BLUEMED

Activity 4.2
Preparatory activities in pilot sites

Deliverable 4.2.2
Survey and 3D documentation of the pilot sites

June 2018

Activity Leader: UNIZG

Deliverable Team: UNICAL, UNIZG, ATL

Summary

1. Overview

According to BLUEMED's project proposal, during Activity 4.2 "Preparatory activities in pilot sites", some preliminary activities have been conducted in the identified 4 test sites. These activities have included, among others, the survey and 3D documentation of the selected underwater archaeological sites.

This document reports the results of the optical and acoustic survey campaign that has been carried out by a multidisciplinary team composed of the BLUEMED partners UNICAL, UNIZG and ATL with the aim to collect 3D data that will be used for the creation of the underwater virtual scenarios. These virtual scenes will run both in the Virtual Diving systems that will be deployed in KACs and in the underwater tablets for the creation of the Augmented Diving systems.

2. Methodology for 3D reconstruction of underwater archaeological sites

The 3D reconstruction of a submerged archaeological site is a long and difficult process because of the underwater environment. UNICAL, within the VISAS project has designed and developed a method that exploits the high-resolution data obtained from photogrammetric techniques with recent advances in the construction of acoustic micro bathymetric maps in order to build three-dimensional representations combining the resolution of optical sensors with the precision of acoustic bathymetric surveying techniques. In fact, while the acoustic techniques are usually adopted for acquiring a great amount of data at long distances even under bad visibility conditions, on the contrary, the optical techniques are more suited for close-range acquisitions and allow for gathering high-resolution, accurate 3D data and textures, but the results are strongly influenced by turbidity. The method exploits the joined use of these technologies to obtain a complete representation of the underwater scene and to geo-localize the optical 3D model using the bathymetric map as a reference.

The method develops in the following phases: after a first inspection of the site in order to localize the areas of greatest importance from an archaeological point of view, the integrated survey is realized. Subsequently, the optical and acoustic data are aligned by using geometrical features correspondences in both acoustic and optical representations. For this purpose, we use the information coming from accurate depth measurements (with errors on positioning < 1cm) obtained employing a high frequency multibeam equipment. Furthermore, to improve the accuracy on positioning, some additional measures can be performed by using custom opto-acoustic markers placed on the seabed. Finally, the opto-acoustic multi-resolution 3D model of the whole underwater archaeological site is generated by merging the high-resolution textured 3D model of the archaeological remains and mapping the 2D images of the surrounding area onto the low-resolution polygonal mesh obtained from the acoustic bathymetry.

The main steps of the proposed methodology are shown in Figure 1.

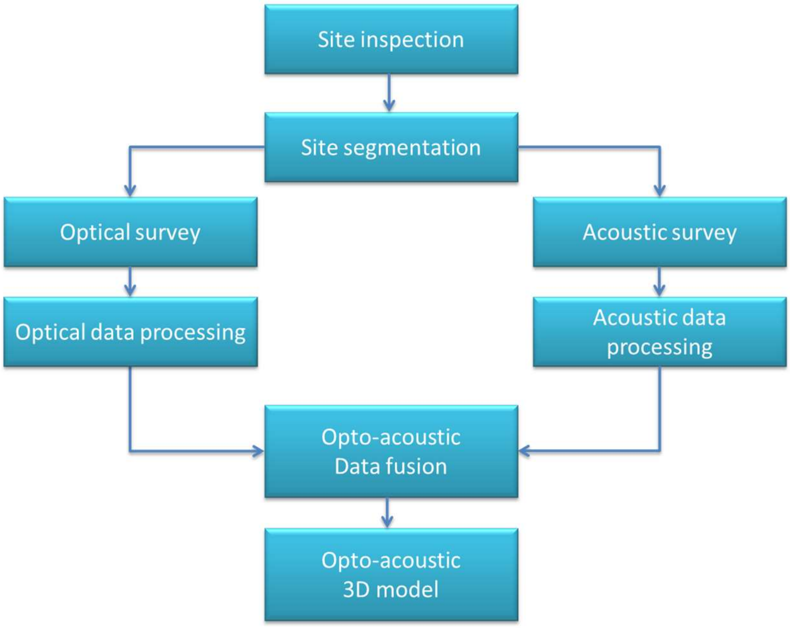

Figure 1. Processing pipeline of acoustic and optical data

The optical and acoustic data are fused by using a target–based registration approach. This technique is based on the detection of homologous geometrical entities (features) between the two representations and their subsequent alignment. For this purpose, we can use man-made targets placed on the seabed or the geo-location of some GPSs (Ground Control Points) performed by adopting an USBL system. In the first solution, taking into account that the reflective properties of the optical and acoustic signals vary according to the materials to be used, we have opted for leveraging the high reflectivity of the air in water, so we have designed custom opto-acoustic markers built from aluminium structures covered by bubble wrap. These markers, clearly visible in both representations, are manually identified in order to obtain a rough alignment of the optical and acoustic point clouds. In the second solution, the location, orientation and scaling of the optical 3D models on the acoustic map is performed using the geo-referencing data. In both cases the registration is refined by means of an automatic registration algorithm, i.e. the Iterative Closest Point (ICP).

Using the information coming from accurate depth measurements (with errors on positioning on the order of centimetres) obtained with the high frequency multibeam equipment, the geo-referencing of the optical point cloud ends up to be a by-product of the registration step.

The last steps of the process consist of meshing and texturing the opto-acoustic point cloud of the underwater archaeological site. Meshing of point clouds may be carried out using a dedicated software. We use JRC 3D Reconstructor®, which has the ability to create a mesh by using an efficient multi-resolution algorithm and to perform further refinements of the model by using the point cloud as reference, so that the model reconstruction is performed in a coarse-to-fine fashion.

In order to place textures on the 3D model, we use a technique based on the projection and blending of 2D images on the 3D surface. In particular, since the camera poses are known downstream of the optical 3D reconstruction process, we can directly map the high-resolution images on the portion of the 3D surface of the model representing the archaeological remains. For this purpose, we selected an image subset, because the averaging among neighbourhood values during the blending on the images works better if performed on a largely overlapped area (due to the reduction of blurring).

The low-resolution polygonal mesh of the seabed is in turn obtained from the acoustic bathymetry and textured with a tile-based texture mapping approach that just requires to set some sample images of texture tiles instead of a large texture.

3. Survey and 3D reconstruction activities on the Italian pilot site

3.1 Activities on the Marine Protected Area (MPA) of Capo Rizzuto

As reported in Deliverable 4.2.1, UNICAL, as responsible of the Capo Rizzuto pilot site, has carried out during the summer 2017 a surveys campaign at the underwater Roman wreck of "Cala Cicala" (Crotone) with the aim of testing the methodology designed in WP3 studies concerning the documentation, restoration and conservation protocol for Underwater Cultural Heritage (UCH). Even though the preliminary study for launching the pilot action was planned for spring 2018, we have decided to move up the activity in June 2017 in order to test the effectiveness of the methodology and confirming the proposed approach as a best practice one, ready to be replicated in the other pilot sites.

3.2 Activities on the Underwater Archaeological Park of Baiae

a) Acoustic Survey

Acoustic survey operations at Baiae pilot site have been conducted by UNIZG-FER team on 14-18.5.2018 with the aim of creating bathymetric maps that have been used by the MiBACT-ISCR Underwater Conservation Unit (NIAS) team to plan the restoration activities during the campaign held in the summer season 2018 (see D4.2.3). The main emphasis of this operation was to gather as much bathymetric data of the site as possible, so the ASV with bathymetric sonar was mostly deployed for survey missions. For this reason, the ROV has not been used for visual inspection of the site, and UAV has not been used since we did not have official permission for operating it in the Baiae port area.

The boundary of the survey area has been determined based on a GIS map provided by the local diving center from which an operation boat has been rented as well. Survey missions were planned in a shape o dense lawnmower patterns, with a high percentage of along-track overlap between sonar swaths (30m distance between survey lines at 120 degrees of sonar swath angle of view), as well as across-track overlap with additional perpendicular lawnmower patterns (Figure 2).

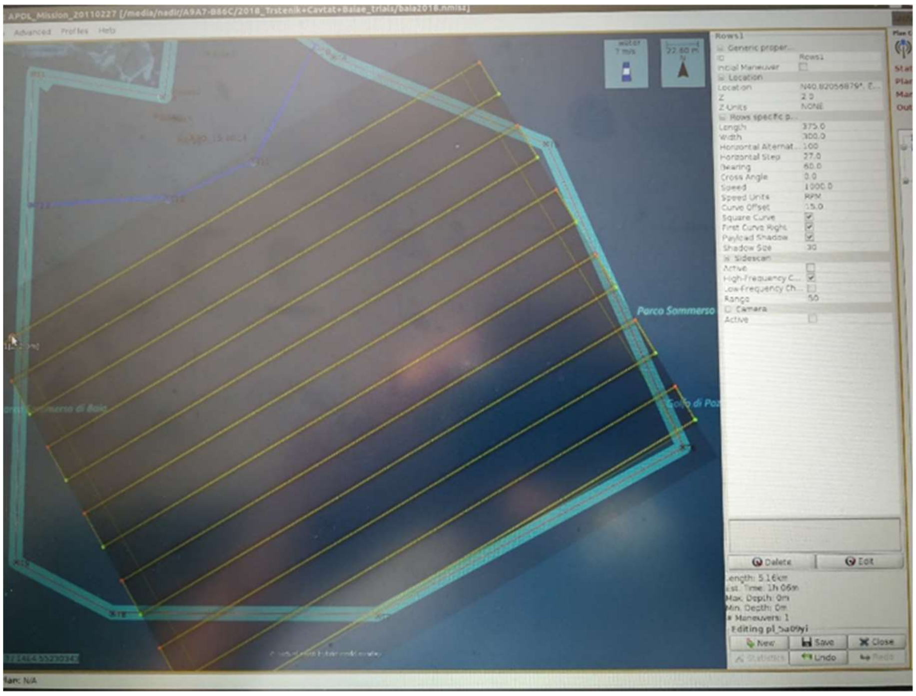

Figure 2. A preliminary lawnmower coverage plan in Neptus mission command and control software for the ASV with an onboard bathymetry sonar for Baiae pilot site.

A boat was rented from the local diving center for the bathymetry and photogrammetry data collecting operations by the surface and underwater autonomous marine vehicles. It was quite spacious so deployment and recovery of the autonomous vehicles by the crane was not problematic (Figure 3).

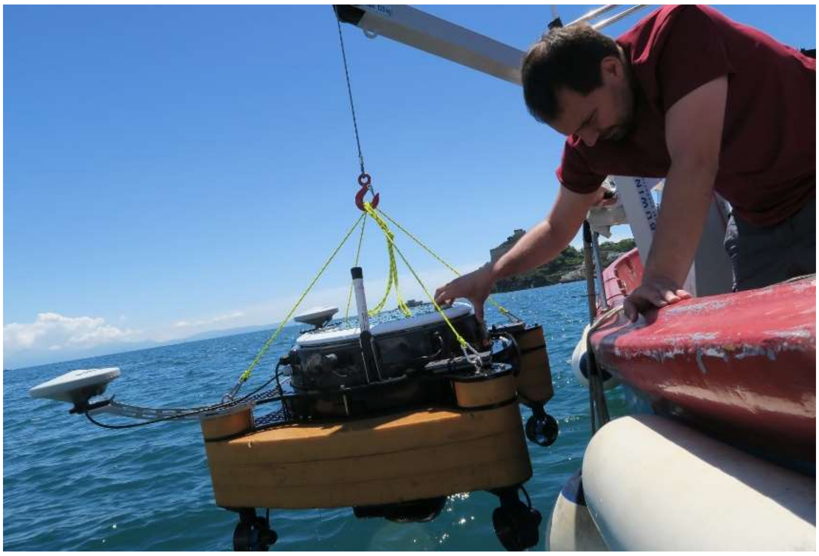

Figure 3. Deployment of the ASV by a transportable crane.

The autonomous surface vehicle (ASV) PlaDyBath was operated by Đula Nađ, who designed lawnmower-shaped survey missions along and across the area of interest in the Baiae bay. The missions were planned with 90-120˙ field of view angle of the Norbit multibeam sonar used for bathymetry, having in mind to cover the whole area with complete overlap between any two adjacent along-track survey lines, and also having across-track survey lines to maximize the amount and quality of the bathymetry data as much as possible, and to avoid holes in the bathymetry map. As soon as one mission would finish, the sonar data and position/attitude data were transferred from the ASV to a laptop, and bathymetry data were processed. Meanwhile, another mission was started, so data collection and processing were parallelized as much as possible (Figure 4).

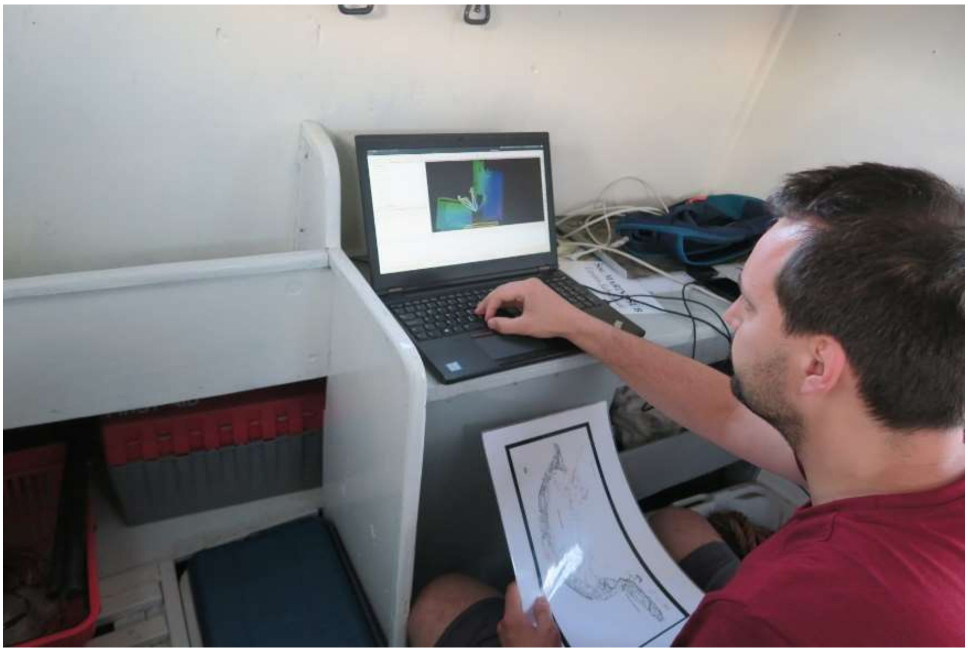

Figure 4. Analysis of the acquired bathymetric data

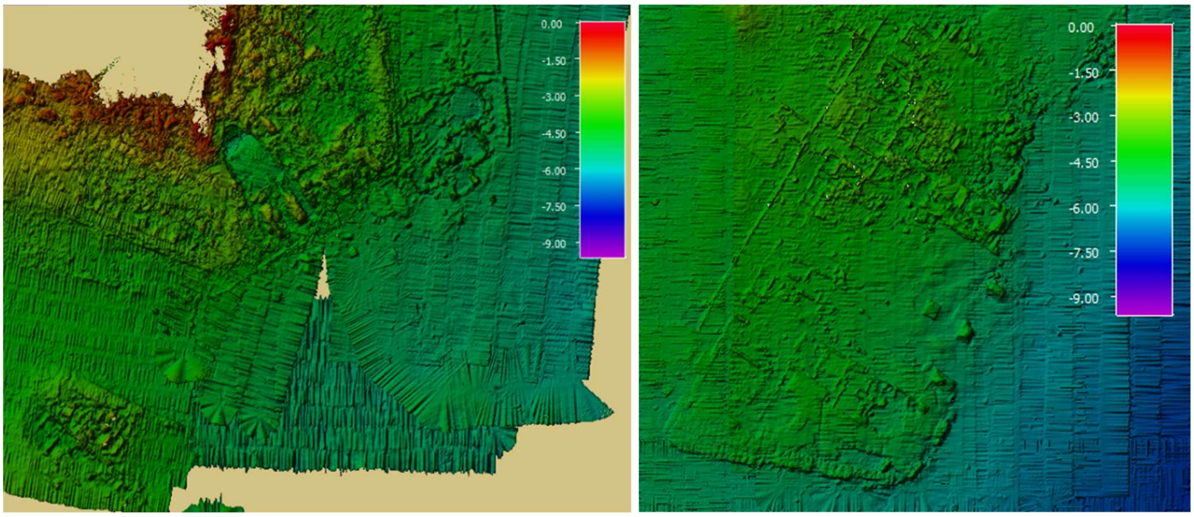

Figure 5. Details of the Baiae pilot site’s bathymetry.

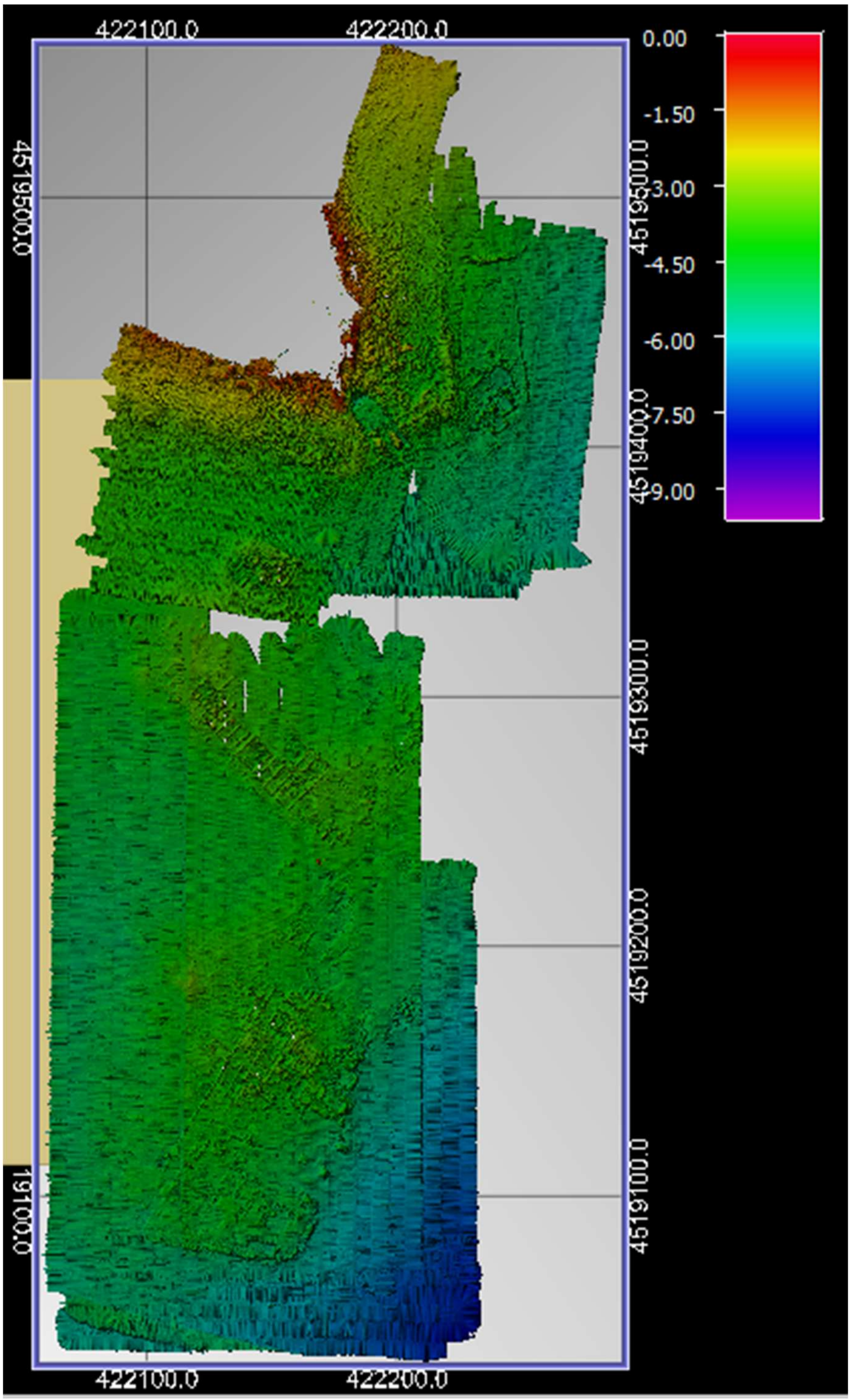

Figure 6. Preliminary results of the whole Baiae pilot site's bathymetry

AUV was operated by Nadir Kapetanović, and was used for additional side-scan sonar imaging of the pilot site, examples of which are given in a composite side-scan sonar imaging results overlaid in Google Earth (Figures 7,8). It has also been deployed for gathering visual data of the site at 2m altitude from the seafloor, but due to problems with its underwater localization, it drifted a lot from the set coverage plan when it was underwater during the whole mission.

