2023 IMEKO TC-4 International Conference on
Metrology for Archaeology and Cultural Heritage
Rome, Italy, October 19-21, 2023

Geophysical and geoarchaeological investigations in the Submerged Archaeological Park of Baia (south Italy)

Crescenzo Violante[1], Enrico Gallocchio[2], Fabio Pagano[2], Nikos Papadopulos[3]

[1] Institute of Heritage Science (ISPC), RES-DATA Lab, National Research Council (CNR), via G. Sanfelice, 8, 80133 Naples (Italy), crescenzo.violante@cnr.it
[2] Phlegraean Fields Archaeological Park (PAFLEG), Palazzo de Fraja - Pozzuoli (NA), fabio.pagano@cultural.gov.it; enrico.gallocchio@cultura.gov.it
[3] Laboratory of Geophysical Satellite Remote Sensing and Archaeoenvironment, Institute for Mediterranian Studies, Foundation for Research and Technology, Nikiforou Foka 130, Rethymno, 74100, Crete, Greece, nikos@ims.forth.gr

***Abstract* – In this paper we present the activities and the preliminary results of archaeo-geophysical and geoarcheological investigations carried out by ISPC_CNR in the Submerged Archaeological Park of Baia (southern Tyrrhenian Sea) in the two-year period 2020-2022 in in the frame of a research agreement with the Phlegraean Fields Archaeological Park (PAFLEG). The surveys were undertaken as part of three marine campaigns carried out in collaboration with the Norbit Subsea of Trondheim (Norway), the Subseafenix of Ravenna (Italy) and the Institute for Mediterranean Studies (IMS) - Foundation for Research and Technology Hellas (FORTH). This latter activity was founded by the 'Integrated Platform for the European Research Infrastructure on Heritage Science' (IPERION HS).**

The collected data have enabled the characterization and mapping of the archaeological and geological features of the seabed and shallow sub-seabed at very and ultra high resolution, with important and innovative implications on the protection and management of the underwater cultural landscape.

Introduction

The study and documentation of cultural heritage with geophysical and remote sensing techniques is continuously developing as technology advances, providing increasingly detailed dataset for interpreting cultural sites in different environmental contexts. In the marine environment, the integration of remotely sensed data acquired by sonar systems from ships and marine drones, and the analysis of seafloor acoustic imagery and bathymetry, provide an advanced digital database from which to extract information, build models and develop algorithms for archaeological and geo-archaeological research, and develop applications for the reconstruction and preservation of underwater artefacts and cultural landscapes [1]. In addition, modern seismic imaging techniques have proven to be effective tools for obtaining high-resolution data of buried built environment beneath the seabed, even in shallow water areas [2].

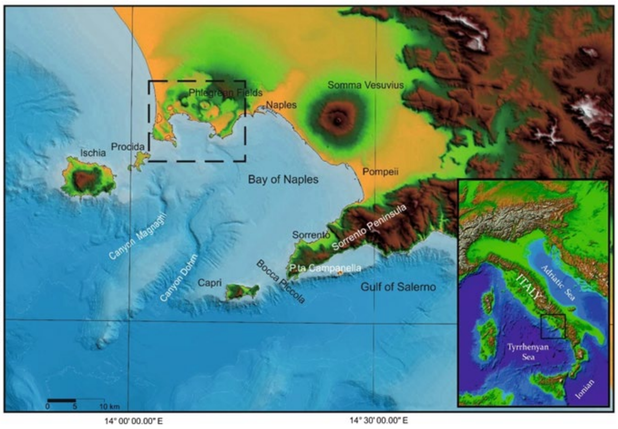

Fig. 1. Location of the study area.

The methods with the greatest potential for classifying and mapping submerged archaeological objects involve the use of multibeam echosounders (MBES), primarily designed to provide quantitative bathymetric data and subordinately seafloor reflectivity, and parametric sub-bottom profilers (SBPs) for producing acoustic images of buried objects and palaeo-topographies. Modern systems cover large areas of the ocean floor from a safe distance, while resolving the 3D shape of submerged objects with high detail. These techniques generate very high resolution data that are repeatable and quantifiable and that can be easily integrated with other scientific and terrestrial data. They are used on discrete sites, such as shipwrecks [3, 4], as well as large stretches of seabed to reconstruct ancient submerged landscapes of cultural interest [5, 6].

