



Investigating the Microarchaeological Record at Underwater Sites: Operating an On-Site Laboratory During the Antikythera Shipwreck Excavation

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Abstract

Underwater excavations require an immense amount of logistics and have inherent time limitations. Underwater challenges such as nitrogen toxicity, underwater color change, and dive time limits increase with working depths, affecting the interpretation of archaeological contexts. Thus, underwater excavations involve methods and approaches to extract the maximum information from small areas while providing a comprehensive understanding of the archaeological record. Here, we present the benefits of using an on-site laboratory comprising a microscope, binocular microscope, Fourier transform infrared spectrometer and blue light inspection device. Three case studies are presented, focusing on the identification of stratigraphic boundaries, as well as the preservation and identification of archaeological materials. The results show a complex stratigraphic sequence containing seven layers divided into four mineralogical units: (1) Calcite, (2) Calcite and aragonite, (3) Aragonite, and (4) Dolomite. Additionally, the use of an on-site laboratory is effective in preventing the misidentification of archaeological materials, which could affect the final interpretation of the archaeological site (e.g., glass, lead, bone), and enabling the identification of materials invisible to the naked eye, such as opaline phytoliths. In the case of the Antikythera shipwreck, the on-site laboratory facilitated the examination of stratigraphy and quality of the archaeological context while streamlining excavation practices and documentation. Furthermore, the on-site laboratory allowed for the assessment of material preservation and provide crucial insights to inform post-excavation treatments and analysis of artifacts.

Keywords Underwater archaeology · Nautical archaeology · Geoarchaeology · FTIR · Phytoliths

Introduction

Investigating macro and microscopic archaeological context is essential for obtaining a comprehensive understanding of archaeological sites. Large-scale features such as architectural elements, shipwreck remains, and a wide range of other artifacts or eco-facts, are

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part of the macroarchaeological record. On the other hand, the microarchaeological record reveals the archaeological remains that are not visible to the naked eye, such as anthropogenic micro-remains, ash pseudomorphs, phytoliths and dung spherulites (Cabanes 2020; Gur-Arieh and Shahack-Gross 2020), or changes in the molecular structure of artifacts (e.g., heated sediment, Berna et al. 2007). This invisible record can be traced within archaeological sites both on land and in marine environments (Ogloblin Ramirez et al. 2021; Shahack-Gross 2017). By integrating interpretation of macro and microfinds, a more holistic view of the archaeological site under study can be achieved. Complex anthropogenic and natural activities can be deciphered, including technological innovation, subsistence strategies, use of space, and long-term environmental impacts (Cereda et al. 2023; Edgeworth 2010; King et al. 1990; Shahack-Gross 2017; Shahack-Gross et al. 2005; Stein and Teltser 1989; Weiner 2010).

Typically, macroarchaeological records are examined and documented *in situ*, and data acquisition is carried out to facilitate the microarchaeological analysis and interpretation after completion of the fieldwork. However, on-site laboratories are becoming common in modern terrestrial archaeological excavations, providing immediate access to analytical tools and expediting the processing, analysis, and interpretation of microarchaeological records (Frahm and Doonan 2013; Hodder 2017; Shahack-Gross 2017; Weiner 2010). As a result, a synergetic multidisciplinary team can pose new questions and interpretations on a day-to-day basis while still in the field.

It has been shown that if analytical instrumentation and microarchaeological specialists are available on site, excavations can benefit from microarchaeological interpretations proposed while the fieldwork is in progress (Frahm and Doonan 2013; Hodder 2017; Shahack-Gross 2017; Weiner 2010, 261–262). We note multiple advantages of an on-site laboratory: (1) It allows for immediate integration of analysis results into the ongoing excavation, promoting a problem-solving approach that provides timely answers and refines research questions. By analyzing samples on site, research questions can be efficiently tested and adjusted, leading to a more effective selection of samples for off-site analysis. (2) Because excavation is a destructive process, the integration of real-time information helps adjust the excavation process according to the nature of the materials being exposed. By obtaining and analyzing samples interactively, the number of samples required for accurate mapping can be significantly reduced. (3) On-site laboratories are valuable for mapping feature boundaries, aiding in understanding site formation processes and stratigraphic complexities. (4) Collaboration between archaeologists who simultaneously interpret microscopic and macroscopic records enhances communication, team cohesion, and overall excavation quality.

It should be noted that on-site laboratories are suitable only for a preselected set of analyses, restricted by available instrumentation and the specialty of the employed scientific personnel. In addition, their use comes at an increased operational cost comparable to that of dedicated analytical facilities in specialized research institutions. Nonetheless, the use of on-site laboratories is increasingly preferred in modern terrestrial archaeology (Frahm and Doonan 2013; Hodder 2017; Shahack-Gross 2017; Weiner 2010).

On-Site Instrumentation for Underwater Archaeology

The application of on-site laboratory analysis in the field of underwater archaeology has been relatively limited thus far. While efforts have been made to develop instrumentation and techniques to enable *in situ* analysis, the use of on-site laboratories, similar to those

employed in terrestrial archaeology, has not been fully explored in the field of underwater archaeology.

Previous methodological work has been performed to study underwater sediment profiles by analyzing in situ pH, sulfide, and redox potential (Gregory 2020). Furthermore, X-ray fluorescence (XRF) technology has been used for in situ analysis in marine archaeology and these instruments are capable of determining the elemental composition of various materials, making them valuable tools for studying archaeological and geological formations. Efforts have been made to adapt XRF devices for underwater use, enabling divers to conduct real-time elemental analysis on submerged objects and features (Sengang et al. 2014; Wogman and Nielson 1980). Additionally, the incorporation of XRF technology into remotely operated vehicles (ROVs) offers the potential for more efficient and precise underwater analysis (Breen et al. 2011). Similarly, laser-induced breakdown spectroscopy (LIBS) has been used to analyze the elemental composition of aqueous solutions and submerged solids for environmental and archaeological studies, providing quantitative chemical analysis (De Giacomo et al. 2007; Lazic et al. 2005, 2007; Matsumoto and Sakka 2021; Pešić 2014; Pichahchy et al. 1997). These techniques have provided marine archaeology with in situ methodologies, providing insight into the composition of submerged archaeological sites with detailed stratigraphic parameters while simultaneously describing their formation processes.

