

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 4th 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

1 **1. Introduction**

2 ~~This work discussed in this paper represents~~

3 **1. Introduction**

4 This paper presents a key element of a major maritime archaeological
5 research programme carried out in the Bulgarian EEZ between 2015 and

2019 , funded by the Julia and Hans Rausing Trust under a permit issued
by the Bulgarian Ministry of Culture. Primary research (Figure 1). Its
primary goals focussed on the impacts of Late Pleistocene and Holocene en-
vironmental 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.
. 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

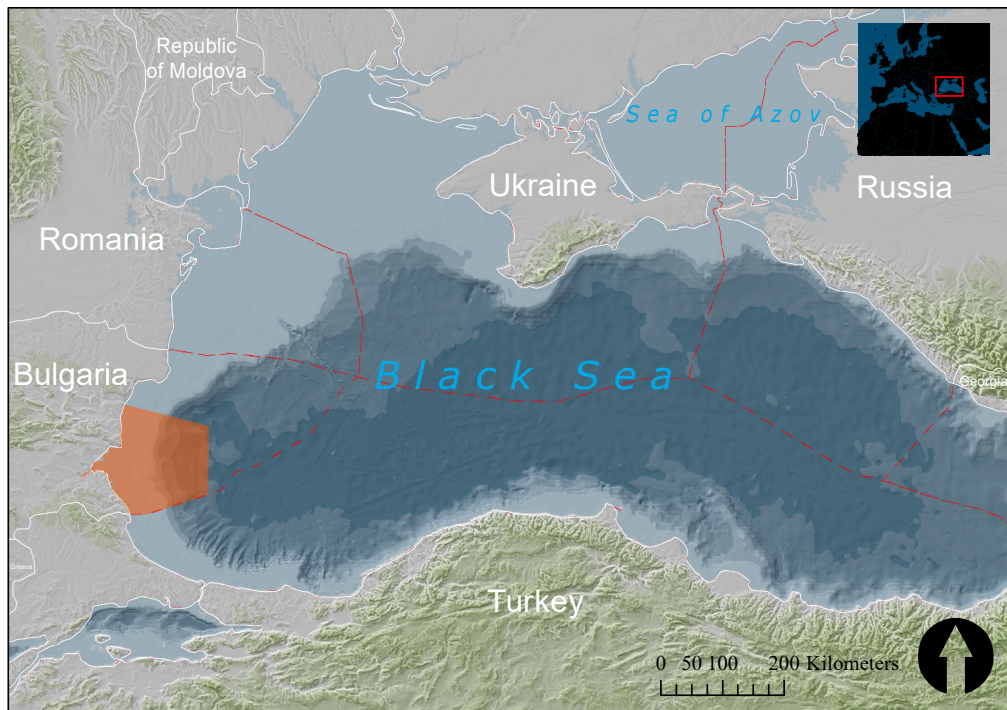


Figure 1: Map of the Black Sea showing the area of study (and permit of work of the Black Sea MAP) of this paper in orange and with red dotted lines, the EEZ of each of the Black Sea's countries. Data GEBCO and GSHHG.

31 and Holocene transgression, a programme of geophysical survey and geologi-
32 cal core sampling was designed to enable palaeoenvironmental reconstruction
33 of the Bulgarian shelf at a resolution not ~~possible hitherto~~ previously achieved.
34 This was reasoned to be ~~a~~ prerequisite for any substantive understanding of
35 both prehistoric communities and those that developed into the increasingly
36 complex societies of later prehistory and subsequent historical cultures.

37 Details of the geophysical and geological sampling programmes are re-
38 ported elsewhere (Adams ~~et al.~~ ~~in prep.~~ et al. in prep) while this paper
39 focuses on what might be termed maritime connectivity. ~~—~~

40 ~~In all periods maritime connectivity,~~ , namely the connectivity within and
41 between ~~communities,~~ societies implemented through maritime infrastructure
42 and technologies. This would have been a key factor of human life ~~;~~ reflected
43 in the exploitation of marine resources, coastal locations of prehistoric set-
44 tlements (many now lying underwater) and the wrecks of boats and (later)
45 ships.