This paper presents the activities and the preliminary results of archaeo-geophysical and geoarchaeological investigations carried out in the Protected Marine Area and Submerged Archaeological Park of Baia (Fig.1) in the two-year period 2020-2022 as part of a research agreement with the Archaeological Park of the Campi Flegrei (PAFLEG). The geophysical investigations included bathymetric and seismo-stratigraphic surveys at very-high and ultra-high resolution, and ERT surveys in selected coastal and marine areas of the Baia submerged site. Visual inspections of the seabed by means of ROV systems have been also performed.

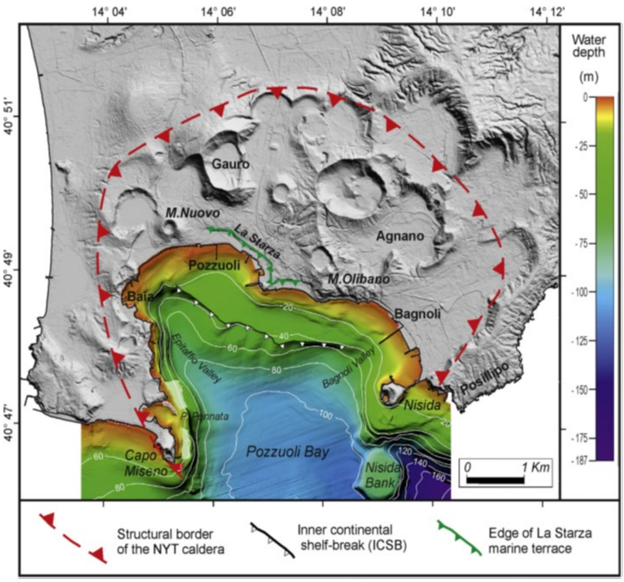

Fig.2. Geological sketch of the study area.

I. THE STUDY AREA

The study area is located in the Caldera Flegrea, an active volcanic area (Fig. 2), characterized by frequent earthquakes, hydrothermal events and slow ground uplift and subsidence phenomena known as bradyseism [7]. Over the past millennia, bradyseism has caused the submergence of large sectors of the coast and significant changes to the marine-coastal landscape. The study area is also characterized by the presence of gas emissions on the seabed. Several thermal springs with hot water emissions (up to 93°C) containing methane, Sulphur dioxide, arsenic and carbon dioxide are located 1,500 meters south of Pozzuoli (the Secca delle Fumose) between -10 and -15 m depth.

The Roman city of Baiae was founded in the Gulf of Pozzuoli (NA) on the shores of a coastal lake (the Baianus Lacus), which was connected to the sea by an artificial channel (Fig. 3). Due to bradyseism, a large part of the city including residential villas and other Roman artefacts and structures dating from the 1st century B.C. to the 4th century A.D. were inundated by the sea. The ruins of luxury buildings, domus, mosaics and mooring ports are now submerged up to a depth of approximately -15 m. Among the most important structures that surrounded the Baianus Lacus are the Nymphaeum of Claudius (1st century BC), a bath complex of two buildings near the Nymphaeum and a large villa attributed to the Pisoni family. The latter has a rectangular plan and consisted of several rooms with much of the inner sector occupied by gardens surrounded by apses and columns. Geological data indicate that the site of Baiae was active at least until the end of the 4th century AD, a period in which it began its decline following the onset of bradyseism and the consequent flooding of entire areas of the town [8].

