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Marine geo-archaeological mapping using Unmanned Surface Vehicle (USV). Case study: ancient semi-submerged settlement of Grotta Naxos, Greece☆

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ABSTRACT

The surveying, exploration and documentation of underwater cultural heritage (UCH) sites are rapidly entering a new era with the evolution of technology. Marine remote sensing techniques enable an adapted approach to the study area, overcoming the difficulties and limitations of conventional means and acting in a non-intrusive, non-destructive manner. This research is a marine geo-archaeological survey the case study of which is the semi-submerged site of Grotta, the north coastal zone of the ancient city of Naxos, Cyclades, in Greece. To meet the peculiar needs of the site with the presence of antiquities in ultra-shallow waters (0 to −5 m), a catamaran Unmanned Surface Vehicle (USV) was employed for the concurrent retrieval of shallow geoacoustic data and visual footage, equipped with acoustical and optical sensors. The collected acoustic datasets were processed to create bathymetric view and georeferenced mosaics of high-resolution and metric precision to map and investigate the submerged residential remains. Additionally, photogrammetric methods was applied for creation of 3D models and orthophotomosaics of the ancient structures located on the seabed, facilitating a better record of their individual characteristics. Both acoustic datasets were incorporated into GIS Software, where diverse spatial information was utilized to generate conclusive maps of the study area. This field research aims to demonstrate the adaptive use of USV's in challenging environments for the exploration and documentation of underwater archaeological sites and the simultaneous acquisition of multi-level information without damaging the marine antiquities.

1. Introduction

The Mediterranean basin area possesses an outstanding archaeological significance concentrating a rich number of underwater archaeological sites along its shores (Bailey, 2004; Flemming and Redknap, 1987; Franco, 1996; Galanidou et al., 2020; Marriner and Morhange, 2007; Parker, 1987). Coastal environments, since antiquity, consist favorable areas for the development of early human habitation, providing vital resources, facilitating trade and communication offering strategic advantages that support urbanization (Braudel, 1972; Broodbank, 2013; Horden and Purchell, 2000). With gradual sea level rise over the millennia due to eustatic, and relative sea-level change variations (Lambeck, 1995; Lambeck et al., 2002; Rovere et al., 2016), the archaeological remains from prehistory and historical times that are now submerged below the sea, serve as witnesses of the ancient activity (Auriemma and Solinas, 2009; Bailey and Flemming, 2008; Benjamin et al., 2017; Flemming, 1999).

To protect and preserve these invaluable partially or fully underwater sites from natural and human-induced threats (Gasperini et al., 2022; Georgiou et al., 2021b; Pourkerman et al., 2018; Stewart, 1999), the European Union has developed and implemented specific policies and directives that frame as a whole the remains of the Underwater Cultural Heritage (UCH) (Valletta, 1992; ICOMOS Sofia, 1996; UNESCO, 2001). In response to the growing threat, scientific research plays a crucial role in protecting these cultural sites by meticulously recording and documenting them, not only ensuring the preservation of their

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historical significance, but also enhancing our understanding, contributing to the development of effective protection and conservation strategies (Bryan, 2017; Cacciotti et al., 2024; Cochran et al., 2006; Georgiou et al., 2021a; Hafner et al., 2022; Marzeion and Levermann, 2014).

Over the past decades, underwater surveys and documentation of UCH sites through scuba diving and conventional research vessels using geophysical instruments side-scan sonar (SSS), sub-bottom profiler (SBP), single-beam / multi-beam echosounder (SBES/MBES) have been broadly utilized to explore submerged landscapes, shipwrecks, and ancient coastal settlements providing invaluable knowledge for the interpretation of past human civilization highlighting the cultural importance of underwater heritage (Chalari et al., 2009; Ferentinos et al., 2020; Geraga et al., 2020, 2017; Gifford et al., 1985; Papatheodorou et al., 2011; Plets et al., 2013). However, these traditional approaches often face limitations. Diver-based surveys are constrained by human endurance, safety concerns, inefficiency in covering large areas and requirement of extensive human resources. While vessel-mounted surveys have unlimited potential in detecting and mapping deep and/or buried under sediments UCH, they struggle with restricted access to shallow or obstructed waters due to their size and draft.

Recently, advances in technology like Unmanned Surface Vehicles (USVs) are revolutionizing marine archaeological and geo-archaeological research (Kapetanović et al., 2020; Mattei et al., 2018a; Ødegård et al., 2016; Giannakopoulos et al., 2023). USVs, which are remotely operated or autonomous vessels, can survey large areas even in challenging shallow waters with precision, overcoming hazards in navigation and limited boat accessibility by reaching places that are difficult or dangerous for human divers and research vessels (Dobref et al., 2018; Liu et al., 2016; Mattei et al., 2024; Nikolakopoulos et al., 2018). These technologies allow for more efficient and comprehensive surveys, reducing the time and cost associated with traditional methods while surpassing the restrictions that conventional techniques meet, making previously inaccessible sites discoverable and documentable.

In this publication, we present the methodological approach and technological advantages of utilizing an autonomous USV robotic vessel for the comprehensive, non-intrusive, and non-destructive multilevel marine geophysical survey of underwater archaeological purposes.

By employing advanced marine geophysical miniaturized sensors, including a compact side-scan sonar and single-beam echosounder, the autonomous USV enables simultaneously precise and efficient exploration and mapping of antiquities and the morphological evolution of the seabed. To complement the geophysical survey with acoustic sensors, the vehicle employed optical sensors for ground-truthing and underwater photogrammetric techniques to create 2D mosaics and 3D metric models, providing a more detailed documentation of the ancient submerged structures and a more comprehensive examination of the site. In light of the remarkable advancements in USV technology—marked by ever-evolving mapping capabilities, multi-functionality, and significant operational ability—this study leverages these innovations to address critical challenges in shallow water archaeology, such as the large spatial extent of sites with frequently fragmented areas of interest, the presence of archaeological material indistinguishable from the surrounding environment, and the challenges of conducting systematic surveys due to wave-induced conditions. By utilizing a multi-sensor, adaptive USV-based approach, this research introduces a novel method that not only integrates acoustic and visual data collection concurrently but also enhances survey efficiency and accuracy in environments where traditional methods fall short, thereby effectively contributing to the mapping and assessment of archaeological site conditions. The aim of this study was the detailed mapping of the semi-submerged archaeological site of Grotta Naxos, located in the Cyclades, Greece, using advanced documentation techniques in an ultra-shallow water environment (0–5 m). The research objectives are as follows:

