Deep Sea Archaeological Survey in the Black Sea – Robotic Documentation of 2,500 Years of Human Seafaring.

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Abstract

Between 2015 and 2017 the Black Sea Maritime Archaeology Project (Black Sea MAP) discovered and recorded 65 shipwreck sites dating from the 4th Century BC to the 19th Century AD in the Bulgarian Exclusive Economical Zone (EEZ). Using state-of-the-art remotely operated vehicles to survey the seabed, the team captured more than 250,000 high-definition (HD) photographs; hundreds of hours of ultra high-definition (UHD) video together with acoustic bathymetric, laser, side-scan sonar and seismic data. The wrecks were located in depths from 40 to 2,200 metres – those shipwrecks in the deeper range presented extraordinary archaeological preservation due to the Black Sea's anoxic conditions. This paper will introduce the range of deep-sea optic and acoustic survey techniques to accurately record and

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create 3D and pseudo 4D models of the shipwrecks. It will focus on a Early 4^{th} Century BC shipwreck demonstrating the project's survey strategy as well as adaptations developed in response to operational conditions; the implementation of deep sea robotics to generate georeferenced high-resolution photogrammetric models and the benefits this has as an on-site, as well as a post-cruise, interpretative tool. It demonstrates that in-theatre acquisition and processing of high-quality datasets is a working reality and has fundamental implications for management as well as the advantages that this brings to the archaeological research process: Firstly, in the creation of spatio-temporal models, i.e., 4D representations of a site pre and post archaeological excavation and secondly, in monitoring such wreck sites, and provides a viable non-intervention tool for the assessment of sites as part of a long-term management strategy. It also shows the value of well-funded collaboration between academia and industry and that deep water archaeology can and must be totally in accordance to the 2011 United Nations Educational, Scientific and Cultural Organization (UNESCO) convention.
Keywords: Deep Sea Archaeology, photogrammetry, shipwrecks, Black Sea, anoxic preservation, underwater robotics

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1. Introduction

This paper presents a key element of a major maritime archaeological research programme carried out in the Bulgarian EEZ between 2015 and 2019 (Figure 1). Its primary goals focussed on the impacts of Late Pleistocene and Holocene environmental change on human populations present in the region. The Black Sea has experienced a cycle of fluctuation levels over the Quaternary, and when eustatic sea levels were low, the Black Sea became isolated from the Mediterranean and global ocean system (Badertscher et al., 2011; Özdoğan, 2011). The timing of these periods, the nature of the basin, changes in salinity and lake levels, and the subsequent process of transgression have been fiercely debated (Ryan et al., 1997; Hiscott et al., 2007; Yanko-Hombach et al., 2007; Yanko-hombach et al., 2011; Yanko-Hombach et al., 2017; Lericolais et al., 2009, 2011; Lericolais, 2017; Soulet et al., 2011; Yanchilina et al., 2017). Archaeological questions relate to the fact that land exposed during periods of lower lake levels would certainly have been exploited by human groups and just as certainly lost again as the water level rose and reconnected with the global ocean reservoir via the Sea of Marmara and the Bosphorus Strait, Sea of Marmara, Strait of the Dardanelles and the Aegean Sea region of the Mediterranean.

This warmer, post-glacial environment of the Holocene (starting c. 11.5kya) saw the transition from mobile hunter-gatherer groups of the Upper Palaeolithic and Mesolithic periods to sedentary societies of increasing complexity in the Neolithic, Eneolithic/Chalcolithic, Bronze and Iron Ages. If a more accurate chronology of environmental processes including Black Sea water level changes could be generated, both constraints on and affordances for human populations would be better understood.

Noting the marked disparity in the interpretation of events, chronology and process across the research community regarding the Late Pleistocene and Holocene transgression, a programme of geophysical survey and geological core sampling was designed to enable palaeoenvironmental reconstruction of the Bulgarian shelf at a resolution not previously achieved. This was rea-

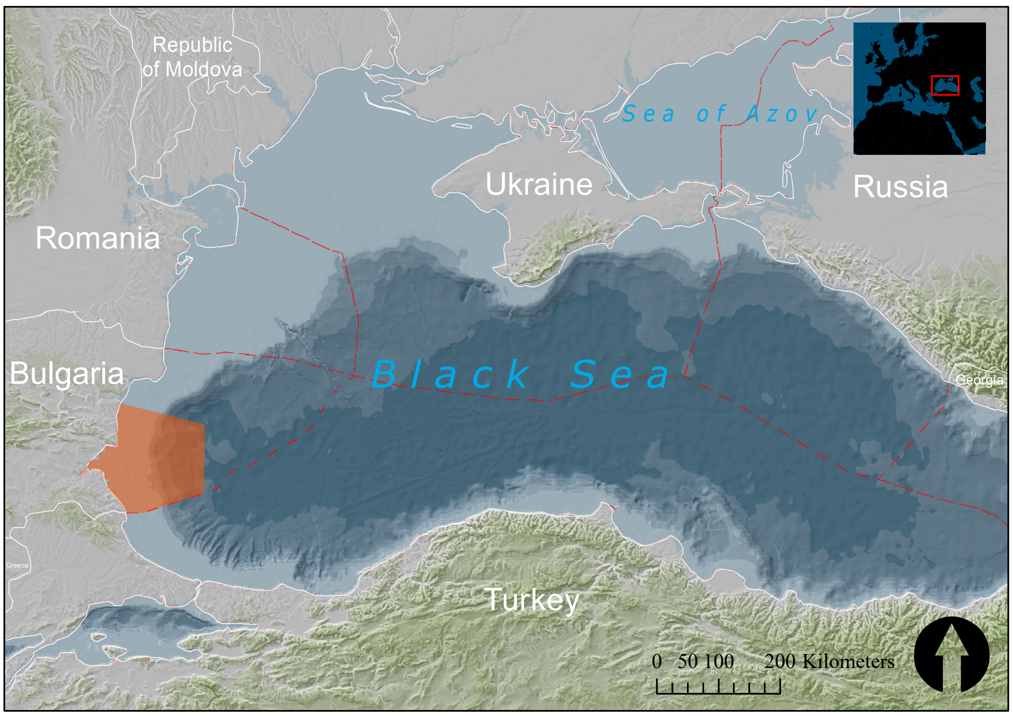

Figure 1: Map of the Black Sea showing the area of study (and permit of work of the Black Sea MAP) of this paper in orange and with red dotted lines, the EEZ of each of the Black Sea's countries. Data GEBCO and GSHHG.

soned to be prerequisite for any substantive understanding of both prehistoric communities and those that developed into the increasingly complex societies of later prehistory and subsequent historical cultures.

Details of the geophysical and geological sampling programmes are reported elsewhere (Adams *et al.* in prep) while this paper focuses on what might be termed maritime connectivity, namely the connectivity within and between societies implemented through maritime infrastructure and technologies. This would have been a key factor of human life reflected in the exploitation of marine resources, coastal locations of prehistoric settlements (many now lying underwater) and the wrecks of boats and (later) ships.

For these reasons it was assumed that during the course of surveying 2000 km^2 of the seabed shipwrecks would be discovered and this proved to be the case. By September 2017, 65 wrecks had been recorded in depths from 40 to 2,200 metres, ranging in date from the late 19^{th} Century, back through the Ottoman, Byzantine, Roman and Greek periods. Due to the anoxic (oxygen-free) conditions of the Black Sea below c. 150m, many of these ships, particularly at deeper depths, were in extraordinary condition (Figure 2). While some might be judged less important against criteria such as age, type, rarity, historical significance, etc., others were clearly of global importance, comprising the best preserved examples yet discovered of their respective periods and in some cases the only one so far found. This paper details how their recording was approached and carried out as well as discussing implications for subsequent research and contributions to knowledge.

From this perspective, the shipwreck research follows other deep water work done in the Black Sea (Ballard et al., 2001; Ward and Ballard, 2004;

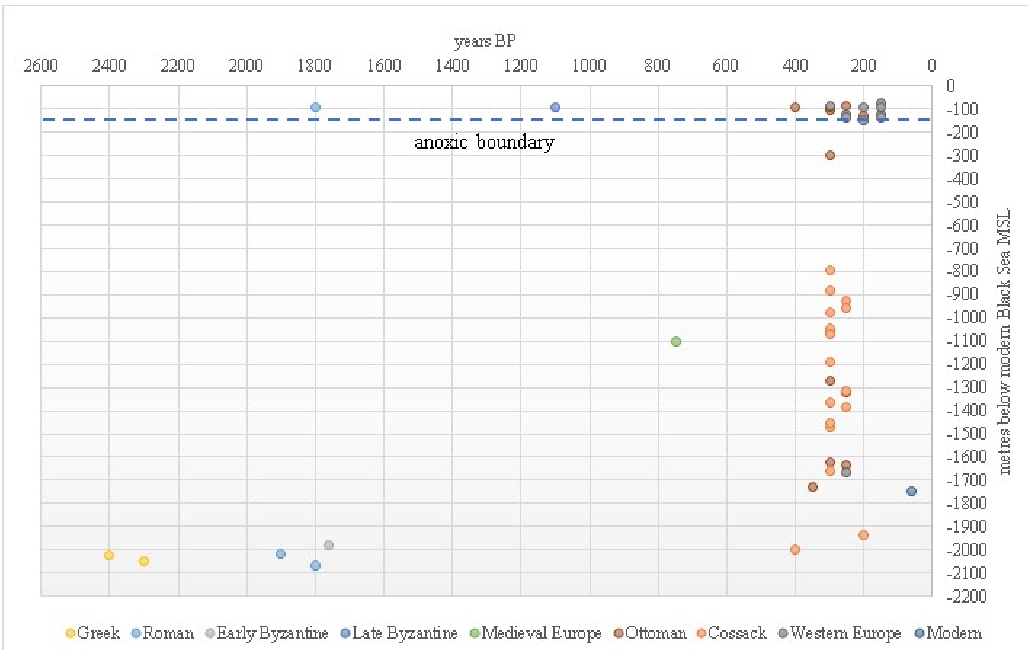

Figure 2: Graph showing the relationship between the chronology and depth of the shipwrecks discovered and recorded by Black Sea MAP. Those found below the anoxic horizon (c. 150m) presented extraordinary level of preservation.