46 For these reasons it was assumed that during the course of surveying 2000
47 km² of the seabed shipwrecks would be discovered ~~;~~ and this proved to be
48 the case. By September 2017, 65 wrecks had been recorded in depths from
49 40 to 2,200 metres, ranging in date from the late 19th Century, back through
50 the Ottoman, Byzantine, Roman and Greek periods. Due to the anoxic
51 (oxygen-free) conditions of the Black Sea below c. 150m, many of these
52 ships, particularly at deeper depths, were in extraordinary condition (Figure
53 2). While some might be judged less ~~importance~~ important against criteria
54 such as age, type, rarity, historical significance, etc., others were clearly of
55 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.

1.1. *Archaeological imperatives*

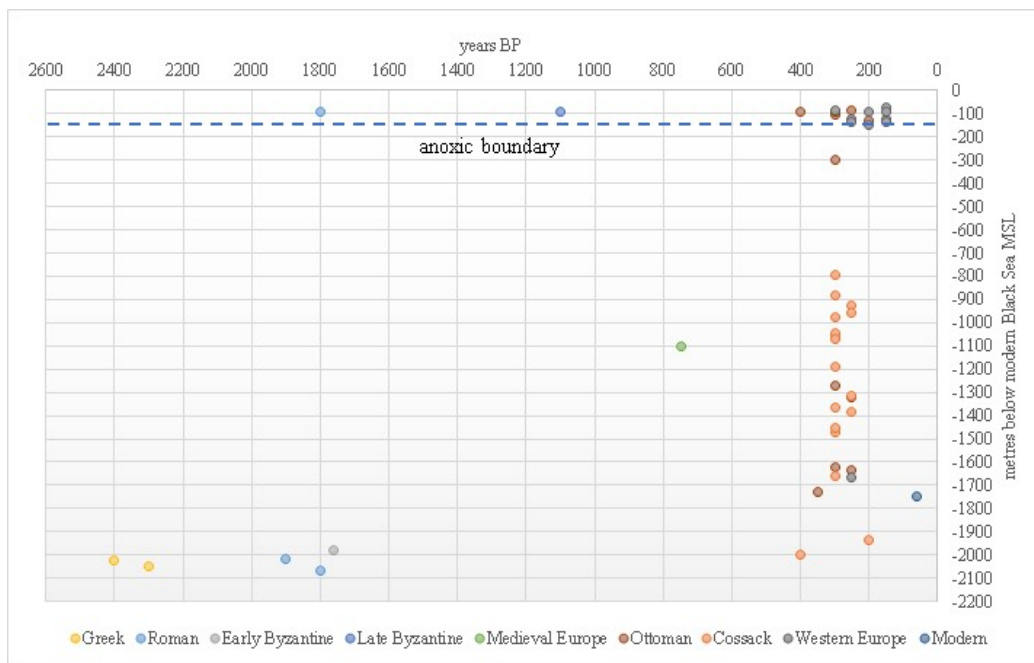


Figure 2: Graph showing the relationship between the chronology and depth of the shipwrecks discovered and recorded by Black Sea MAP. Those found below the anoxic horizon (c. 150m) presented extraordinary level of preservation.

From this perspective, the shipwreck research follows other deep water work done in the Black Sea (Ballard et al., 2001; Ward and Ballard, 2004; Ward and Horlings, 2008).

64 2. Archaeological imperatives

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

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

88 The underwater excavation that arguable marks the beginning of a pro-

89 fessional maritime archaeology in which ethics as well as the methodology
90 of archaeology were embedded in the trajectory of research, from the devel-
91 opment of research questions through to publication and display, was that
92 carried out at Cape Gelidonya, Turkey, in 1960 (Bass, 1966; Bass et al.,
93 1967). One of the contrasts between this project and those that preceded it
94 was the greater proportion of time devoted to careful observation and record-
95 ing relative to that spent excavating and raising material (Bass et al., 1967).
96 The project established a standard that other projects then attempted to
97 meet, something of a challenge in the more turbid waters in other parts of
98 the world.

99 Such a place was the south coast of England, where, in 1982, King Henry
100 VIII's warship, *Mary Rose* (1545) was recovered from the waters of the Solent
101 (Rule, 1982). This was the climax of 11 years underwater excavation in which
102 the difficulties of all forms of underwater recording were a constant driver to
103 enhance existing techniques or develop entirely new ones. The project's pol-
104 icy was to test every available system that might enhance the archaeological
105 process. To this end ultrasonic cameras, sector-scanning sonars, black and
106 white and colour video cameras (Rule, 1982), photomosaics and photogram-
107 metry, integrated with 3D slant-ranging (Adams and Rule, 1991; Rule, 1989),
108 all were tried alongside various acoustic systems. As early as 1975 the Par-
109 tridge Rangemeter - a forerunner of Sonardyne acoustic survey systems, was
110 used to control the production of the first plan of the entire site, an area
111 of 55 x 30m, in conditions where underwater visibility averaged 1.5m (Rule,
112 1982, 92, 102 and Kelland, 1994).