- The implementation of a methodological approach for the coastal survey which accurately records the position of the submerged structures and ensures metric precision for the archaeological documentation;
- The parallel achievement of range and resolution for detecting targets in large-scale marine coastal survey that may hold potential archaeological interest; and
- the application of a cost-efficient and non-invasive methodology that is environmentally sustainable

2. Survey area

2.1. Survey area and physiography

The archaeological site of Grotta is located on the northwest side of the island of Naxos, in Cyclades, Greece, and occupies the coastal and partly underwater part north of Naxos Town (Chora) over which now the modern residential area and port facilities have spread.

The study area is divided into two distinct sectors: Sector A, corresponding to present Grotta's beach, and Sector B, which includes the modern North Port Basin (Prolimenas) (Fig. 1). Both sectors are characterized by the presence of submerged stone architectural remains of undetermined chronology at ultra-shallow waters ranging from zero to −5 m. The area of Sector A extends 340 m in length and 130 m in width, oriented along an east–west axis. The region encompasses the submerged front of the entire beach's length, bordered to the east by the steep slopes of Aplomata hill and to the west by the artificial road connecting the beach to the islet of Palatia. Sector B extends into an area of approximately 220 m in length and 260 m in width and includes almost the entire northern port basin. The area is bounded to the east by the road that forms the western boundary of Sector A, to the south by the dock, and to the north by the modern breakwater of the commercial port.

In terms of the physiography of the study area is influenced by prevailing winds, primarily from the north directions, with minimal wind activity from the east and west. The average annual wind speed is 12.6 mph (Iowa State University database). Wave conditions follow this wind pattern, with significant wave heights averaging 0.70 m, and ripples primarily driven by northern and southwestern winds (Evelpidou et al., 2021; Soukissian et al., 2008).

2.2. Archaeological background

The archaeological importance of the study area was uncovered through decades of archaeological research starting with G. Welter in 1930 and continuing by N. Kontoleon (1949–1974) and V. Lambrinoudaki (1976–1985). Archaeological excavations brought to light material remains (portable and non-portable) that reveal the long and complex history of Grotta Naxos making the site as one of the most significant palimpsests of the Aegean region (Kontoleon, 1967; Lambrinoudakis, 2001, 1988; Lambrinoudakis and Philaniotou-Hadjianastasiou, 2001; Vlachopoulos, 2019, 2003). Earliest human traces dated back to the Late Neolithic period (4500 BCE) and continue throughout the Prehistoric and Historic times illustrating the development of a significant insular society with almost uninterrupted residential phases until present days (Lambrinoudakis, 2018, 2006; Philaniotou, 2006; Zaphiropoulou, 1988). Over the millennia, gradual sea-level rise (Lambeck, 1995; Lambeck et al., 2002; Lambeck and Purcell, 2005) has caused a significant part of the urban area to submerge below the water's surface, with the stone walls of buildings still visible on the seabed (Vlachopoulos, 2008, 2006). Unlike the extensive research conducted on land, the submerged area has not been thoroughly investigated. The area's unique characteristics, including strong winds, challenging wave conditions and shallow waters, did not allow an extensive archaeological research so far (Papathanasopoulos, 1981). As part of the broader archaeological study of the site, only an