Ward and Horlings, 2008; Brennan et al., 2013).

2. Archaeological imperatives

Inherent in archaeological practice is a range of methods for recording and documenting discoveries made in the field or the laboratory. Indeed the importance of recording had been recognized before archaeology became a recognized discipline. Antiquarians, whether acting in an official role or, as many did, in a private capacity, quickly recognized that the veracity of the record, whether it be a written description, a drawing, a cast or later, a photograph, was a pre-requisite for any degree of informed analysis. As the modern discipline of archaeology emerged in the late 19^{th} century it was also recognized that recording must necessarily be at the heart of a discipline that aimed to recover the human past through activities of excavation and sampling that were inherently destructive. Recording mitigated that destruction by underpinning the processes of information retrieval and analysis, in turn enabling interpretation and publication.

This is why archaeology as a discipline, both on land and under water, has been an early adopter of every newly developed means of recording and representation and why in many cases it has contributed to the development of such techniques. The rapidity with which new methods were tried underwater was due to the initiative of various practitioners who were well aware that meeting their archaeological obligations depended on the degree to which they could meet the challenges imposed by the underwater environment. It is not within the scope of this paper to discuss these challenges in detail or to provide a detailed history of the discipline but some of the key developments that underpin current practice are worth reviewing.

The underwater excavation that arguable marks the beginning of a professional maritime archaeology in which ethics as well as the methodology of archaeology were embedded in the trajectory of research, from the development of research questions through to publication and display, was that carried out at Cape Gelidonya, Turkey, in 1960 (Bass, 1966; Bass et al., 1967). One of the contrasts between this project and those that preceded it was the greater proportion of time devoted to careful observation and recording relative to that spent excavating and raising material (Bass et al., 1967). The project established a standard that other projects then attempted to meet, something of a challenge in the more turbid waters in other parts of the world.

Such a place was the south coast of England, where, in 1982, King Henry VIII's warship, *Mary Rose* (1545) was recovered from the waters of the Solent (Rule, 1982). This was the climax of 11 years underwater excavation in which the difficulties of all forms of underwater recording were a constant driver to enhance existing techniques or develop entirely new ones. The project's policy was to test every available system that might enhance the archaeological process. To this end ultrasonic cameras, sector-scanning sonars, black and white and colour video cameras (Rule, 1982), photomosaics and photogrammetry, integrated with 3D slant-ranging (Adams and Rule, 1991; Rule, 1989), all were tried alongside various acoustic systems. As early as 1975 the Partridge Rangemeter - a forerunner of Sonardyne acoustic survey systems, was used to control the production of the first plan of the entire site, an area of 55 x 30m, in conditions where underwater visibility averaged 1.5m (Rule, 1982, 92, 102 and Kelland, 1994).

On this and many other projects, the limitations of conventional techniques highlighted the need for accurate, rapid methods for recording complex three-dimensional structures and the 3D locations of artefacts and other objects of significance. At that time however, most underwater recording was a series of 2D techniques combined in such a way as to enable 3D projections; it was difficult and slow. Structural recording relied primarily on tape measures and on other mechanical means of measuring distances and angles. Photography was used to record features and aspects of archaeological practice but in a period before digital photography, reliable results were hard to obtain, particularly in turbid water and low light, without expensive wide angle lenses and powerful strobes, not to mention knowledge and skill. Some experiments were made with orthomosaics (Stewart, 1991) and photogrammetry (Green, 2016, 99-122; Rule, 1989 and Baker, 2014) but at that time software and computational capacity restricted the progress that was possible.

The development of digital photography coupled with faster processors and greater data storage capacity began to have a significant effect on recording practice in the 1990s. On the Skerki Bank of the Central Mediterranean in 1997, black and white digital photomosaics of six deep water shipwrecks were produced on board the research vessel during the three weeks of the cruise (Ballard et al., 2000; Singh et al., 2000). Following the cruise the mosaics were draped over the digital elevation models (DEMs) of the sites to produce an accurate 3D survey of the entire site and every visible artefacts (McCann and Oleson, 2004). Although entirely digital, this process was still time-consuming. However, in 2005 similar techniques were applied to a Classical period wreck in Chios, Greece. A colour mosaic integrated with a DEM was produced, this time within 24 hours (Foley et al., 2009).

The next significant advance was the development of photogrammetric software that was both easy to use, at least in terms of basic procedure, and which produced accurate and quantifiable results. Programmes such as Agisoft Photoscan made the practical application of photogrammetric techniques for the recording of complex three-dimensional structures underwater a reality for teams who did not necessarily include specialists or those with access to other bespoke software.

The Mars Project in Sweden, a project to record the wreck of the warship *Mars* (75m deep) lost in 1564, saw the production of a substantial 3D model of the remains using Agisoft Photoscan. The model was produced from tens of thousands of diver-based images taken with 24mpx cameras and built over three seasons of work from 2011 by Ingmar Lundgren (Eriksson and Rönnby, 2017).

The Black Sea Maritime Archaeology Project sought to achieve high-definition photogrammetric recording of well-preserved wreck sites like *Mars*, but in water depths of over 2000m using deep water robotics.

3. Remote operated vehicle (ROV) generated photogrammetry

Survey work of any sort at these depths requires robotics and this in turn requires vessels large enough to deploy them. Since 2003 a successful partnership between academia and industry has facilitated several projects using advanced offshore systems. This was initially created through a partnership between the Swedish offshore survey company MMT (Marin Mätteknik) and the Maritime Archaeology Research Institute at Södertörn (MARIS) University, Sweden, later joined by the Centre for Maritime Archaeology (CMA), Southampton. With funding in place for archaeology in the Black Sea, a core partnership was established with the Centre for Underwater Archaeology (CUA), Sozopol in Bulgaria and the University of Connecticut, USA.

Two vessels on long-term charter to MMT and their industrial partners Reach Subsea were used to locate and record the newly discovered shipwrecks in the Bulgarian Black Sea: *Stril Explorer* in 2016 (Figure 3a) and *Havila Subsea* in 2017 (Figure 3b). Both are DP2-rated Multi Purpose Support Vessels (MPSVs) used for high precision tasks and surveys within the offshore industry. The methodology and equipment applied was the same on both vessels barring some improvements on the camera systems made in 2017, when it was decided to use a wider angle lens for the acquisition of photogrammetric data. Irrespective of these changes the methods described are applicable to the surveys carried out on both vessels (Figure 4).

3.1. Camera and lights setup

3.1.1. WROV

Two work-class remote operated vehicles (WROVs) (from Kyst Design in 2016 and HD Shilling Robotics in 2017: (Figure 5), on the basis of their quotidian use in industrial tasks and their success rate suggested these tools to be ideal for underwater archaeological surveys using photogrammetric techniques. The principal camera used in the pursuit of high resolution three-dimensional modelling was the wide angle Cathx A1000 Ivanoff camera rated to a maximum operating depth of 4000m and capable of taking

(a) *MPSV* Stril Explorer. *Image Black Sea MAP*

(b) *MPSV* Havila Subsea. *Image Black Sea MAP*

Figure 3: Survey vessels used in the Black Sea during the expeditions of 2016 and 2017

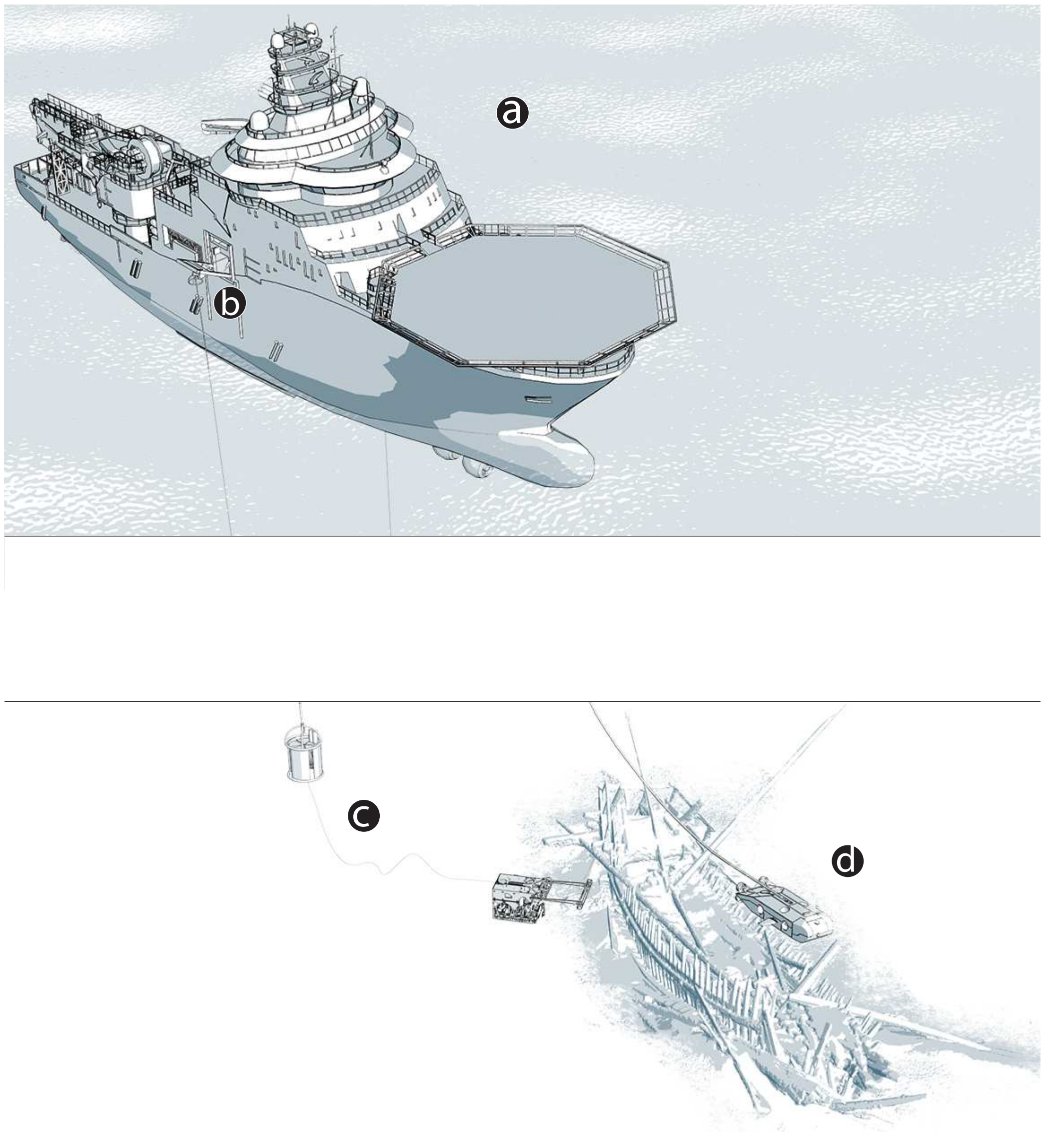

Figure 4: Schematic showing the deployment of the work-class remote operated vehicle (WROV) and the *Surveyor Interceptor (SROV)* to record underwater archaeological sites. (a) *MPSV* Havila Subsea holds position using her dynamic positioning system (DP)2 systems. (b) remote opperated vehicles (ROVs) are deployed from the side hatches on each side of the vessel. (c) the WROV reaches tether management system (TMS) depth and moves to the target to begin the survey. (d) the SROV glides over the shipwreck collecting data and sending it to the vessel through fibre-optics. Image the authors.

stills at 1.59mm/pixel at a range of 5m.