This study introduces the use of an on-site geoarchaeological laboratory, as it was used during the latest underwater excavation of the first century Before Current Era (BCE) Antikythera shipwreck, describing the preparation process, the challenges encountered, and the benefits. This paper presents specific case studies related to sediment characterization, the state of preservation of archaeological material, and the correct identification of such materials, which are common issues in shipwreck excavations. The correct identification of stratigraphic layers requires both field and laboratory data (Goldberg and Macphail 2006, 28). Generally, shipwreck stratigraphic units have been simply divided into two layers: aerobic layers (poor preservation) and anaerobic layers (good preservation) (e.g., Ward et al. 1999; O'Shea 2002). However, sedimentological analyses of shipwreck stratigraphic layers are rare. Our study aimed to examine the complex stratigraphic sequence at the Antikythera shipwreck via field and laboratory observations. The preservation of archaeological materials varies depending on their surrounding environment. However, the complete range of post-depositional processes affecting underwater archaeological sites is unknown, as is the full spectrum of materials that may be preserved (Bailey 2014; Shaha-Gross et al. Submitted). Our investigation aimed to characterize the state of preservation of the archaeological layers by analyzing the macro (e.g., shells, bone) and microscopic (e.g., phytoliths) records. Small fragments from picking can be easily confused, and secondary minerals can mask the interpretation. Thus, the on-site laboratory was used to avoid misidentification of materials and to recognize secondary processes affecting the site.

The Antikythera Shipwreck and the Documented Investigations

Environmental Setting

The remains of a Roman-era merchantman ship loaded with an unusual cargo of works of art was accidentally discovered in 1900 by sponge divers at a water depth between 40 and 50 m (m) off the Eastern coast of Antikythera Island in Greece (Fig. 1).

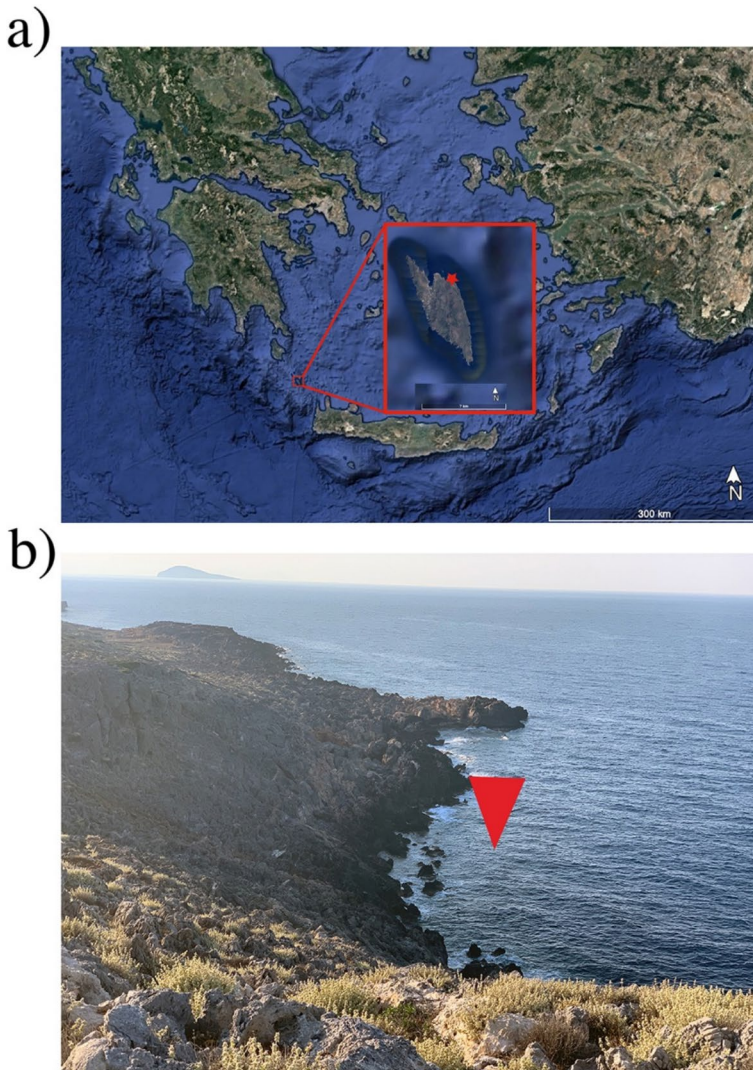


Fig. 1 a Satellite image of Greece indicating the location of the studied area with a red rectangle (image modified from Google Earth). b The environmental setting of the studied area is indicated with a red arrow. Note the proximity to the cliff, which is mainly composed of dolomite (photo by I. Ogloblin Ramirez)

The topography of this coastal region is dominated by rocky cliffs that descend steeply into the sea and are subject to erosion caused by rising sea levels and high-energy wave action. A visible horizontal mark that encircles the entire coast, a few meters above the water line, is indicative of a major geological uplifting event that took place during historical times (Pararas-Carayannis and Mader 2010; Pirazzoli et al. 1982, 1996; Stiros 2001, 2010). Underwater, the rocky slope in the shipwreck area is characterized by medium and large boulders, which are occasionally separated by pockets of loose sediments. The slope continues to a depth of approximately 52 m, where it levels out over a slightly tilted

50 m wide sand-filled plateau, oriented North–South. At 58 m in depth, a sharp drop-off descends to 80 m, where the seabed ultimately flattens to a gradually inclined sandy terrain (Williams et al. 2016).

Archaeological Excavations

Three main expeditions were carried out at the Antikythera shipwreck. In 1900, one of the first documented underwater archaeological operations started at Antikythera; this excavation was operated by the hard hat sponge divers who discovered the site, aided by the Hellenic Royal Navy, and supervised by Greek government officials (Svoronos 1903, 9–14).

Between November 1900 and September 1901, the sponge divers recovered a large assemblage of artifacts, among which were various pieces of marble and bronze works of art, luxury items including glassware and jewelry, pottery, furniture, and individual elements of the wooden ship. Human osseous remnants were also found. Among the findings from this Antikythera expedition is a sophisticated astronomical device capable of performing complex mathematical calculations (Svoronos 1903). No other similar device from this period exists. The object is the most precious artifact that was found at the shipwreck and is known worldwide as the “*Antikythera Mechanism*”.

During the mid 1950s, the Antikythera shipwreck drew the attention of the French sub-sea explorer Jacques-Yves Cousteau. Cousteau and his group were invited in 1976 by the Hellenic Republic to produce a documentary series on the unexplored underwater wonders of Greece. Under this framework, they worked at the Antikythera shipwreck. “*The Jacques Cousteau Odyssey*” series of four films was produced, including “*Diving for Roman Plunder*”, a narration on the underwater excavation of the Antikythera shipwreck. A photomosaic of the excavated area was created, various objects were discovered, and their locations were noted on a general area map. Artifacts recovered at that time include marble and bronze statuary pieces, pottery, few isolated parts of the ship’s wooden hull, currency, and human and animal skeletal remains (Dumas 1976; Kolonas 1976).

