3,695 | 1,173 | – 6,524 | 514,129,013 | 4,409,980,368 | – 6,186 |
| Item 12 | 6,173 | 0,043 | – 5,891 | 514,138,881 | 4,409,979,238 | – 5,553 |
| Item 13 | – 4,007 | – 1,079 | – 6,727 | 514,128,701 | 4,409,978,116 | – 6,389 |
| Item 17 | 4,884 | – 2,531 | – 5,433 | 514,137,592 | 4,409,976,664 | – 5,095 |
| Item 18 | – 5,763 | 2,502 | – 10,116 | 514,126,945 | 4,409,981,697 | – 9,778 |
| Item 19 | 3,708 | – 1,857 | – 4,335 | 514,136,416 | 4,409,977,338 | – 3,997 |
| Item 20 | – 0,740 | 3,657 | – 5,143 | 514,131,968 | 4,409,982,852 | – 4,805 |

**Table 3** Trigonometric calculation made to determine the length in meters of side B necessary for the planimetric geopositioning (X,Y,Z) of the submerged pieces of the Font of Ses Aiguades cave (Author; Manuel J. Fumds)

| Number Piece | Depth (m) | Depth (side A) | Length (hypotenuse) | Azimuth | Azimuth correction | Calculation(side B) |
|---|---|---|---|---|---|---|
| 2 | 5,1 | 3,1 | 5,2 | 80 | 260 | 4,174,925,149 |
| 5 | 2,8 | 0,8 | 1,7 | 30 | 210 | 1,5 |
| 7 | 4,3 | 2,3 | 3,7 | 30 | 210 | 2,898,275,349 |
| 8 | 4,3 | 2,3 | 4,2 | 140 | 320 | 3,514,256,678 |
| 10 | 5,6 | 3,6 | 5,6 | 90 | 270 | 4,289,522,118 |
| 12 | 6,1 | 4,1 | 7,6 | 260 | 80 | 6,399,218,702 |
| 14 | 4 | 2 | 3,1 | 270 | 90 | 2,368,543,856 |
| 15 | 2,9 | 0,9 | 1,7 | 160 | 340 | 1,44,222,051 |
| 19 | 4,5 | 2,5 | 4,2 | 280 | 100 | 3,374,907,406 |
| 20 | 4,7 | 2,7 | 5,1 | 170 | 350 | 4,326,661,531 |

## Discussion

The results of this investigation highlight the complexity of underwater prospecting in an almost exhausted and plundered deposit, since the remaining archaeological artifacts are only found in a significant percentage in the lower and deeper parts of the cone. The great difficulty in creating a geodatabase of the different ceramic remains found in the Font of Ses Aiguades cave made it necessary to study the record of each of the pieces inventoried in the museum of Mallorca. Additionally, the meticulous observation of the planimetry obtained by Gràcia (2001), the drafting of two catalogs and interpretation reports of the site, combined with the important academic and public dissemination of details regarding the historical and heritage value of the site complemented this database (Torres and Delgado 2009).

A total of twenty-seven new objects could be fully documented using the three-dimensional model during the fieldwork campaign in 2020. However, multiple pottery sherds and other objects were found in the cavity that require further work. We found, among the georeferenced and inventoried objects in our study, ceramics of three historical periods: Roman, Islamic, and modern. These data corroborate the conclusions of the 1998 expedition.

The extraction of numerous artifacts in the 1998 field season left few classifiable archaeological objects in situ on the site surface, although it is likely that under the tons of submerged rockfill mixed with ceramic fragments in the cone and under the silty sediments in the deeper parts of the cave there are hundreds of additional fragments to study and catalog that must be properly collected using standardized archaeological methods.

## Archaeological Novelty

After comparing the manual topography carried out in 1998 by the Gràcia team (Gràcia et al. 2001), and the 3D model created in our study (Figs. 4 and 9), we observed notable differences in the geopositioning of the archaeological materials.

The 3D model allows us to inventory the current archaeological remains and compare their real locations with those indicated in the 1998 reports. The difference between manual topography and our 3D photogrammetric model differs significantly, sometimes to the extent of inhibiting the completion of the deposit database due to the difference in data obtained.