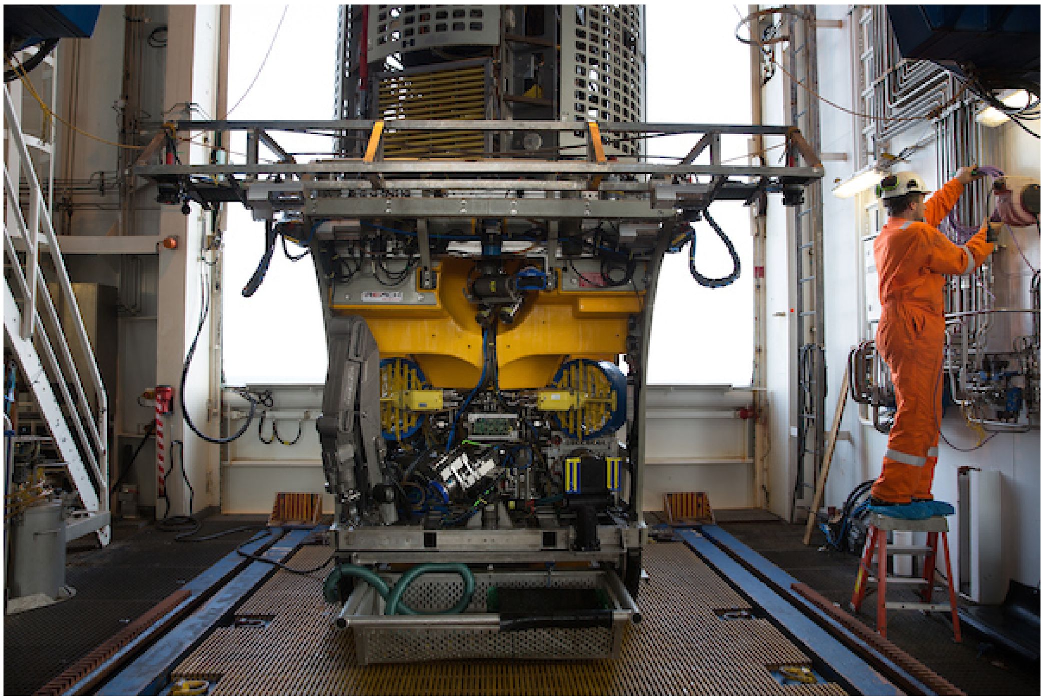

Figure 5: Image showing the Shilling Robotics HD work-class remote operated vehicle (WROV) being prepared on deck by the engineers for one of many shipwreck survey dives. Photograph Jodi Hilton.

Typically, sub-sea cameras have consisted of cameras and/or sensors that were initially designed for use in air which are then modified to fit into a subsea housing and be controlled remotely. Operating in the sub-sea environment with very little available light can lead to long exposure times, often as high as 20-30msec per image. In air, these exposure times cause very little issue, but when that camera is taken sub-sea and is fixed to a vehicle which is travelling at speed through suspended sediment, the results can be images with large amounts of blurring.

If the camera is attached to a vehicle travelling at 1 Knot (0.51m/sec), then an exposure time of 30msec will equate to the vehicle having moved 1.53cm during the image capture. To avoid this problem, Cathx has taken the approach of using cameras with fast, high-end lenses, in conjunction with high lumen output lights. The cameras directly control the lights, and this ensures that the camera's exposure time is exactly matched to the output from the light-emmitting diode (LED) strobe lights. Typical exposure times for the images gathered during trials were in the region of 1-2msec (see Figure 6 for a comparison of imagery from each available sub-sea camera).

(a) low-light standard definition (SD) camera image.

(b) colour SD camera image.

(c) wide angle HD camera image.

(d) Cathx UHD stills camera image.

Figure 6: Using the decorated tiller of an Ottoman vessel found at 300m deep this figure compares the the image quality from the different cameras systems mounted on the WROV.

The configuration of lights on the WROV not only allowed for faster exposures avoiding blurriness during the survey, but also reduced shadows. This is a known issue of underwater photogrammetric surveys, as moving light casts shadows that migrate across the scene preventing alignment of even closely overlapping images (Pacheco-Ruiz et al., 2018).

As shown in Figure 7 (1): the LED-based strobe lights were mounted on an hydraulically adjustable gantry, are located above the cameras and directed at a 38 degree angle away from the camera lens (a-b). The ability to vary both the extension of the gantry above and forward of the cameras as well as the power of the lights, allowed an optimum lighting configuration to be achieved for each survey.

On each occasion, as the WROV reached the targeted depth a primary inspection of the sites was conducted, permitting an assessment of the extent of the site and plan the trajectory of the survey. An initial calibration of light intensity and its distance from the camera was conducted by the WROV and survey teams. Adjusting the focal distance of the camera and the white balancing was also done remotely allowing for an ideal trajectory and altitude of survey modifying the settings as the survey was conducted.

Analogous to spray painting an object, to capture the wreck the WROV is piloted through a course that collects images of every part of the structure. This was achieved by first flying the WROV around the perimeter of the wreck as close to the seabed as possible. The cameras were mounted low down on the WROV so these images provided views into the wreck structure and upwards to capture the under surfaces of projecting timbers. This was then repeated at higher levels and completed with vertical flyovers look-

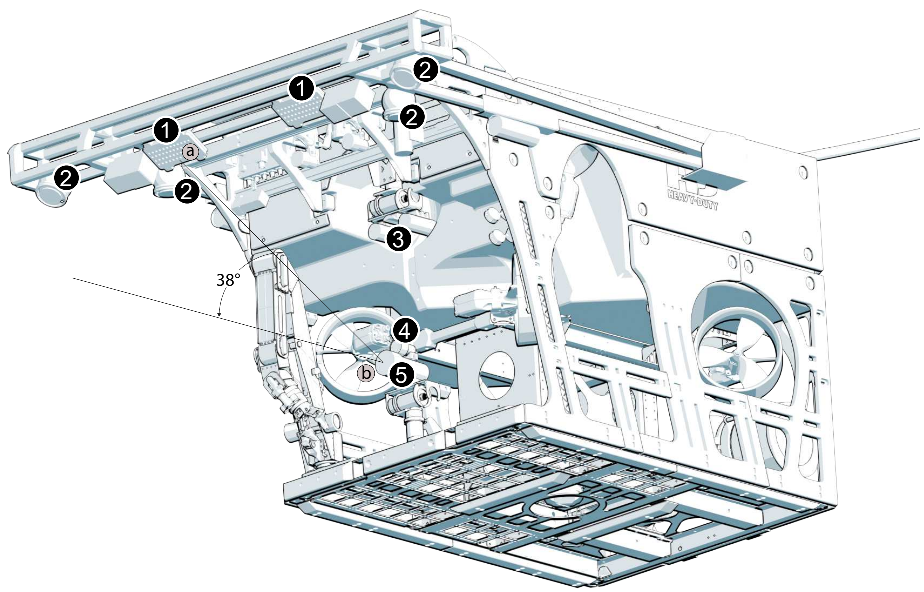

Figure 7: Image showing the standard configuration of lights and cameras for deep sea archaeological photogrammetric survey mounted on the Shilling WROV. (1)LED-based strobe lights (Aphos 32), which when triggered by the stills Cathx camera illuminate the scene to capture high resolution photogrammetric data. (2) Array of 10,000 lumen, LED SeaLite diffusion lights used for video capturing as well as global illumination of the scene. (3) Dual SD video cameras used for general navigation and auxiliary video documentation. (4) HD camera for detailed archaeological inspections and complimentary footage for photogrammetric datasets. (5) Cathx A1000 Ivanoff stills camera used as the principal tool for documenting underwater archaeological material. Image the authors.

ing down. Staying within maximum camera-to-subject distance, (partially dependent on visibility and projecting hazards, meant that the number of circuits required to obtain complete coverage was depending on the size of the site (Figure 8c).

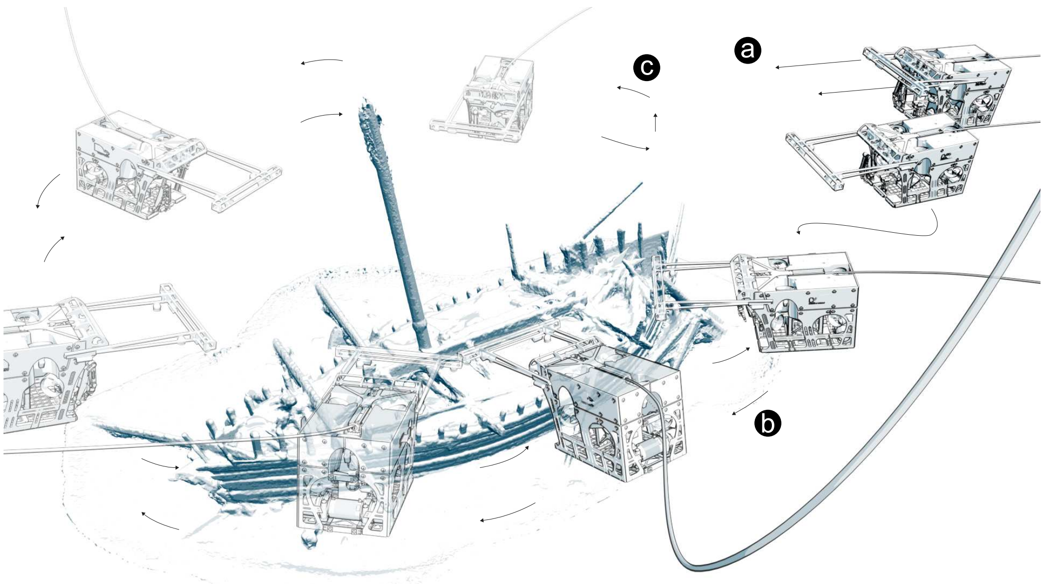

Figure 8: Image showing the survey methodology used to generate underwater photogrammetry using the Shilling WROV. (a, b) The WROV reaches the target and deploys the lighting rig to achieve optimum light diffusion and avoid shadow contamination. (c) Triggered from the surface the stills Cathx camera begins to capture high resolution images as the WROV performs an initial 360 degree coverage of the target. Image the authors.