Figure 7. Deployment of the AUV for side-scan sonar survey mission

Figure 8. Overlay of three side-scan sonar survey missions' data with visible outlines of ancient walls.

A crosshatch coverage plan for “Villa a Protiro” site was designed, in which the AUV dives out after finishing each transect, and records video of the site during the whole duration of the survey mission. Since the average depth at the site was approx. 6m, this meant that the AUV will not lose most of the mission time on diving and resurfacing. The camera integrated into the AUV is a 1.4 MP network camera, which is synced with a LED flash at maximum 15fps. The crosshatch coverage plan is designed based on the desired operating altitude, horizontal and vertical viewing angles of the camera, length and width and north-east orientation of the effective survey area, desired along- and across-track overlap percentage, and surge speed of the vehicle.

4. Survey and 3D reconstruction activities on the Croatian pilot site

4.1 Activities on the underwater archaeological site of Cavtat

a) Acoustic Survey

The first objective of the operations conducted in the underwater archaeological site of Cavtat has been the creation of a detailed bathymetry of the area containing both amphorae and dolia to be used for the realization of the underwater virtual scenario representing this site. Moreover, during the survey campaign, the integration and testing of the short baseline (SBL) acoustic positioning system in the autonomous surface vehicle for underwater tablet localization and communication has been performed. Also, a diver-friendly Android application for the interaction with the autonomous surface vehicle has been tested.

The UNIZG-FER team used a catamaran rented from the diving center Epidaurum from Cavtat as support vessel for their research purposes, deploying and recovering the surface and underwater vehicles, planning survey missions etc. All the equipment was stored safely in the diving center Epidaurum overnight for charging batteries (Figure 9).

Figure 9. UNIZG-FER equipment stored in Epidaurum diving center, Cavtat, Croatia for overnight batteries charging

In the first step of the fieldwork, the UNIZG-FER team, namely Đula Nađ, Milan Marković, and Nadir Kapetanović, with the help of the crew from the diving center Epidaurum, have located the area where amphorae cage and the site containing the dolia were. Then, a more accurate position has been determined by using the side-scan sonar data gathered by the AUV (Figures 10, 11).

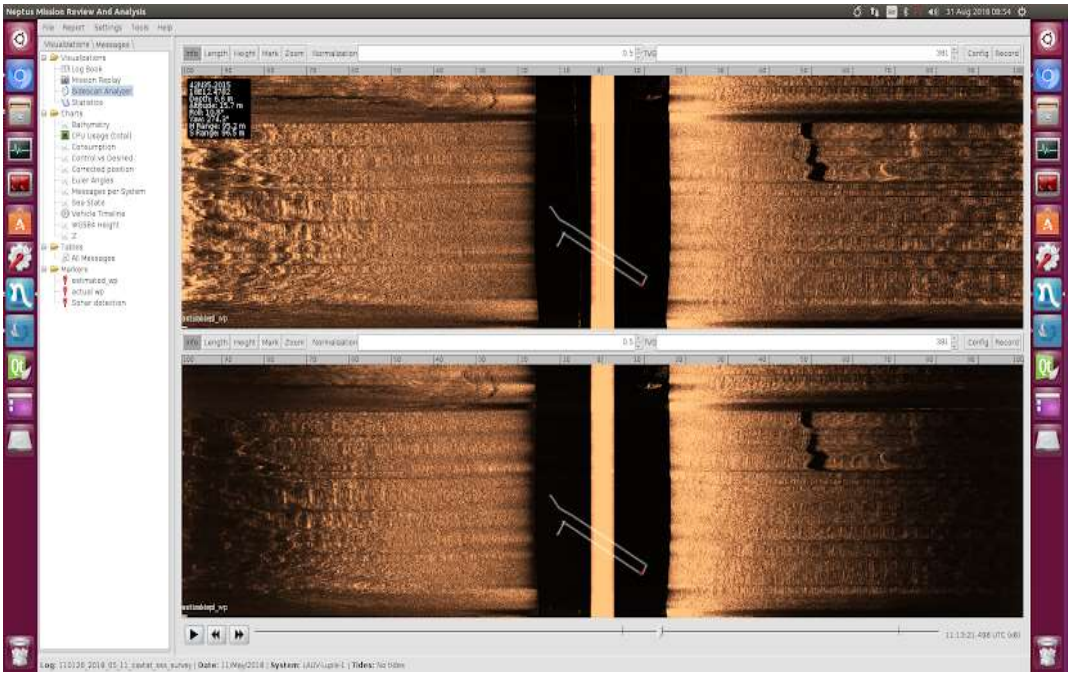

Figure 10. Side-scan sonar imaging of the amphorae cage site.

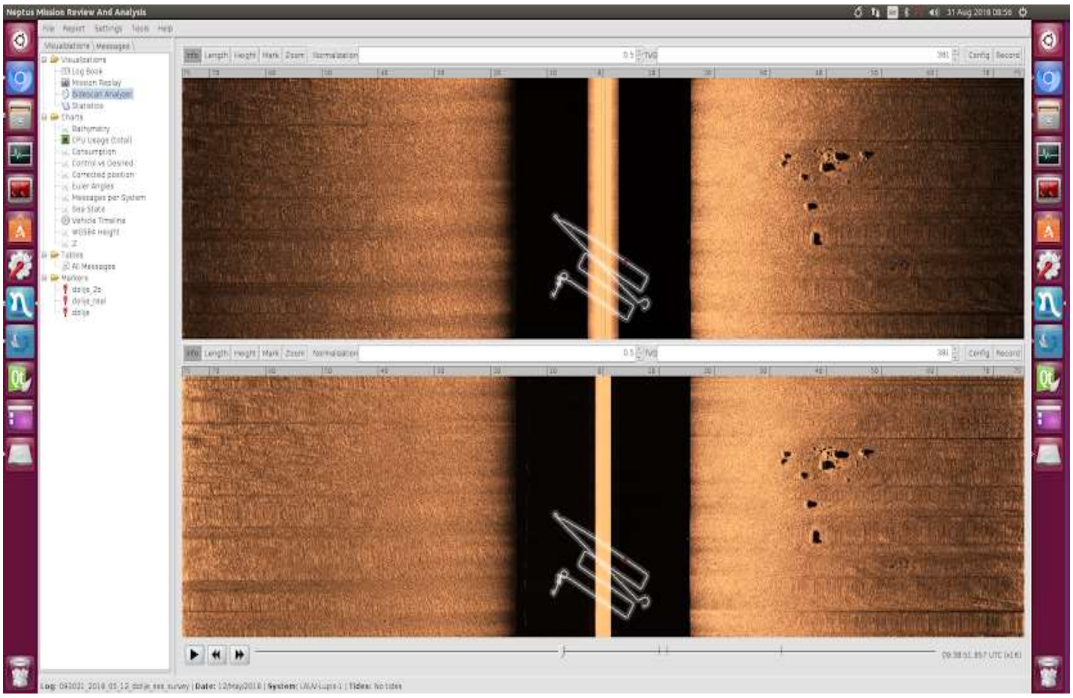

Figure 11. Side-scan sonar imaging of the dolia site.

This enabled for the bathymetry sonar mounted ASV to perform general survey missions to get low-resolution bathymetric data without much sonar swath overlapping, as more detailed bathymetry missions at Cavtat site were planned for June.

As been previously done in Baiae pilot site, the survey missions have been planned to be conducted by following a shape of dense lawnmower patterns, with a high percentage of along-track overlap between sonar swath, as well as across-track overlap with additional perpendicular lawnmower patterns. Results are shown in Figure 13.

The diver localization system with the SBL mounted below the second ASV provided by UNIZG-FER has been successfully tested. In detail, in the first phase of in-sea tests, the ASV was tied to the stern of the rented catamaran in order to estimate the localization accuracy (**Errore. L'origine riferimento non è stata trovata.**). After successful initial in-sea testing, the ASV was deployed for station keeping in the vicinity of the divers' buoy, to behave as a reference point in the developed Android application for diver's underwater tablet (Figure 12).

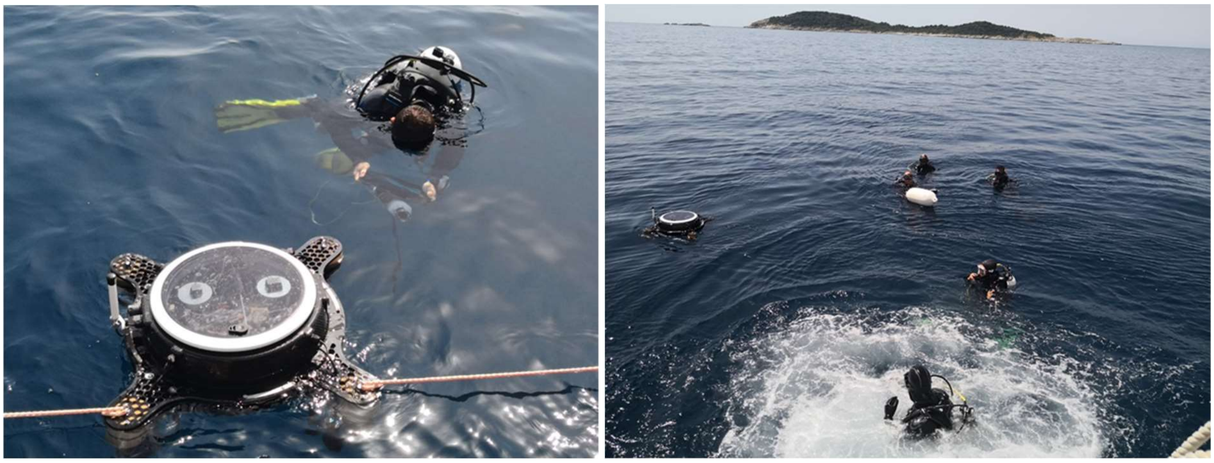

Figure 12. In-sea testing of the integrated SBL diver localization system (left). SBL ASV in dynamic positioning mode at the reference buoy position for the divers (right).

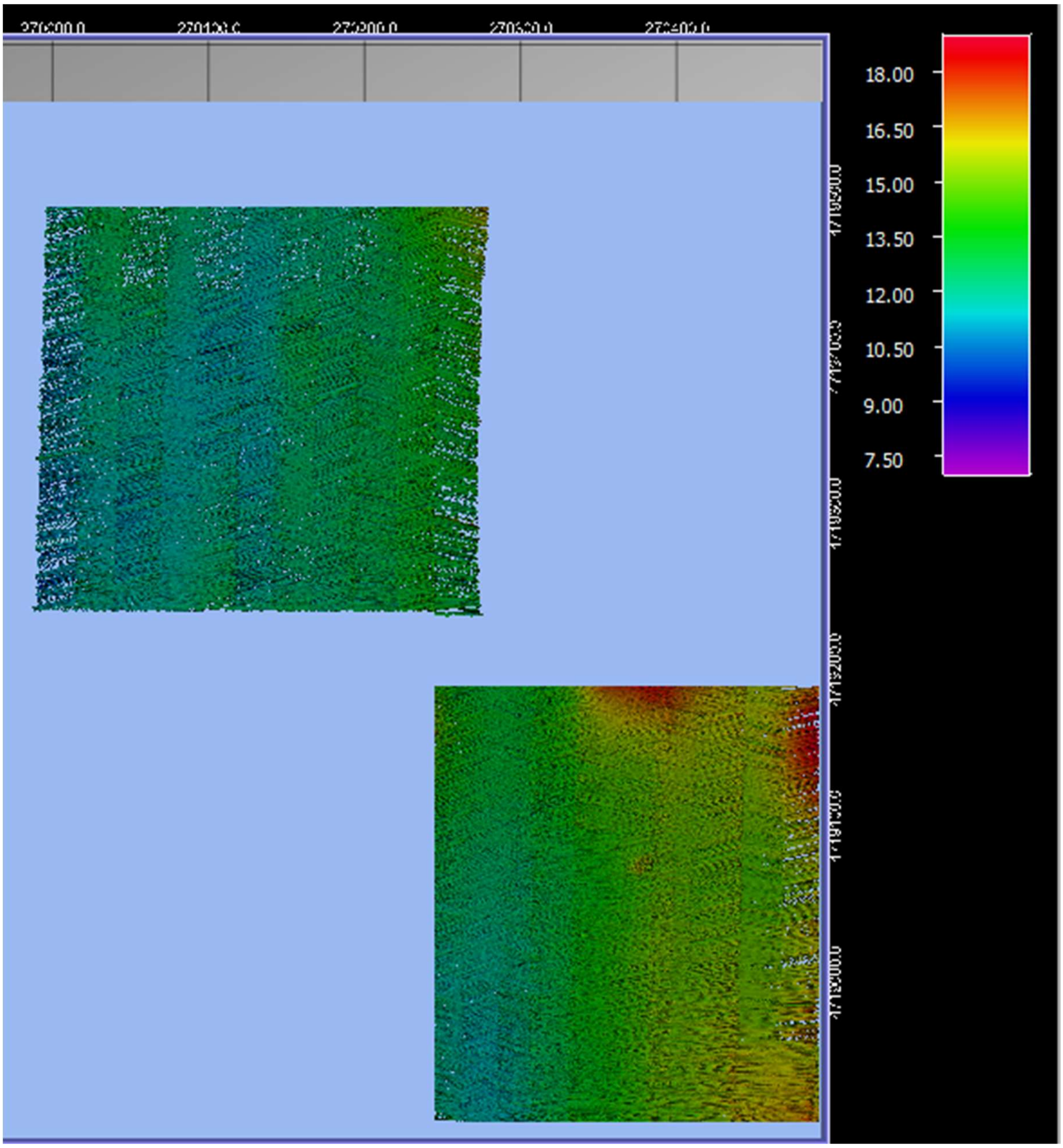

Figure 13. Results of Cavtat pilot site's bathymetry.

b) Underwater Optical Survey

The Regional Development Agency of Dubrovnik-Neretva County (DUNEA), as responsible of the Croatian pilot site, has taken over the task of organizing the photogrammetric survey on the two underwater sites from Classical Antiquity situated in front of Supetar Islet near Cavtat (the dolia site and the amphorae shipwreck site). The University of Zadar applied to the DUNEA Agency to carry out the planned activities at the underwater sites. The offer was accepted, and necessary permission was obtained from the Conservation Department of the Croatian Ministry of Culture in Dubrovnik, on behalf of representatives of all project partners involved in the pilot activities. During the period 7-17 June 2018 the work was carried out, with logistic support provided by Diving Centers Epidaurum from Cavtat and Foka from Šimuni (island of Pag) as well as the Institute for Maritime Heritage ARS NAUTICA.

The University of Zadar accepted the obligation to prepare two sites for underwater documentation, create virtual 3D models and a resulting location plan with characteristic cross sections obtained from photogrammetry model for both sites, and provide descriptions of the current site conditions, including marking ten points of interest. The final goal is to embed appropriate content on placards to be mounted under water, which will provide visiting divers information about the most interesting details of the site. At the dolium shipwreck site, it is also envisaged to conduct a trial excavation to check for the potential existence of wooden ship remains, in order to maximize site data available to the general public. A detailed description of the results of the activities is reported in **Annex 1** of this document "**Report Cavtat 2018**".

ROV has been used for a preliminary optical data collection, mainly at the dolia site. Easily deployable, and manually controlled, ROV has been shown to be very useful, especially since there is a direct visual link through the tether back to the operator’s screen.

In the post-processing phase, a 3D model of one dolium has been generated from down sampling a 25fps HD video from ROV's logs (Figure 15). The biggest problem with the use of frames extracted from the recorded video is motion blur, which renders 3D models of relatively less quality compared to the ones generated from still photographs of a DSLR camera with an external high-power flash. Nonetheless, this opens a possibility to document an underwater archaeological site much faster and with much less logistics compared to the case when divers record the site.

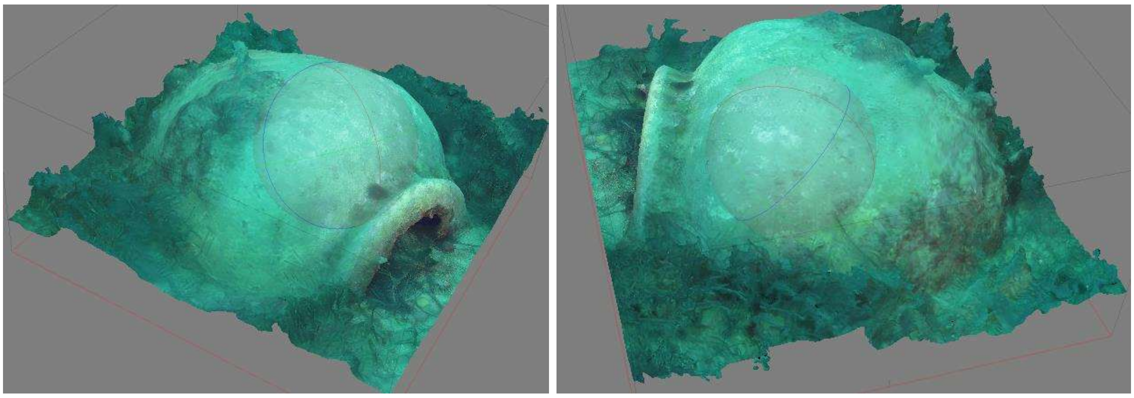

Figure 14. Photogrammetric 3D reconstruction of a dolium based on frames from ROV's camera

c) Coastline 3D Reconstruction

One of the goals of this Cavtat survey campaign has been to gather dataset for photogrammetry of the island close to these two underwater archeological sites that would, later on, be useful for 3D reconstruction as a backdrop when the users dive out to the surface in the virtual reality environment. The UAV that the UNIZG-FER team brought took HD photos of the island in a crosshatch coverage plan, with 70% across- and along-track overlap between adjacent photos, at an altitude of 40m for safety reasons. The results of the quick photogrammetry post-processing of the photos are given in Figure 16.