In 2012, the Ephorate of Underwater Antiquities of the Hellenic Ministry of Culture and Sports initiated the latest research program at the Antikythera shipwreck under the direction of Dr. Aggeliki Simosi. During 2012 and 2014, the status of the shipwreck was inspected via mixed gas technical diving, swath bathymetry, side scan sonar surveys, and simultaneous localization and mapping (SLAM) via an autonomous underwater vehicle (AUV) and surveys using an ROV. Underwater excavation began in 2015 using a diver-operated hydrolift setup. Important finds with characteristics similar to those previously recovered from the site, such as fragments of marble and bronze works of art, glassware, jewelry, wooden ship remains, and human osseous remains, were recovered (Williams et al. 2016). Since 2021, the program has continued under the Swiss School of Archaeology in Greece, under the codirection of Dr. Simosi and the professor of classical archaeology from the University of Geneva, Dr. Lorenz Baumer (Simosi et al. 2022).

The Shipwreck

The shipwreck event was dated to approximately 60 BCE based on numismatic evidence, with recent views suggesting pushing the dating a few decades later. This evidence suggests contact with the cities of Pergamum and Ephesus, and a variety of other goods (e.g., Syrian glass) indicate more interactions with the Eastern Mediterranean

coast. Overall, a westward journey of the ship can be assumed, possibly toward a major Roman port (Castrizio 2021; Tselekas 2012).

The dimensions of the Antikythera ship can only be estimated from the cumulative cargo volume and the size of the surviving ship remains, which are very few and in overall poor condition. All available data are indicative of a large vessel (Kaltsas et al. 2012; Svoronos 1903, 13).

Methods

Fieldwork

Between 2015 and 2021, various statuary fragments and other parts of the ship and its cargo were discovered underwater using geophysical methods (e.g., metal detection) and through excavation. A fragmented marble base (plinth) was also identified and documented in 2021 near the location of previous discoveries, below a large boulder. During 2022, an excavation aimed to expose a pristine section of the shipwreck site and assess the state of its preservation as well as to study the formation processes affecting it. Five 2 × 2 m squares, partially covered by natural boulders, were excavated at a depth of 42 m (Fig. 2a).

A detailed plan was formulated to recover the plinth by relocating three large boulders without damaging sensitive archaeological materials. A grid system was used for mapping, initially with cameras on an AUV and later with higher-resolution photogrammetry. The excavation area consisted of five squares: D129, D130, D131, E130, and B131 (Fig. 2b, c). Before the excavation began, archaeologists inspected the newly exposed area both visually and via a metal detector. The excavation area was regularly documented through photography, photogrammetry, and high-definition video. The operation was carried out over two seasons, in 2022 and 2023.

The divers utilized mixed gas diving techniques (Enriched Air Nitrox) with predetermined decompression profiles. Diving support vessels (M/V TYPHOON, M/V Poseidon and M/V Nikolas) and Rigid Inflatable Boats (RIBs) were used for lifting and other auxiliary purposes.

Sample Collection

The geoarchaeological sampling strategy aimed to answer a variety of different research questions. Bulk sediment samples were collected from the cross-sections of the excavation, which were assigned to specific stratigraphic layers and loci. A total of 22 bulk samples were collected within each stratigraphic layer to obtain information about possible horizontal and vertical changes while analyzing the preservation of anthropogenic materials and defining the boundaries and importance of each stratigraphic layer (Fig. 3). Furthermore, specific archaeological materials such as bone or shells were directly targeted to appreciate their state of preservation. Additionally, three control samples were collected outside the shipwreck area, at a distance of 50–100 m west of the last visible traces of wreckage (ANT-2023-32, ANT-2023-34, ANT-2023-35). One sample from the bedrock of the cliff was collected as a control sample (ANT-2023-12).

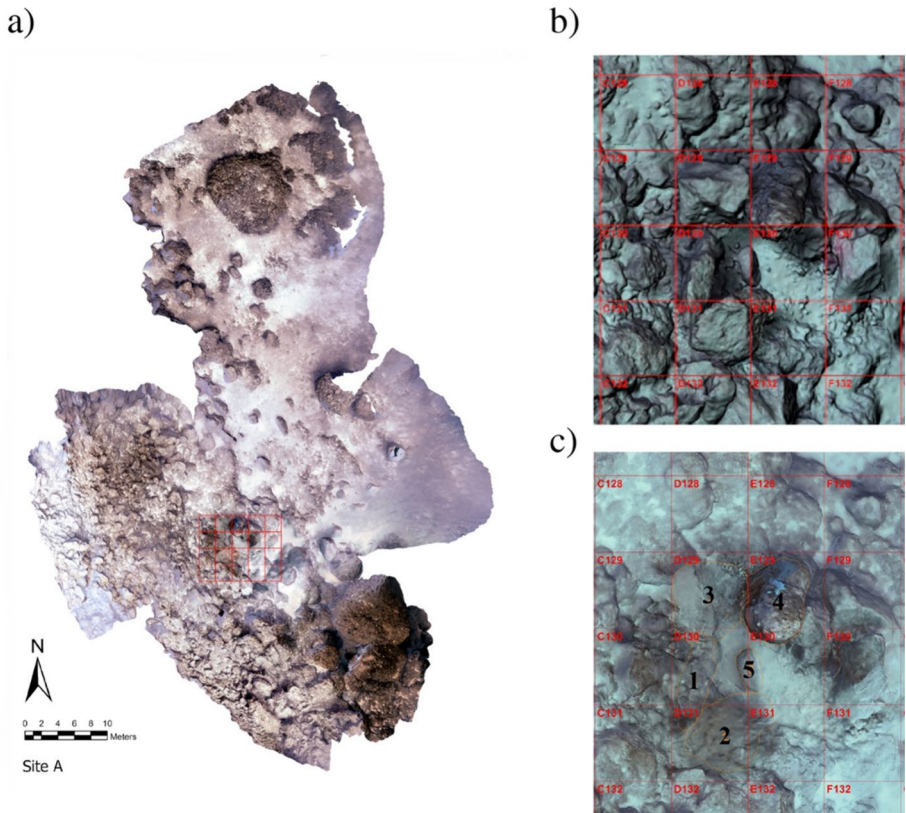


Fig. 2 **a** 3D photogrammetry model of Area A. Note the grid system oriented north to south by numbers and west to east with letters. The red grid indicates the excavated area during the 2022 and 2023 excavation seasons. **b** 3D photogrammetry model of the excavation area prior to the removal of large boulders in the Sq. D129, D130, and D131. **c** 3D photogrammetry model of the excavation area after the removal of boulders. The orange numbers indicate the boulders found in the excavation area. 1 to 3 were removed (**b** and **c** by E. Costa)

Field Analyses

A field laboratory facility was set up at Potamos on Antikythera, which included a binocular microscope (Stereo-Zoom Microscope Trinocular [mit Griff] Greenough), a microscope (polarized microscope trinocular Inf Plan), and Fourier Transform Infrared (FTIR) spectroscopy. Both microscopes were attached to a tablet camera (ODC 241). In addition, blue light inspection equipment was used to detect collagen in the bones (Fig. 4).