On upstanding structures, including the remains of masts or standing rigging, the vehicle made a spiral ascent using the same image rates and camera calibration (Figure 9). The aim of this was to conduct a seamless survey of the target ensuring overlap and continuity, reducing the issues that can be introduced by trying to construct a model from multiple surveys (Eriksson and Rönnby, 2017).

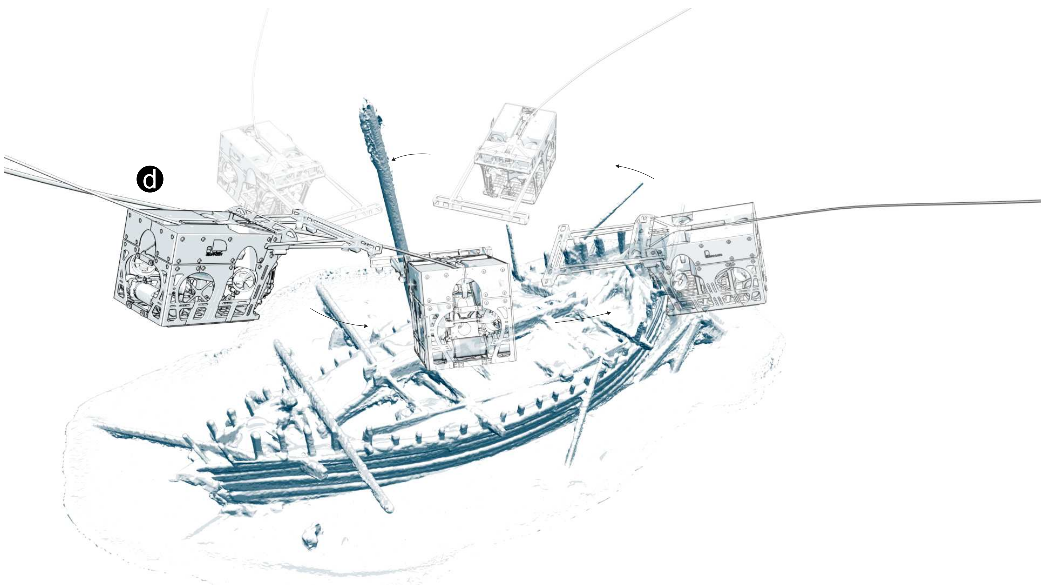

Figure 9: Photogrammetric survey, second phase (d) Once the outside of the shipwreck has been captured the WROV pilot then positions the WROV over the shipwreck to obtain vertical and oblique views the upper and internal structure and, in the case of this Roman wreck the upstanding mast, moving from bottom towards the top. Image the authors.

3.1.2. SROV Surveyor Interceptor

Complementary to the WROV the project also benefited from the use of a revolutionary vehicle designed for high speed survey the *Surveyor Interceptor* was in many ways the project's most important tool, carrying all the required geophysical systems as well as cameras and laser bathymetry. It was the principal tool for the collection of high-resolution geophysical data in 2016-17 and for relocating features and anomalies located in 2015.

The *Surveyor Interceptor (SROV)* (Figure 10) presents a very different configuration than its work class counterpart. It is designed to cruise in forward motion close to the seabed, following predefined transects. As the SROV 'flies' over the target, two Edgetech hydrophones collect sidescan sonar data (Figure 11: 1), two dual head EM2040 multibeam echosounders (Figure 11: 4) collect bathymetric data down to 10cm resolution, an Edgetech 2205 bottle with a DW-106 transducer collects seismic data with a pulse of 1.5-10KHz at 12 ms with a 3.5Khtz frequency and three Cathx cameras (Figure 11: 2) collect high-resolution imagery supplemented by the strobes (Figure 11: 5) and laser bathymetry (Figure 11: 3) to scale the photogrammetric models.

The three cameras located under the SROV (Figure 11: 2) have a vertical orientation and are spaced to allow a coverage of 2-5m when flying at altitudes of 5m or below. On small shipwrecks without any standing structures the entire survey could be completed in only 15 minutes. In both this mode (shipwreck surveying) as well as long distance prospection at higher flying heights (20-30m altitude), high-resolution data in real time make the SROV the ideal deep sea archaeological prospection and recording tool. During 2016

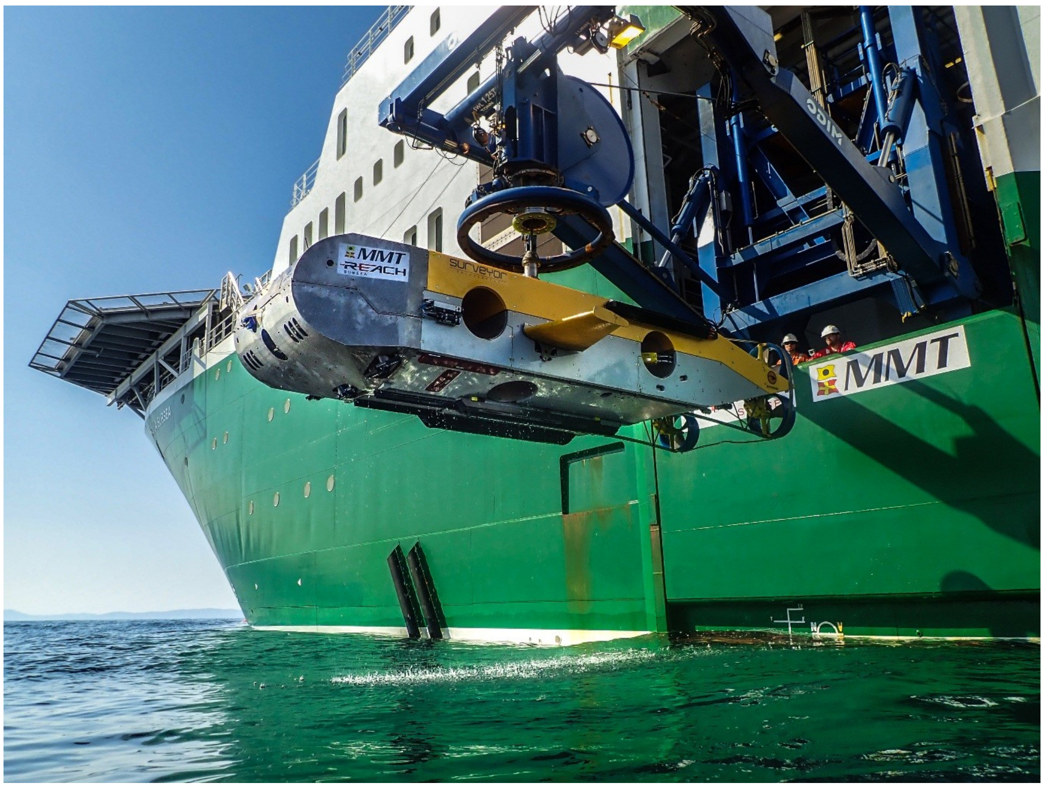

Figure 10: Image of SROV launched from MPSV *Havila Subsea*. Image the authors

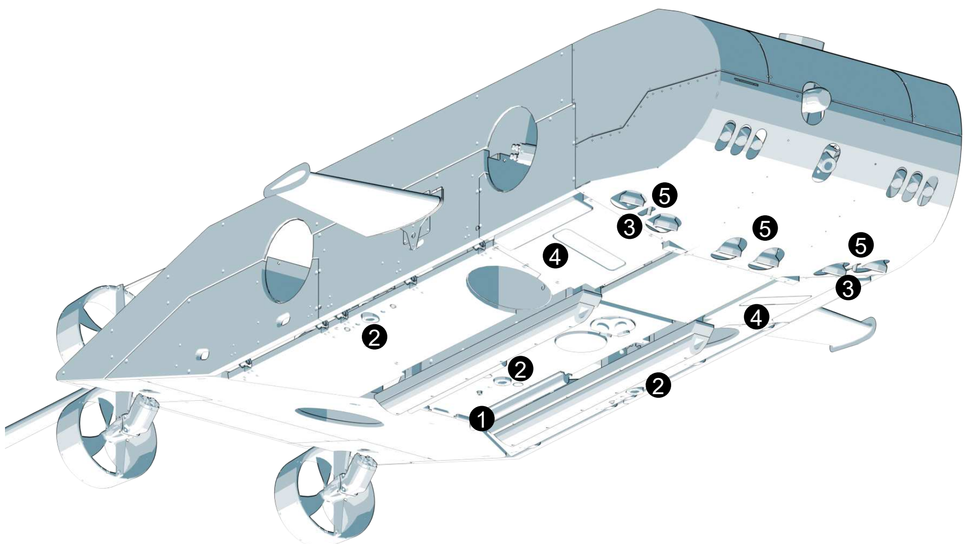

Figure 11: The standard configuration of equipment mounted on the SROV to capture photogrammetric and geophysical data. (1) Edgetech hydrophones. (2) UHD Cathx camera, the main tool for capturing photogrammetric data. (3) Green laser bathymetry system, one of the methods of scaling the photogrammetric datasets. (4) Dual head EM2040 multibeam systems. (5) Cathx LED lights used in a backward-facing position to help reduce the shadow creation. Image the authors.

and 2017 *Surveyor Interceptor* surveyed several thousand line kilometres, setting a new speed record of 6.34 Kts and a record depth of 2234m.