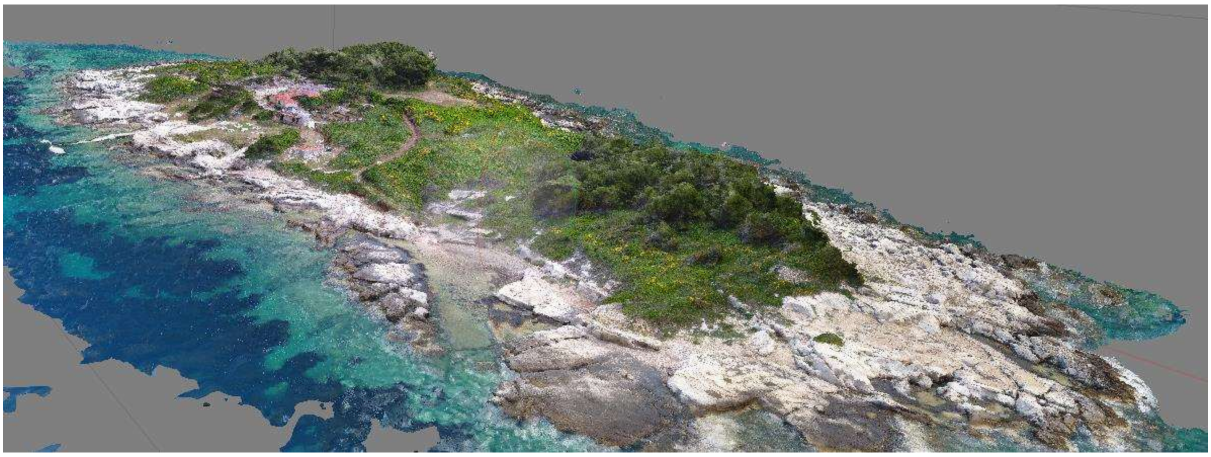

Figure 15. 3D reconstruction of the island Supetar in front of Cavtat bay, close to the location of the amphorae cage and dolia sites.

5. Survey and 3D reconstruction activities on the Greek pilot site

5.1 Activities on the underwater archaeological site of Alonissos

a) Acoustic Survey

UNIZG-FER team has been arrived at Steni Vala on 07.10.2018 and has performed the preparation work for the survey activities on 08.10.2018. Surveying missions have been started on 09.10. ASV PladyBath has been used to gather the bathymetric data of the seabed near Peristera island, which UNIZG-FER team has reached by boat rented from Ikion diving center in Steni Vala. Moreover, the compass of the AUV Lupis has been once more calibrated, and its accuracy in diving and navigational operations has been tested (Figures 16, 17, 18, 19).

Figure 16. Operational boat used by UNIZG-FER team

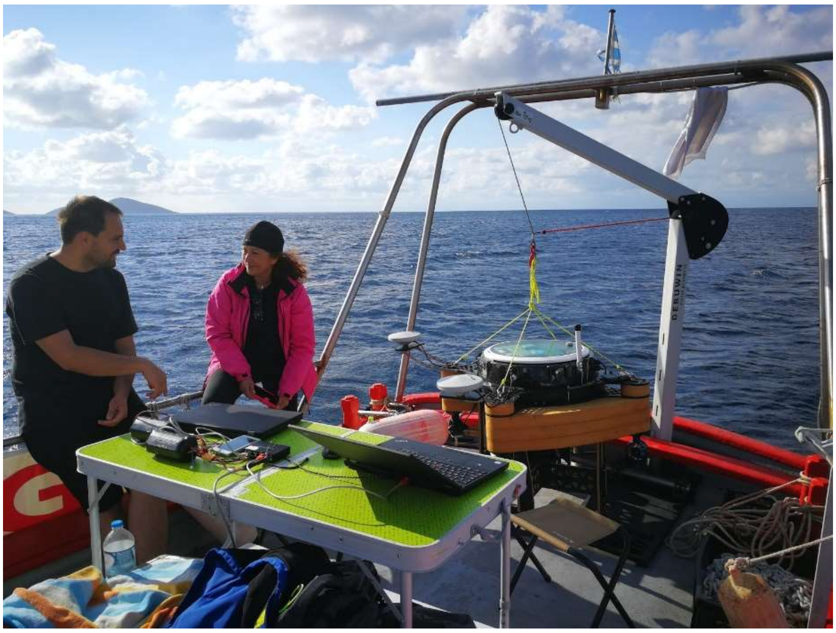

Figure 17. ASV PladyBath ready to be deployed using a transportable crane

Figure 18. AUV Lupis deployment from the side of the boat

Figure 19. UNIZG-FER team analyzing gathered bathymetry and side-scan data as soon as they are collected from the ASV and the AUV.

On 10.10.2018, one of the AUV's servo motor controlling its fins unexpectedly broke after a side-scan sonar survey mission of the site. Despite the team's efforts to remove the fault, and because of limited time on land due to sea trials, unfortunately, the AUV could not be used in the following missions. A georeferenced mosaic of the collected side-scan sonar survey mission around the pilot site is given in Figure 20.

Figure 20. Side-scan sonar mosaic of the Peristera site georeferenced and shown in Google Earth

The ASV PladyBath has been used to gather bathymetric data of the underwater archaeological site in more detail, with a narrow angle of view of the sonar, and high percentage of swath overlap between neighboring survey lawnmower lanes. A wider sonar angle of view, but again with high percentage of overlap between consecutive survey lanes has been used to gather bathymetric data of the pilot site's surrounding area. The overlay of all survey missions planned and executed by the ASV are given in Figure 21, as well as wide area bathymetry and more detailed bathymetry of the pilot site itself.

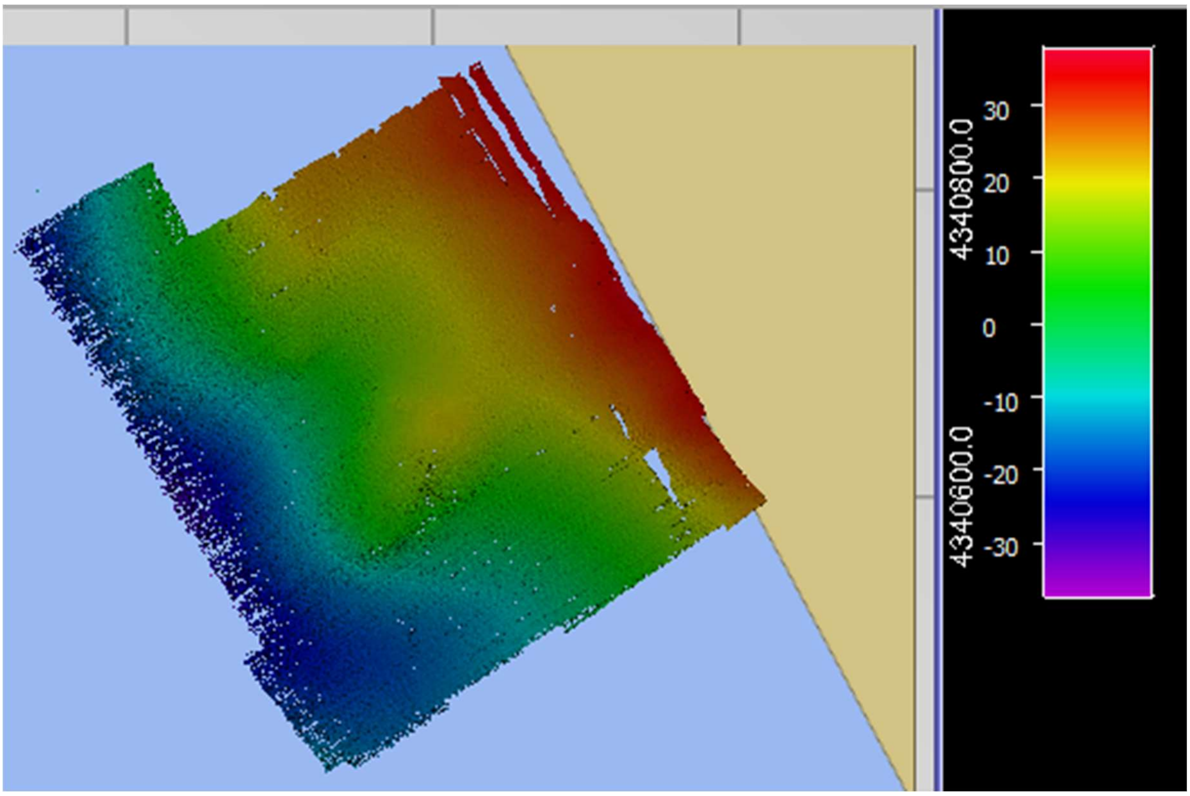

Figure 21. Results of bathymetry of the area surrounding the Peristera pilot site

b) Underwater Optical Survey

The optical 3D survey of Peristera shipwreck has been conducted by UNICAL team. It has arrived in Steni Vala on 05.10.2018. The day after, the team has started with the preparation of the site to conduct the photogrammetry activities (creation of the geodetic control network through the positioning of underwater markers, take measurements of the distance among the markers, etc.). In particular, twelve markers have been positioned in order to create the geodetic control network both to correct the scale and distortion of the photogrammetry model. The activities have been conducted at a depth between 27 to 32 meters, with a maximum bottom of 20 minutes without decompression obligation. For this reason, small teams' of 2/3 people have worked together in order to maximize the numbers of dives (Figure 22).

Figure 22. The UNICAL team during some measuring activities in the Peristera shipwreck site.

The photogrammetric acquisition started on 07.10.2018. A Sony A7II (24.0MP, 3:2), equipped with a Sony Zeiss 16-35mm f.4 lens inside of an Easydive Leo 3Wi house with two Ikelite DS161 strobes has been used to take images. The reflex camera has been used in manual exposure mode, setting values between 1/250 and 1/320 of a second for the exposure time and an aperture between f-5.6 and f-8. In order to ensure the adaptation of exposure to variable lighting conditions and to avoid the acquisition of over-exposed and under-exposed areas, the automatic ISO sensitivity function has been used. In order to test the effects of the in situ white balance correction, the images have been acquired using the pre-measured value obtained by acquiring an underwater white balance panel by Lastolite. The pictures have been taken following a standard aerial photography layout: the diver swims at depth of about 2 meters, taking overlapping pictures along straight lines that cover the whole area in North-South direction. Another set of images has been acquired in East-West direction. The occluded areas, not visible in vertical pictures, have been acquired using oblique photographs (Figure 23). The complete dataset includes a total of about 1044 images, covering an area of about 30 m x 15 m.

Figure 23. A diver during the photogrammetric survey.

On 11.10.2018, UNICAL team with the support of the ATL team has took GPS points of the twelve markers used for the control network in order to geo-refence the model and merge it with the acoustic one.

In order to assess the quality of the image dataset, a preliminary orthophoto of the shipwreck has been created. A total scale error of 0.2 m and a geo-refence error of 1.9 m have been obtained (Figure 24).

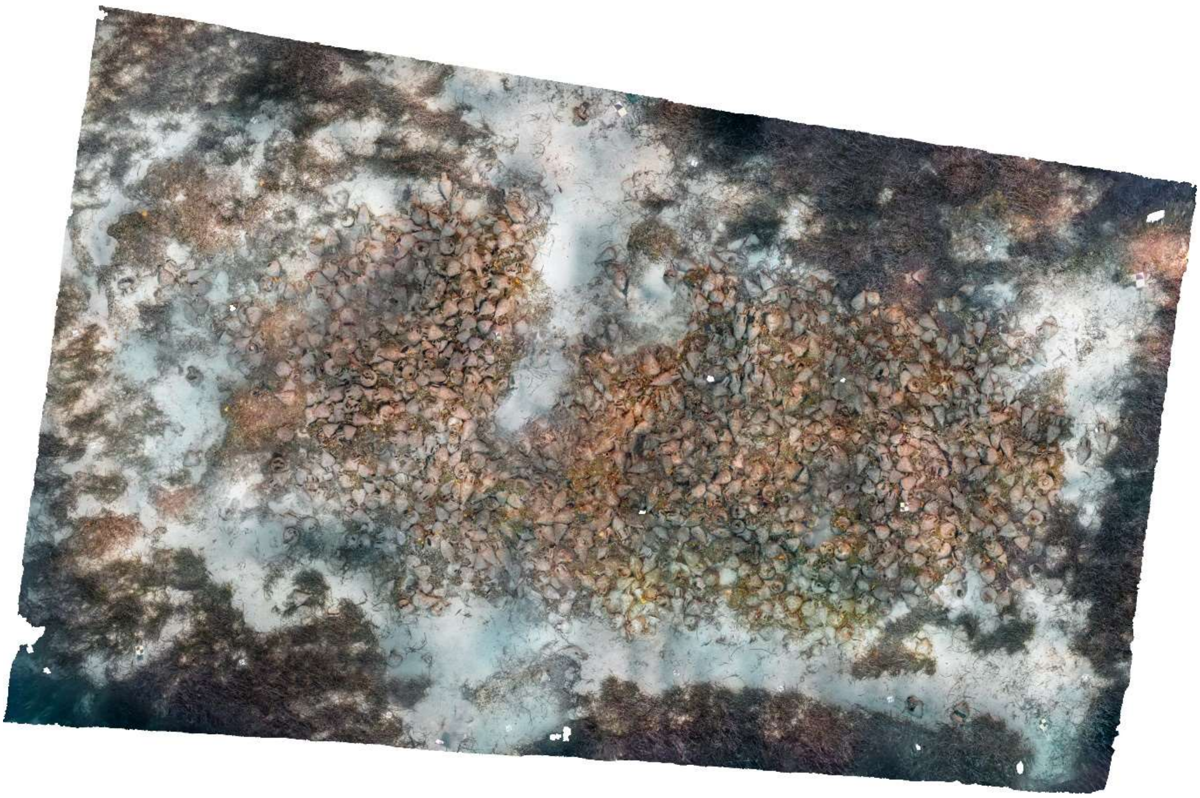

Figure 24. Orthophoto of the Peristera shipwreck

c) Coastline 3D Reconstruction

DJI Phantom 4 UAV was used to gather photos of the Peristera island part just in front of the pilot site. It was programmed to execute a crosshatch mission at altitude of 40m, and a 70% along- and across-track overlap between photos. The resolution of its photos is 12MP. Preliminary results of 3D reconstruction of the Peristera island part is given in the Figure 25, based on 381 photos.

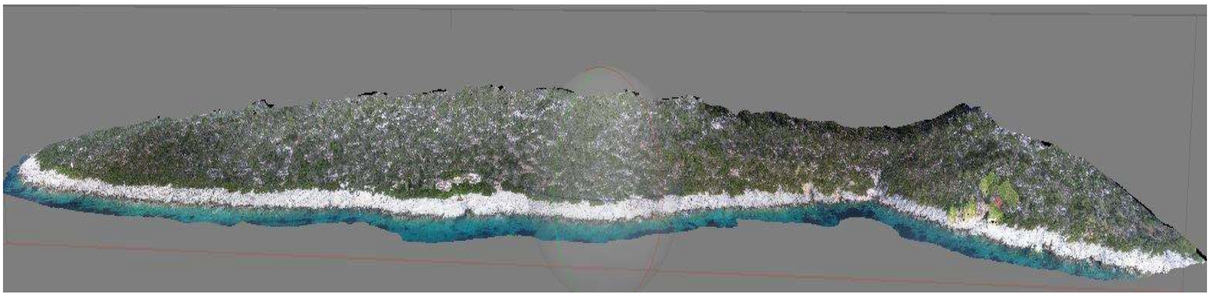

Figure 25. Preliminary 3D reconstruction of the part of Peristera island in front of the pilot site.

5.2 Activities on the underwater archaeological site of Amaliapolis

a) Acoustic Survey

UNIZG-FER team arrived to Amaliapolis on 12.10.2018. Because of a favorable weather forecast for the weekend, the surveying missions started on 13.10. Sites in front of the Kikinthos island, Glaros cape, and Telegraphos cape were surveyed for two days each. ASV PladyBath gathered bathymetric data of the pilot sites which UNIZG-FER team reached by the boat rented in Amaliapolis, shown in the Figure 26.

Figure 26. Operational boat in the Amaliapolis port, ASV PladyBath safely secured on boat's bow.

ASV PladyBath gathered bathymetric data of the pilot sites in more detail, with a narrow angle of view of the sonar, and high percentage of swath overlap between neighboring survey lawnmower lanes. A wider sonar angle of view, but again with high percentage of overlap between consecutive survey lanes were used to gather bathymetric data of the pilot sites' surrounding areas. The overlay of all survey missions planned and executed by the ASV are given in the Figures below, as well as wide area bathymetry and more detailed bathymetry of the pilot site itself.

Island Kikinthos pilot site

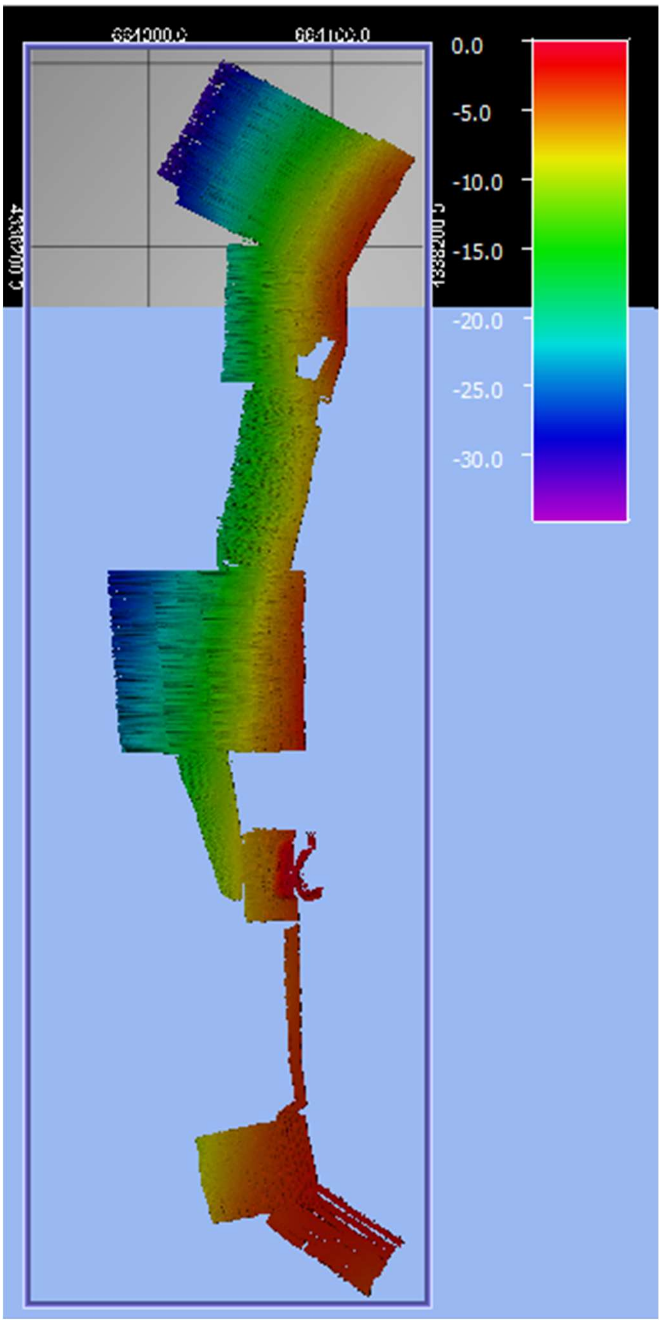

Figure 27. Results of bathymetry of the area surrounding the Kikinthos pilot site. Data collected on 13th and 14th of October 2018.