We found the geoposition of the submerged artifacts to be in reverse chronology, opposed to what is expected with the oldest material located below the most modern. This leads us to suggest that the archaeological site was altered, probably at the end of the 1950s when a large quantity of stones fell into the well due to the construction of a quarry. In addition, the extraction of archaeological material in 1998 also irreversibly modified the site, altering the original location of the archaeological artifacts (Molina De Dios 1995). Now, using the 3D model created, it will be possible to monitor the submerged deposit and control future looting.

Additionally, our 3D model will be used for identifying and geopositioning Roman amphorae, Islamic ceramics, and Mallorcan pitchers. Water was extracted from the cave of the Font of Ses Aiguades from the second century BCE to the twentieth century CE for different uses and with periods of intensive extraction. There is a constant use of its waters from approximately 30 BCE to 70 CE, and although its use surely continued in the following centuries, among the materials analyzed in this study, only Byzantine production amphoras were found between the sixth and eighth centuries CE.

## Propose Methodology

When considering georeferencing in an underwater context, the percentage of precision will depend directly on the acceptable topographic tolerance, since a high tolerance will lower the reliability and specificity of the model. In our case, knowing the coordinate of Point 0 (P.0.) within a centimeter allowed us to supply the photogrammetric software a concrete reference point, which was used to extrapolate specific coordinates of the ceramic dispersion. In doing so we were able to generate a database that successfully enumerates, orders, and classifies the archaeological remains.

However, the precision necessary to obtain georeferenced coordinate points in an underwater and confined environment varies depending on certain physical aspects such as the geometry of the cave and the distance between the site and the outside. Undoubtedly, photogrammetry allows for methodological rigor, saving considerable time and expense, while obtaining defined action protocols, and real data acquisition (Drap et al. 2013; Balletti et al. 2015; Yamafune 2016). The problem arises when, although a fully scaled and oriented model may exist, its specific georeferencing is unknown because a correct topographic Point 0 is missing (Fumás 2023).

The economic cost of photogrammetric techniques in the study of submerged cavities is often prohibitively expensive due to the technical and human resources necessary to obtain results (Nocerino et al. 2019). Until recently, finding an exact location within a submerged cavity with little or no visibility was a complex task that required repeating the dive of the diver who had previously worked in that location. However, new navigation consoles, such as the ENC3 of SEACRAFT (https://seacraft.eu/products/navigation-console/enc3/#full-set-dedicated-to-seacraft-scooters), can be used to navigate in a cave to exact coordinates. Thus, information can be shared with other cave divers, which guarantees the continuity of the prospecting work without the need to have the original divers of the exploration. This is useful if the study area is far from the mouth of the underwater cave, especially if the dimensions of the cavity are important or if the particular area is far from the guide line (Fumás 2022a).

## Comparison of the Results Between Both Techniques

When it comes to comparing the results between the coordinates obtained by a photogrammetric program and by trigonometric calculations from manual measurement, it is important to weigh the pros and cons. It is logical to think that the photogrammetric technique will always be more exact and objective, since the intrinsic algorithms of the program allow an infinitesimal calculation of the data obtained. Therefore, we find that the manual method is superior purely for economic reasons as it does not have any other added advantage. Photogrammetry is faster, more efficient, and safer, and reduces immersion time and exponentially increases the chances of success.

Logically, the need to find a cheaper alternative method led the project to opt for manual measurements, knowing these could be verified with an empirical method such as photogrammetry. In our case, we found the manual results were highly accurate after executing the Pythagorean trigonometric formula to obtain side B and compare the results. We were able to verify that the percentage of error or difference between both readings was minimal. In our case, the percentage of error between both measurement methods, verified with the QGIS software in a planimetric context without taking H or Z into account, was 2.1%. From our point of view, this is a completely acceptable error if we understand the great technical difficulty we face when trying to take underwater measurements in confined environments and with low visibility, while overcoming physical challenges such as maintaining tension of the tape measure. In addition, the positioning error of Point 0 (P.0.) can generate a cumulative error in the measurements. Finally, we assert that there will always be a subjective factor in manual measurement, assuming an unknown topographic tolerance if it