The sediment samples were air-dried for 24 h prior to further analysis. The mineralogical composition was detected using FTIR. Spectra were collected using the KBr method in transmission mode between 4000 and 400 cm (cm) using a Nicolet iS5 (Thermo Scientific) spectrometer (OMNIC 9.3 software). The samples were sieved through a 4 mm mesh and a 2 mm mesh to separate the pebbles and granules from the coarse sand. The sediment in each bag was inspected under a binocular. Then, collecting of small archaeological materials of about 2 mm (possibly pottery, marble, glass or bronze) was accomplished using binoculars. Further investigation of the sediments was performed by preparing grain-mount

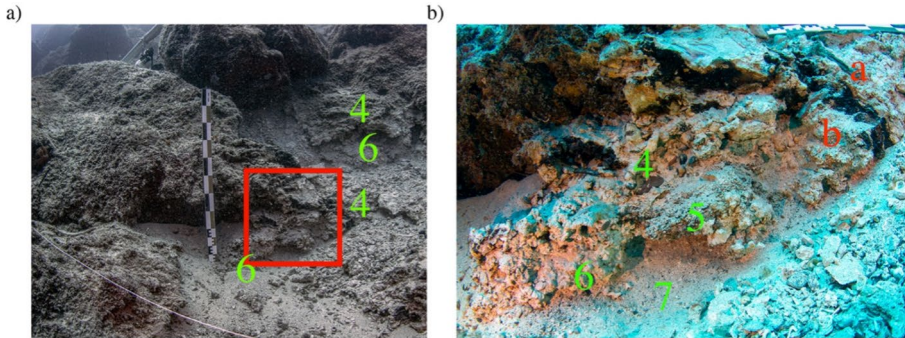


Fig. 3 Photographs of Sq. D131 looking west. **a** Cross-section of the site. The green numbers indicate the locations of the stratigraphic layers except for Layer 3. Note that the numbers 4 and 6 are repeated due to the steepness of the cliff. **b** Close-up of the stratigraphy (red rectangle in **a**) showing the distinction between Layers 4 and 5 due to the grain sizes and the contact between the partially cemented Layer 6 and the fine white sediment from Layer 7. The red letters indicate **a** treenails and **b** pottery. (Photograph by N. Gianoulakis)



Fig. 4 Instrumentation of the on-site laboratory from left to right: petrographic microscope, binocular microscope, FTIR spectrometer and an analytical balance

slides of sieved sediment using Entellan mounting medium and observing the sediment under a polarized microscope. Microscopic observations were performed to clarify the sediment composition and the variety of archaeological materials within the various layers. The microscopic description of the sediments was performed following Stoops (2003). Blue light was used to recognize the preservation of collagen on bone samples. It has been demonstrated that bone and tooth samples exposed to alternative light sources in the Ultra Violet and Blue Light Spectra (peaking at 365 nm/450 nm) react by exhibiting fluorescence

emissions in the yellow range (590 nm). This phenomenon is attributed to radiation-induced excitation of both organic (collagen) and inorganic (hydroxyapatite) elements of the bone, with the first presenting a more intense reaction than the second. Subsequently, bone and tooth samples with higher collagen concentrations are fluorescing stronger (Bachman and Ellis 1965; Mazel 2017; Miranda et al. 2017). Subsequently, the mineralogical preservation of samples was corroborated using FTIR (Asscher et al. 2011).

Case Studies

Stratigraphic Boundaries

The Antikythera excavation revealed a sequence of seven distinct stratigraphic layers, each providing valuable insights into the environmental and archaeological processes affecting the site (Fig. 3). These stratigraphic layers are described from top to bottom.

Layer 1 is composed of larger boulders covering the excavation area. The boulders are composed of dolomite, as indicated by the peaks at 2500, 1440, 880, and 730 cm^{-1} (Fig. 5a). Additional natural samples, collected from the bedrock in the cliff, exhibit the same mineralogical signal (Table 1).

Layer 2 (10–20 cm thick) consists of marine encrustations typically found above and below boulders. Living marine organisms (e.g., red algae, serpulid worms, and spirorbid worms) have been observed within Layer 2. This layer lacks archaeological materials. Mineralogically, Layer 2 is composed of aragonite, based on the peaks at 1476, 857, 713, 700, and 1083 cm^{-1} (Fig. 5b).

Layer 3 (10–40 cm thick) is composed of loose sediment trapped between boulders (Layer 1). The sediments consist of coarse calcareous sand and marine organisms, with some archaeological materials. Abundant angular pebbles and cobbles are found. Pottery sherds, small marble pieces and bronze nails were collected from this layer. The fine loose sediment in Layer 3 is composed of aragonite and calcite (2500, 1420, 875, and 712 cm^{-1}), as indicated by the FTIR analyses (Fig. 5c, Table 1).

Layer 4 (40–90 cm thick) is a lithified layer. This layer consists of lithified yellow sediment rich in archaeological materials, angular pebbles, and cobbles. Large marine organisms such as Murex shells have also been observed. Patchy coloration changes are commonly observed, likely resulting from contact with metallic objects such as bronze (green) or iron (black/reddish). Archaeological materials are highly abundant in this layer. Intact bronze nails and tree nails, as well as pieces of wood with copper fragments, were recovered. Ceramics and marble pieces are also frequently encountered. A human tooth and various human bones were identified. It is important to note that the marble sculptures found between Layers 3 and 4 exhibit different preservation states. While marble fragments in contact with Layer 3 are affected by marine organisms, the fragments in Layer 4 are well preserved. This is corroborated by the high abundance of organic materials (e.g., wood). Layer 4 represents the richest archaeological layer encountered during the excavation. Large consolidated fragments (pebble, cobble grain-sized) are observed. FTIR analyses indicate that the mineralogical composition of the lithified sediment is calcite based on 2500, 1434, 875, and 712 cm^{-1} peaks (Fig. 5d).