Cape Glaros pilot site

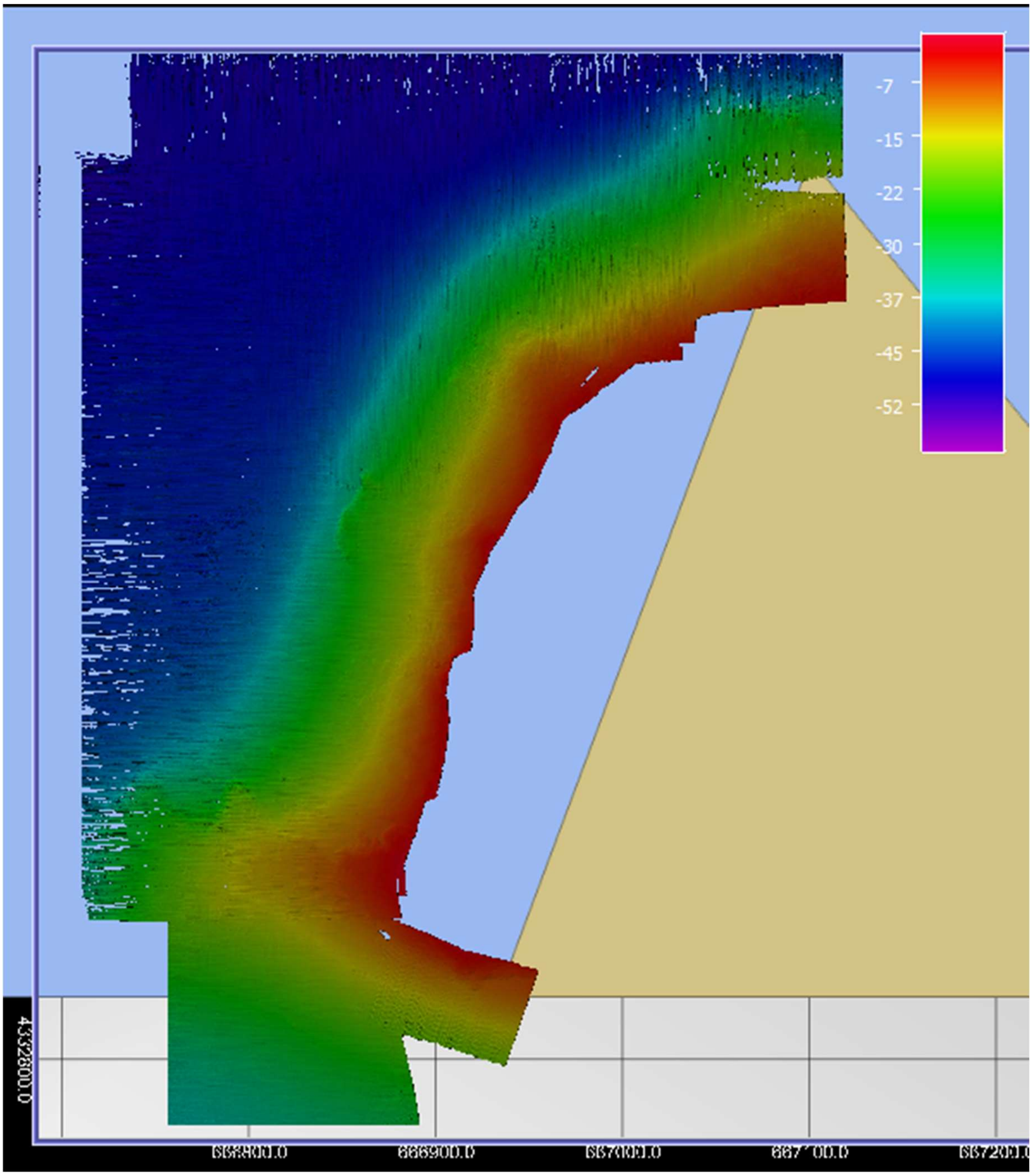

Figure 28. Results of bathymetry of the area surrounding the Glaros pilot site. Data collected on 15-17th October 2018.

Cape Telegrafos pilot site

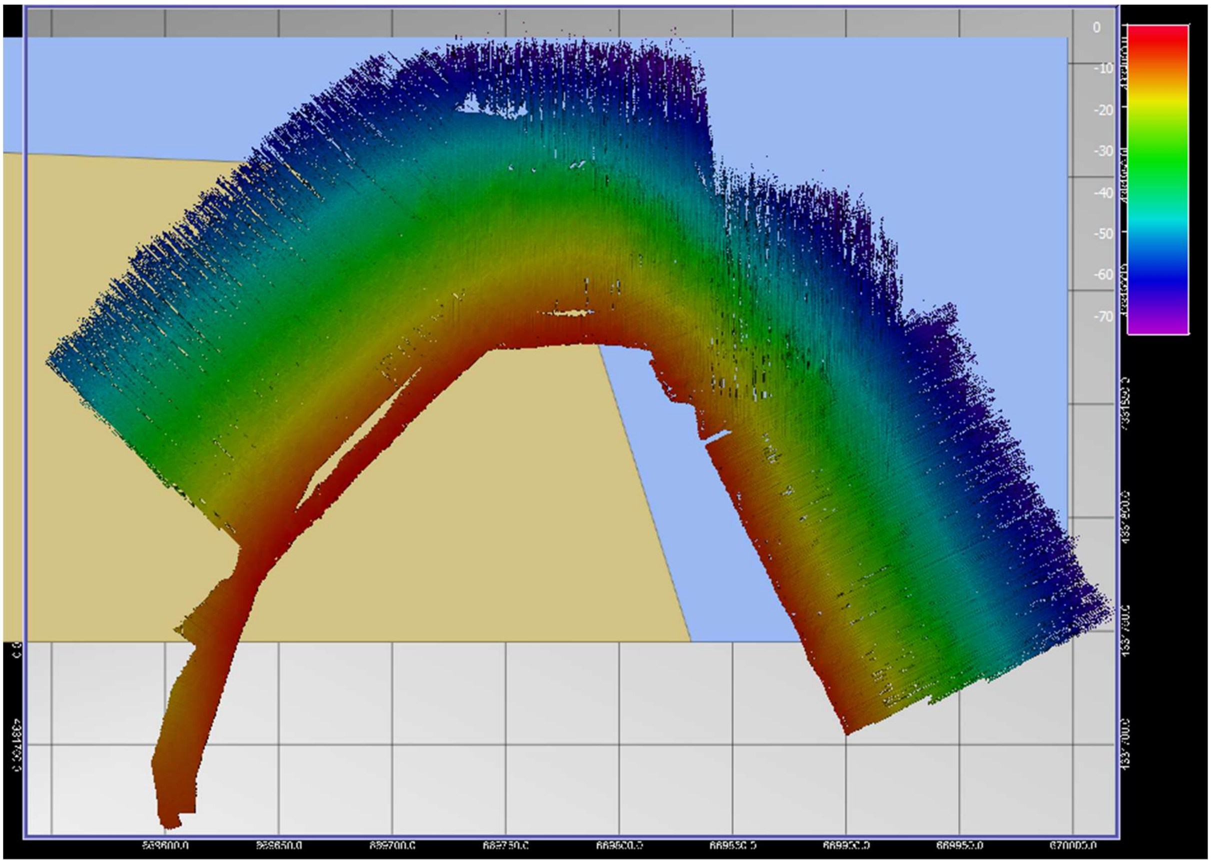

Figure 29. Results of bathymetry of the area surrounding the Telegraphos pilot site. Data collected on 18th of October 2018.

b) Underwater Optical Survey

UNICAL Team has started the work in the Amaliapolis site on 13.10.2018. The first day, the underwater archaeological site in front of the Kikinthos island has been prepared in order to proceed with the photogrammetric survey. In particular, a geodetic control network has been created using 18 markers placed on seabed at a depth between 3 m and 20 m, covering an area of about 30 m x 30 m (Figure 30).

Figure 30. The team preparing the area for photogrammetry activities

The photogrammetric acquisition started on 14.10.2018. A Sony A7II (24.0MP, 3:2), equipped with a Sony Zeiss 16-35mm f.4 lens inside of an Easydive Leo 3Wi house with two Ikelite DS161 strobes has been used to take images. The reflex camera has been used in manual exposure mode, setting values between 1/250 and 1/320 of a second for the exposure time and an aperture between f-5.6 and f-8. In order to ensure the adaptation of exposure to variable lighting conditions and to avoid the acquisition of over-exposed and under-exposed areas, the automatic ISO sensitivity function has been used. In order to test the effects of the in situ white balance correction, the images have been acquired using the pre-measured value obtained by acquiring an underwater white balance panel by Lastolite. The pictures have been taken following a standard aerial photography layout: the diver swims at depth of about 3 meters, taking overlapping pictures along straight lines. Another set of images has been acquired in orthogonal direction. The occluded areas, not visible in vertical pictures, have been acquired using oblique photographs. The complete dataset includes a total of about 3223 images. An orthophoto has been created to assess the quality of the acquired image dataset (Figure 31).

Figure 31. Orthophoto of the Kikinthos shipwreck site.

The work in the underwater archaeological site located in front of the Glaros Cape has started on 16.10.2018. Considering the total area to be acquired (3350 sqm), the team has decided to split it in 3 smaller areas. The first day, in order to prepare the site for the photogrammetric acquisition, markers and rulers have been put on the seabed to define the boundaries of every area and to create the local geodetic control networks.

Due to the dimension of the area to be acquired, a multi-resolution 3D reconstruction approach has been used to optimize the time spent underwater. In particular, the archaeological finds, which require a 3D reconstruction with a high level of detail, have been acquired using a Sony A7II with Sony Zeiss 16-35mm f.4 lens inside an Easydive Leo 3Wi house and 2 Ikelite DS161 Strobes, while the acquisition of the seafloor at a lower detail has been carried out using a GoPro Hero 7 set in video mode, equipped with 2 Easydive Revolution 15000 lumens light.

A preliminary 3D reconstruction has been carried out in order to assess the effectiveness of the proposed multi-resolution approach. The 3D model of the first area has been created from 1350 frames extracted from the GoPro videos and mixed with the high-resolution images shot with the Sony A7II. The dense cloud is composed of 70.949.807 points. Then a low-polygon 3D model has been created (Figure 32).

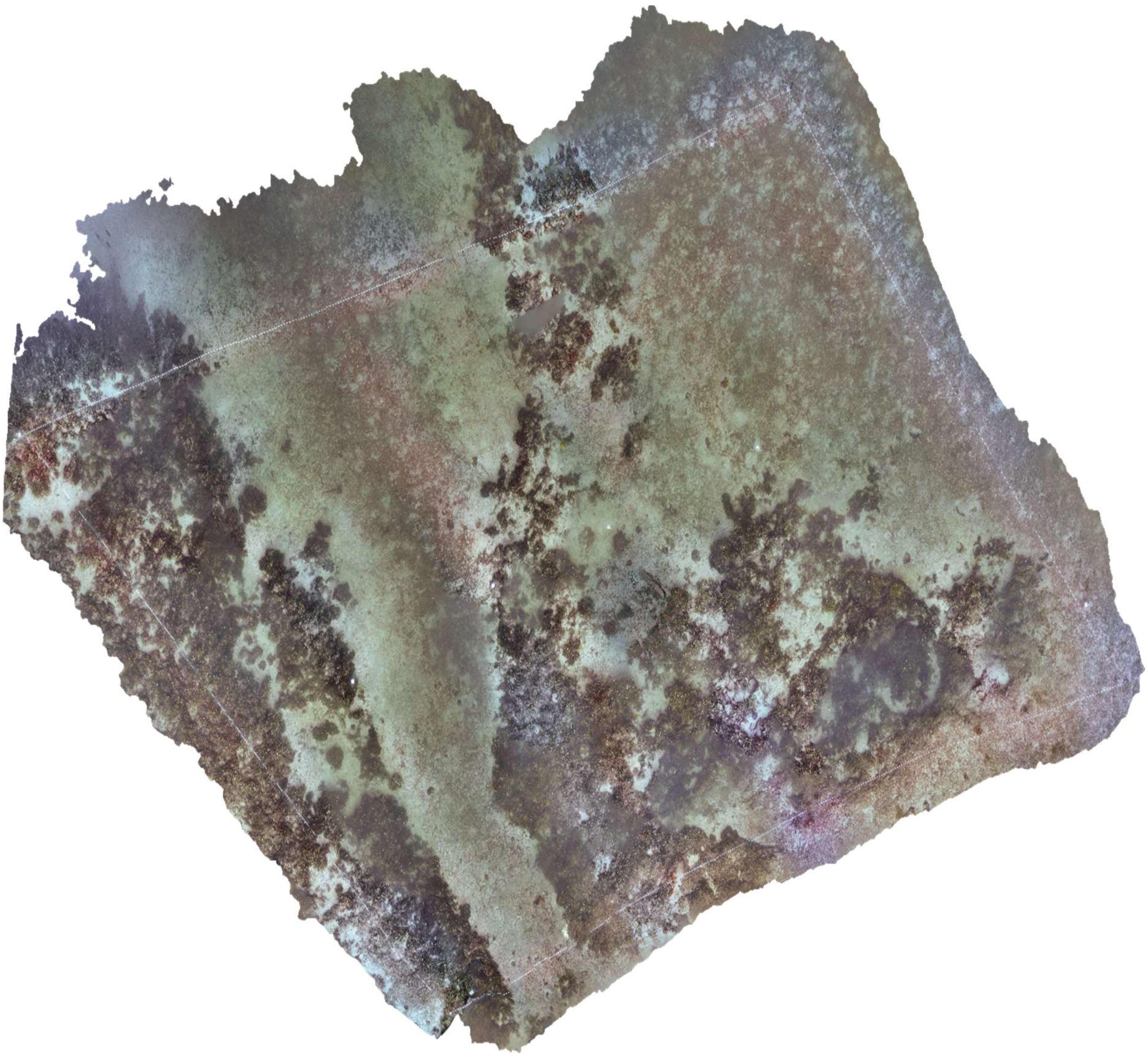

Figure 32. Low-polygon 3D model (200.000 polygons) of the first area of the Glaros underwater archaeological site.

The 3D model of the second area has been created from 1460 frames extracted from the GoPro videos and mixed with the high-resolution images shot with the Sony A7II. The dense cloud is composed of 81.198.730 points. Then a low-polygon 3D model has been created (Figure 33).

Figure 33. Low-polygon 3D model (160.000 polygons) of the second area of the Glaros underwater archaeological site.

The 3D model of the last area has been created from 1467 frames extracted from the GoPro videos and mixed with the high-resolution images shot with the Sony A7II. The dense cloud is composed of 72.307.604 points. Then a low-polygon 3D model has been created (Figure 34).

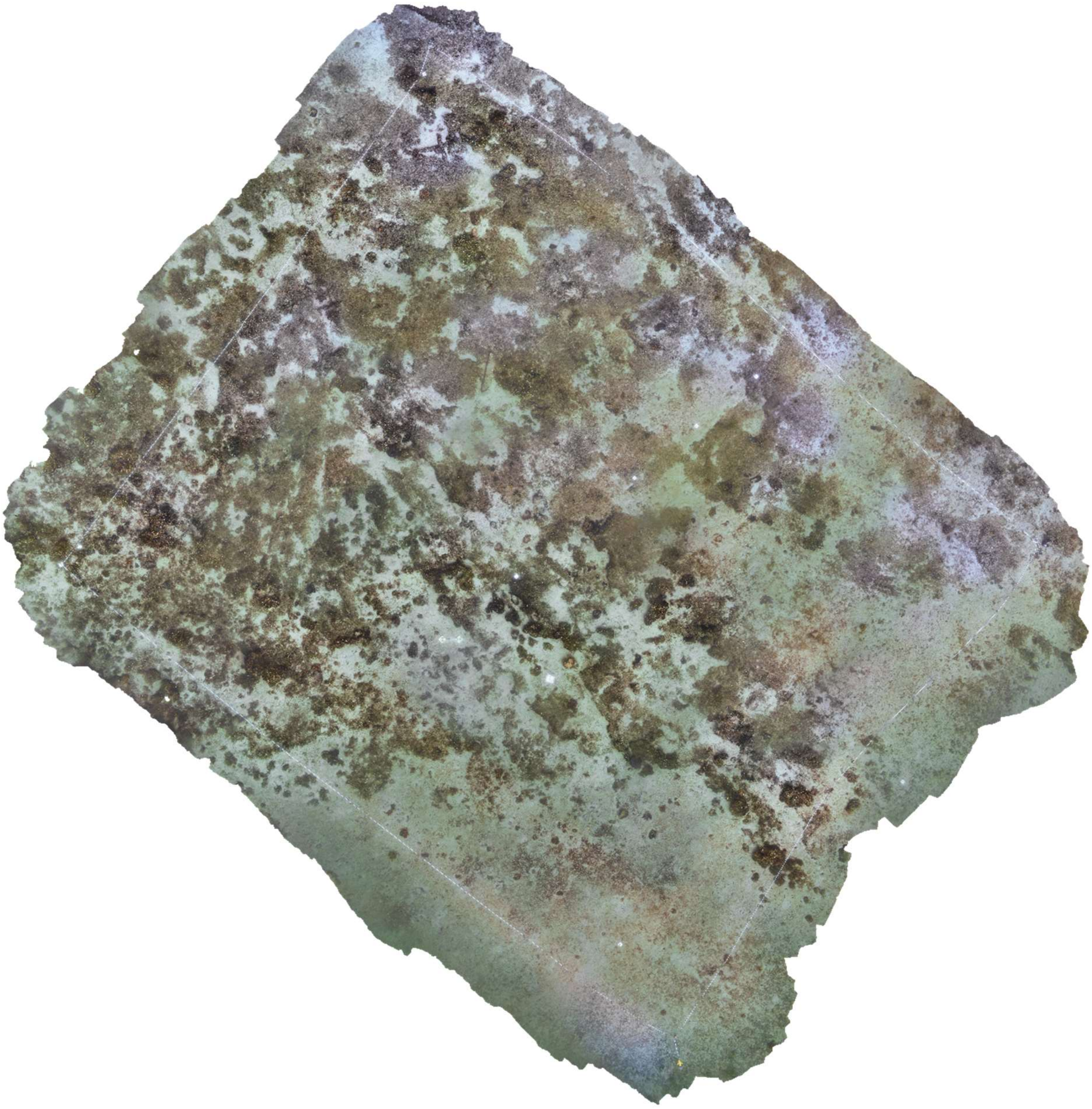

Figure 34. Low-polygon 3D model (144.000 polygons) of the third area of the Glaros underwater archaeological site.

The work in the underwater archaeological site in front of the Telegraphos island started on 19.10.2018. The UNICAL team has worked together with the ATL team. After the preparation of the site (creation of the geodetic control network and acquisition of the GPS coordinates of the markers) the photogrammetric acquisition has been carried out using a Canon 5D MarkIII plus equipped with a Canon L 8-15mm lens inside an Ikelite house. The complete dataset includes a total of about 1602 images, covering an area of about 50 m x 25 m. An orthophoto has been created to assess the quality of the acquired image dataset (Figure 35).