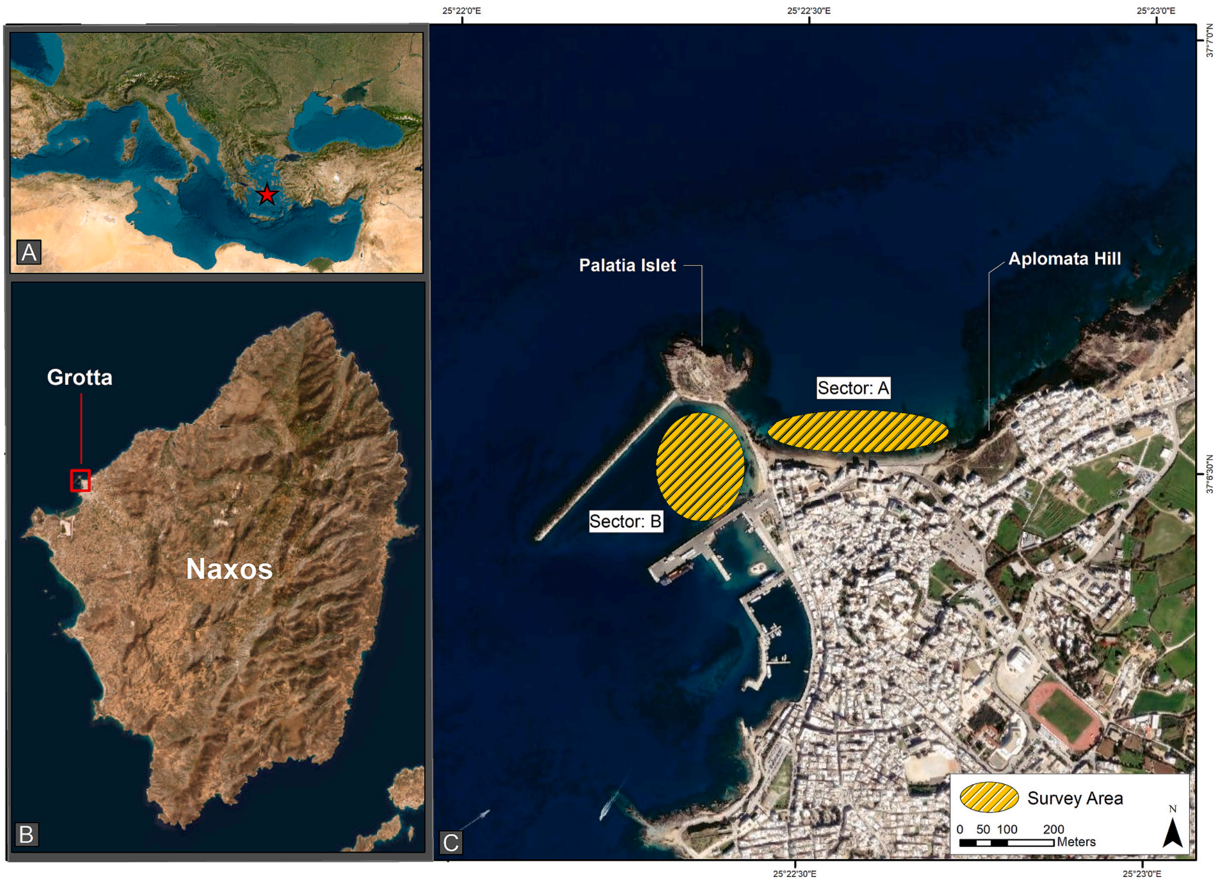

Fig. 1. (A) Location of Naxos Island in the Mediterranean Sea, (B) The archaeological site of Grotta, situated on the northwest part of the Naxos, (C) Map of the surveyed area.

underwater reconnaissance was conducted in 1980–1981 from the Ephorate of Underwater Antiquities under G. Papathansopoulos (Papathanasopoulos, 1981).

3. Materials and methods

A. Survey design and Instrumentation

For the simultaneous retrieval of high-quality shallow water geo-acoustic data and visual information aimed at multi-scalar mapping, an electric-powered USV equipped with low-cost miniaturized payload acoustic and optical sensors was employed (Fig. 2 B). This configuration was selected to provide a cost-efficient and non-invasive methodology, without environmental impact, while ensuring maximum data resolution and precise positional recording, which is crucial for documenting submerged structures and supporting archaeological analysis, even when the object of interest is located at a depth of 40 cm. The equipment chosen for the survey requirements included a compact system of a side scan sonar (SSS) (455/800 kHz) and a broadband chirp single beam bathymetric sonar (SBES) (83/200 kHz), integrated into the Lowrance Elite FS 9 Ti´ system (Fig. 3). The high frequency SSS was utilized to acquire acoustic backscatter intensity, which provides detailed information on the geomorphology of the seafloor and aids in detecting potential archaeological targets across a broad range with high resolution, thus supporting large-scale surveys effectively. The swath width for the sonar was configured to 30 m, resulting in a 90 % overlap between adjacent survey lines, ensuring high accuracy and data quality. Concurrently, the SBES collected bathymetric data on the seabed's evolution, contributing to the precise mapping providing co-spatial depth-position information of submerged antiquities. This combination of sensors, along with the USV's efficiency in covering extensive areas, ensures the necessary range and resolution for detecting both small- and large-scale archaeological targets. In parallel, to verify structures mapped by geophysical methods, visual data was obtained for ground-truthing and photogrammetric analysis using a GoPro Hero 7 high-definition camera, which was vertically mounted (90°) above the sonar transceiver, centered along the USV's axis (Fig. 3). The camera was configured to capture high-resolution images (1920 × 1080 pixels) at 0.5-second intervals, producing a continuous sequence of overlapping frames recording the entire area covered by the vessel's tracklines. This integration of optical sensors enables refining spatial resolution and enhancing the identification of subtle features that may indicate archaeological significance, further ensuring the robust reliability of the interpreted results. During the concurrent SSS-SBES-Camera survey, 43 survey lines were conducted with a lane spacing of 5 m, covering a total length of 7.8 km and an area of 90,000 m^2 (Fig. 2 A). The navigation of the robotic vessel and geospatial data reference were managed using a Real-Time Kinematics (RTK) H-RTK F9P high-precision GNSS receiver, which obtain an accuracy of 10 mm in *x-y* positioning. Throughout the survey, the vessel operated autonomously, following a pre-planned navigation course layout with a fixed speed maintained at 1 knot to ensure optimal data quality from both sensors.

B. Data Processing and Software.

The SSS sonograph morpho-acoustic data, in raw.sl2 format, were processed using the SeaView Mosaic (Moga software). Radiometric and geometric adjustments were applied to improve the accuracy, visual clarity, and interpretability of sonar data, creating a GeoTIFF mosaic that represents both sectors of the study area. The mosaicing resolution achieved 0.01 m, providing a detailed and highly accurate representation of the seafloor's geomorphology and archaeological remains. Both mosaics were processed in GIS ArcMap (v.10.8.1) (Esri, 2020) to