Layer 5 (max. 20 cm thick) represents a contact between Layer 4 and Layer 6. It shares the same mineral composition (calcite), as corroborated by the FTIR results. Layer 5 is a

Fig. 5 Fourier-transform infrared (FTIR) spectra of the bulk samples, shells and bones. **a** Dolomite identified in Layer 1, **b** Aragonite identified in Layer 2, **c** Calcite and aragonite identified in Layer 3, **d** Calcite identified in Layers 4 to 7, **e** Marine shell composed of calcite with some aragonite, typical from Layers 4 to 7, **f** Marine shell composed of aragonite, **g** Carbonated hydroxy-lapatite identified within the bone samples

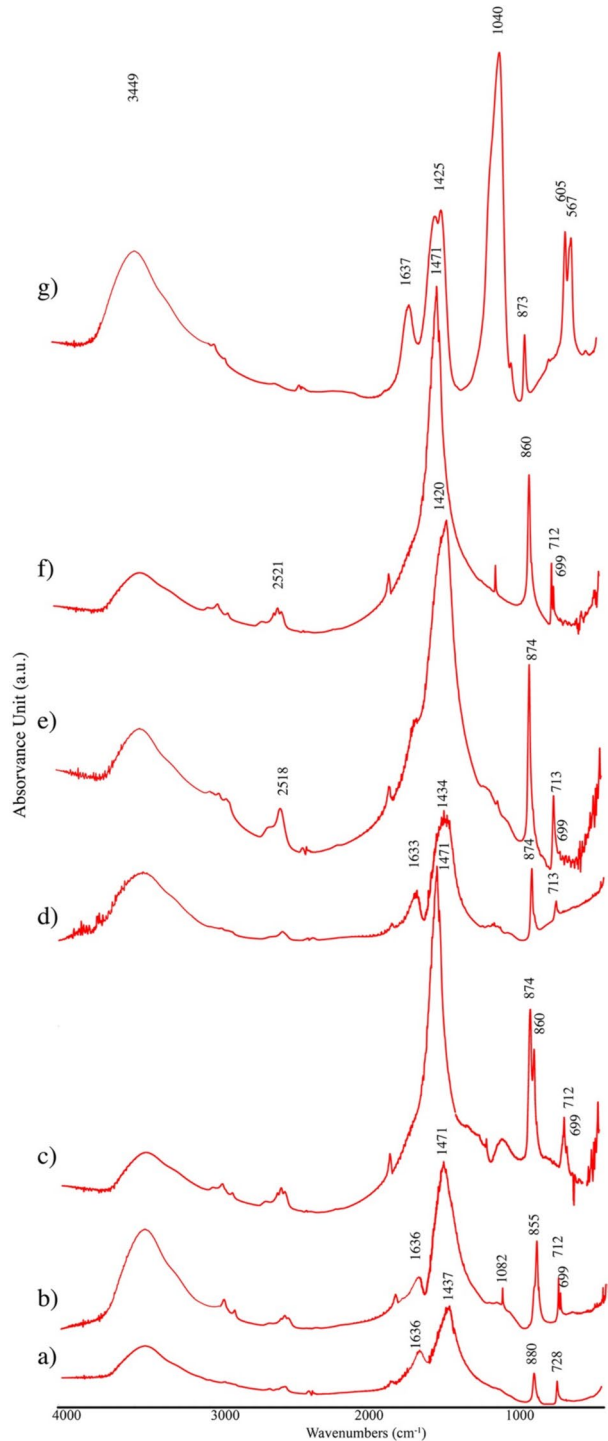


Table 1 Bulk sediment samples indicating their stratigraphic context, physical characteristics and mineralogical analysis

Layer no.	Description	Sample no.	Mineralogy
1	Large dolomite boulders	ANT-2023-13	Dol
2	Marine encrustation	ANT-2023-4	Arg
3	Loose calcareous sediment	ANT-2023-33	Arg
		ANT-2023-3	Arg
		ANT-2023-25	Arg
		ANT-2023-36	Arg
		ANT-2023-37	Arg
4	Yellow cementation of pebble and cobbles	ANT-2023-11	Cal
		ANT-2023-23	Cal
		ANT-2023-24	Cal
		ANT-2023-30	Cal
5	Grey cementation of coarse sand	ANT-2023-2	Cal
		ANT-2023-5	Cal
		ANT-2023-6	Cal
		ANT-2023-29	Cal
6	White sediment partially cemented with archaeological materials	ANT-2023-1	Cal
		ANT-2023-7	Cal
		ANT-2023-9	Cal
		ANT-2023-14	Cal
		ANT-2023-28	Cal
7	White sediment partially cemented	ANT-2023-15	Cal
		ANT-2023-27	Cal
Controls	Loose sand between boulders	ANT-2023-32	Arg
		ANT-2023-34	Arg
		ANT-2023-35	Arg
	Bedrock cliff	ANT-2023-12	Dol

The mineralogical composition was determined via FTIR spectroscopy

Dol dolomite, *Arg* aragonite, *Cal* calcite

lithified layer consisting of smaller grains (sand grains) than Layer 4. Archaeological materials are abundant, as in Layer 4.

Layer 6 (max. 50 cm thick) consists of lithified white sediment with archaeological materials and angular pebbles and cobbles. The layer is characterized by patchy lithification of very fine whitish calcareous sand grains, medium calcareous sand and abundant marine organisms and archaeological materials. Within this layer, large artifacts such as pottery fragments, bronze fragments, marble pendants and human bones were found. Additionally, some pebbles are covered with white pendants, identified as calcite using FTIR.

Layer 7 was not fully excavated; thus, its total thickness is unknown. This layer is similar to that of Layer 6 and is characterized by a white sediment partially lithified, medium calcareous sand and abundant marine organisms but with lower amounts of pebbles and cobbles than Layer 6. Some large pebbles and cobbles are covered by white pendants identified as calcite using FTIR, similar to what was observed in Layer 6. Archaeological materials are not present, and the layer is classified as sterile.

The use of an on-site laboratory has facilitated the identification, description and definition of these stratigraphic layers. Furthermore, four different mineralogical units within the site were identified: (1) dolomite, (2) aragonite, (3) a mix of aragonite and calcite, and (4) calcite. These mineralogical units represent events within the site. The calcite layers are associated with the seabed on which the shipwreck landed. Aragonite crust represents modern marine crust. The dolomite layer is associated with landslides due to storms or tectonic activities, and the mixture of aragonite and calcite layers represents loose sediment covering the archaeological materials. Additionally, the various mineralogical units help us to understand the formation processes at the site. The lithification of the calcite layer must have occurred after the wreck event. However, the formation processes responsible for the lithification of the calcite layers are still unclear. The presence of groundwater at the site and the tectonic activity of the region may have played a role in facilitating the precipitation of aragonite into calcite which may be responsible for the 1434 cm peak in Layer 4–7. Further studies are being performed to corroborate this possibility. However, this lithification process has played a major role in the preservation of archaeological materials, as confirmed by the preservation of marble within this layer in comparison to the marble fragments in Layer 3. Additionally, the presence of organic material preserved within this layer corroborates that lithification generated an anaerobic environment that protects organic and inorganic archaeological materials.