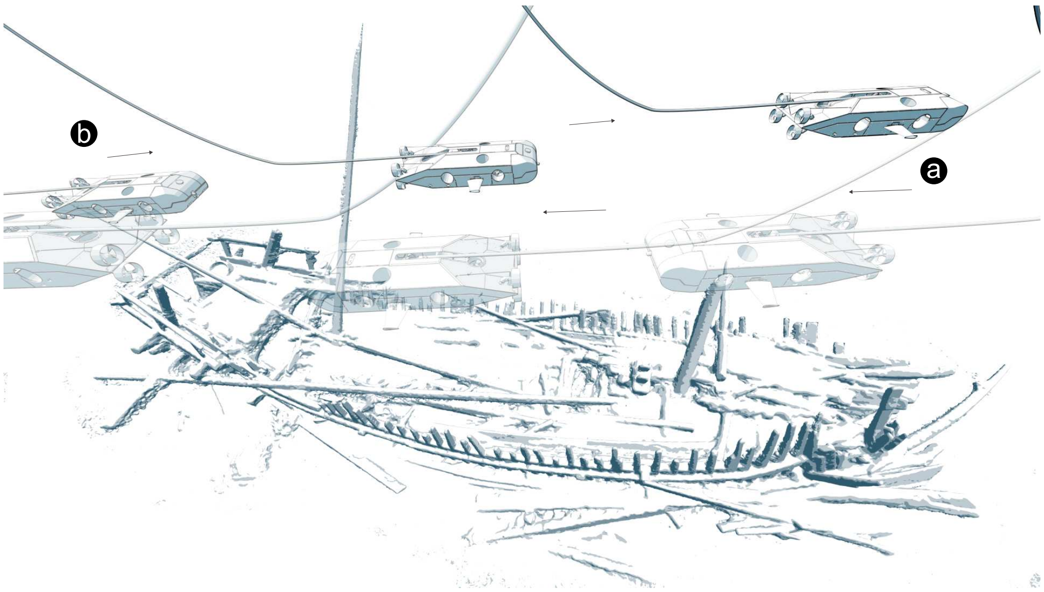

Figure 12: Figure showing the general methodology used to survey deep sea archaeological sites in the Black Sea using the SROV. (a) The SROV makes an initial fly-over, in which it will capture optical and acoustic data simultaneously. (b) adjacent passes will ensure overlap of data and full coverage of the shipwreck. Image the authors.

3.2. Geolocation and scaling

Ideally the resolution of a digital model generated from photogrammetry should be complemented by similarly accurate scaling. In shipbuilding, ‘scantlings’ dimensions of key structural elements, as well as the relationships between them, can be diagnostic of period and/or type. Even where this is possible some fundamental dimensions are necessary for even the most basic site records. Scaling underwater can be achieved in a number of ways. The most common one is by capturing in the scene an object of known dimensions (Rule, 1995). In our case a $50x50x50$cm cube was placed within one of the selected shipwrecks and captured from every possible angle (Figure 13). Within Agisoft PhotoScan Pro (1,3,3 build 4827) the cube was assigned the known dimensions allowing the software to translate this scale to the entire model.

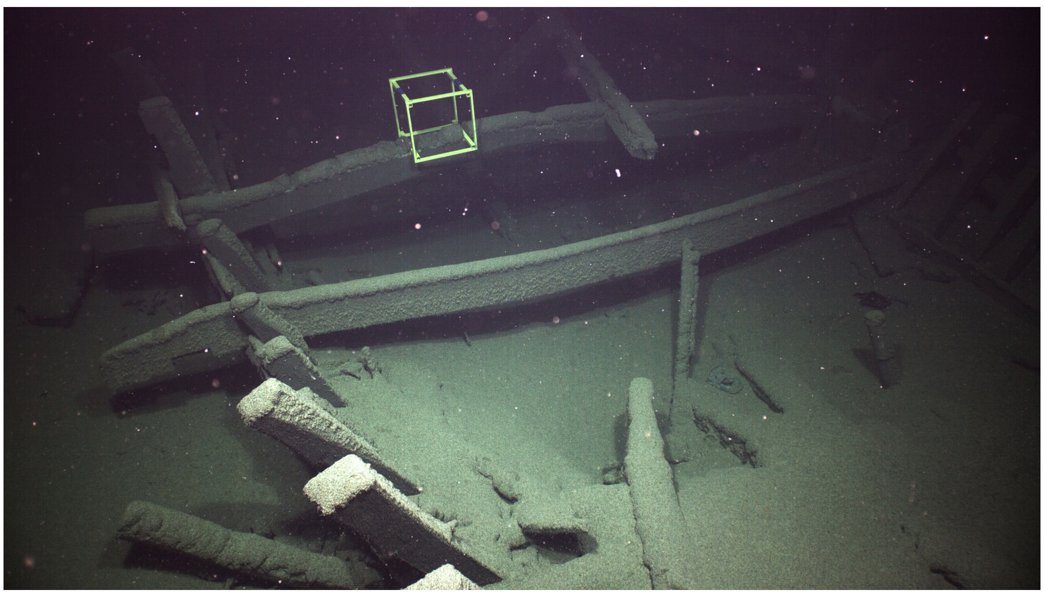

Figure 13: Figure showing the $50x50x50$cm cube after it was placed by the WROV on a visible location on top of the timber structure of one of the Roman shipwreck sites studied. Image the authors.

This method however presents some disadvantages. On the one hand, the possibility of placing an object on archaeological sites might not always be possible. Secondly this method does not include a position in the real world so it is necessary to reference the model after the scaling has been performed.

A second method used was through comparing the results of the point cloud produced from the photogrammetric survey with one generated and scaled by a different method such as swath bathymetry or laser scanning. This has the advantages of not only scaling and geolocating the photogrammetric model, but also of assessing the accuracy of the models by comparing both point clouds. This method is preferred as it allows for a more comprehensive comparison of the site. However, as most of the comparison is done manually, the resolution of the reference point cloud needs to be high enough to show features that can be unequivocally matched with those shown photogrammetrically.

The cameras have also been designed to allow inputs such as navigation information, and time stamping, so that the resulting images contain as much information about when and where they were captured as possible.

Through the different inputs the images contain information such as exposure time, aperture, and gains. This is integrated with positional data from the WROV, to include latitude, longitude, pitch, roll, heading as well as depth of the sensors and altitude from the seabed.

3.2.1. Deep sea camera geolocation.

The positioning system on each of the Cathx cameras is derived from multiple sensors mounted either on the ROVs or on the vessels navigational and positioning interface. On each of the ROVs are three inertial navigation system (INS). First, the main and origin of the ROVs positioning - Sonardyne's 'Sprint', an altitude and heading reference system (ARHS), INS, which consists of 3 ring laser gyros and three linear accelerometers that produce accurate real time motion and attitude measurements when interfaced with ultra short base line (USBL), Teledyne and Schilling Robotics'

RDI Workhorse 1200khz doppler velocity logger (DVL), pressure depth and external position.

Secondly the ROVs are also equipped with high-performance sub-sea INS for deep waters, the iXblue ROVINS and PHINS. These supporting INSs synchronise with the readings of Sonardyne's Sprint to achieve repeatedly accurate sub-sea positioning information allowing for one metre errors in positioning at the depths operating in the Black Sea. The positioning data is then interfaced to QPS Quinsy 8.18.1 software, a suite of hydrographic applications that covers a whole range of sensor data, from data acquisition to chart production.

The cameras mounted on the ROVs platforms are subject to a dimensional control survey (Dimcon) where their recorded offset is relative to the 'Sprint' centre and are measured using a total station or alternatively a photogrammetric survey prior to diving. The later method producing very good results within a millimeter accuracy (Figure 14). These relative camera offsets are then input into the Qinsy interface which assigns the values the navigation data and thus exporting the absolute positioning through the Cathx interface.

The advantage of recording all this metadata with each image is in the reduced post processing time. Tools such as Photoscan Pro can read the latitude and longitude information in an image *Exif* files, reduce the number of images it attempts to match images against each other. The positioning method applied in this paper also adds pitch, yaw and roll information to each image, creating 'camera positions' that are interpreted by Agisoft Photo Scan Pro, and allow them to be imported into any other geographic information

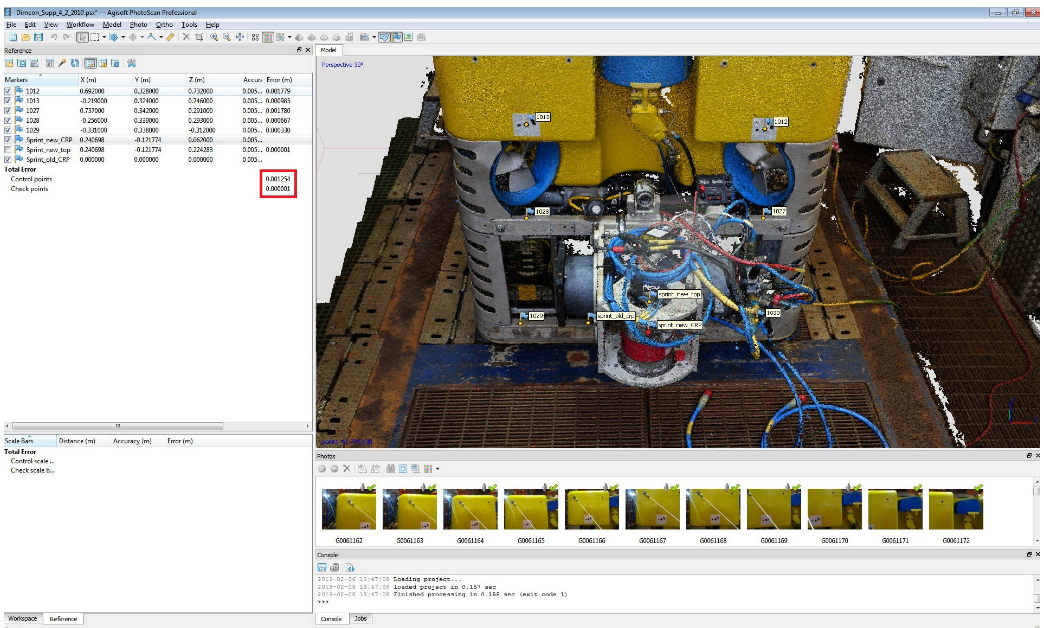

Figure 14: Results of the Dimcon of the Sprint INS mounted aft of the WROV using Agisoft Photo Scan software. The red rectangle shows the error of the photogrammetric model in metres. Image the authors.

systems (GIS) subsequently.