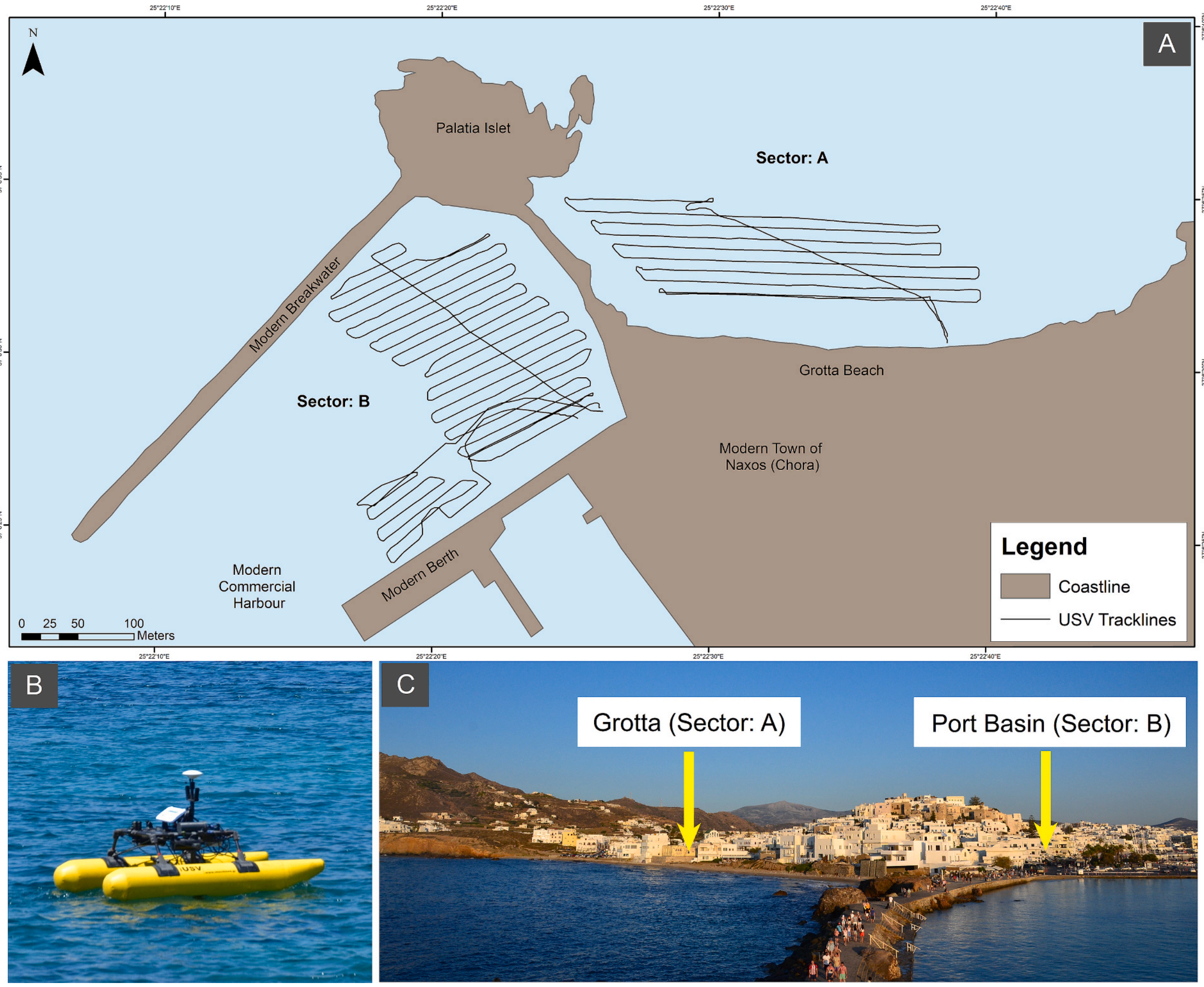

Fig. 2. (A) Map showing the tracklines of the USV, equipped with a side-scan sonar, single-beam echo-sounder, and action camera, in the surveyed area. (B) The USV robotic vessel in operation. (C) Photograph of the two surveyed sectors, taken from Palatia islet.

construct the final maps of the submerged area.

The SBES original bathymetric data collected from sonar is in the.sl2 format, similar to the side-scan sonar data. These formats contain depth (bathymetric) information. The data were processed using Surfer (Golden software) to adjust the depth values so that the sea surface represents zero, and were then exported into standard CSV format. The bathymetric data points, stored as comma-separated values, contain spatial coordinates (X and Y) and depth (Z). This raw format is imported into the ArcMap platform, which supports bathymetric analysis, where the data are finally converted into other geospatial formats such as GeoTIFF or Shapefiles (SHP) for the preparation of the final bathymetric map.

3.1. Experimental photogrammetric Implementations

During the course of the ground-truthing survey, carried out by the USV, over eleven thousand snapshots were collected with same density to insure 80 % overlap between images. The visual survey aimed to: i) provide a comparative source of information to verify the data gathered from the side-scan sonar (SSS), which together will offer a valuable resource for more accurate mapping of the study area, and ii) support the experimental creation of 2D photomosaics and 3D models of archaeological structures lying on the seabed, contributing their detailed documentation.

To achieve the application of photogrammetric techniques on the ancient structures in this research, two key factors must be fulfilled: i) the vehicle's path must coincide with the underwater remnants, and ii) the camera's view range must encompass the visual recording of overlapping elements between the survey lines followed by the vehicle. From the dense set of visual data, a sample of 33 overlapping images was used to create a photomosaic and 3D model that most accurately documenting an archaeological structure from Sector B. The images captured from distance of 2,10 m covering both the exposed remains and the surrounding underwater terrain, an area of 46.2 m^2. Post-processing of the collected data was carried out using Agisoft Metashape Professional® software (v.2.0.2) (Agisoft, 2024). The structure-from-motion (SfM) algorithm was employed to align the photos, producing a dense 3D point cloud. Each step of data visualization was processed on "high" settings for mesh, texture, and *ortho*-rectified photomosaic. The resolution of the orthorectified photomosaic is 0.874 mm/pix.

4. Results

4.1. Multi-scale mapping

Sector: A.

The morphoacoustic data collected from Sector A (Grotta Beach) (Fig. 1 C, 2C) provide a comprehensive view of the seabed's evolution and the distribution of the antiquities situated on it. Along almost the entire length of the beach displays a gradual slope from 0 to −2.5 m, followed by a sharp change in inclination, reaching heights of up to 2 m. This steep slope is particularly pronounced in the central area of the beach's frontage, before the seabed continues its smooth progression (Fig. 4).