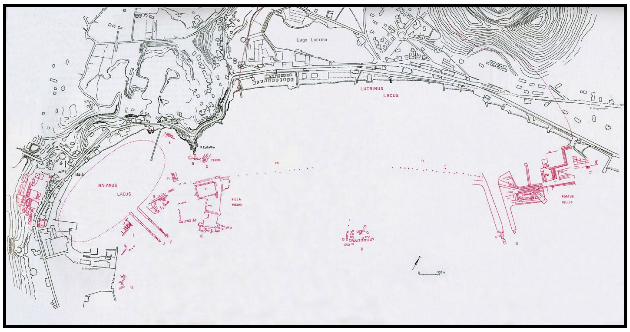

Fig.3. Archaeological map of the study area [14].

II. MATERIALS AND METHODS

A. Acoustic remote sensing

In the aquatic environment, acoustic waves are the most efficient means of investigation because of their ability to propagate through water (up to several kilometers) without significant attenuation. The level of attenuation depends on frequency and is greatest for high frequencies. The acoustic energy carried during propagation can be used to make measurements of the traversed medium.

Underwater acoustic remote sensing based on sonar systems has been used to locate and document underwater archaeological sites and objects occurring at seabed or buried beneath marine sediments. Bathymetric and backscatter data as well as those derived from surveys with sub-bottom profilers have been used for studies on site formation aimed at assessing the impact of physical, biological and chemical processes on an archaeological site over time [9].

Sonar systems are designed to generate electrical signals that are converted to acoustic energy by a transducer-transmitter that generates a sound pulse in the water column at a given frequency. The acoustic energy of the signal returning from the bottom (echo) is then converted into electrical energy through a transducer-receiver. In addition, these systems measure the arrival times of the returning echoes).

Multibeam bathymetry. Two models from Norbit Subsea were used to carry out the bathymetric surveys, the WINGHEAD i77h model (Fig. 4) and the WINGHEAD i80S model, both with a working frequency of 400 kHz and operating in a bathymetric range from a minimum of 0.5 metres up to approximately 300 metres. These are integrated systems consisting of three elements: a curved transducer, a small Sonar Interface Unit (SIU) and a pair of GNSS receivers in which the processing of the seabed detection takes place inside the sonar head, which also integrates an Applanix Ocean Master high-performance inertial navigation system. Both systems perform bathymetric measurements with an accuracy of up to 2 cm (according to IHO certification) and a resolution of approximately 1 cm.

Fig.4. Sonar head of the WINGHEAD i77h MBES system

The survey took place in November 2021 in the zone A of the Baia MPA at a seabed depth ranging from 1 and 10 meters. The survey lines were spaced to ensure 100% coverage of the investigated seafloor.

The processing of bathymetric data was carried out using the Qimera post-processing module of the QPS Qinsy software. Data processing included the following steps: 1) position correction, using a module for automatic correction of anomalous data 2) depth correction, using a module for tidal compensation and 3) statistical data control. The obtained high density point cloud allowed a gridding with a bin size of 10 cm.

Subbottom profiling investigation. The seismic survey was conducted with the SES-2000 parametric echosounder (PES). This is a compact system consisting of a small transducer (~20 × 20 cm; Fig. 8) and a receiver unit with analogue-to-digital signal conversion elements. The acoustic source simultaneously transmits two slightly different high-frequency signals (typically 100 and 110 kHz) at high pressures. The interaction of two high frequencies at high pressure generates new frequencies in the water. One of these is the 'difference frequency' (DF) and is between 6 and 14 kHz. This new low-frequency signal has a very narrow beam width of ±1.8° (independent of frequency), high directivity with virtually no side lobes during transmission and a bandwidth similar to the primary frequency signal (100 kHz). This configuration allows very high vertical and horizontal resolutions (cm/dm range) and a better signal-to-noise ratio than linear SBP[10].