Preservation of Archaeological Materials

Archaeological materials are often susceptible to degradation over time. Therefore, understanding the state of preservation of archaeological materials is important for interpreting and evaluating archaeological records. Post-depositional processes, including chemical, physical and biological, can alter the original composition, structure and appearance of archaeological materials. In the case of the Antikythera shipwreck, three types of materials were selected and identified to assess the state of preservation: shell, bone, and phytoliths.

At least four shell samples were obtained from each stratigraphic layer (2, 3, 4, 5, 6, and 7) of the site, except for Layer 1. The samples from Layers 3–7 consisted of *Murex* shells (*Bolinus brandaris*) and cone shells (*Conus betulinus*), which were originally composed of aragonite, while the samples from Layer 2 were related to date mussels (*Lithophaga lithophaga*) also composed of aragonite (Brysaert 2007; Kogure et al. 2014) (Table 2; Fig. 6). As indicated by FTIR analysis, all the samples from the marine crust (Layer 2) and the loose sediments of Layer 3 were composed of aragonite, while the shells identified in Layers 4 through 7 were composed of calcite or aragonite (7 out of 16 samples were composed of calcite) (Fig. 5e, f). The preliminary analysis of shells indicated the initial transformation of aragonite into calcite in the lithified layers. Further analyses are being performed to clarify the causes of this transformation, which may be associated with the lithification of those layers.

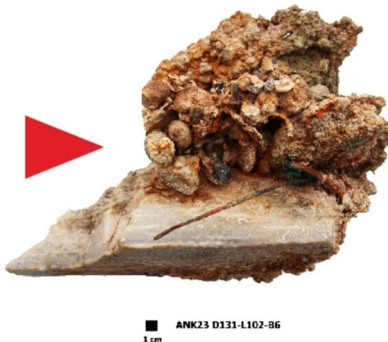
A total of five bones and two human teeth were collected during the two excavation seasons. One bone from Layer 4 and another from Layer 5 were selected for analysis of their preservation stage, including the amount of collagen present, which indicates their suitability for radiocarbon dating and possible DNA analysis. The bones were initially examined under blue light, revealing the preservation of collagen inside the bone structure, as indicated by the stronger reflection of blue light in this area (Fig. 7). FTIR analysis was also conducted on both the inside and outside of the bone samples, confirming the excellent preservation of the carbonate area. Grinding curves were generated

Table 2 Shell samples indicating their stratigraphic context, species and mineralogy

Layer no.	Shell no.	Specie	Mineralogy
2	1	<i>Lithophaga lithophaga</i>	Arg
	2	<i>Lithophaga lithophaga</i>	Arg
	3	<i>Lithophaga lithophaga</i>	Arg
	4	<i>Lithophaga lithophaga</i>	Arg
3	1	<i>Conus betulinus</i>	Arg
	2	<i>Conus betulinus</i>	Arg
	3	<i>Conus betulinus</i>	Arg
	4	<i>Conus betulinus</i>	Arg
4	1	<i>Bolinus brandaris</i>	Arg
	2	<i>Conus betulinus</i>	Cal
	3	<i>Bolinus brandaris</i>	Arg
	4	<i>Bolinus brandaris</i>	Cal
5	1	<i>Bolinus brandaris</i>	Cal
	2	<i>Conus betulinus</i>	Arg
	3	<i>Conus betulinus</i>	Arg
	4	<i>Conus betulinus</i>	Cal
6	1	<i>Bolinus brandaris</i>	Cal
	2	<i>Conus betulinus</i>	Arg
	3	<i>Conus betulinus</i>	Arg
	4	<i>Bolinus brandaris</i>	Arg
7	1	<i>Conus betulinus</i>	Cal
	2	<i>Conus betulinus</i>	Arg
	3	<i>Conus betulinus</i>	Arg
	4	<i>Conus betulinus</i>	Cal

The mineralogical composition was determined via FTIR spectroscopy
Arg aragonite, *Cal* calcite

a)



b)



Fig. 6 Marine shells analyzed in this study: **a** *Bolinus brandaris* and **b** *Conus betulinus*. (Photographs by O. Manousos and P. Birchler Emery)

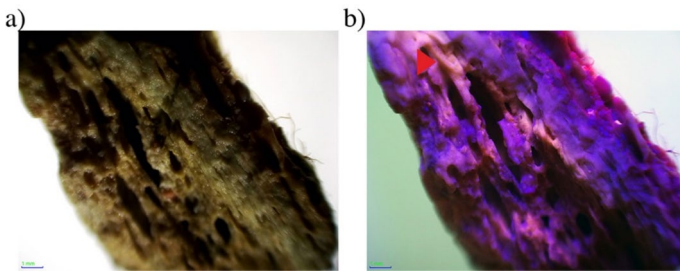


Fig. 7 Microphotographs of bone fragments. **a** Bone under normal light and **b** bone under blue light. Note the yellow color (red triangle) indicating collagen

to estimate the preservation stage using the splitting factor methodology described by Asscher et al. (2011). The results indicated the presence of hydroxyapatite based on the peaks observed at 1453, 1415, 1040, 565, 605, and 872 cm^{-1} (Fig. 5g). The Infrared Splitting Factor (IRSF) is between 2.8 and 3.3, indicating that collagen may be extracted from relatively well-preserved bone. Differences in preservation between the inside and the outside were not noted using FTIR.

Phytoliths are tiny structures made of opal ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) that can form within the cells and tissues of plants. These silica-based structures provide valuable taxonomic information due to their distinct morphologies, and their inorganic nature allows them to be preserved for millions of years (Cabanes 2020). Phytoliths possess remarkable preservation potential, as their silica composition makes them highly resistant to decay, enabling their survival in archaeological deposits over long periods of time. This makes phytoliths excellent indices for assessing the preservation of archaeological sites. Phytoliths can even be preserved after plants have undergone processes such as burning or digestion (Cabanes 2020; Shahack-Gross 2011). While certain depositional events, such as wildfires, or postdepositional processes, such as bioturbation, can potentially impact phytolith assemblages, their overall effects are generally not significant (Cabanes 2020; Piperno 2006). However, it is important to note that high temperatures exceeding 700 °C can cause the melting and loss of distinctive phytolith shapes, thus affecting their preservation. Additionally, alkaline pH conditions can lead to partial or complete dissolution of phytoliths (Cabanes 2020; Cabanes et al. 2011, 2012; Cabanes and Shahack-Gross 2015). Due to the alkalinity of seawater, which has an average pH of 8.1, and the high porosity of the coarse calcareous sediment at the site, it was not expected that phytoliths would be preserved within this specific archaeological site. However, phytoliths were identified in grain mounts from two of the four archaeological layers. Layers 4 and 5 exhibit well-preserved opal phytoliths with distinct anatomical features (Fig. 8). Delicate phytolith morphologies were not identified. The predominant shapes observed were elongate psilate and long-cell verrucae. However, dissolution marks were not observed indicating that the lack of delicate morphologies may be due to the origin of the phytoliths rather than a preservation issue. Unfortunately, quantifications and detailed morphological analysis could not be conducted due to the unavailability of appropriate equipment in the on-site laboratory. The presence of phytoliths may be attributed to local seaweed, but marine organisms producing phytoliths have not been identified anywhere in the world. Further quantification and identification analyses will be performed following the extraction procedure of Katz et al. (2010).