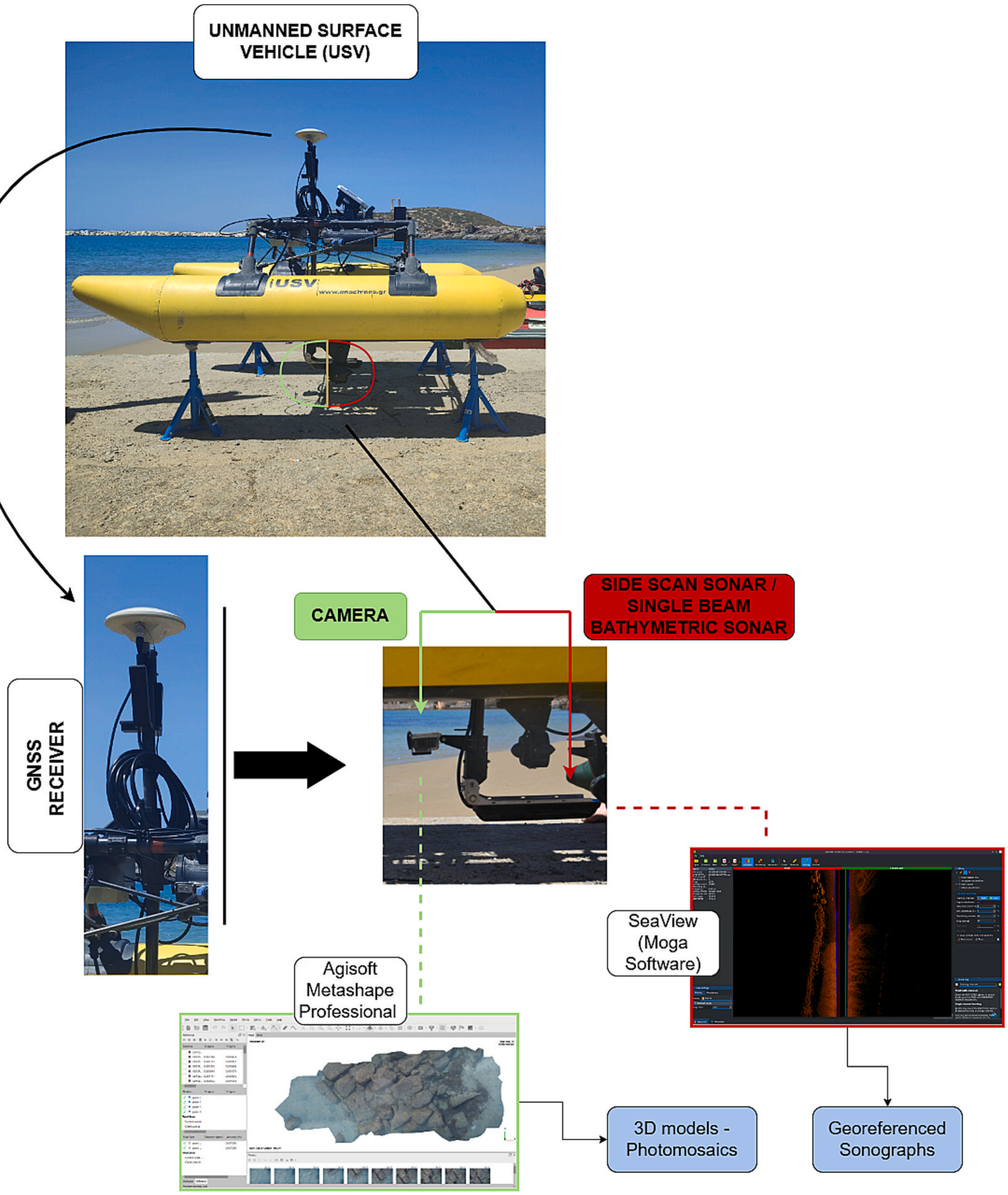

Fig. 3. Diagram showing the USV equipment and its data processing software.

This transition, as documented by the georeferenced mosaic of the side-scan sonar, marks the boundary between two distinct tonal patterns, representing different seabed compositions. Specifically, one area is depicted by high reflectivity (light tone), with or without acoustic shadows, and is associated with the hard substrate of the natural rocky formation (beachrock), as well as coarse sediments (cobbles and boulders). In contrast, the second distinct area is characterized by low reflectivity (dark tones) and is defined by loose sediments that extend into the deeper region (Fig. 5 A).

It is noted that this rocky area hosts the entirety of the antiquities, which are densely scattered but not always in an organized arrangement. Due to the rocky composition of the substrate, the identification of archaeological remains becomes challenging, as the material exhibits similar reflectivity but differs in geometric pattern, shape, and texture (Fig. 5 E). However, with the aid of visual verification (ground-truthing), it is possible to clarify the complex image provided by the mosaic, distinguishing the archaeological elements from the substrate (Fig. 5).

The archaeological remains commence at the shoreline of Grotta beach and extending within a zone measuring up to 50 m in width and 300 m in length and are situated at depths ranging from 0 to −3.5 m. Among the dispersed archaeological remnants, six structures have been identified that exhibit distinct architectural forms and are designated as I-VI (Fig. 5 A). Despite their partial preservation, these structures demonstrate the highest degree of integrity and are located along the isobath of −1.50 m (±30 cm), while their orientation is aligned along an east–west axis parallel to the shore. As we approaching closer to the shore, the spatial distribution of the remains becomes increasingly fragmented. Scattered architectural features are present throughout the entire area, displaying localized concentrations without forming any coherent structural arrangement, a phenomenon that is reflected in the chaotic pattern recorded by the side-scan sonar.

Sector: B.

The present survey conducted in Sector B (Prolimenas) (Fig. 1 C, 2C) reveals a different profile in comparison to Sector A. The bathymetry of the North Port Basin predominantly exhibits a gradual change in depth (Fig. 4). However, in the southwestern region, a significant depth gradient is observed, transitioning from −2 m to −6.5 m, marking a slope, likely resulting from dredging operations within the port.