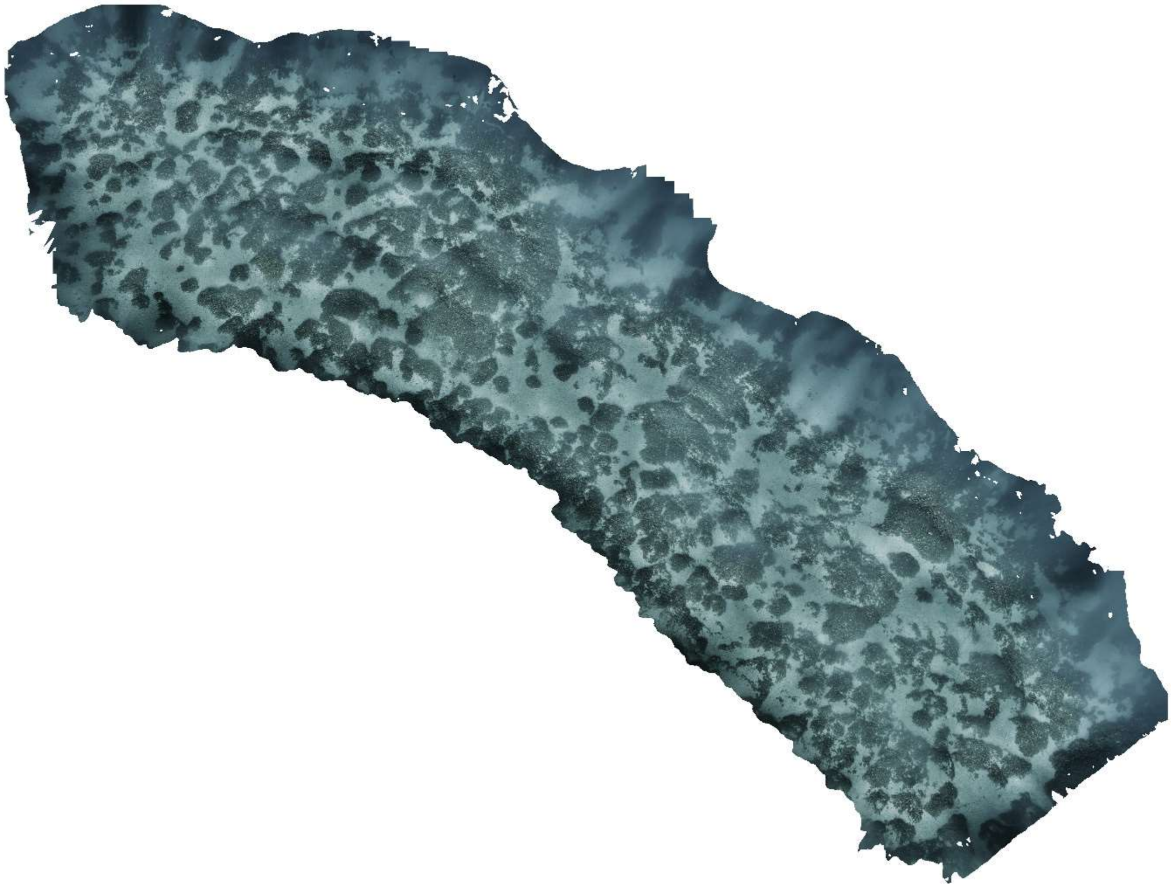

Figure 35. Orthophoto of the Telegraphos underwater archaeological site.

c) Coastline 3D Reconstruction

DJI Phantom 4 UAV was used to gather photos of the pilot sites' surroundings. On these pilot sites it was flown in the manual mode at an altitude of approx. 10-15m, slowly to ensure high percentage of photos overlapping. The camera was oriented directly towards the shore, to get more details of the shore which will be closer to the divers in the VR when they get to the surface, and less details of the vegetation and hills in the distance. Preliminary results of 3D reconstructions of the Kikintos island and capes Glaros and Tilegrafos are given in the Figures below.

Island Kikintos pilot site

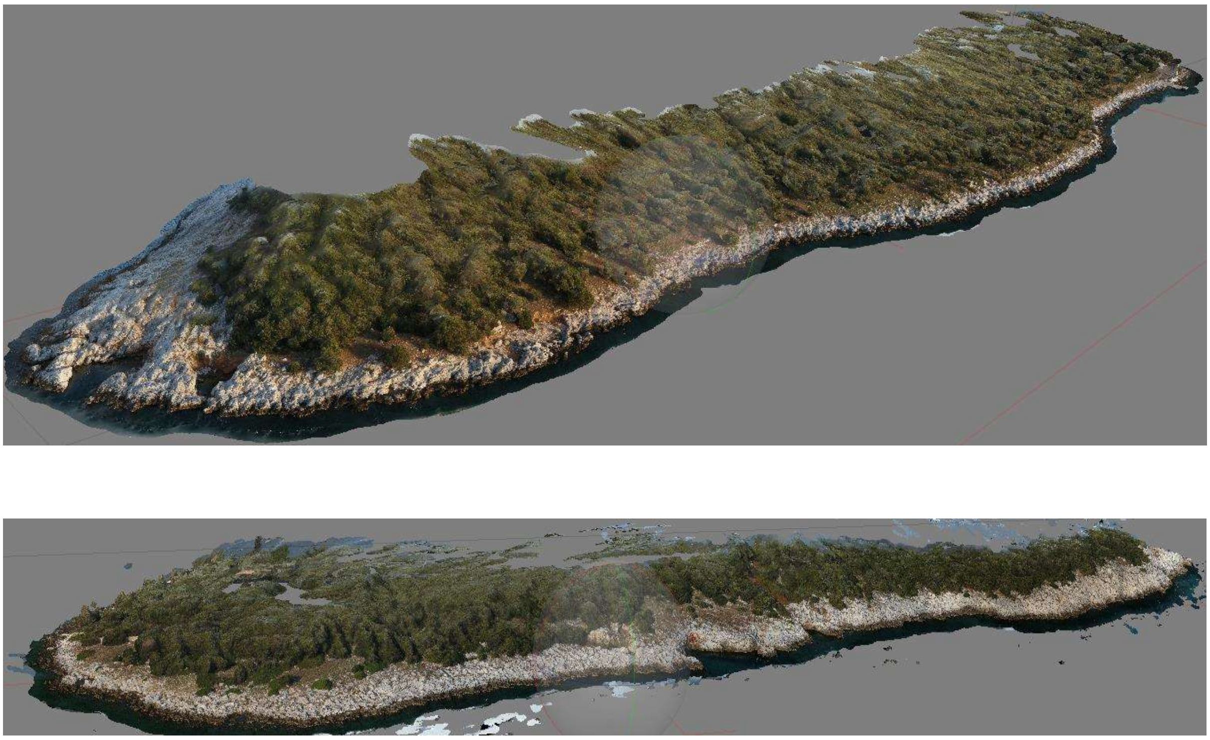

Figure 36. Preliminary 3D reconstruction of the part of Kikintos island in front of the pilot site (above), and its outer side as well (below), based on 288 and 318 photos for front and outer side, respectively.

Cape Glaros pilot site

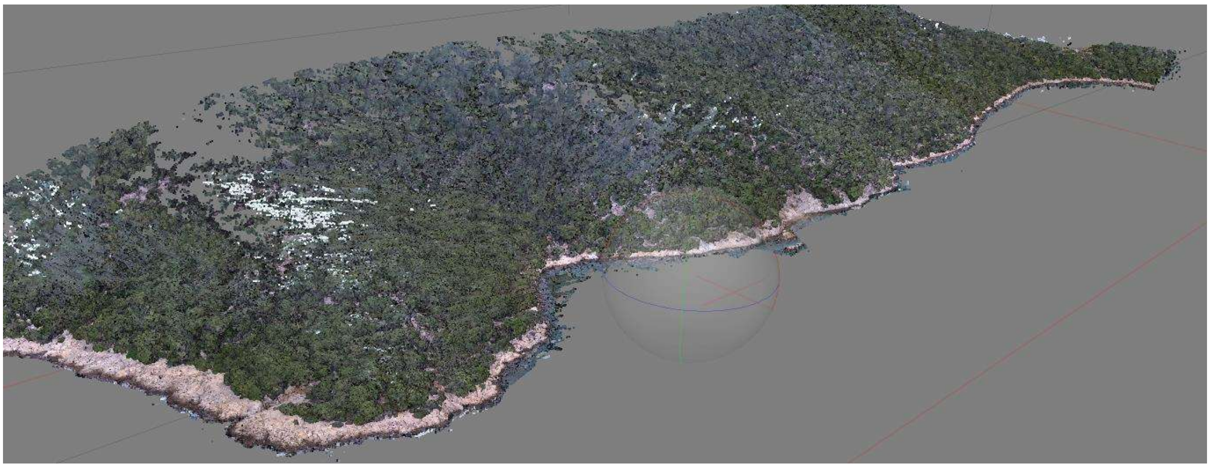

Figure 37. Preliminary 3D reconstruction of the part of Glaros cape in front of the pilot site, based on 500 photos.

Cape Telegrafos pilot site

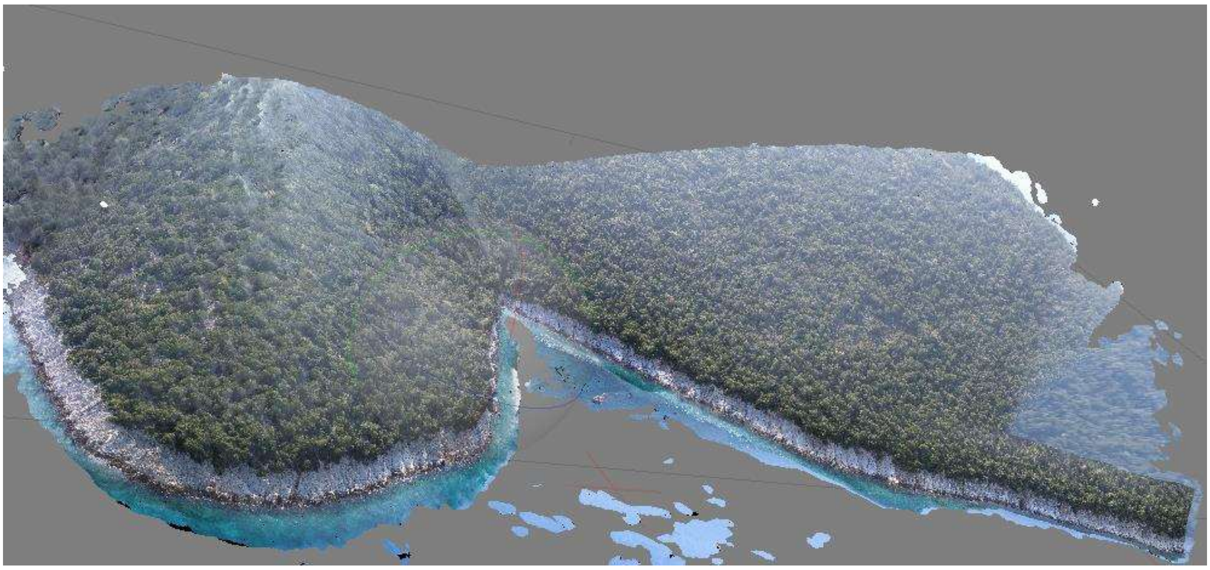

Figure 38. Preliminary 3D reconstruction of the part of Tilegrafos cape in front of the pilot site, based on 525 photos.

UNIVERSITY OF ZADAR
Department of Archaeology

CAVTAT,
ISLET OF SUPETAR

7 – 17 June 2018

BLUEMED Project

Underwater archaeological research report

Authors:

Asst Prof. Dr Irena Radić Rossi
Katarina Batur, Research Assistant

Contents

1. General information

Position: Supetar Islet in front of Cavtat:

1) Shipwreck site with *dolia* cargo, 1st century AD
2) Shipwreck site with amphorae cargo, 3rd / 4th century AD

County / Municipality: Dubrovnik – Neretva County / Cavtat Municipality

Methodology: Underwater archaeological recording and trial excavations

Investor: Public institution The Regional Development Agency Dubrovnik-Neretva County DUNEA

Contractor: University of Zadar, Department of Archaeology

Dates: 7th – 17th June 2018

Team of experts:

Responsible persons
Irena Radić Rossi, University of Zadar, fieldwork director
Katarina Batur, University of Zadar, deputy field director
Vedran Dorušić, Diving Center Foka Ltd., dive master

Archaeologists
Ines Šelendić, Institute for Maritime Heritage ARS NAUTICA, Tkon
Dino Taras, Archaeological Museum Zadar
Kotaro Yamafune, A.P.P.A.R.A.T.U.S. Ltd.

Other collaborators
Marino Brzac, Institute for Maritime Heritage ARS NAUTICA, Tkon, underwater photographer

Logistical support:
DC Epidaurum Ltd., Cavtat
DC Foka Ltd., Šimuni (Pag Island)
Institute for Maritime Heritage ARS NAUTICA, Tkon (Pašman Island)

Research vessel:
Registration number: 99CT
Type: catamaran
Owner: Epidaurum Ltd.
Length: 17 m

2. Introduction

The BlueMed international project is co-funded by the European Regional Development Fund (ESF) in the framework of the Interreg Mediterranean program. Among many activities, the BlueMed project aims to create new presentations of underwater archeological sites, to develop an effective model for promoting and developing tourism in various Mediterranean regions. Two locations in Italy, one in Greece and one in Croatia were selected for pilot activities.

One of the Croatian partners is the Regional Development Agency of Dubrovnik-Neretva County (DUNEA), which took over the task of organizing pilot activities on two underwater sites from Classical Antiquity situated in front of Supetar Islet near Cavtat, as well as activities related to a presentation center in Konavle. The University of Zadar applied to the DUNEA Agency to carry out the planned activities at the underwater sites near Cavtat and to provide consulting services when organizing the presentation center in Konavle. The offer was accepted, and necessary permission was obtained from the Conservation Department of the Croatian Ministry of Culture in Dubrovnik, on behalf of representatives of all project partners involved in the pilot activities. During the period 7-17 June 2018 the underwater portion of this work was carried out, with logistic support provided by Diving Centers Epidaurum from Cavtat and Foka from Šimuni (island of Pag) as well as the Institute for Maritime Heritage ARS NAUTICA.

The University of Zadar accepted the obligation to prepare two sites for underwater documentation, create virtual 3D models and a resulting location plan with characteristic cross-sections obtained from photogrammetry model for both sites, and provide descriptions of the current site conditions, including marking ten points of interest. The final goal is to embed appropriate content on placards to be mounted under water, which will provide visiting divers information about the most interesting details of the site. At the dolium shipwreck site, it is also envisaged to conduct a trial excavation to check for the potential existence of wooden ship remains, in order to maximize site data available to the general public.

3. Situation

During the late 1990s, the diver Boris Obradović from the Epidaurum diving center in Cavtat noted and reported the existence of two well-preserved sites and one devastated site near the Supetar islet in front of Cavtat, which had already been known to the local diving community. The first site consisted of a group of large ceramic *dolia* (massive transport jars) from the 1st century BC, the second site consisted of several hundred cylindrical North African amphorae datable to the 3rd or 4th century AD, while the third, less well-preserved site had numerous Lamboglia 2 amphorae fragments (roughly datable to the 1st century BC to 1st century AD) and a smaller number of better preserved examples.

The first two sites impressed the experts with their excellent state of preservation, so it was decided to leave the artifacts *in situ*, document the current state at both locations, and then install a protective iron cage over the North African amphorae site to protect the amphorae. The initial idea was the establishment of an underwater archeological park, but the idea never reached fruition. The idea was reborn as part of the BlueMed project, resulting in this year's preparations.

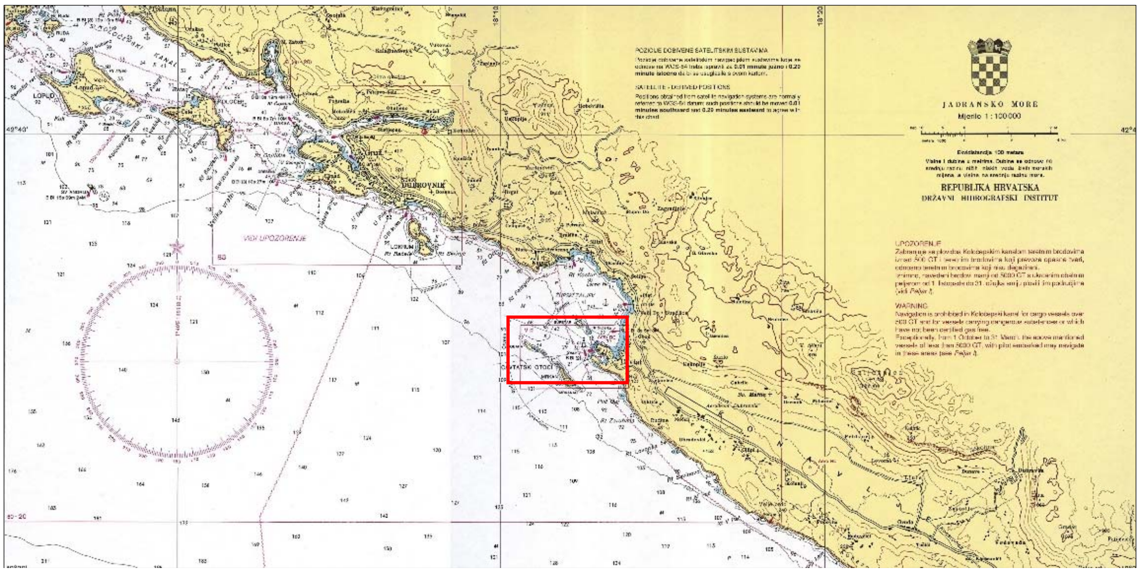

Fig. 1 The location of Cavtat and islet Supetar southeast of Dubrovnik on a nautical chart

Fig. 2 Highlight contains the archaeological sites in the area of Supetar island. The first two sites impressed the experts with their high state of preservation. Therefore, it was decided to leave the ancient remains on the bottom, and place a protective iron cage over the amphorae site.

The dolia site:

The site where the *dolia* were discovered is the only example of this type of site in the Adriatic. It is believed that ships equipped with *dolia* had the function of a 'tanker', with large capacity to store and transport wine, olive oil, or grain in bulk. It is assumed that the *dolia* were intentionally built into the ship's hold as a structural part of the ship, rather than on and off loaded as cargo containers; obviously, this demanded special strength and design of the ship's hull.

In 1996 the *dolia* site was sketched and photographed. The documentation campaign consisted of marking the positions of the artifacts with the aim of producing a site plan, and performing trial excavations at selected positions, to check for the existence of wooden ship structure preserved in the deeper layers of the sediment. Unfortunately, the trial excavations did not yield positive results; the resulting site plan was published, along with brief descriptions, in several different publications over the years.

Fig. 3 Research vessel above the *dolia* site; the islet of Supetar is to the right
(photo: E. Šilić, 2016.)