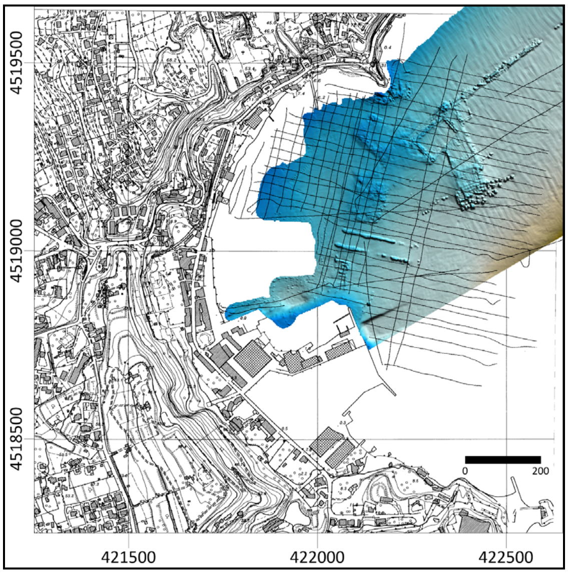

Fig.5. Subbottom survey grid

Over 40 km of very high resolution PES profiles were acquired with a survey grid consisting of 29 lines oriented in the WNW-ENE direction and 20 lines in the NNE-SSW direction, covering a total area of 0.5 km^2 (Fig. 5). The bathymetric interval of the investigated area is 1-15 m. The average spacing distance between survey lines was approximately 20 m. The survey was carried out on board of a rubber boat with shallow draught. PES transducer was fixed on an iron pole and attached to the side of the boat (Fig. 16).

The high ping rate (up to 40 pulses/s) used during the survey, combined with low speed (2-3 knots), allowed for very high lateral sampling (data points every 5-10 cm along the line). The POS-MV WaveMaster inertial navigation system made it possible to filter wave motion and determine the vessel's position with centimeter accuracy. Acquisition frequencies ranged from 6 to 12 kHz with a pulse duration of 100 μs. This resulted in a vertical resolution of 0.1 m.

Underwater ROV inspection. Underwater visual documentation was carried out using a BluRov2 remotely operated vehicle (ROV) from BluRobotics equipped with a Low-Light HD camera (Fig. 10) for monitoring benthic features (up to 50 m). Video images and photos acquired during the survey were transmitted to a monitor located on board and monitored in real time by the operator.

B. Underwater Electrical resistivity tomography (U-ERT)

Resistivity methods use direct or alternating current fields to measure the electrical potential of the corresponding current [11]. Various arrays (or configurations) always based on the use of four electrodes are used for ERT surveys. The choice of the appropriate array for a given investigation depends on different factors such as the area of investigation, the nature and depth of the targets, the properties of the subsurface, the type of equipment and the depth of investigation.

Fig.6. Layout of dynamic ERT lines superimposed on a Google Earth satellite image of the study area.

Generally this technique is used in horizontal mapping mode (i.e. a fixed configuration of electrodes moving along a profile or grid, providing the horizontal distribution of resistance), but it can also be adapted to measure the vertical distribution of resistance. Electrical resistivity tomography is generally performed along parallel transects in an attempt to map soil resistivity properties in a 3D context [12]. For marine areas, the choice of survey mode (static or dynamic; Fig. 6) is fundamentally based on the thickness of the water column and the actual seabed conditions. In areas where the water depth exceeds 1 m, the dynamic mode is applied in order to maximize the resolution of ERT images both in terms of stratigraphic mapping and the detection of buried targets [13].

III. PRELIMINARY RESULTS

A. Multibeam bathymetry

The MBES survey covered the Zone A of the Baia Marine protected Area. The remains of the Villa dei Pisoni, the Thermae of the Lacus and the Nymphaeum of Claudius are located in this area. The acquired multibeam bathymetry data allowed the production of ultra-high resolution maps that describe the archaeological, sedimentological and geomorphological features of the investigated marine area in great detail. In particular, ultra-high resolution MBES data revealed new archaeological features such as the presence of a fishpond along the southern side of the Villa dei Pisoni and a docking areas in the northern side. The high density point cloud also allowed the construction of three-dimensional models of the seabed features and archaeological remains (Fig. 7).