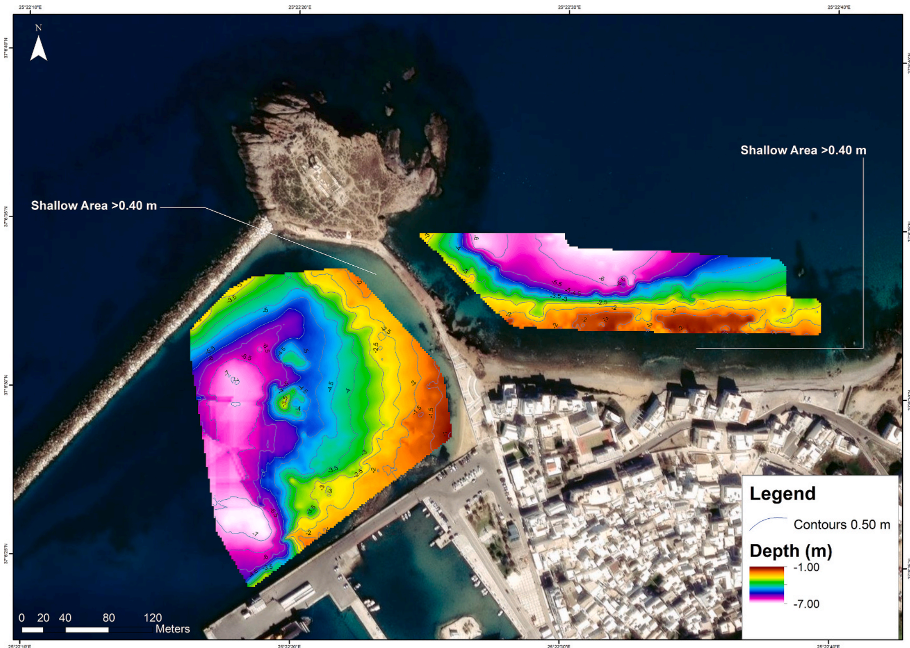

Fig. 4. Bathymetric map of the survey area.

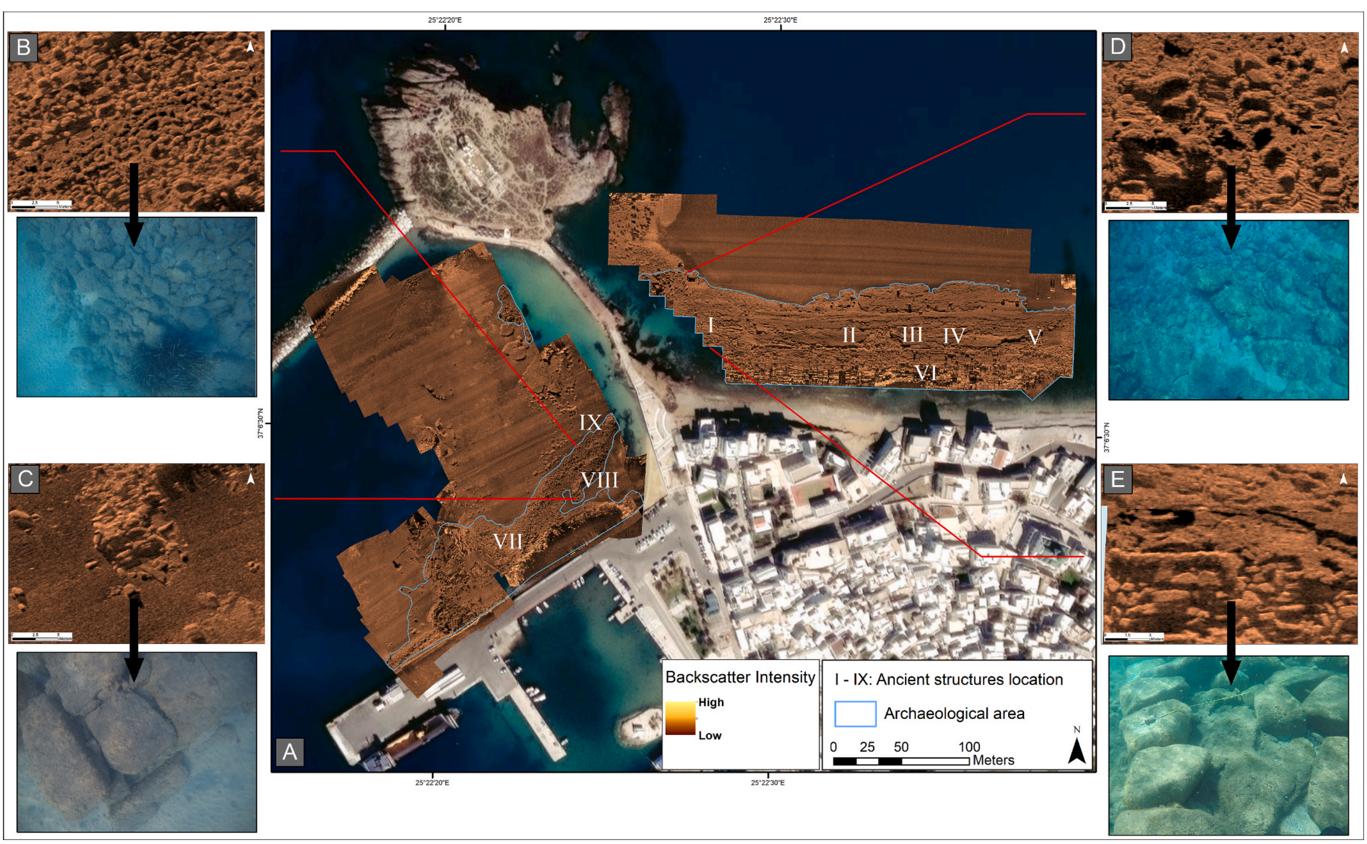

Fig. 5. (A) Side-scan sonar mosaic of the surveyed area, with the location of the submerged ancient structures (I-IX). (B-E) Selected close-up views of underwater targets, each paired with sonar imagery and corresponding underwater photographs. (B) Concentration of stones, part of the manmade structure IX. (C, E) Densely constructed masonry of Structure VIII and Structure I respectively. (D) Scattered, unprocessed stones, part of the natural seabed.

Additionally, two elevated seabed features are located in the central area, positioned at the transition between shallow and deeper waters (Fig. 4).

Similarly, in the case of Sector B, the side-scan sonar (SSS) data reveal two areas characterized by distinct tonal patterns, which indicate variations in the seabed. This sector is predominantly composed of loose sediments (sand), as reflected in the darker tonal patterns observed in the sonar imagery. In contrast, the lighter tonal patterns correspond to biological elements of the seabed (*Posidonia oceanica* and an unidentified type of vegetation), natural features (hard substrate), and anthropogenic remains (targets of archaeological significance) (Fig. 5 A).

The differing texture and geometry represented in the mosaic, along with the use of visual verification, enable the identification of scattered archaeological remains, allowing for a clear distinction from other features of the seabed (Fig. 5 C).