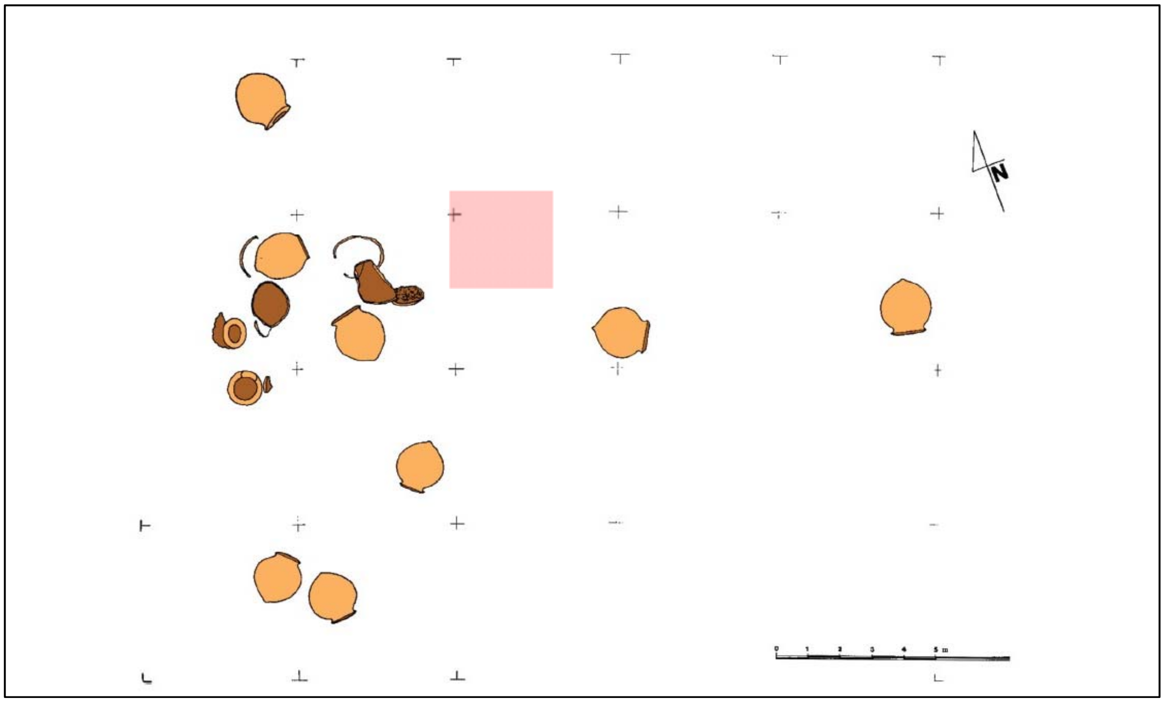

Fig. 4 The site-plan (Miholjek 2008); the pink square designates the location selected for the trial excavation

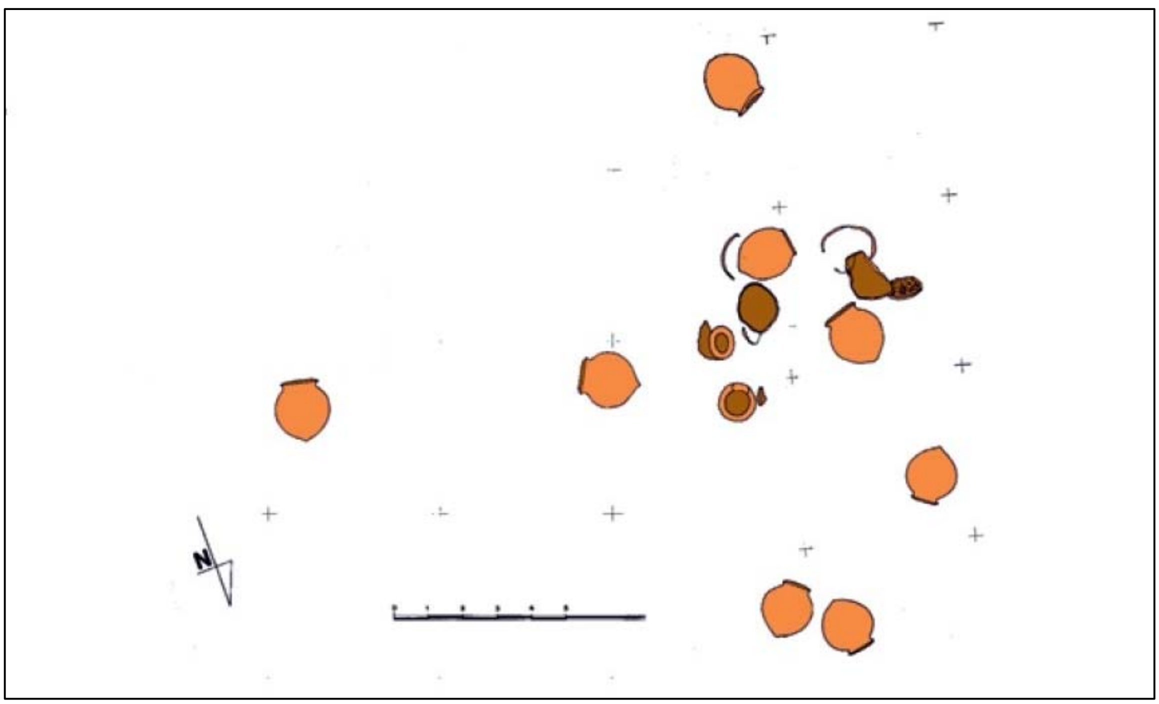

Fig. 5 The site-plan (Frka, Mesić 2012)

The site lies on a flat sandy sea bottom, about 200 m southwest of Supetar, so it is not easy to locate without knowing its exact position. According to the published data, initial research located eight completely preserved *dolia* and several *dolium* fragments, based on which it was concluded that there were originally at least ten complete *dolia* carried on board the ship.

The amphorae shipwreck site:

The shipwreck with the North African amphorae cargo lies at a depth of 27 meters, in the vicinity of the *dolia* wreck. The amphorae site is one of eight sites in Croatian waters which are protected with an iron cage. There are 600 amphorae visible in the surface layer, but the total number of amphorae is believed to be considerably higher because amphorae cargoes of this nature were typically carried in two to three layers.

The remains of the cargo nicely outline the shape of a sunken ship, so it can be concluded that the ship sank upright and landed on its keel at the sea bottom. A trial trench on selected outlines of the site confirmed suspicions that wooden ship remains were present, and that the amphorae were arranged in several layers. The remains of two iron anchors were also recorded in the surface layer.

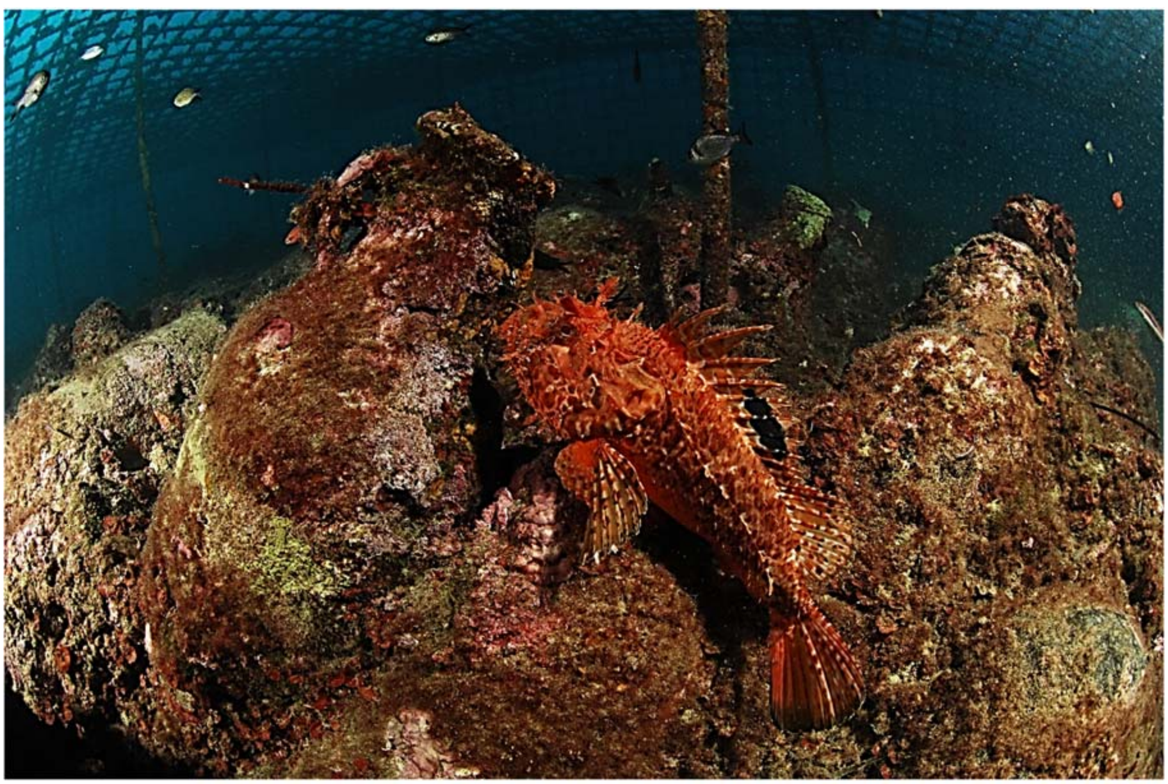

Fig. 6 The situation at the amphorae site in 2009 (photo: M. Brzac).
The abundance of floral and faunal species is caused by morphology and protection of the site

Although most of the amphorae belong to the North African cylindrical type, typologically classified in the group Keay 20, a smaller number belong to the Late Roman 2 classification. According to the typological determination of objects from the cargo, the site can be dated to 3rd /4th century AD.

The iron cage positioned above the site in the late 1990s quickly degraded, and in 2014 it was replaced by a new, more massive and corrosion resistant structure.

Fig. 7, 8 Degradation of the iron cage after two decades (photos: M. Brzac)

4. Research and results

After completing the documentation of the conditions at both sites, and setting up an iron cage on the amphorae site, the sites were not revisited to perform additional documentation until 2016, when the *dolia* site was revisited in preparation for documentation using more modern survey methodology techniques. At that time, the site was more thoroughly studied, and several inaccuracies were detected in the site plan. These inaccuracies were corrected in the documentation produced in 2018. Similar site plan inaccuracies were detected, then corrected in 2018 at the amphorae site.

The imprecise nature of the earlier site documentation is a logical consequence of 1990s documentation methodology, which was limited to unscaled photography combined with hand drawings of the amphorae. Thanks to modern technology, today we are able to create virtual 3D models of high precision and to read large amounts of archaeologically accurate data from them. The BlueMed project provided the opportunity to apply these new technologies at the two sites near Supetar islet, which is particularly important for testing current documentation methodology on well-preserved sites already known to the public.

The *dolia* shipwreck site:

The documentation of the site began by reviewing previously published documentation. As stated, the site had previously been briefly described in the literature several times, but the individual finds were never recorded in detail, nor precisely categorized typologically. Upon revisiting the site, the orientation and position of isolated specimens in the eastern part of the site plan were noted to not coincide completely with the actual situation; additionally, north was found to be labelled backwards (to the south) in the original site plans.

For the purpose of producing photogrammetric documentation of the site and the individual finds, all *dolia* were marked with labels consisting of the letter D and a unique corresponding number. The intact (complete) *dolia* were labeled D1 - D8, while labels D9 - D11 were placed in the main concentration of *dolia* fragments, which had previously been identified in the sketch of the site. Those fragments prove the existence of at least three additional *dolia*. *Dolia* D9 is buried in sediment from which only the rim and part of the body protrude, but it seems to be completely preserved.

North of the D5 *dolium*, in the southern part of the site, a large fragment was noticed, then labelled D12. It probably belongs to another *dolia*. Thus, the number of detected *dolia* has increased to 12, but considering the overall situation at the site, it is possible that there are still more, as-yet undetected, preserved *dolia* buried in the sediment. This hypothesis could be tested using a sub-bottom profiler.

By analyzing the actual situation in relation to the sketch published in 2008, the following was established:

1) the positions of *dolia* D1, D2 and D4-D7 were accurately mapped with proper orientation between each other;
2) the position of *dolium* D3 was drawn with wrong orientation and to the south of the actual position of the *dolium*;
3) the position of *dolium* D8 was mapped with the wrong orientation and too close to the main concentration of the finds;
4) the north direction on the old plan is incorrect;
5) fragments which are laying in the sediment to the north of *dolium* D5 were not recorded (now labeled as D12).

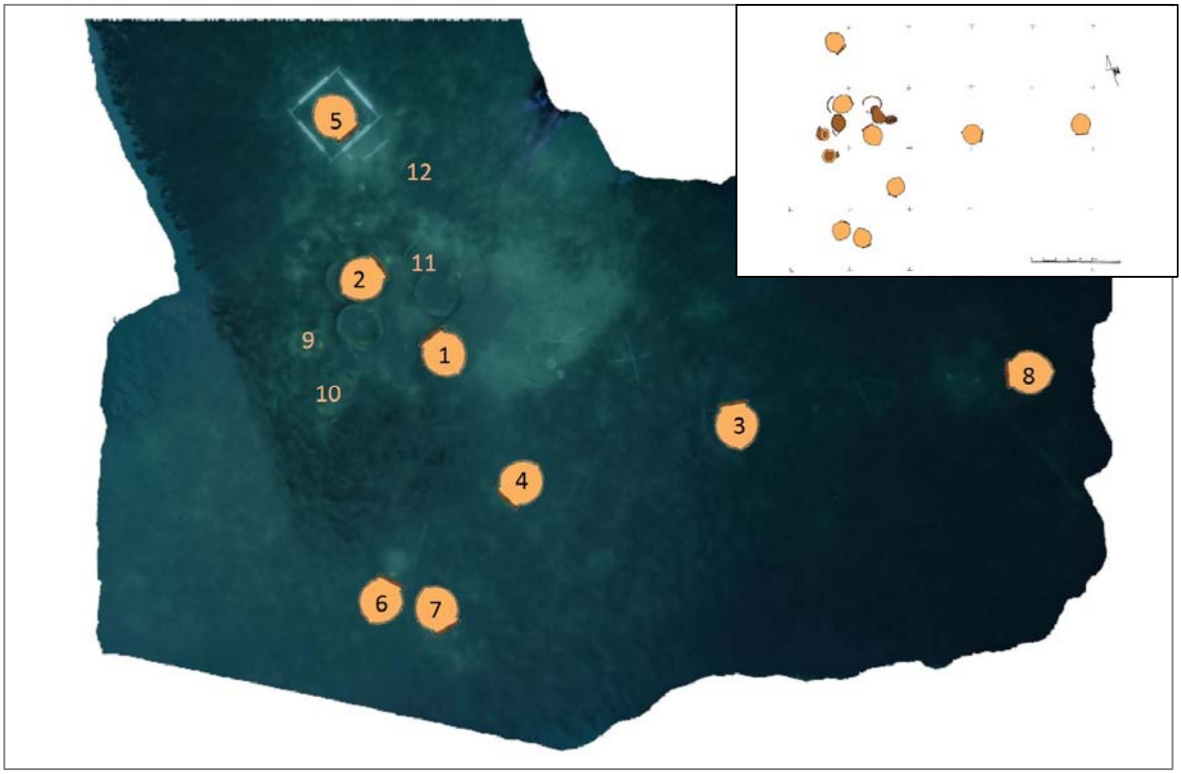

Fig. 9 The actual position of *dolia* according to preliminary orthogonal photography, exported from a preliminary photogrammetry model of the site; in the upper right of the diagram, for comparison purposes, is the plan published in 2008. Differences in the orientations of *dolia* D3, D8 and D4 were noted; additionally, north on the drawing actually points to the south.

The sediment around *dolium* D10, located in the group of *dolia* D1 and D2, was removed. It was determined *dolium* D10 is broken, but during sediment removal well-preserved wooden ship remains were discovered. The construction was covered with a layer of sediment up to half a meter thick. The detected part has been initially interpreted as hull planking, built in the mortise and tenon joint technique used during ancient times. Ships using this construction style were assembled shell-first, with frames inserted after the entire hull had been completed. The width of the tenon is about 10 cm and the thickness of the planking ranges from five to seven cm. This is massive planking for an ancient ship, clearly selected due to the necessity for hull strength to support the *dolia* cargo.

Fig. 10 Cleaning the preserved part of the ship's hull next to *dolium* D10 (photo: K. Yamafune)

Fig. 11 The remians of the ship's construction revealed under *dolium* D10 (photo: K. Yamafune)

Owing to the discovery of ship planking remains, we were able to determine the orientation of the ship's hull, and to some extent the dynamics of the shipwreck. It seems that the ship sunk on its side, so the *dolia* rolled off of the ship's deck. However, more details about the ship and its sinking can only be obtained through additional systematic archaeological research at the site.

Fig. 12, 13 The remains of ship's planking with the mortise and tenon joinery

(photo: K. Batur)

At the final stage of recording the remains of the ship's construction, several fragments were sampled at the site. One of the fragments was sent for date analyses by radiocarbon isotope dating (Annex 2), while other fragments were documented in detail. Currently those fragments are undergoing the desalinization process.

After all the necessary preparations had been made, photogrammetry recording was done at the site, which resulted in a virtual 3D model, site-plan, and a characteristic cross section.

The amphorae shipwreck site:

During the first visit to the site, it was noted that the amphorae were covered by a large amount of marine growth. Although this had been noticed before, it seems that the amount of the growth has risen, probably as a consequence of biofouling from the protective iron cage.

After evaluating the existing situation, two dredges were moved into the iron cage, and during the next two days the site was cleaned of grass and sediment. The amphorae were partly cleaned with brushes, but after corresponding with a marine biologist, it was decided that the biofouling would not be entirely removed. The task was simply too demanding, considering that living marine organisms were being destroyed, and additionally their regrowth would not be prevented by removing existing biofouling from the surface of the amphorae.

Fig. 14 Initial situation at the amphorae site under the protective iron cage (photo: K. Yamafune)

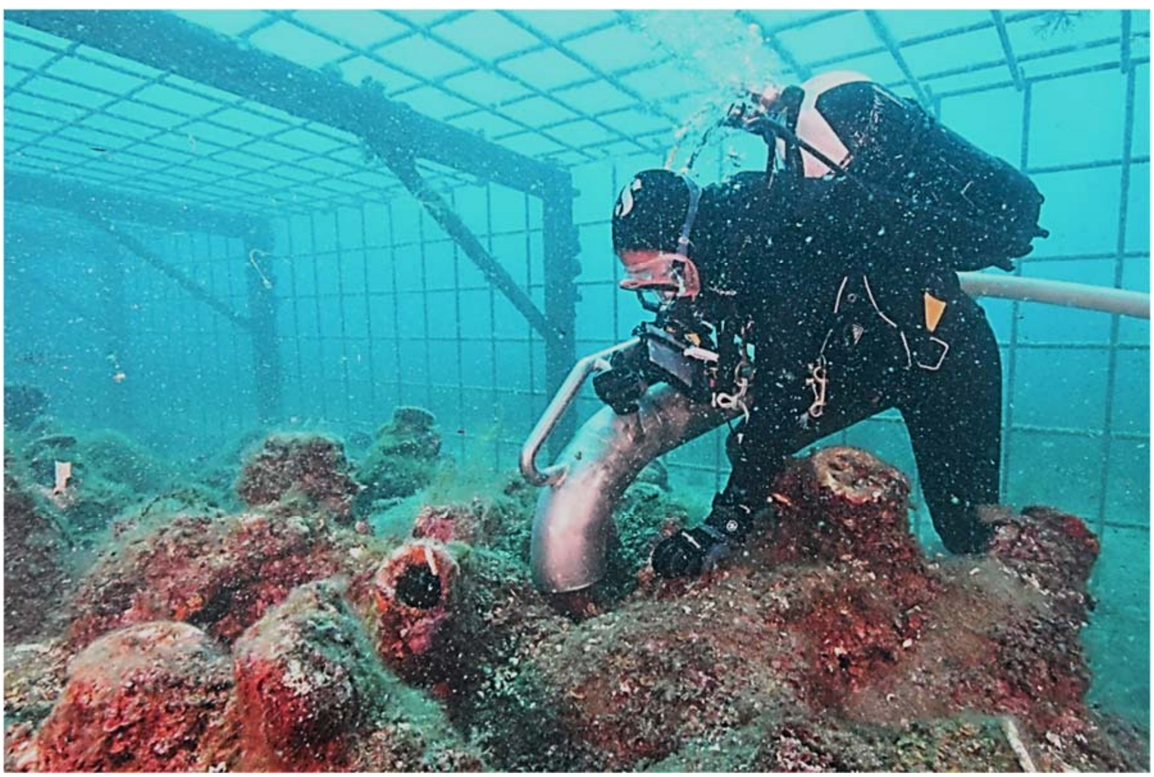

Fig. 15 Cleaning the site and preparing for the recording (photo: K. Yamafune)

Fig. 16 The site-plan built during in the 1990s; the two different amphora types can be recognised in ship's cargo and are displayed in different colors (Miholjek 2008: 63).