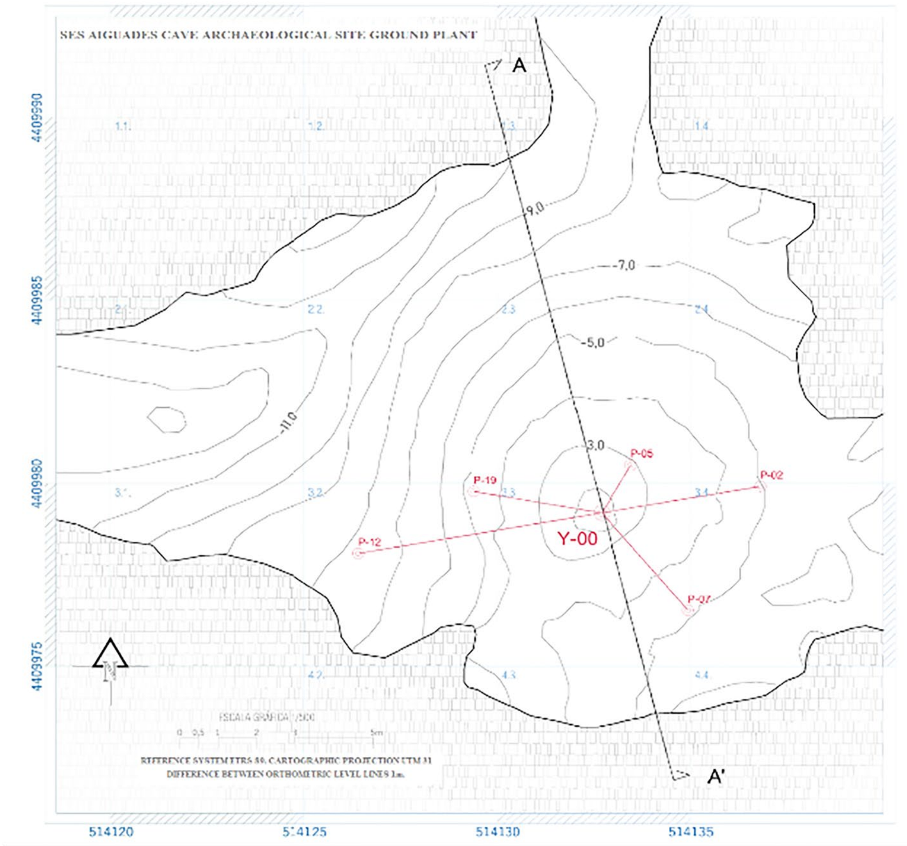


**Fig. 10** Schematic demonstrating the method used in obtaining rigorous control points through the use of wire mapping with the MNEMO device (Author; Pablo Cantuel)

is not compared with another type of measurement or calculation method like thread reader MNEMO (Kister 2017; Fumás 2022a, 2023)(Fig. 10).

## Conclusion

The use of registration techniques and manual georeferencing combined with photogrammetry exponentially improved the planimetry of the site (Fig. 3). When comparing results of the accuracy between the coordinates obtained by photogrammetric geopositioning versus manual calculation it must be understood that (1) the photogrammetric technique will always be more precise and rigorous, (2) only by obtaining rigorously recorded coordinates such as through photogrammetry will we be able to validate a work protocol, and (3) a professional technical and human team, viable budget, and rigorous security standards are necessary.

The importance of georeferencing applied to the study of submerged archaeological cave sites ranges from obtaining results regarding their internal topography to knowledge of their spatial context, whether local or global. This opens the possibility to compare cartographies or spatial data from different periods, making it easier to monitor the site and guard against looting or other destructive activities.

The results obtained here allow the generation of an archaeological action protocol that can be used both in archeology and in cave rescue. This study has implications for the continued study of the Font of Ses Aiguades through the data collected, as well as already proving archaeological contextualization of the entire submerged area (Fumás 2021, 2023).

**Author contributions** A.B.C.F. and H collaborated in the research and wrote or helped write this article. D. E. and G made all the graphic documentation of the article.