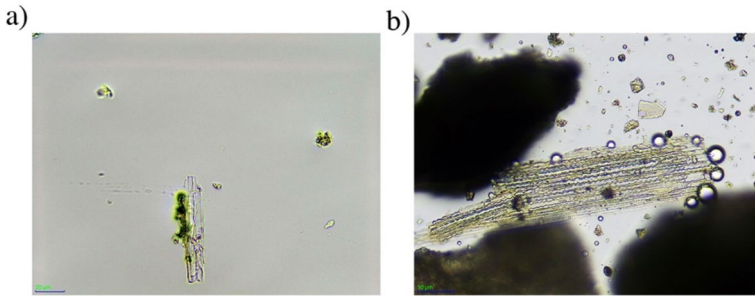


Fig. 8 Anatomical composition phytoliths identified in grain-mount samples. **a** Elongated psilate and **b** long cell verrucate

Identification of Archaeological Materials

Accurate identification of archaeological materials is not always straightforward. Post-depositional processes may obscure the original characteristics of different artifacts, and similar materials can be misinterpreted by naked eye observation. New methodological techniques enable the examination of archaeological materials at the microscopic and molecular levels, providing detailed insights into their composition.

In our particular case, the incorporation of FTIR spectroscopy avoids three specific mistakes in interpretation. Initially, upon sieving the material, small fragments (1–2 mm in size) of transparent material were observed, which were initially suspected to be related to glass due to the low amount of quartz sources on the island (Fig. 9a). However, through FTIR analysis of 15 selected samples, it was systematically determined that both the transparent and white grains were quartz, based on the presence of peaks at 1087, 1163, 798, 779, 515, 460, and 695 cm^{-1} , thus preventing misidentification (Fig. 9a).

Furthermore, a potential organic component was observed in the seabed. Upon collection and examination on land, the material was suspected to be of organic origin due to its fragile texture and sulfuric smell (Fig. 9b). However, FTIR analysis revealed that it was actually an inorganic material composed of dolomite, clay minerals and quartz (Fig. 9b).

Finally, some of the lead fragments that were collected exhibited signs of post-depositional processes, which affected their identification. Certain lead fragments were observed to be coated with a blue color (Fig. 9c). Subsequent FTIR analysis indicated the presence of cerussite (PbCO_3) based on the presence of peaks at 1395, 1051, 839, and 678 cm^{-1} (Fig. 9c). Cerussite is a lead carbonate mineral that commonly forms as a secondary mineral due to the influence of carbonate-rich water (Boyatzis 2021). It is worth noting that our sample may have been mixed with other elements, such as copper (Cu) or iron (Fe), which could not be fully identified.

Discussion

Underwater excavations, especially those conducted in deep water, are associated with complex logistics and increased financial costs. Here, we introduce an underwater excavation protocol that includes limited intervention/high-accuracy recording

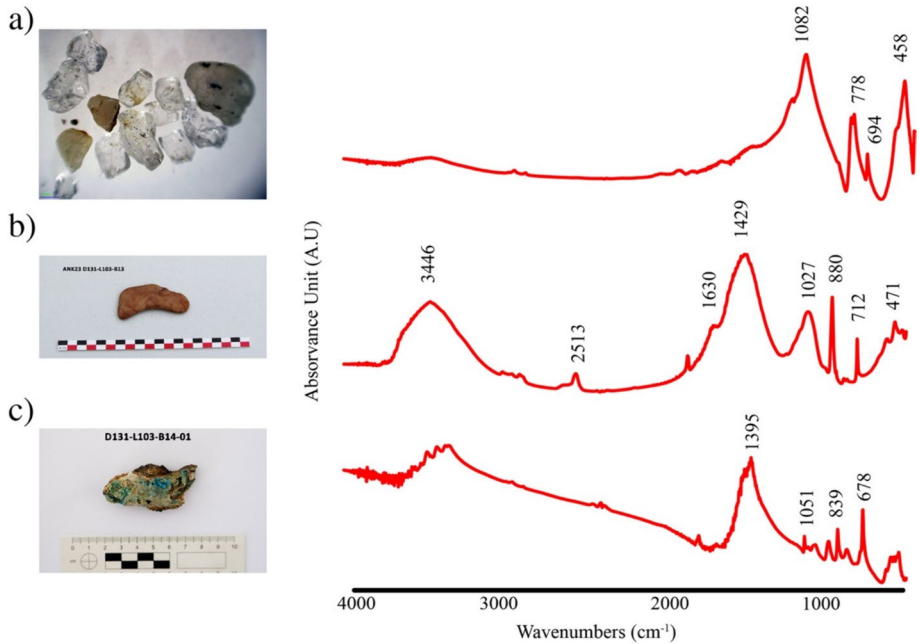


Fig. 9 Photographs and FTIR spectra of archaeological remains. **a** Quartz grains that were misidentified as glass by naked-eye observation. However, the FTIR spectrum indicates they are mainly composed of unaltered quartz. **b** An inorganic component mainly composed of dolomite with some amount of clay and quartz. **c** Lead artifacts. Note that the piece of lead on the right of the image has a blue coloration. The blue coloration was identified as cerussite, as indicated by the FTIR spectrum. (Photographs: I. Ogloblin Ramirez and P. Birchler Emery)

and documentation techniques supported by an on-site geoarchaeological laboratory. Detailed and timely archaeological data are obtained, enhancing the quality of the research and improving excavation strategies, sampling and processing. This methodology can be easily applied while operating on most working platforms, including coast-based facilities or expedition ships. Expedition ships often work for months before being able to access dedicated institutions. This approach could provide rapid results, guide costly expeditions, and facilitate post-excavation processing as materials sometimes sit for months or even years waiting for study and interpretation.