113 On this and many other projects, the limitations of conventional tech-

114 niques highlighted the need for accurate, rapid methods for recording com-
115 plex three-dimensional structures and the 3D locations of artefacts and other
116 objects of significance. At that time however, most underwater recording was
117 a series of 2D techniques combined in such a way as to enable 3D projec-
118 tions; it was difficult and slow. Structural recording relied primarily on tape
119 measures and on other mechanical means of measuring distances and angles.
120 Photography was used to record features and aspects of archaeological prac-
121 tice but in a period before digital photography, reliable results were hard to
122 obtain, particularly in turbid water and low light, without expensive wide
123 angle lenses and powerful strobes, not to mention knowledge and skill. Some
124 experiments were made with orthomosaics (Stewart, 1991) and photogram-
125 metry (Green, 2016, 99-122; Rule, 1989 and Baker, 2014) but at that time
126 software and computational capacity restricted the progress that was possi-
127 ble.

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

139 was produced, this time within 24 hours (Foley et al., 2009).

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

147 The Mars Project in Sweden, a project to record the wreck of the warship
148 *Mars* (75m deep) lost in 1564, saw the production of a substantial 3D model
149 of the remains using Agisoft Photoscan. The model was produced from tens
150 of thousands of diver-based images taken with 24mpx cameras and built over
151 three seasons of work from 2011 by Ingmar Lundgren (Eriksson and Rönnby,
152 2017).

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

156 **3. Remote operated vehicle (ROV) generated photogrammetry**

157 Survey work of any sort at these depths requires robotics and this in turn
158 requires vessels large enough to deploy them. Since 2003 a successful part-
159 nership between academia and industry has facilitated several projects using
160 advanced offshore systems. This was initially created through a partnership
161 between the Swedish offshore survey company MMT (Marin Mätteknik) and
162 the Maritime Archaeology Research Institute at Södertörn (MARIS) Univer-

sity, Sweden, later joined by the Centre for Maritime Archaeology (CMA), Southampton. With funding in place for archaeology in the Black Sea ~~the partnership linked to~~, a core partnership was established with the Centre for Underwater Archaeology (CUA), Sozopol in Bulgaria and the University of Connecticut. ~~Extending the partnership with MMT was a foregone conclusion.~~ USA.

Two vessels on long-term charter to MMT and their industrial partners Reach Subsea were used to ~~inspect and survey~~ 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. ~~Both are rated DP2, meaning the vessels' computer controlled have built-in redundancy and are capable of maintaining position within one metre in up to 22-knot winds without the use of any physical anchoring, necessary for deployment in deep water.~~

~~Survey vessels used in the Black Sea during the expeditions of 2016 and 2017~~

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). ~~Applanix POS MV is the main positioning system for the survey equipment used on the vessels. The system uses two antennas which receive corrections from the C-bosses. The detects all movements the vessel makes and sends that data to the POS~~

188 ~~MV for further calculations. This setup allows the vessels to count with a~~
189 ~~navigational accuracy of 6 to 7 cm.~~

190 3.1. Camera and lights setup

191 3.1.1. WROV

192 ~~The Two~~ work-class remote operated vehicles (WROVs) (from Kyst De-
193 sign [in 2016](#) and HD Shilling Robotics [in 2017](#); (Figure 5), [on the basis of](#)
194 their quotidian use in industrial tasks and their success rate suggested these
195 tools to be ideal for underwater archaeological surveys using photogrammet-
196 ric techniques. The principal camera used in the pursuit of high resolution
197 three-dimensional modelling was the wide angle Cathx A1000 Ivanoff camera
198 rated to a maximum operating depth of 4000m and capable of taking stills
199 at 1.59mm/pixel at a range of 5m.