## Declarations

**Competing interests** The authors declare no competing interests.

## References


Abdelaziz M, Elsayed M (2019) Underwater photogrammetry digital surface model (DSM) of the submerged site of the ancient lighthouse near Qaitbay fort in Alexandria Egypt. Int Arch Photogr Remote Sensing Spatial Inform Sci 17(42):1–8

Arroyo-Cabrales et al (2015) Underwater archaeology and prehistory: the case of the cenotes in Mexico. World Herit Heads 5:54

Bahn P, Renfrew C (2008) Arqueología. Conceptos clave. Ediciones AKAL

Balletti C et al (2015) Photogrammetry in maritime and underwater archaeology: two marble wrecks from Sicily. Opt Arts Archit Archaeol V 9527:95270M. https://doi.org/10.1117/12.2184802

Barba-Meinecke H, Chávez AP, León GQ (2022) El Patrimonio cultural subacuático en la región de la Península de Yucatán México. Revista Contacto 1(3):258–292

Barba-Meinecke H (2020) Proyecto de salvamento arqueológico U Lu'umil Maaya Wiiniko'ob: Un análisis del sureste mesoamericano. Proyecto marco de salvamento arqueológico "Tren Maya" estados de Chiapas, Tabasco, Campeche, Yucatán y Quintana Roo. Informe de Actividades Arqueología Subacuática de la Coordenación Nacional de Arqueología. Instituto Nacional de Antropologia e Historia (INAH): 53

Bitelli G et al (2017) Historical photogrammetry and terrestrial laser scanning for the 3D virtual reconstruction of destroyed structures: a case study in Italy. Int Arch Photogramm Remote Sens Spat Inf Sci 42:113–119

Bowens A (2009) Underwater archaeology: the NAS guide to principles and practice, Second Edition, https://doi.org/10.1002/9781444302875

Campbell PB (2017) An introduction to archaeology in underwater caves. In: Campbell PB (ed) The archaeology in underwater caves. The Highfield Press, Southampton, pp 5–25

Campbell P B (2018) Future directions in underwater cave research. Archaeol Underw Caves-United Kingdom, 287Y293

Carandini A (1997) Historias en la tierra: manual de excavación arqueológica. Crítica, Barcelona

Chase ASZ, Chase DZ, Chase AF (2017) LiDAR for archaeological research and the study of historical landscapes. In: Geotechnologies and the environment, pp 89–100. https://doi.org/10.1007/978-3-319-50518-3_4

Chibunichev AG et al (2018) Photogrammetry for archaeology: collecting pieces together. Int Arch Photogramm Remote Sens Spat Inf Sci 42:235–240

Colom E, Járrega R (2020) Un excepcional conjunt d'àmfores laietanes trobades a la Font de Ses Aiguades (Alcúdia,Mallorca). Estudis sobre ceràmica i arqueologia de l'arquitectura. Homenatge al Dr. Alberto López Mullor. Barcelona., pp. 253–262

Colom E, Járrega R (2018) Un extraordinario e inédito caso de ánfora reparada. La Dressel 2–3 de la Font de ses Aiguades (Mallorca, Illes Balears). Boletín Ex Oicina Hispana 9:19–21

Davila F, Camacho E (2012) Georreferenciación de documentos cartográficos para la gestión de Archivos y Cartotecas. "Propuesta Metodológica". http://www.ign.es/web/resources/docs/IGNCnig/CTC-Iberc arto-V-Georreferenciacion.pdf

Domindo I, Burke H, Smith C (2007) Manual de Campo del Arqueólogo. Ariel, Barcelona

Domínguez M, Fernández Matallana F, Casaban Banaclocha JL (2013) Métodos de documentación arqueológica aplicados en arqueología subacuática: el modelo fotogramétrico y el fotomosaico del pecio fenicio Mazarrón-2 (Puerto de Mazarrón, Murcia). SAGVNTVM. Papeles Del Laboratorio De Arqueología De Valencia 44:99–109. https://doi.org/10.7203/sagvntvm.44.1683

Drap P et al (2013) Underwater photogrammetry for archaeology. What will be the next step? Int J Herit Digit Era 2(3):375–394. https://doi.org/10.1260/2047-4970.2.3.375

Fraser CS, Edmundson KL (2000) Design and implementation of a computational processing system for off-line digital close-range photogrammetry. ISPRS J Photogramm Remote Sens 55(2):94–104

Fumás M (2021) El Proyecto IASCM (Investigación Arqueológica Subacuática en las Cuevas de Mallorca). Una investigación multidisciplinar aplicada al campo de la arqueología subacuática prospectiva en cavidades kársticas sumergidas. Iberae Num 6:8–13

Fumás M (2022a) Métodos y técnicas de prospección topográfica aplicada a la arqueología en cavidades cársticas sumergidas con visibilidad cero. El Proyecto Falconera Revista Atlántica-Mediterránea 24:61–86