3.3. Rapid cluster processing

As the images were captured, both by the SROV and by the ROV, these were uploaded through fibre optics onto the ship's mainframe server. This made such media readily available to all of the members of the archaeological processing team who then fed these to a number of processing clusters available throughout the network. Two Dell Precision Tower 7810 were used as the main processing nodes. The CPU processing power came from the 16 cores (2 x Intel(R) Xeon(R) CPU E5-2699 v3 @ 2.30 Ghz) with additional 192 GB of RAM, whilst the GPU processing was supplied by an NVIDIA Quadro6000 graphics card for each workstation. Additional support nodes were created within the ship's server by using networked virtual environments and thus adding thee extra nodes for data processing speed. These virtual machines were customisable and where launched in five simultaneous instances of 19 cores (2 x Intel(R) Xeon(R) CPU E5-2699 v3 @ 2.30 Ghz) and 96 GB of RAM each.

4. Quantifying archaeological intervention

Photogrammetry was implemented to record the impact of the archaeological excavations carried out on a number of selected shipwrecks. Sediment accumulation on the sites after their sinking meant that diagnostic features, such as the shape and position of the steering assemblages, their fastenings and tool marks, the shape of the the rudder blades together with the remains of *in situ* material culture, such as elements of the cargo and crew personal belongings, were obscured by burial and may need to be exposed for further study.

4.1. The Early 4th Century BC shipwreck

This was the case with what was later demonstrated to be an Early 4th Century BC shipwreck found at 2,122m in the abyssal plain of the Black Sea. Seabed sediments obscured some features that were potentially diagnostic of period, vessel type and origin, including the steering assembly, particularly the rudder blade.

First, a general survey of the shipwreck was made using the techniques described above (Figure 15), thus achieving a high-resolution, pre-disturbance, photogrammetric record. Excavation was then carried out using a water induction dredge powered by the WROV hydraulic systems and controlled through a Schilling *Titan4* kinesthetic feedback robotic manipulator. The exposure of the archaeological remains were then resurveyed using photogrammetry. Both pre- and post-excavation phases were documented producing photogrammetric datasets to which the archaeological impact assessment was done using GIS root mean squared (RMS) superficial spatial analytical functions to understand and quantify the impact of the archaeological excavations (Figure 16). This method has been also been successfully trial and tested during the Black Sea MAP excavations of the prehistoric settlement of Ropotamo in 2016 (Pacheco-Ruiz et al., 2018).

The vessel showed strong similarities to a ship shown on the 5th century BC Siren Vase in the British Museum (Figure 17), providing the first indication of a possible age. To confirm the age of the vessel, a few timber samples were recovered by the WROV for the purpose of direct dating and

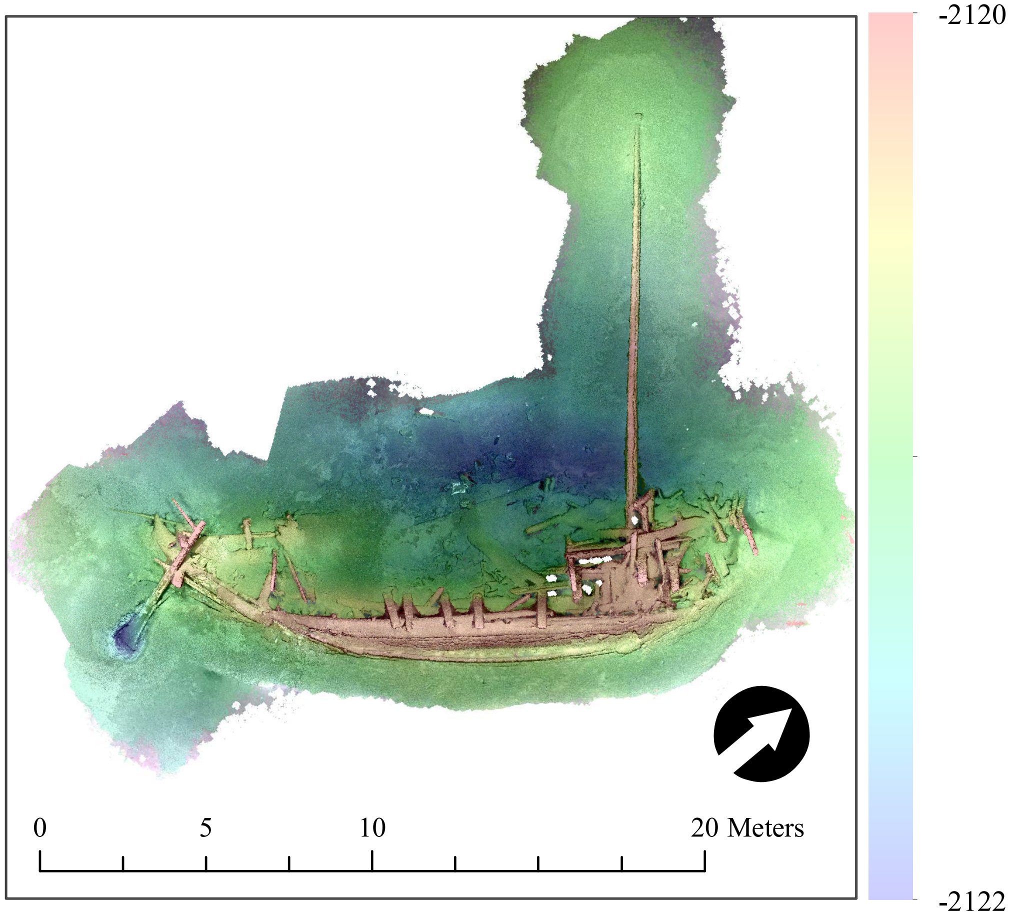

Figure 15: Photogrammetric site plan of an Early 4th Century BC shipwreck represented as a DEM from the photogrammetric model and the orthomosaic, resulting from the alignment of more than 2000 images. Image the authors.

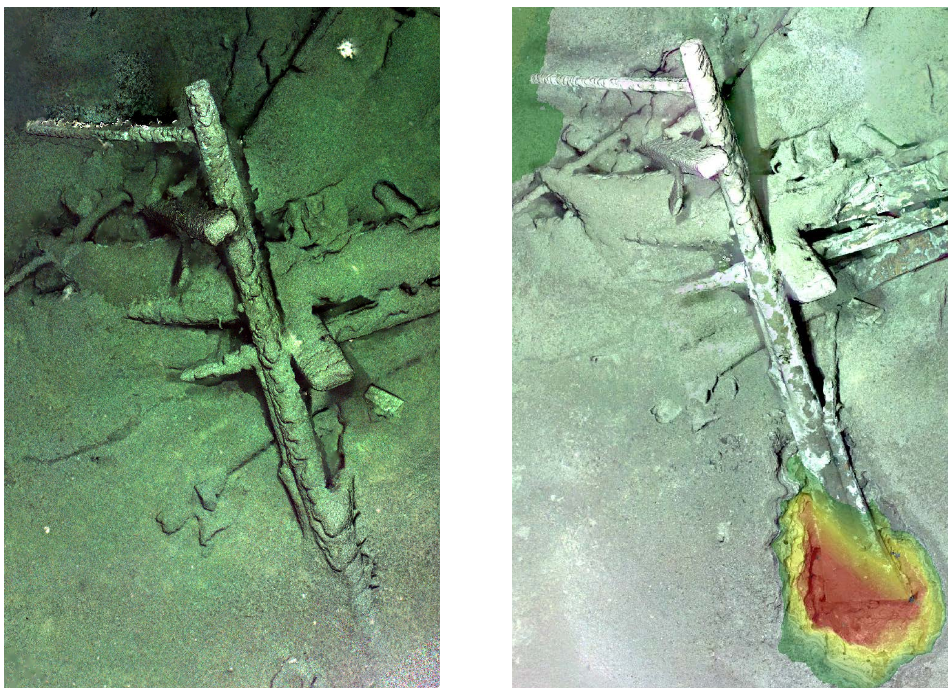

Figure 16: Comparative images showing both phases of the deep sea archaeological excavation of the rudder assembly and its recording. Left: the pre-disturbance survey. Right: the rudder assembly after the intervention using RMS comparison. All heights are zeroed to the seabed surrounding the wreck. Images the authors.

species identification. A recovered starboard side plank (4 dates; timber in two parts: T1/C and /D) and a possible thwart (1 date; timber T2/A), both identified as *Pinus sp. sylvestris* group, most likely *Pinus sylvestris* (Scots pine) or *Pinus nigra* (Austrian / Black pine), and a possible oar loom (1 date; sample T3/A), identified as *Fagus sp.* (beech) (see Supplementary Material) The starboard side hull planks and thwart are associated with the main hull structure and therefore, unless replaced during the lifetime of the wreck, can provide ages associated with a Maximum Construction Date (MCD: *terminus post quem*), whereas the oar loom could have been added at any point between construction and the last voyage of the vessel. To constrain the MCD age estimate, a Bayesian statistical model was created in OxCal 4.3.2 using a Phase model (Bronk Ramsey, 1995, 2001)(Figure 18). As none of the timbers had sapwood remaining upon them, the date at which felling took place cannot be established. A sapwood age correction (13±4 years) was added to improve the MCD estimate, based upon studies of modern *Pinus sp.* by Björklund (1999) Gjerdrum (2004), Mörling and Valinger (1999) and Pinto et al. (2004). One date from the centre of Timber T1/C (SUERC-78853) is identified as an outlier, following the methodology of Bronk Ramsey (2009), and omitted from the model. The resulting model has good overall agreement (Amodel=110) and provides an MCD estimate of *410-370 cal.* BC (95.4% probability) and probably *410-380 cal.* BC (68.2% probability), confirming that construction could have been as early as the beginning of the Early 4th Century BC.