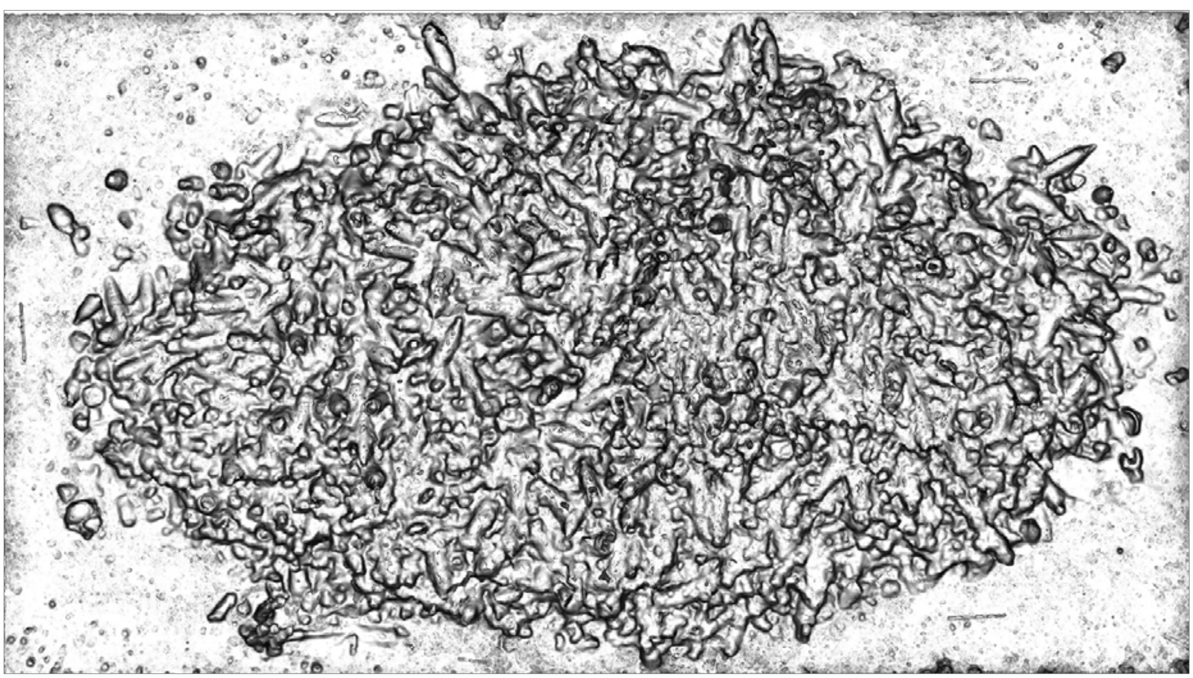

Fig. 17 The site-plan, automatically generated from the 3D model; different positions of amphorae are noted, as well as a significant increase in encrustation (photo: K. Yamafune)

Surface cleaning was also hampered due to the presence of moray eels living in some of the amphorae; after surface cleaning was considered complete, the site was recorded by photogrammetry. As in the case of the *dolia* shipwreck, a virtual 3D model, site plan and characteristic cross sections were produced.

5. Points of interest

As previously stated, it was necessary to designate ten points of interest for each site. Based on these points, an underwater site tour will be established.

Dolia shipwreck site:

On the site, the logical points of interest must include the entirely preserved *dolia*, as well as the accumulations of fragments. Next to each point, new information will be provided (drafting of content is in progress):

1) *Dolium* D5;
2) Accumulation of *dolia* fragments D11 / D12;
3) *Dolium* D2;
4) Accumulation of *dolia* fragments D9 / D10;
5) *Dolium* D1;
6) *Dolium* D4;
7) *Dolium* D6;
8) *Dolium* D7;
9) *Dolium* D3;
10) *Dolium* D8.

Remark: Numbers assigned to *dolia* are just working labels, they will be renamed in the presentation.

Fig. 18 View of *dolium* D5 (point of interest 1), (photo: K. Yamafune)

The amphorae site:

1) Entire cage;
2) The entrance;
3) Iron anchors;
4) North African amphorae with perforation;
5) The highest point of accumulated amphorae;
6) Amphora spike;
7) Amphora in standing position;
8) North African amphora in horizontal position;
9) North African amphora with perforation for pouring out contents;
10) The bottom of amphora Late Roman 2 type.

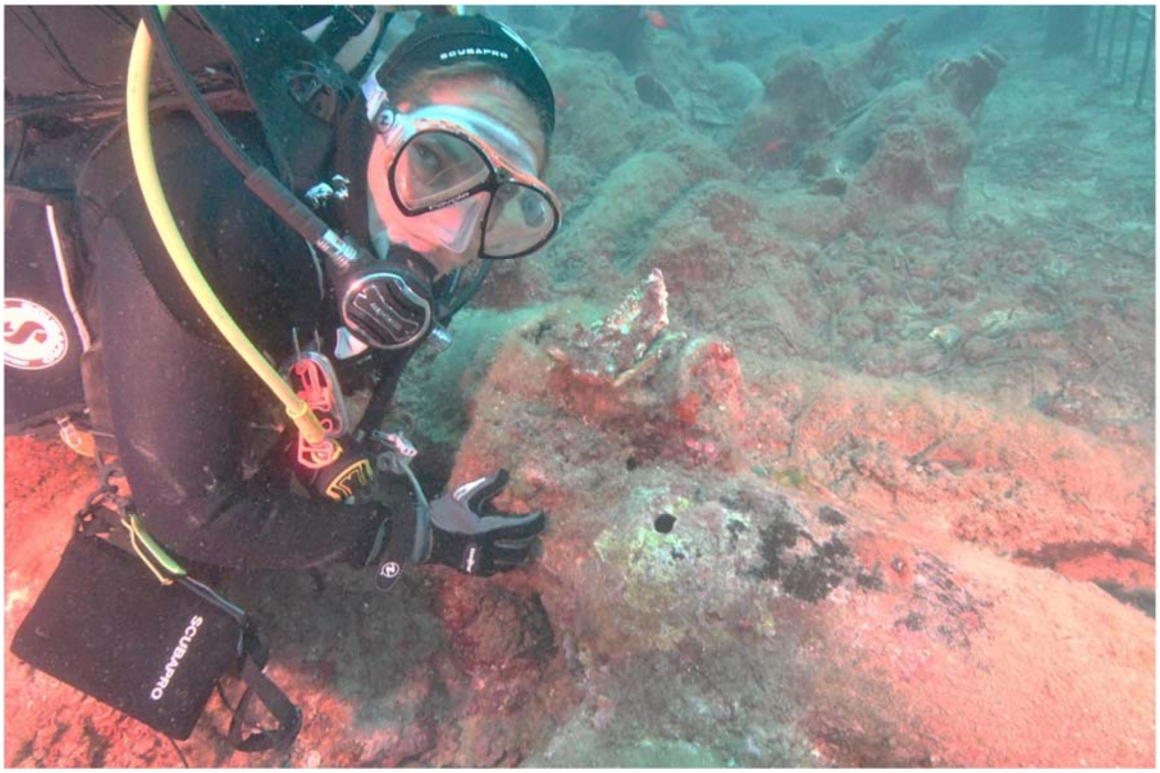

Fig. 19 Perforation at the bottom of an amphora, for pouring out the contents (point of interest 9), (photo: K. Yamafune)

6. Amphorae from devastated site on the northern side of Supetar islet

The site on the northern side of Supetar islet was never studied in its entirety. During the site evaluation in the late 1990s, recovery of entirely preserved and partly damaged amphorae was organized. Amphorae were found at different depths, from 10 to 60 meters, and according to the statement of Boris Obradović, the director of the Epidaurum Diving Center, there was a noticeable amount of sherds preserved on the sea bottom. After recovery, amphorae were stored in the well of Villa Banac in Cavtat, the building which then housed local government offices.

Considering the fact that Villa Banac was recently sold, and a new owner will take over the building, afternoon dives on the last day of the excavations were cancelled to organize the removal of these amphorae from the well. The goal was to recover the amphorae, and relocate them to a storage room managed by the Local Heritage Museum of Koavle. Amphorae recovery was executed with the help of cave divers with speleological equipement. The amphorae were recovered, placed on the terrace, and washed with the tap water. The samples of pottery sherds were taken for archaeometry analyses.

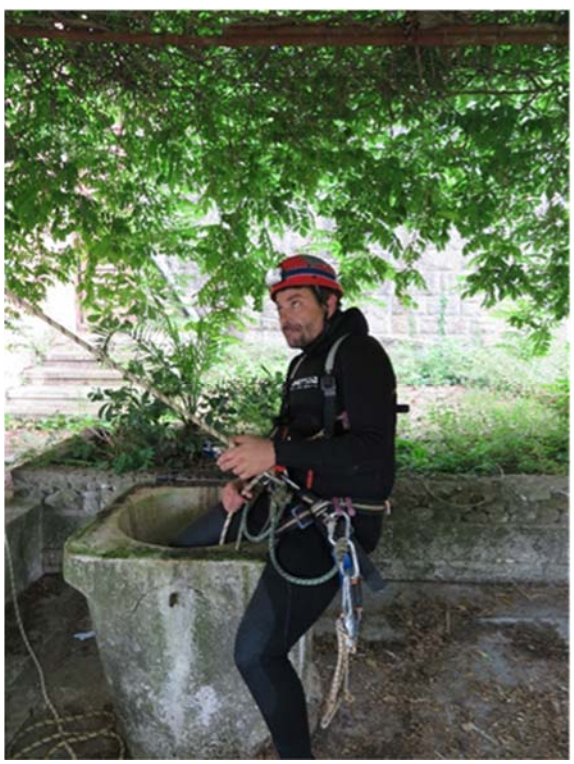


Fig. 20, 21 Diver entering the well; amphorae recovery using net, rope and pulley block
(photos: I. Šelendić)

Fig. 22 View of the cistern while the diver is descending (photo: I. Šelendić)

Fig. 23 Putting amphorae on the terrace of Villa Banac (photo: I. Šelendić)

7. Professional opinion

Archaeological sites on the seabed around Supetar islet are decidedly attractive for underwater presentation. The site with the *dolia* cargo is of special interest due to the large dimensions of pottery vessels, leaving every visitor amazed. Additionally, much interesting information exists about *dolia*, including mythological stories and anecdotes which could be used for presentation purposes.

The existence of similar sites has been attested on the coast of the Tyrrhenian sea, as well as on the coast of southern France and southeastern Spain. Based on analogies with archaeological finds, it is dated to the 1st and 2nd centuries AD. Stamps on the *dolia* from those sites often contain the name of family Pirani, the owner of a workshop in the city of *Minturnae*, contemporary Minturno in the Lazio region of Italy.

Fig. 24 Conceptual reconstruction of a ship with built-in *dolia* for the transport of larger amounts of the wine (R. Roman, CCJ, FR)

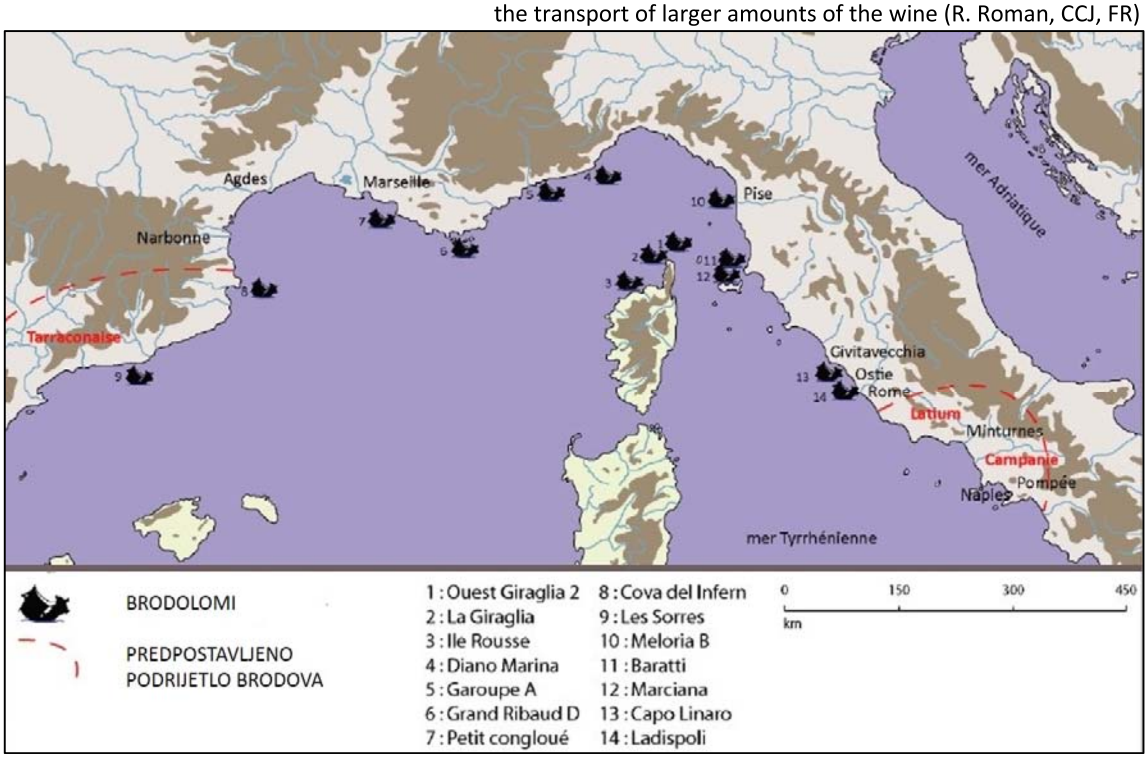

Fig. 25 Map of western Mediterranean shipwreck sites with *dolia* cargo (S. Marlier)

The Cavtat *dolia* wreck site is unique in the Adriatic, offering the only evidence of such a transport ship operating in this part of the Roman world. The site is easy to reach, and the finds on the seabed offer a unique experience during visits. High resolution videos and 3D models of the site, as well as selected samples of the ship's wooden construction, will be included as site presentation materials in the presentation center in Konavle.

Considering the exceptional character of the site, future tourism promotions could include the organization of archaeological excavations, and include participation of amateur divers under the supervision of qualified experts. An actual site visit should definitely enhance the attractiveness of visiting the exhibit.

The amphorae site is more challenging due to the smaller size of the amphorae and the existence of a protective cage positioned above the site. Due to safety reasons, it is not possible to bring visitors inside the cage. Just like the *dolia* shipwreck, this site is an attractive diving location where visitors can learn about historical culture and natural heritage. Virtual presentation of the site is especially interesting, because it allows all visitors to experience details which are not typically accessible.

Execution of this project is important to determine the viability of such an underwater visitor attraction. This work should optimize the visitor experience, and feedback should allow continuous improvement as well as the collection of new site information, to engage visitors both on land and under water.

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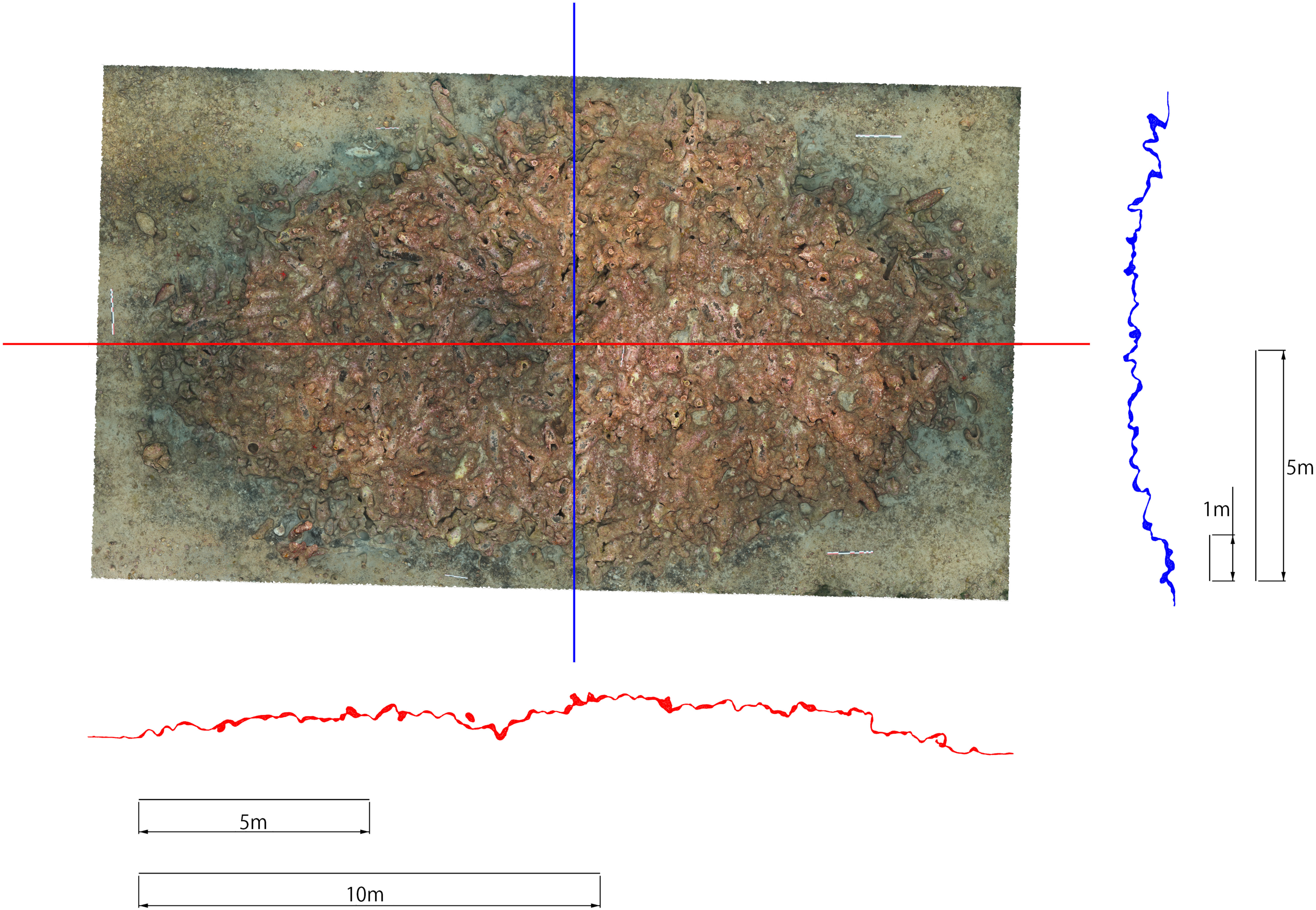
ANNEX 1