Fumás M (2022b) Métodos y técnicas de prospección topográfica aplicada a la arqueología subacuática en cavidades sumergidas : el estudio arqueo métrico de la Cueva del Sistema Sa Gleda – Camp des Pou ( Manacor -Mallorca- ). SPAL

Fumás M J (2023) Métodos y técnicas de prospección arqueológica en cavidades sumergidas. University of Cádiz

García D (2014) Análisis espacial de evidencia arqueológica sumergida: cenote Holtún de Chichén Itzá. Universidad Autónoma de Yucatan

Giaime M et al (2017) In search of Pollentia's southern harbour: Geoarchaeological evidence from the Bay of Alcúdia (Mallorca, Spain). Palaeogeogr Palaeoclimatol Palaeoecol 466:184–201. https://doi.org/10.1016/j.palaeo.2016.11.023

Gómez S (2018) The sacred Island of Venus Marina an ancient sacred reference for navigation in the Bay of Cádiz. Revista Atlántica-Mediterránea 20(2018):1–227

Gràcia F et al (2001) Notícia Preliminar del Jaciment Arqueològic de la Font de Ses Aiguades (Alcúdia, Mallorca). Endins Publicació D'espeleologia 24:59–74

Gràcia F (2015) Les cavitats Subaquàtiques de les Zones Costaneres del Llevant i Migjorn de Mallorca, TDX. Dissertation, Universitat de les Illes Balears. http://hdl.handle.net/10803/382836

Green J, Gainsford M (2003) Evaluation of underwater surveying techniques. Int J Naut Archaeol. https://doi.org/10.1016/j.ijna.2003.08.007

Hodges R (2001) Review of the corrupting sea: a study of mediterranean history, by Peregrine Horden, Nicholas Purcell. Int Hist Rev 23(2):377–379. http://www.jstor.org/stable/40108680

Huber F (2009) Investigaciones Arqueológicas Subacuáticas En Cenotes y Sistemas De Cuevas Inundadas De Yucatán : Un Proyecto De Cooperación Germano-Mexicano - Campaña 2009:22–28

Huber F (2014) Tauchgang in die Totenwelt : prospektions- und Dokumentationsmethoden Tauchgang in die Totenwelt. Mar pp. 366–393

Kister S (2017) MNEMO User guide v1.6, pp. 1–42

León C (2003) Metodología de la arqueología subacuática. Monte Buciero 9:109–125

Maarleveld T, Guérin U, Egger B (2001) Manual para actividades dirigidas al Patrimonio Cultural Subacuático: directrices para el Anexo de la Convención de la UNESCO de 2001. UNESCO

Maarleveld T, Guérin U, Egger B (2013) Manual para actividades dirigidas al Patrimonio Cultural Subacuático. UNESCO

Marlasca R, López J (2014) Aprovisionamiento de agua y culto en la prehistoria pitiusa. Treballs del Museu Arqueològic d'Eivissa i Formentera pp. 397–411

McCarthy J, Benjamin J (2014) Multi-image photogrammetry for underwater archaeological site recording: an accessible, diver-based approach. J Marit Archaeol 9(1):95–114

Ministerio de Cultura (2009) Libro Verde del Plan Nacional de Protección del Patrimonio Cultural Subacuático Español. Subdirección General de Publicaciones, Información y Documentación. España, Secretaría General Técnica

Molina De Dios R (1995) Líneas férreas industriales de las Baleares. 150 años de Ferrocarril en España. I Congreso de Historia Ferroviaria pp. 1–18

Moya J, Muñoz F J (2017) Fotogrametría de restos arqueológicos subacuáticos. El Modelo del Pecio Bou Ferrer. Actas de las II Jornadas de Museos y Colecciones Museográficas Permanentes de la Comunidad Valenciana. Nuevas tecnologías aplicadas a la gestión turística del patrimonio arqueológico

Moyes H, Montgomery S (2016) Mapping ritual landscapes using Lidar. Adv Archaeol Pract 4(3):249–267. https://doi.org/10.7183/2326-3768.4.3.249

Munar S, Sastre M A (2010) El portus de Pollentia. Resultats preliminars de la intervenció arqueològica al solar del carrer Corall, cantonada amb carrer Maristany (Port d'Alcúdia). VI Jornades d'Estudis Locals d'Alcúdia pp. 31–46