From 65 shipwrecks recorded, four were subject to small-scale targetted excavations using the above mentioned techniques. Two of them between

Figure 17: Image of the 5th Century BC Siren Vase. Image The British Museum.

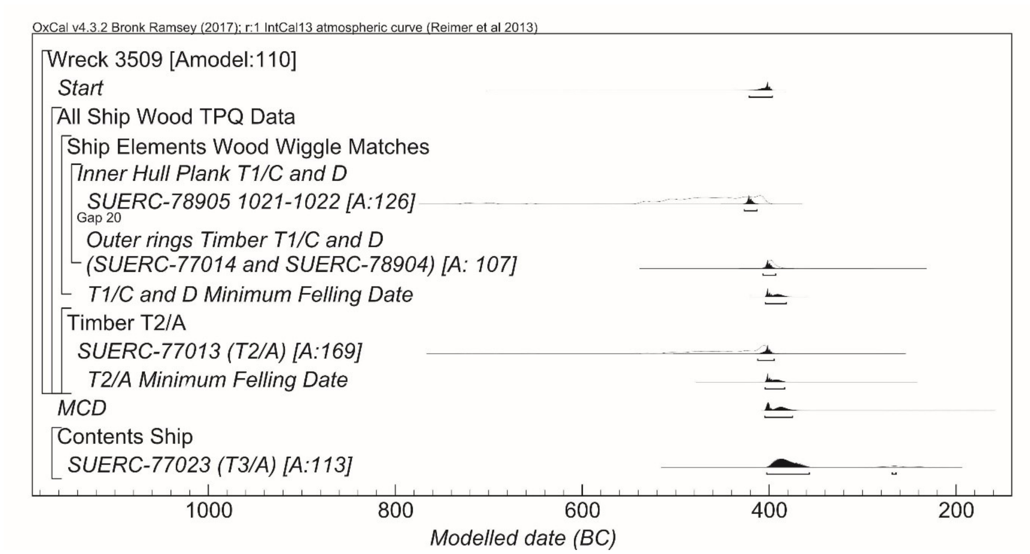

Figure 18: Phase model for the Early 4th Century BC shipwreck.

92-94m and two between 1,900 and 2,122m deep. We believe the latter is the deepest underwater archaeological excavation ever to be undertaken.

5. Implications

In any survey the archaeologist and surveyor needs to design an optimised procedure to achieve the required results in the minimum time and therefore at minimum cost. Every measurement, every image – should have 'analytical destiny' (Carver, 1985). Advantages of these new techniques are both the speed with which the data are collected and the deep sea environments where these can be utilised. Accuracy for accuracy's sake is a waste of time and money but here there are no penalties. Scaled photogrammetric surveys can be achieved very rapidly. The difference between a survey conducted for monitoring purposes as opposed to definitive, high resolution 3D recording is not so much related to the time taken to acquire the data but the qualities of the cameras and lighting array used. Additional time taken to refine the model post-cruise is less cost-dependent. In this case accurate 3D data of well-preserved hulls is demonstrably useful in various ways including hull reconstruction and performance analysis.

6. Adding to the database

Among the 65 wrecks discovered between 2015 and 2017 are some of the best preserved examples of naval and merchant vessels from the periods of Greek, Roman, Byzantine, Italian Medieval and Ottoman seafaring.

Surprisingly, there is relatively little known of Black Sea Seafaring even in periods when powerful empires controlled the majority of the traffic. To obtain this many well-preserved wrecks, even if a tiny sample of those that must exist, nevertheless provides a substantial injection of hard data to complement written history. The immediate benefit is a substantial increase in our knowledge and understanding of seafaring and maritime traffic in the Black Sea at both local and regional scales and across sequential cultural periods. Individual shipwrecks are often described as 'time capsules' and can be fascinating as individual discoveries. As Muckelroy pointed out, ships often represent a pre-industrial society's most complex technology (Muckelroy, 1978, 3). As such they offer high resolution views of their parent societies. Even better however, is a series of shipwrecks, for this constitutes longitudinal data providing insights into technological development, trade, warfare and strategies of competition and control that punctuated the cycles of human affairs, what the analiste historian Fernand Braudel described as the *Duree Moyene* (Braudel, 1972).

Comment on individual wrecks or even on the trajectories of each of the major periods represented is beyond the scope of this paper but in terms of seafaring technology it is immediately evident from Figure 2 is that the vessels from later periods were lost near the coast whereas many of the earliest vessels foundered tens of miles offshore. There are exceptions of course and as a sample these 65 wrecks do not allow definitive conclusions but there are reasons why this might be so. Ships from later periods had greater control over their propulsion and steerage and could afford to sail nearer to what it is effectively a lee shore hundreds of miles long, prevailing winds being from the North East. Vessels from earlier periods, whether under oar and/or sail, had less control and may well have intentionally steered NE after entering the Black Sea, gaining sea room until heading for the coast at a time and place of their choosing. Being this far from shore in what were effectively open boats, would have been perilous in storm conditions and this is undoubtedly the reason so many ancient ships lie so far out from the coast. Sedimentation rates, driven by the major rivers such as the Danube entering the Black Sea, have deposited large volumes of sediment across the Bulgarian shelf, with significantly less transported to the basin apron and deep sea (abyssal) plain. Dimitrov (1990) suggests sedimentation rates reaching 3-4mm yr^{-1} within the central area of the shelf which would mean an early Roman wreck, for instance, could be buried 6-8m below the modern seabed. A bias in the visibility of older wrecks to areas of lower sedimentation rates would therefore make their detection more successful in areas of lower sedimentation on the shelf or further offshore within the deep sea.

Lying far below the anoxic boundary, in the absence of any mechanical agency, these wrecks survive in a condition that makes accurate hull reconstruction possible. In order to understand the complex technology referred to above, lines plans are being generated that in turn facilitate performance analysis using the procedures of ship science, something that would be impossible in the absence of reliable 3D data. As well as providing the means for scientific analysis these finds throw considerable light on the ways in which these ships were represented by artists at the time. Ships are represented in many media such as sculpture, murals, ceramics and mosaics, depicted in various levels of detail depending on the purpose of the image. Modern scholarship has often pondered the nature of representation including the degree of fidelity between the depictions and the reality from which they derived (Villain-Gandossi, 1994; Flatman, 2007; Greenhill, 1995; Adams and Rönnby, 2013). The discoveries during the Black Sea MAP show that in many cases where an artist represented a vessel in detail, there is strong correlation with the reality that survives on the bed of the Black Sea.

7. Access to the Deep Sea

The results achieved in the 2016 and 2017 seasons exceeded expectations in the sense that it was assumed that much of the processing would be carried out post-cruise but already in 2016 it was possible to keep pace with the surveys to the extent of having a model of proven fidelity within hours of the survey. In 2017, as we refined our procedure of image capture and post processing, it was usual to have aligned the images (the crucial part of the photogrammetric process), before the WROV had left the site. Subsequent generation of point cloud, mesh and then rendering (and in 2017 the

3D printing of scaled models) could be done at leisure, though still usually completed within 24 hours.

During the early development of maritime archaeology there was some discussion about the necessity for archaeologists to dive where the site being investigated was in the diving range. The longstanding consensus (shared by the present authors) is that this is desirable whenever possible. The immediacy of being on the site confers considerable advantages (Adams and Rönnby, 2013, 86). However, for sites beyond the diving range submersibles are the only way in which an archaeologist can 'be' on site and then it is debatable to what degree this confers benefits over and above experiencing the site from the control van of an ROV. A sense of immediacy there certainly is and one gets a far better appreciation of scale and of site topography and relief for example by comparison to the flattening effect of seeing even hi-res images on screen. This may speed up the process of understanding the site considerably although this is to some extent offset by the advantages an ROV has in both endurance and accessibility. Recent development of UHD video and now the use of photogrammetry as reported in this paper go some way to bringing the researcher to the site or rather the site to the researcher. Being able to explore a detailed 3D model of the shipwreck, either as a 3D print or through a virtual reality (VR) platform allows consideration of enigmatic aspects, almost always resulting in recognition of features not appreciated or understood at first sight even when watching UHD video footage. In one case, on close inspection of a 3D photogrammetric model of a wreck that was relatively broken up and which had initially defied identification, it was realised to be Roman, something that might never have happened had the record of the site only been conventional video.

Maritime archaeology in very deep water is now a reality, and one of the ways in which the use of the necessary resources can be justified is the speed with which several sites can be located and recorded in a very short time, something that has considerable significance for the advancement of our understanding of the maritime past and for the protection and management of the resource, including monitoring sites and prioritising future work.

The other major factor is the ways in which these technologies and methodologies enable the research aims, methods and results to a reach a wider audience through various experiential modes of extended reality (XR), namely Virtual Reality (VR), Mixed Reality (MR) and Augmented Reality (AR) platforms (Figures 19). In the experience provided this is similar to Telepresence, pioneered by Dr Robert Ballard, where seabed video was transmitted via satellite direct into schools in real time throughout North America (Brennan et al., 2018). This was both innovative and imaginative and in principle this has never been surpassed, though these days the down link can be streamed to the internet and data can be accessed by associated scientists ashore. Black Sea MAP considered Telepresence but for logistic reasons chose to bring the students to the ships and to use the aforementioned digital platforms (developed since Telepresence was first used) as they are becoming part of the routine fabric of extending knowledge in museums, schools, web portals and all digital interactive platforms. Once the digital content has been created the potential audience is huge and depending on design, the experience is more interactive and open-ended, albeit without the immediacy of Telepresence. Some of the most exciting potential of digital modelling and reconstruction is related to the time depth of archaeological sites in general and shipwrecks in particular which are wonderful vehicles for experiential approaches that will enable the viewer/wearer/player to explore time and processes of change as well as space, landscape, structure and things.

8. Recording a finite resource under threat

As well as the immediate research benefits of such discoveries, these surveys comprise the first step in preservation by record, but will also lead to preservation by law as well. The coordinates of each find as well as the surveys are lodged with the Bulgarian authorities and with the Centre for Underwater Archaeology at Sozopol. Bulgaria has a more integrated system of marine management than many other countries. It was the second State to ratify the UNESCO *Convention on the Protection of the Underwater Cultural Heritage* (2001) and the heritage authorities have sight of relevant permit applications in all marine zones. Deep water shipwreck sites of outstanding archaeological importance are therefore probably safer in Bulgarian waters than almost anywhere else. This is important due to the fact that these technologies are available anyone with the financial resources to deploy them. While those sectors are principally the military and industry, the latter includes private ventures that are either blatant treasure hunting or ill-disguised forms of the same.