Site-plans and characteristic sections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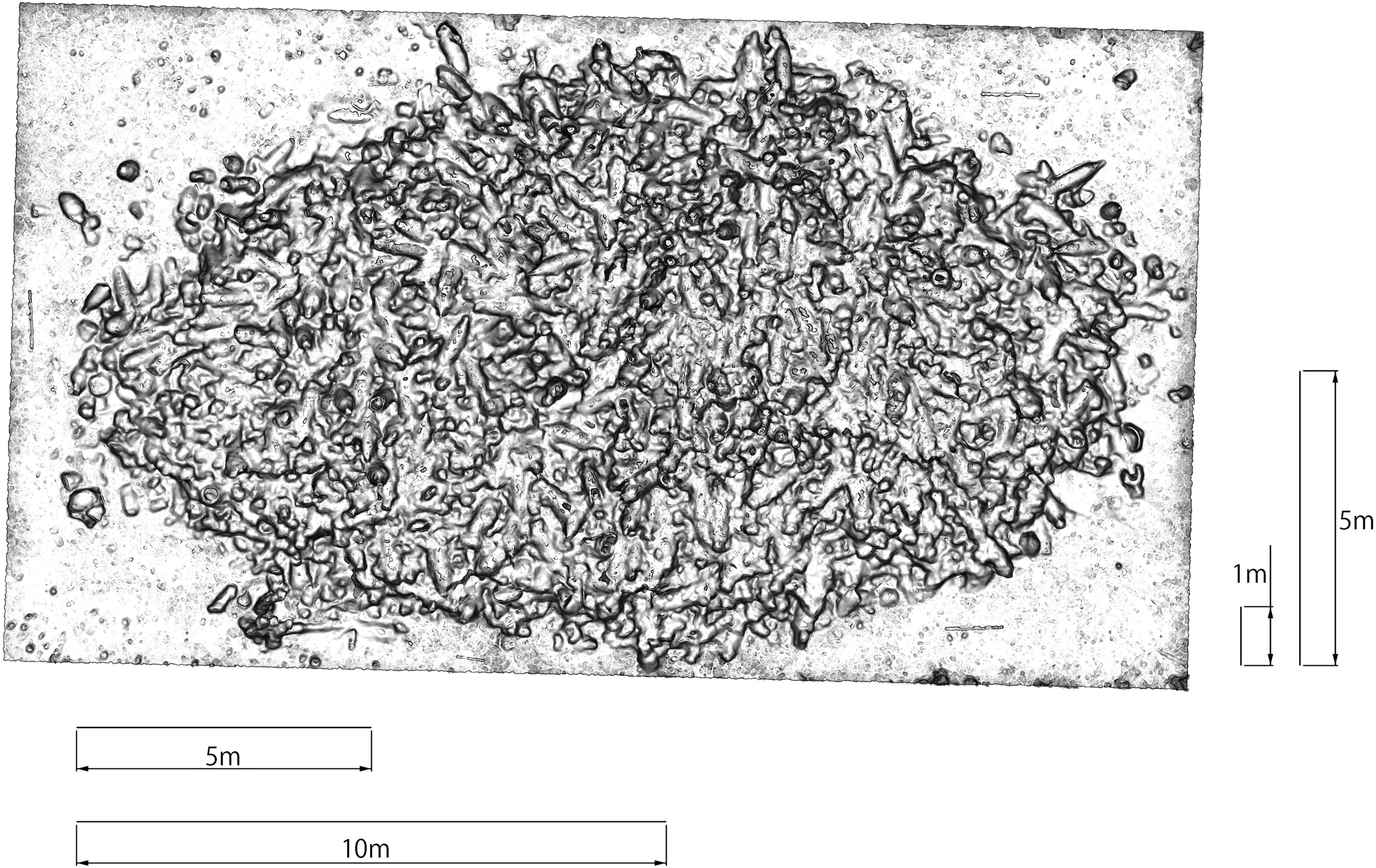
1m
5m
10m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5m
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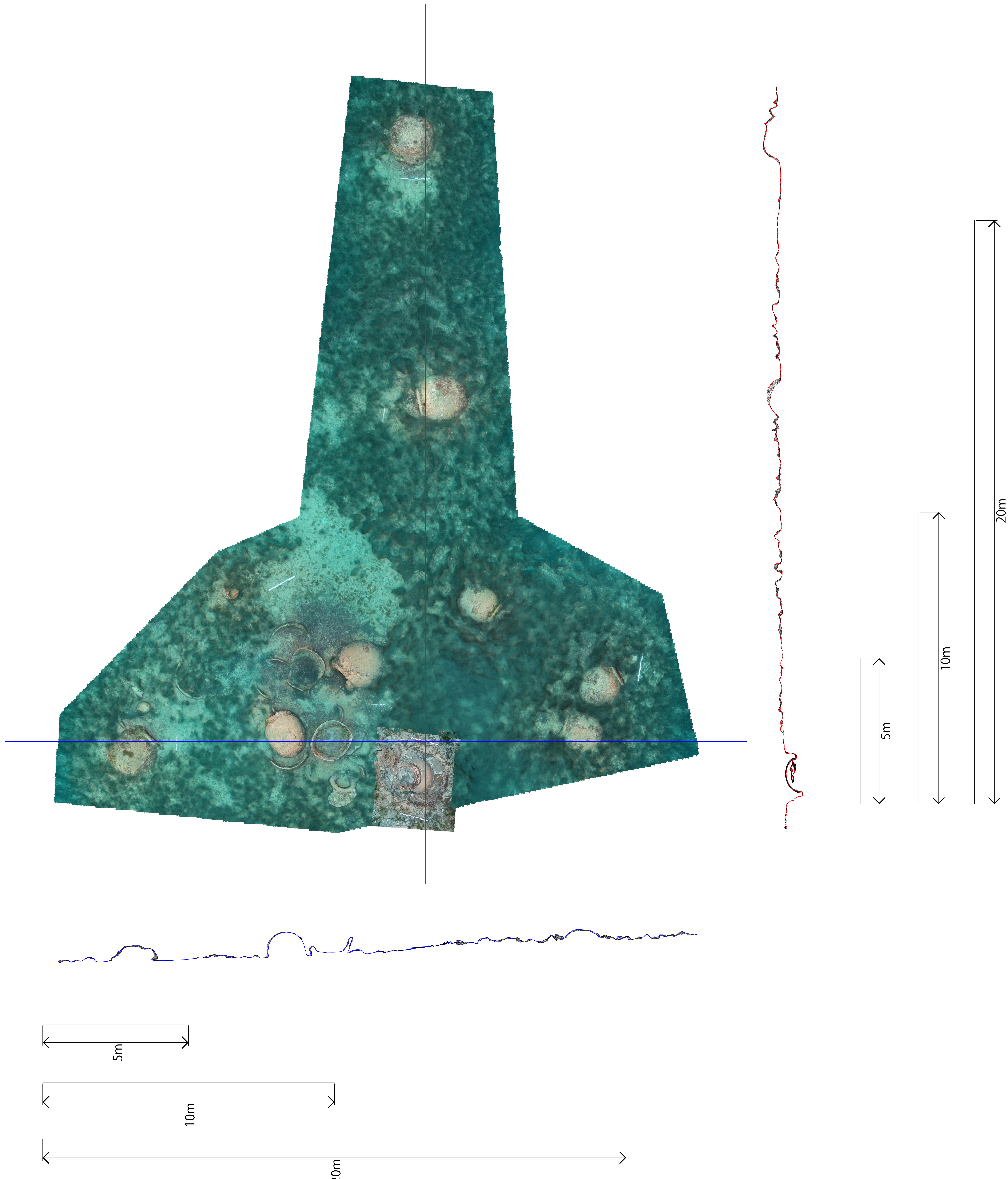
5m
10m
20m
5m
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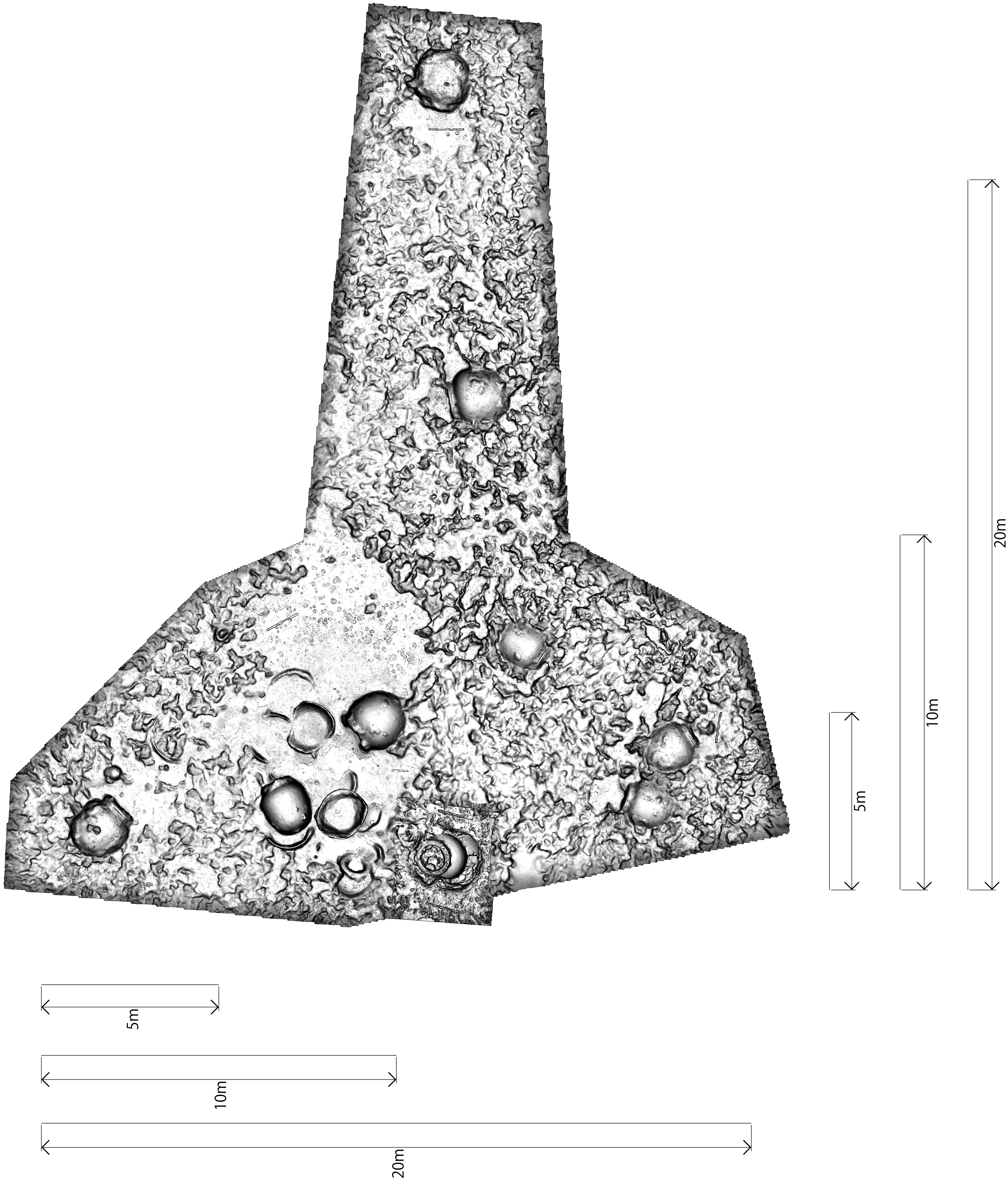

5m
10m
20m
5m
10m
20m

ANNEX 2

Results of radiocarbon dating of the wooden elements from the dolia shipwreck site

Beta Analytic Inc
4985 SW 74 Court
Miami, Florida 33155
Tel: 305-667-5167
Fax: 305-663-0964
beta@radiocarbon.com

Mr. Darden Hood
President

Mr. Ronald Hatfield
Mr. Christopher Patrick
Deputy Directors

ISO/IEC 17025:2005 Accredited Test Results: Testing results recognized by all Signatories to the ILAC Mutual Recognition Arrangement

July 20, 2018

Dr. Irena Radic Rossi
University of Zadar
Obala Kralja Petra Kresmira IV. 2
Zadar, 23000
Croatia

RE: Radiocarbon Dating Results

Dear Dr. Radic Rossi,

Enclosed is the radiocarbon dating result for one sample recently sent to us. As usual, specifics of the analysis are listed on the report with the result and calibration data is provided where applicable. The Conventional Radiocarbon Age has been corrected for total fractionation effects and where applicable, calibration was performed using 2013 calibration databases (cited on the graph pages).

The web directory containing the table of results and PDF download also contains pictures, a cvs spreadsheet download option and a quality assurance report containing expected vs. measured values for 3-5 working standards analyzed simultaneously with your samples.

The reported result is accredited to ISO/IEC 17025:2005 Testing Accreditation PJLA #59423 standards and all pretreatments and chemistry were performed here in our laboratories and counted in our own accelerators here in Miami. Since Beta is not a teaching laboratory, only graduates trained to strict protocols of the ISO/IEC 17025:2005 Testing Accreditation PJLA #59423 program participated in the analysis.

As always Conventional Radiocarbon Ages and sigmas are rounded to the nearest 10 years per the conventions of the 1977 International Radiocarbon Conference. When counting statistics produce sigmas lower than +/- 30 years, a conservative +/- 30 BP is cited for the result. The reported d13C was measured separately in an IRMS (isotope ratio mass spectrometer). It is NOT the AMS d13C which would include fractionation effects from natural, chemistry and AMS induced sources.

When interpreting the result, please consider any communications you may have had with us regarding the sample. As always, your inquiries are most welcome. If you have any questions or would like further details of the analysis, please do not hesitate to contact us.

Thank you for prepaying the analyses. As always, if you have any questions or would like to discuss the results, don't hesitate to contact us.

Sincerely ,

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Mr. Christopher Patrick
Deputy Directors

ISO/IEC 2005:17025-Accredited Testing Laboratory

REPORT OF RADIOCARBON DATING ANALYSES

Irena Radic Rossi
University of Zadar

Report Date: July 20, 2018
Material Received: July 02, 2018

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 498396	**SC_2018_D10**	**1900 +/- 30 BP**	IRMS δ13C: -25.4 o/oo

(88.5%)	**50 - 180 cal AD**	**(1900 - 1770 cal BP)**
(5.0%)	**186 - 214 cal AD**	**(1764 - 1736 cal BP)**
(1.9%)	**28 - 39 cal AD**	**(1922 - 1911 cal BP)**

Submitter Material: Woody Material
Pretreatment: (wood) acid/alkali/acid
Analyzed Material: Wood
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 78.94 +/- 0.29 pMC
Fraction Modern Carbon: 0.7894 +/- 0.0029
D14C: -210.64 +/- 2.95 o/oo
Δ14C: -217.10 +/- 2.95 o/oo(1950:2,018.00)
Measured Radiocarbon Age: (without d13C correction): 1910 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -25.4 o/oo)

Laboratory number **Beta-498396**

Conventional radiocarbon age **1900 ± 30 BP**

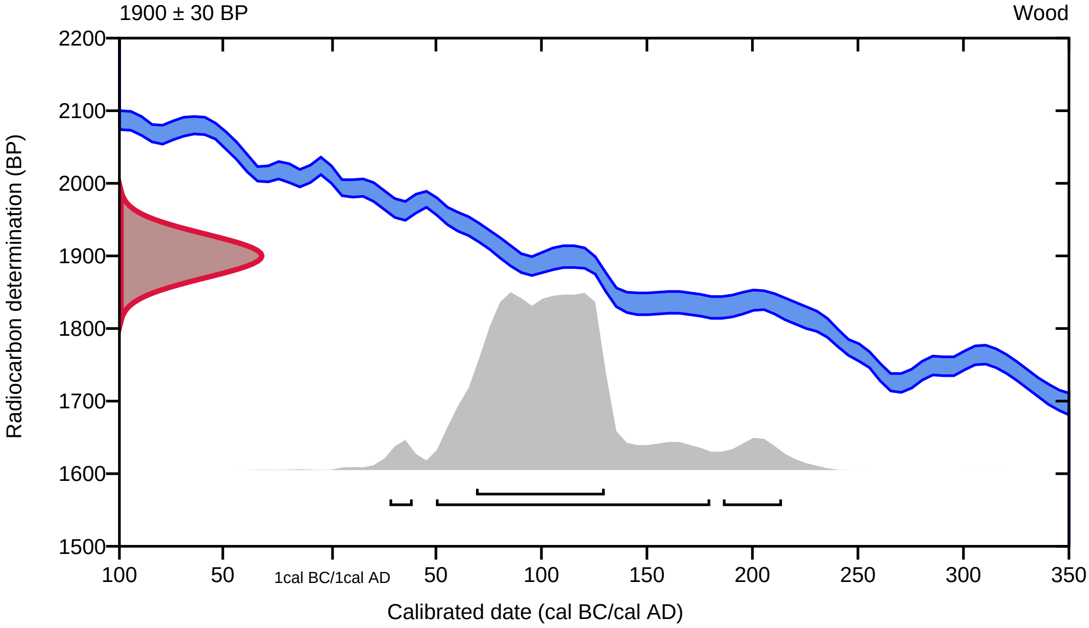
95.4% probability

(88.5%)	50 - 180 cal AD	(1900 - 1770 cal BP)
(5%)	186 - 214 cal AD	(1764 - 1736 cal BP)
(1.9%)	28 - 39 cal AD	(1922 - 1911 cal BP)

68.2% probability

(68.2%)	69 - 130 cal AD	(1881 - 1820 cal BP)

SC_2018_D10



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

Beta Analytic Radiocarbon Dating Laboratory
4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • Email: beta@radiocarbon.com

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ISO/IEC 2005:17025-Accredited Testing Laboratory

Quality Assurance Report

This report provides the results of reference materials used to validate radiocarbon analyses prior to reporting. Known-value reference materials were analyzed quasi-simultaneously with the unknowns. Results are reported as expected values vs measured values. Reported values are calculated relative to NIST SRM-4990B and corrected for isotopic fractionation. Results are reported using the direct analytical measure percent modern carbon (pMC) with one relative standard deviation. Agreement between expected and measured values is taken as being within 2 sigma agreement (error x 2) to account for total laboratory error.

Report Date: July 26, 2018
Submitter: Dr. Irena Radic Rossi

QA MEASUREMENTS

Reference 1

Expected Value: 96.69 +/- 0.50 pMC

Measured Value: 97.21 +/- 0.30 pMC

Agreement: Accepted

Reference 2

Expected Value: 0.49 +/- 0.10 pMC

Measured Value: 0.49 +/- 0.03 pMC

Agreement: Accepted

Reference 3

Expected Value: 129.41 +/- 0.06 pMC

Measured Value: 129.41 +/- 0.37 pMC

Agreement: Accepted

COMMENT: All measurements passed acceptance tests.

Validation: Darden Hood

Date: July 26, 2018