Navarro J M (2020) Resolución gráfica de explanaciones horizontales en el sistema de planos acotados. Universitat Poliècnica de València

Nocerino E et al (2018) Multi-camera system calibration of a low-cost remotely operated vehicle for underwater cave exploration. Int Arch Photogramm Remote Sens Spatial Inform Sci ISPRS Arch 42(1):329–337. https://doi.org/10.5194/isprs-archives-XLII-1-329-2018

Ogloblin I, Galili E, Shahack-Gross R (2021) Locating submerged prehistoric settlements: a new underwater survey method using water-jet coring and micro-geoarchaeological techniques. J Archaeol Sci 135:105480. https://doi.org/10.1016/j.jas.2021.105480

Pachas R (2009) El levantamiento topográfico: Uso del GPS y estación total. Academia 8(16):29–45. Disponible en: http://www.saber.ula.ve/bitstream/123456789/30397/1/articulo3.pdf

Paper (2009) Libro Verde del Plan Nacional de Protección del Patrimonio Cultural Subacuático Español. Secretaría General Técnica. Subdirección General de Publicaciones, Información y Documentación. Ministerio de Cultura. España

Quirós E (2014) Introducción a la Fotogrametría y Cartografía aplicadas a la Ingeniería Civil. Universida

Ramis D, Santandreu G (2011) Arqueologia de les cavernes de les Illes Balears. Monografies De La Societat D'historia Natural De Les Balears 17(August):317–332

Ramis D et al (2002) The chronology of the first settlement of the Balearic Islands. J Mediterr Archaeol 15(1):3–24. https://doi.org/10.1558/jmea.v15i1.3

Renfrew C, Bahn P (1993) Arqueología: Teorías, métodos y práctica (Vol. I), Madrid: Ediciones Akal. Recuperado el p 21

Rissolo D et al (2015) Novel application of 3D documentation techniques at a submerged Late Pleistocene cave site in Quintana Roo, Mexico. 2015 Digital Heritage pp. 181–182. https://doi.org/10.1109/DigitalHeritage.2015.7413868

Shahack-Gross R (2017) Archaeological formation theory and geoarchaeology: state-of-the-art in 2016. J Archaeol Sci 79:36–43

Vallicrosa G et al (2020) Sparus II AUV as a sensor suite for underwater archaeology: falconera cave experiments. In: 2020 IEEE/OES autonomous underwater vehicles symposium, AUV 2020:0–1. https://doi.org/10.1109/AUV50043.2020.9267935

Yamafune K (2016) Efficient and effective in situ Heritage management: using 3D photogrammetric models to document and assess a site's condition. https://doi.org/10.13140/RG.2.1.4529.8324

Zhukovsky MO, Kuznetsov VD, Olkhovsky SV (2013) Photogrammetric techniques for 3D underwater record of the antique time ship from Phanagoria. ISPRS Int Arch Photogramm Remote Sens Spatial Inform Sci 40:717–721



## Authors and Affiliations

**Manuel J. Fumás Soldevilla[1] · Pablo Cantuel González[2] · Francesc Gràcia Lladó[3] · John Kendall[4] · Florian Huber Wilhelm[5] · Antonio Jesús Talavera Montes[6] · Miguel Ángel Perelló Estelrich[7] · Pablo Fraile Fraile[6]**

✉ Manuel J. Fumás Soldevilla
manuel.fumassoldevilla@alum.uca.es; mjfumas@gmail.com

Pablo Cantuel González
topografia.pangea@gmail.com

Francesc Gràcia Lladó
xiscograciallado@gmail.com

John Kendall
john@gue.com

Florian Huber Wilhelm
f.huber@submaris.com

Antonio Jesús Talavera Montes
ajtalmon@gmail.com

Miguel Ángel Perelló Estelrich
mapesub@hotmail.com

Pablo Fraile Fraile
pabloff1995@hotmail.com

[1] Escuela Internacional de Doctorado en Estudios del Mar (EIDEMAR-UCA), Cádiz, Spain

[2] Topografía Pangea, Madrid, Spain

[3] Societat Espeleològica Balear (SEB), Palma, Spain

[4] Global Underwater Explorers (GUE), High Springs, USA

[5] Scientific Diving Operations (Submaris), Kiel, Germany

[6] Asociación Nacional de Arqueología Subacuática (SONARS), Madrid, Spain

[7] Explorextrem, Palma, Spain