Industrial threat is another factor, ever-present but often invisible. Development is one of the most potent threats to underwater cultural heritage near shore but trawling has potentially disastrous impacts on historic wrecks in offshore fishing grounds. The impacts of trawling on both submerged her-

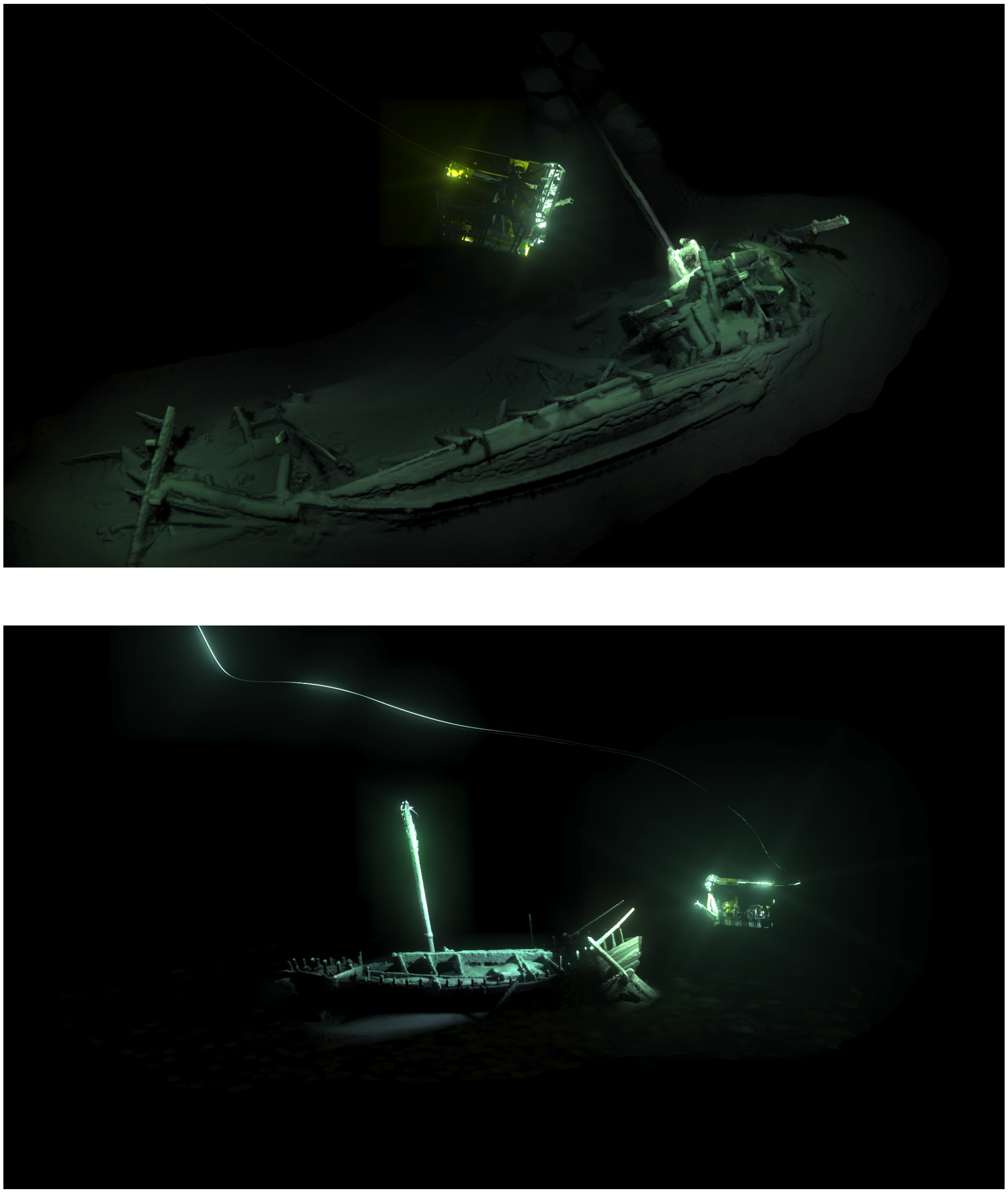

Figure 19: 3D representations of two of the ancient Black Sea shipwrecks based on underwater photogrammetry as a way of transmitting the experiencing of underwtaer sites to a wider audience. Upper: The Early 4th Century BC shipwreck discussed in this paper. Lower: A 1st/2nd Century AD Roman wreck also lying in deep water and recorded by Black Sea MAP. Images the authors.

itage and on benthic communities has been a source of concern at least since the 1980s (Betts, 2000), and more recently (Brennan et al., 2016).

On the Bulgarian Shelf there was a dramatic difference between those wrecks that lay within the trawling zones around offshore fishing ports and those that lay beyond. Within the zones, ship structure protruding above the seabed in some cases had been completely disarticulated and scattered whereas those outside it showed little or no mechanical damage. Happily, very few of the total number of wrecks recorded were heavily damaged but the implications for future protection are clear: future activity, whether trawling, or hydrocarbon exploration (currently being undertaken) can be accommodated within an integrated management system.

9. Conclusion

There have been considerable advances in our capability to discover, record and in some case excavate, robotically in deep water. Accurate and fast data acquisition using ROVs is now possible in the deep sea, with computational capacity now able to rapidly process large datasets to provide comprehensive models in the field. The combination of WROV and SROV platforms also means that a wide range of complementary survey techniques can be used over these sites, enabling photogrammetric models to be accurately scaled and positioned. These models provide researchers without access to the deep sea the ability to make new discoveries about early seafaring, shipbuilding and performance of ancient vessels as well as the long-debated nature of their appearance. The use of photogrammetry has also allowed the dissemination of these discoveries to be made to the general public, with major news outlets throughout 2017-19 showcasing these discoveries and making extensive use of the resultant rendered images.

Unfortunately the technologies employed in the activities on deep water wreck sites are not always driven by research questions or conducted according to internationally accepted best practice. It is hoped that projects such as the Black Sea MAP and the methodologies discussed here constitute a further step along the path towards sustainable investigation and management of cultural heritage in deep water.

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Supplementary Material 1: Radiocarbon Dating

Table S1: *Radiocarbon dates from the 4th century BC shipwreck*

Laboratory Code	**Material Dated**	**Radiocarbon Age BP**	**$\delta^{13}C$ (‰)**	**Calibrated Date**	**Modelled date**
SUERC-77014	Starboard side hull plank T1(D) *Pinus* sp. *sylvestris* group, rings 1 to 4 (1001-1004) from outer edge	2310 ± 24	-26.7	410-260 cal. BC (95.4%)	*410-390 cal. BC* (95.4%)
SUERC-78904	Starboard side hull plank T1(C) *Pinus* sp. *sylvestris* group, rings 1 to 2 (1001-1002) from outer edge	2357 ± 24	-22.2	510-380 cal. BC (95.4%)	*410-390 cal. BC* (95.4%)
Combined SUERC-77014 and SUERC-78904 (2334±17)				410-380 cal. BC (95.4%)	*410-390 cal. BC* (95.4%)
SUERC-78853	Starboard side hull plank T1(C) *Pinus* sp. *sylvestris* group, rings 11 to 12 (1011-1012)	2277 ± 35	-22.6	410-200 cal. BC (95.4%)	Rejected as an outlier A= 5.5%(A'c= 60.0%)
SUERC-78905	Starboard side hull plank T1(C) *Pinus* sp. *sylvestris* group, rings 21 to 22 (1021-1022)	2397 ± 24	-23.0	730-720 cal. BC (0.6%) 710-690 cal. BC (1.0%) 550-400 cal. BC (93.8%)	*430-410 cal. BC* (95.4%)
SUERC-77013	Thwart T2(A). *Pinus* sp. *sylvestris* group, rings 1 to 5 (1001-1005) from outer edge	2374 ± 24	-26.2	540-330 cal. BC (0.5%) 520-390 cal. BC (94.9%)	*730-690 cal. BC (5.3%)* *430-390 cal. BC (90.2%)*
Modelled Maximum Construction Date (MCD)					*410-350 cal. BC (95.4%)* *410-380 cal. BC (68.2%)*
SUERC-77023	Oar loom T3(D) *Fagus* sp., sapwood present	2293 ± 24	-28.5	410-350 cal. BC (84.5%) 290-230 cal. BC (10.9%)	*410-350 cal. BC (93.5%)* *280-260 cal. BC (1.9%)*

OxCal[1] code for 4th century BC wreck

```
Options()
{
 Resolution=1;
};
Plot( )
{
 Sequence( "Wreck 3509")
 {
  Boundary("Start");
  Phase ("All Ship Wood TPQ Data")
  {
   Phase("Ship Elements Wood Wiggle Matches")
   {
    D_Sequence ("Inner Hull Plank T1")
    {
     First ();
     R_Date("SUERC-78905 1021-1022", 2397, 24);
     Gap(20);
     R_Combine("SUERC-78904 and SUERC-77014")
     {
      R_Date("SUERC-78904 1001-1002", 2357, 24);
      R_Date("SUERC-77014 1001-1004", 2310, 24);
     };
    };
    Sequence ()
    {
     Date("=SUERC-78904 and SUERC-77014");
     Interval("Gap Until T1 Felling Date", N(13,4));
```

[1] https://c14.arch.ox.ac.uk/oxcal.html

```
    Date("T1 Minimum Felling Date");
   };
  };
  Phase("Thwart T2")
  {
   R_Date("SUERC-77013", 2374, 24);
   Sequence()
   {
    Date("=SUERC-77013");
    Interval("Gap Until T2 Felling Date", N(13, 4));
    Date("T2 Minimum Felling Date");
   };
  };
 };
 Boundary("MCD");
};
Sequence ("Last Voyage 3509")
{
 Tau_Boundary("=MCD");
 Phase( "Contents Ship Last Voyage")
 {
  R_Date( "SUERC-77023 (T3)", 2293, 24);
 };
 Boundary( "LV");
};
Tau=(LV-MCD);
Tau&= U(0,200);
};
```