The survey of Sector B reveals a differently fragmented and complex representation of the archaeological remains. Specifically, the identified archaeological features consist of an ellipsoidal formation (Structure VII), a densely constructed complex structure (masonry) (Structure VIII), and an extended, elongated stone pile lacking clear cohesion (Structure IX). These archaeological targets are concentrated in the southern part of the study area at depths ranging from −1 m to −3.5 m. Notably, structures VII–XI appear to exhibit a deliberate alignment along the NE–SW axis. Ground-truthing revealed that Structure VIII lies beneath the broader stone pile (Structure IX), and it represents a distinctly organized feature, more similar in function to those found in Sector A. Additionally, a separate assemblage of stones, displaying a geometric pattern consistent with the archaeological remains of the wider area, has been located in the NW part of Sector B, marking it as a potential archaeological target (Fig. 5 A).

4.2. Photogrammetry

Using a single underwater camera mounted on a USV (Fig. 3), a 3D model of a small section of ancient architectural remains was generated. The structure, documented photogrammetrically, belongs to Sector B, designated as number VIII (Fig. 5 C and 6 A, B). Photogrammetry confirmed the presence of a construction that maintains structural integrity and coherence, with its individual features recorded with precision. Particularly noteworthy is the density and uniformity of the arranged stones. These stones are rectangular in shape and fit tightly together, forming a solid and cohesive masonry (Fig. 6 C). It is evident from the structural characteristics that this construction served a different purpose than the surrounding stone piles in the wider area and likely belongs to a different chronological phase. The ancient structure consists of stones of nearly identical size, showing distinct signs of wear. Eight stones were measured, with dimensions ranging between 1.20 m ± 20 cm in length and 0.80 m ± 10 cm in width. Its orientation is NW-SE. From the recorded span of the structure, the maximum recorded length is 4.20 m, and the maximum width is 3.00 m.

5. Discussion

The sea level rise caused by eustatic, isostatic and tectonic factors (Bailey and Flemming, 2008; Benjamin et al., 2017; Lambeck and Purcell, 2005; Pavlopoulos et al., 2012) has submerged ancient coastal landscapes together with archaeological remains lying on them, some dating back to Paleolithic era (Bailey and Sakellariou, 2012; Galanidou et al., 2020; Karavanić and Barbir, 2020; Pavlopoulos et al., 2010; Sakellariou and Galanidou, 2017, 2016).

In particular, along the coasts of the Mediterranean, where great civilizations emerged and flourished the submerged archaeological sites may include parts of port installations, harbors, and even entire cities (Baika, 2008; Boyce et al., 2004; Georgiou et al., 2021a; Levy et al., 2023).

However, with many of these sites being located in shallow waters, access by research vessels is restricted, or they lie at the edge of the coverage range of conventional geophysical systems (Gasperini et al., 2022; Mattei et al., 2018a; Ødegård et al., 2016; Papadopoulos, 2021). Furthermore, the coastal zone often consists of materials such as rocky substrates (Vandarakis et al., 2023), hard geomorphological features like beachrocks (Vousdoukas et al., 2007), or seafloors covered in seagrass (Panayotidis et al., 2022). These conditions diminish the effectiveness of traditional geophysical systems in accurately interpreting data, underscoring the need for the combined use of acoustic and optical tools (Georgiou et al., 2021b; Geraga et al., 2015; Mahon et al., 2011; Mattei et al., 2024, 2018b; Raimondi et al., 2015; Sakellariou, 2007).

The methodological approach used in this research for the multi-mapping of the archaeological site of Grotta Naxos proved remarkably effective, confirming the significant potential of advanced, non-intrusive techniques for the detailed documentation of submerged archaeological sites in shallow water environments with complex geomorphological seafloors (Mattei et al., 2024; Ravnås et al., 2023). This implementation represents a major advancement in the field of underwater archaeology and marine geoarchaeological surveying, offering precise and comprehensive investigation of the site while mitigating the limitations of conventional methods. According to accurate documentation of the submerged archaeological remains was achieved through the acquisition of georeferenced data sets and photogrammetric implications by the integration of acoustic and visual sensors (SSS, SBES, Camera) on the robotic platform. This method enabled the comprehensive and detailed mapping of the spatial distribution of ancient structures and the geomorphological characteristics of the site with metric precision.

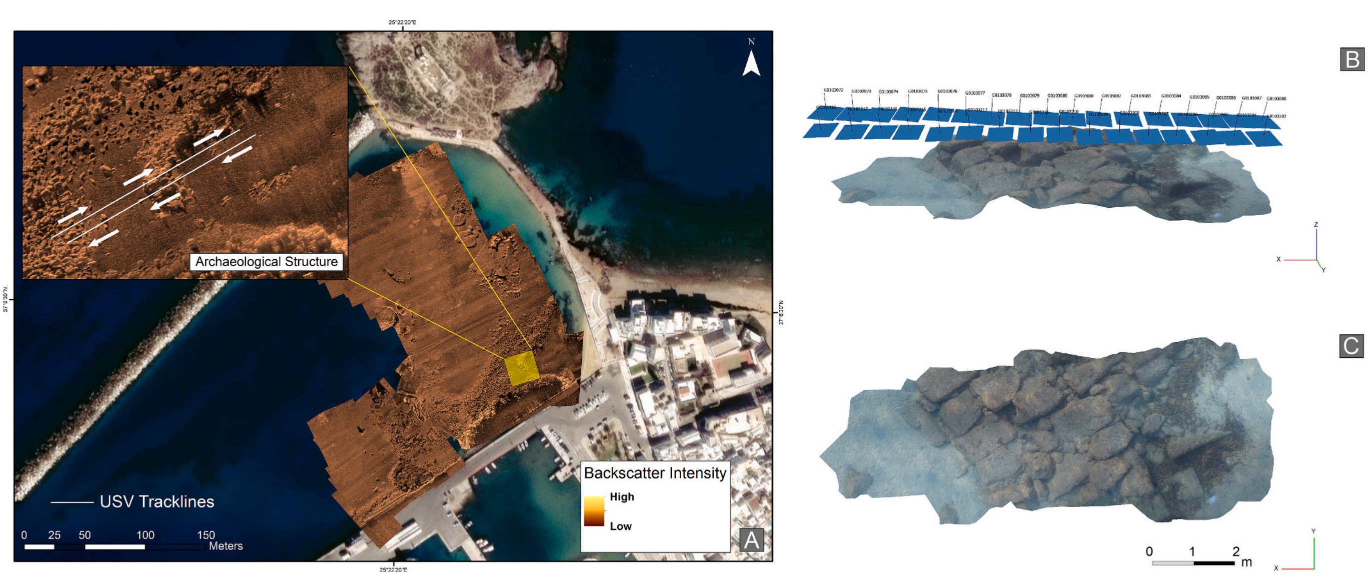

Fig. 6. (A) The location of Structure VIII and the navigation tracklines of the USV for photogrammetric documentation. (B) Images collected above the ancient structure for the creation of a 3D model. (C) Orthophotomosaic of the documented part of Structure VIII.