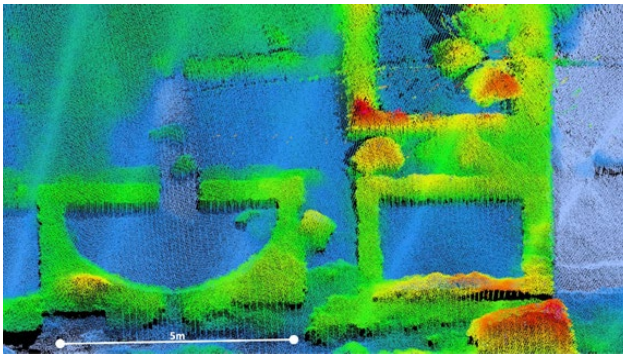

Fig.7. 3D point cloud reconstruction of seabed archaeological features from multibeam data.

B. Sub-bottom profiling data

Geophysical investigations carried out in the submerged Roman site of Baiae with the SES-2000 parametric echo sounder (PES) system proved to be an excellent method in mapping buried archaeological and stratigraphic features in shallow water environment. The acquired PES profiles revealed a detailed image of the stratigraphic organization of the Baianus Lacus (fig. 3). The preliminary interpretation of seismic data indicates a detailed picture of the subseabed morphology with important information on the original features and shape of the ancient Baianus Lacus. Despite low penetration due to multiple reflections in very shallow water, good results have been obtained up to water depth of ca. 1 m. Here buried artificial structures and palaeo-morphologies are detected in the very upper layers of the seafloor. Also, the very high quality of the acquired sub-bottom profiles will provide important information to reconstruct the local geological history of the study area.

C. ROV inspections

Eight ROV transects were carried out at different locations in the Baia MPA. The visual information (video and photos) obtained provided elements for sedimentological, biological and archaeological characterization of the seabed. In particular, it was possible to identify the characters of the archaeological structures and the main associated biological communities. In this meaning, the acquired ROV data allowed to calibrate and validate the information obtained from the above described geophysical investigations, providing indications about the biotic and abiotic component of the investigated seabed.

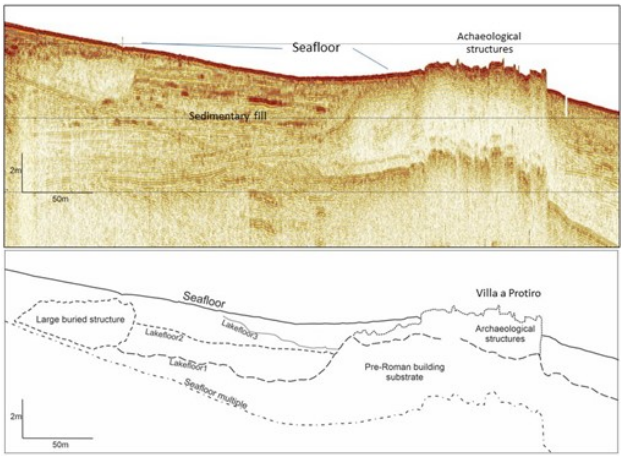

Fig.8. An example of processed PES sub-bottom section (upper figure) with interpretation (lower figure).

D. U-ERT data

Due to the occurrence of a buried large metallic object probably related to a ship's funnel only a part of the ERT profiles acquired in static mode were considered. The 3D resistivity inversion model of these data showed a low RMS error (3.76 %) indicating the good quality of the collected data. The resistive characteristics of the sub-seabed resistivity (first 1.5 m) indicate the presence of probable structural remains belonging to a large building complex.

The spatial distribution of the ten ERT profiles acquired in dynamic mode prevented 3D processing of the tomographic data. All profiles show a thick resistive layer (> 0.8 Ohm-m) with an undulating upper surface at depths greater than 2-2.5 m. Within the upper layers, very shallow resistivity anomalies were detected, which may indicate the presence of archaeological structures. The interpretation of these resistivity anomalies may indicates the presence of buried archaeological structures possible connected with Roman buildings occurring along the coast (Fig. 24).