The use of on-site laboratories in the field encourages the involvement of underwater archaeologists with backgrounds in the natural sciences. This approach facilitates the interpretation of data and brings to light unresolved issues and new field observations that otherwise may not be recognized (e.g., phytoliths). Marine archaeology is often limited to small excavation areas; thus, efforts must be made to extract the maximum amount of information available from the site. The integration of on-site laboratories necessitates the presence of specialists at archaeological sites, however, new approaches, such as geoarchaeology and microgeoarchaeology, in shipwreck archaeology, allows for detailed studies and collaborations that enhance final interpretations.

Archaeological Implications of On-Site Laboratory Conditions

This study showed how onsite instrumentation can help to provide immediate information about artifacts and sediments within submerged sites, providing valuable data for interpretation and contextualization. Our three different case studies demonstrate the ability of an on-site laboratory to assist in the identification of stratigraphic boundaries while also assessing the preservation of the archaeological record.

FTIR analysis has proven useful in identifying boundaries within sediments based on their mineralogical composition. Microscopic observations aid in describing sediment types and the range and intensity of the archaeological record. The identification of those boundaries contributes to reconstructing the site's formation history. The mineralogical composition of the sediments, in combination with other archaeological (bone) and environmental (shells) remains, has highlighted a dramatic change in the depositional environment that requires further investigation. The mineral composition of the sediment and of some of the shells found in Layers 4 to 7 is calcite, as opposed to the sediments and shells from Layers 2 and 3 and the control samples, which are composed of aragonite. Aragonite is a metastable form of calcium carbonate that is more soluble than other carbonates, such as calcite. Its presence in terrestrial sites suggests relatively low levels of carbonate dissolution or recrystallization within the site, indicating stable pH conditions and limited exposure to acidic environments (Toffolo 2020; Weiner 2010). Additionally, other carbonates (e.g., bone) demonstrate the excellent preservation of carbonates within the site (the IRSF value is between 2.8 and 3.3—an IRSF value higher than 3.3 would not preserve collagen. Asscher et al. 2011). Thus, a complex site formation history has been identified for Antikythera, which was not visible via naked-eye observation. A detailed description of the site formation processes is now available following a combination of macro- and micro-archaeological data and historical sources.

These data have significant implications regarding future excavation strategies. In our particular case, the well-preserved archaeological materials (e.g., marble and wood remains) within consolidated Layer 4 and below suggest that future efforts should be concentrated within these stratigraphic layers because they are undisturbed and well preserved. The presence of well-preserved marble sculptures and wood remaining within this layer indicates these layers were part of an anaerobic environment. This information is valuable for interpreting the presence of other microscopic remains that we detected and would have otherwise gone unnoticed, such as phytoliths. The absence of oxygen in the deposits provides evidence of limited or negligible water exchange in those stratigraphic layers between the oxygenated seawater and the interstitial water of the sediment. Consequently, opal (SiO_2) within the sediment is not continuously replenished by water. After an initial dissolution of a certain amount of phytoliths, the chemistry of the sediment pore water becomes saturated with respect to silicon (SiO_2), creating conditions that facilitate the long-term preservation of phytoliths. A similar phenomenon affecting the preservation of opal and calcitic microremains in Neolithic sites along the Carmel Coast (Israel) was described by Ogloblin Ramirez et al. (2023). However, these microremains were originally deposited in a terrestrial environment rich in clay rather than porous calcareous sand. The preservation of phytoliths under underwater conditions requires further study.

The preservation of phytolith assemblages is important not only for understanding site formation processes and preservation but also for providing valuable information from archaeological sites. Further quantification and identification will be undertaken to clarify the presence of phytoliths in Antikythera and their importance.

Archaeological Training for Professional Divers

Marine archaeology, particularly deep-water archaeology, often requires highly skilled divers to undertake risky and complex excavation tasks. However, these professional divers may not always be familiar with archaeological practices, studies and techniques. Antikythera project aimed to train professional divers to accomplish complex archaeological tasks. This has been done through theoretical and practical demonstrations in the field and the laboratory. The training program, approach, and results of our training will be summarized in future publications. However, it is worth mentioning how the utilization of an on-site laboratory has proven to be an excellent tool for educating professional divers about the practice of archaeology, research questions and the detailed investigations necessary to formulate solid and reliable interpretations. Thus, hands-on experience with laboratory equipment (FTIR and microscope) combined with other teaching and training in excavation and post-excavation documentation and analyses allows divers to appreciate the minute details of data that were extracted through their hard work. This generates an environment for the exchange of ideas and knowledge, while divers learn the importance of the archaeological context (micro-context), excavation procedures, and stratigraphic principles.

Future Studies

The on-site laboratory has proven to be tremendously valuable in addressing archaeological inquiries and providing a broader understanding of the preservation of the archaeological record. The sampling procedure necessitates a waiting period of at least one day to allow for the artifacts to dry prior to analysis. In this regard, FTIR spectroscopy is particularly well suited for underwater investigations, as it is not affected by salt, enabling immediate sample analysis following drying. Moreover, on-site laboratories enable analyses to be conducted without the need to transport sediments or artifacts outside of the country where the excavation takes place.

Despite the numerous advantages offered by on-site laboratories, there are limitations in terms of their capacity and the range of analyses they can perform compared to dedicated research institutions. Therefore, further examination and analyses are required at specialized off-site laboratories. The aim of this article is to demonstrate the benefits of an on-site laboratory in terms of day-to-day decision making during fieldwork. However, a detailed interpretation of the implications of this stratigraphic record for understanding formation processes within the Antikythera shipwreck will be performed after off-site laboratory analysis, such as radiocarbon dating or micromorphology.

After two field seasons, we gained a better understanding of the techniques needed to better comprehend the site. In this regard, new instrumentation will be added to our laboratory to enable the extraction and quantification of phytoliths, as well as the accomplishment of morphological analysis. Additionally, due to the abundant presence of metals within the excavation layer, portable X-ray fluorescence will be incorporated to identify diagenetic processes affecting these materials and to detect trace metals within different sedimentary layers. Finally, micromorphological analysis may be the next step toward fully interpreting the site formation processes at the Antikythera shipwreck.

Conclusion

The advent of on-site laboratories in marine archaeology facilitated the immediate processing and analysis of collected samples and data, minimizing the reliance on post-excavation analysis conducted in traditional laboratories while adding new dynamics to excavation practices. This approach not only enhances archaeological interpretations but also expedites our understanding of preservation mechanisms and formation processes.

By combining real-time analytical capabilities with specialized research approaches, researchers can uncover new insights into the past and contribute to the conservation and management of underwater archaeological sites. The development and exploration of on-site laboratories will undoubtedly open up new avenues for underwater archaeological research and techniques while further expanding our knowledge of human history.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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