Additionally, the creation of 2D photomosaics and 3D models for archaeological purposes allowed the thorough study of their morphology (parametrization) providing high metric accuracy of centimeters to millimeters scale data (Georgiou et al., 2021a; Liarokapis et al., 2017; McCarthy et al., 2019; Wright et al., 2020).

In addition, the ability to achieve both range and resolution for detecting targets of archaeological interest on a large scale was met through the combination of diverse sensors, which allowed the acquisition of multiple categories of data, offering high-resolution and detailed representation of wide areas. This dual approach enabled the detection of subtle archaeological features across extensive survey areas while maintaining high precision in reconstructing the study area. Moreover, the optical sensors provided critical validation of the geophysical data, significantly improving the reliability and accuracy of the findings. While USV-based approaches offer numerous advantages, shallow-water environments present several challenges that can affect data acquisition and processing. Environmental factors such as rough seas, strong currents, and depths less than 40 cm are critical determinants of USV operational effectiveness. Highly reflective rocky substrates can diminish the efficiency of acoustic sensors, leading to reduced data capture capabilities. Additionally, the formation of acoustic shadows may obscure the size, shape, and nature of objects, introducing ambiguity, especially in complex underwater settings like submerged archaeological sites. These acoustic returns can distort object images, diminishing the clarity of documentation. On the other hand, optical sensors face challenges such as light refraction distortions and visibility limitations due to turbidity, suspended sediments, all of which decrease the precision of underwater photogrammetric implementation. Despite these challenges, the implementation of autonomous Unmanned Surface Vehicles (USVs) for underwater archaeological surveys offers a cost-effective, efficient, and environmentally sustainable solution, particularly in demanding environments like Grotta Naxos. The capacity of the USV to operate in ultra-shallow areas eliminates the need for vessels and/or large dive teams, extensive human resources, and specialized logistical support. As a result, it offers significantly lower operational costs and survey time compared to traditional surveying methods. The low-power electric motors of the USV further minimize the environmental footprint, making it less disruptive to fragile underwater ecosystems. Moreover, the automated nature of the survey process not only streamlines operations but also offers a scalable approach for future underwater archaeological projects, enhancing efficiency in diverse environments, from marine settings to rivers and lakes, while it can be adapted to various archaeological contexts, such as shipwrecks, submerged installations, and landscapes, by integrating a wide range of specialized sensors. This implementation serves as a crucial tool for evaluating and monitoring the condition of archaeological remains, making it a necessary step towards their protection and preservation (Gkionis et al., 2020; Levy et al., 2023).

6. Conclusions

The research presented in this study highlights the significant advancements achieved in the field of underwater archaeological surveying through the application of autonomous Unmanned Surface Vehicles (USVs) equipped with advanced geophysical and optical sensors. By integrating a compact side-scan sonar, single-beam echosounder, and underwater camera, we successfully conducted a comprehensive and non-intrusive survey of the semi-submerged archaeological site at Grotta Naxos. The dual use of acoustic and optical sensors enabled precise documentation of both the submerged structures and the geomorphological characteristics of the site, offering high-resolution data at centimeter to millimeter scale.

The methodological approach proved effective in addressing the primary objectives of the research. Accurate spatial mapping of submerged archaeological features was achieved with metric precision, while the combination of range and resolution allowed the detection of targets over a large survey area with complex underwater relief. Additionally, the experimental implementation of photogrammetric techniques successfully contributed to the creation of 2D mosaics and 3D models, providing a detailed understanding of the site's morphology and preservation status. These results underscore the importance of multi-sensor systems in producing reliable, high-quality data for both documentation and further interpretation while they are an obligatory step for their protection and conservation purposes against both human-induced and natural threats.

The study further demonstrates the practical benefits of employing an autonomous USV for archaeological surveys, particularly in ultra-shallow water environments. The cost-efficiency, adaptability, and environmental sustainability of this method present a transformative approach to underwater archaeological research. By reducing the need for large vessels and extensive dive teams, while minimizing the environmental impact, this technology offers a sustainable solution for future surveys, particularly in ecologically sensitive or logistically challenging areas.

In conclusion, the integration of USV-based technologies offers a robust, precise, and sustainable means of conducting underwater archaeological surveys. The success of this study not only confirms the potential of this approach for current research but also paves the way for its broader application in the field of marine archaeology and geoarchaeology, contributing significantly to both the documentation and exploration of underwater cultural heritage sites. To further advance this methodology, future research should explore its scalability by integrating additional sensors, such as multibeam echosounders (MBES), sub-bottom profilers (SBP), multi-camera systems, and electromagnetic sensors (e.g., ground-penetrating radars and magnetometers). This will reinforce the scope of the collected data and its discriminative capability, offering a diverse range of information that will actively contribute to the multidimensional exploration of various parameters in submerged archaeological sites. Additionally, incorporating AI and machine learning algorithms will support automated feature detection and classification, streamlining data processing and enhancing the dependability of archaeological and geomorphological interpretations.

CRediT authorship contribution statement

Konstantinos Merkouris: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Geraga:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Formal analysis, Data curation. **Xenophon Dimas:** Writing – review & editing, Data curation. **Andreas Vlachopoulos:** Writing – review & editing, Supervision. **George Papatheodorou:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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