AKNOWDLEGMENT

We would like to thank Stefano Mancini (Subseafenix s.r.l.) and Eduardo Ruspantini (Sealand Adventure s.r.l) for technical and logistic support. This work was supported by the project FOE "Technological innovation for the protection, promotion and protection of Cultural Heritage ", financed by the Italian Ministry of Education - Ministry of University and Research.

REFERENCES

[1] C. Violante, "Acoustic remote sensing for seabed archaeology". Proceedings of the International Conference on Metrology for Archaeology and Cultural Heritage, 2020. Trento, Italy, 21-26. ISBN: 978-92-990084-9-2.

[2] T. Missiaen, "The potential of seismic techniques in marine archaeological research". *Relicta* - Archeologie, Monumenten-en Landschapsonderzoek in Vlaanderen, 2010, 6, 219–236.

[3] R. Plets, R, Quinn, W. Forsythe, K. Westley, T. Bell, S. Benetti, F, McGrath, R, Robinson, "Using multibeam echo-sounder data to identify shipwreck sites: archaeological assessment of the Joint Irish bathymetric survey data" International Journal of Nautical Archaeology, vol. 40 (1), 2011, pp. 87-98.

[4] A. Grzadziel, "Using Remote Sensing Data to Identify Large Bottom Objects: The Case of World War II Shipwreck of General von Steuben", Geosciences, vol. 10, 240, 2020, pp. 1-15, doi:10.3390/ geosciences10060240.

[5] C. Violante "A geophysical approach to the fruition and protection of underwater cultural landscapes. Examples from the Bay of Napoli, southern Italy", In: Aveta, A., Marino, B.G., Amore R. (eds.), La Baia di Napoli. Strategie per la conservazione e la fruizione del paesaggio culturale, vol. 1, pp. 66-70, 2018, ISBN: 978-88-99130.

[6] K. Westley, R. Quinn, W. Forsythe, R. Plets, et al., "Mapping Submerged Landscapes Using Multibeam Bathymetric Data: a case study from the north coast of Ireland. International Journal of Nautical Archaeology, vol. 40(1), pp. 99-112.

[7] G. De Natale, C. Troise, F. Pingue, G. Mastrolorenzo, L. Pappalardo, M. Battaglia, E. Boschi, "The Campi Flegrei Caldera: Unrest mechanisms and hazards", in Troise C. et al. (eds.) Mechanisms of Activity and Unrest at Large Calderas, Geological Society Special Publications, 269, 2006, 25–45.

[8] U. Pappalardo, F. Russo, "Il bradisismo dei Campi Flegrei (Campania): dati geomorfologici ed evidenze archeologiche", in: P. Gianfrotta, F . Maniscalco (Eds) "Forma Maris, Forum Internazionale di Archeologia Subacquea", Pozzuoli (Naples), Massa Editore, Napoli, 2001, 107–129.

[9] R. Quinn, D. Boland, "The role of time-lapse bathymetric surveys in assessing morphological change at shipwreck sites". Journal of Archaeological Science, vol. 37 (11), 2010, pp. 2938-2946.

[10] S. Muller and J. Wunderlich, Detection of embedded objects using parametric sub-bottom profilers, Int. Hydrogr. Rev., 4(3), 2003, 76–82.

[11] S. Hecht and J. W. E. Fassbinder, "A view beneath

the soil: Application of magnetometry and Electrical Resistivity Tomography (ERT) in geoarchaeological research", Geographische Rundschau, 58(4), 2006 38- 45.

[12] K. Simyrdanis, N. Papadopoulos, J.H. Kim, P. Tsourlos, and I. Moffat, "Archaeological Investigations in the Shallow Seawater Environment with Electrical Resistivity Tomography". Journal of Near Surface Geophysics, Integrated geophysical Investigations for Archaeology, 13, 2015, 601 – 611.

[13] N. Papadopoulos "Shallow Offshore Geophysical Prospection of Archaeological Sites in Eastern Mediterranean". Remote Sensing, 2021, 13(7):1237. doi.org/10.3390/rs1307123.