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

208 If the camera is attached to a vehicle travelling at 1 Knot (0.51m/sec),
209 then an exposure time of 30msec will equate to the vehicle having moved
210 1.53cm during the image capture. To avoid this problem, Cathx has taken
211 the approach of using cameras with fast, high-end lenses, in conjunction with
212 high lumen output lights. The cameras directly control the lights, and this



(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](#)

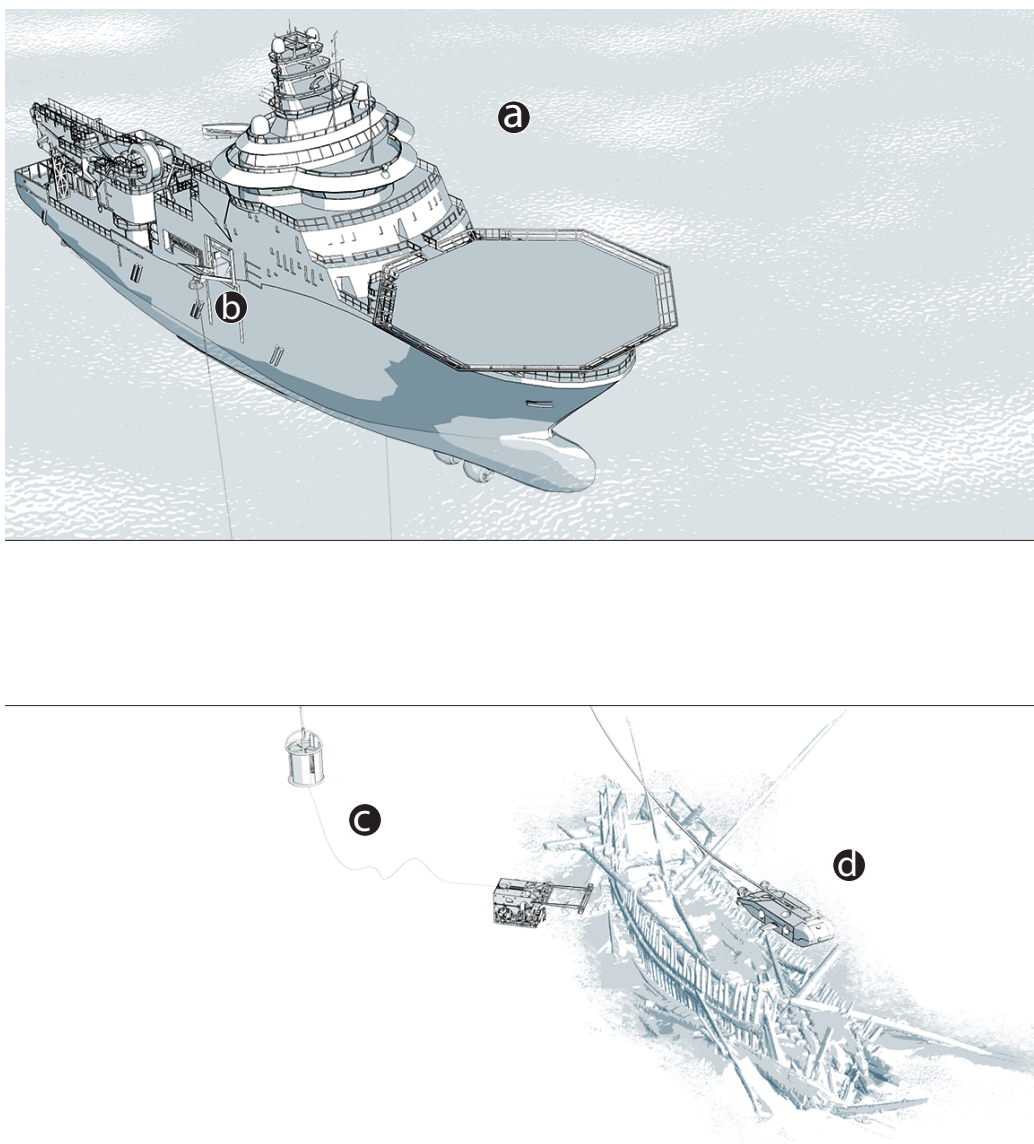


Figure 4: Schematic showing the deployment of the work-class remote operated vehicle (WROV) and the *Surveyor Interceptor* (SROV) to record underwater archaeological sites. (a) *MPSV* Havila Subsea holds position using her dynamic positioning system (DP)2 systems. (b) remote operated vehicles (ROVs) 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.

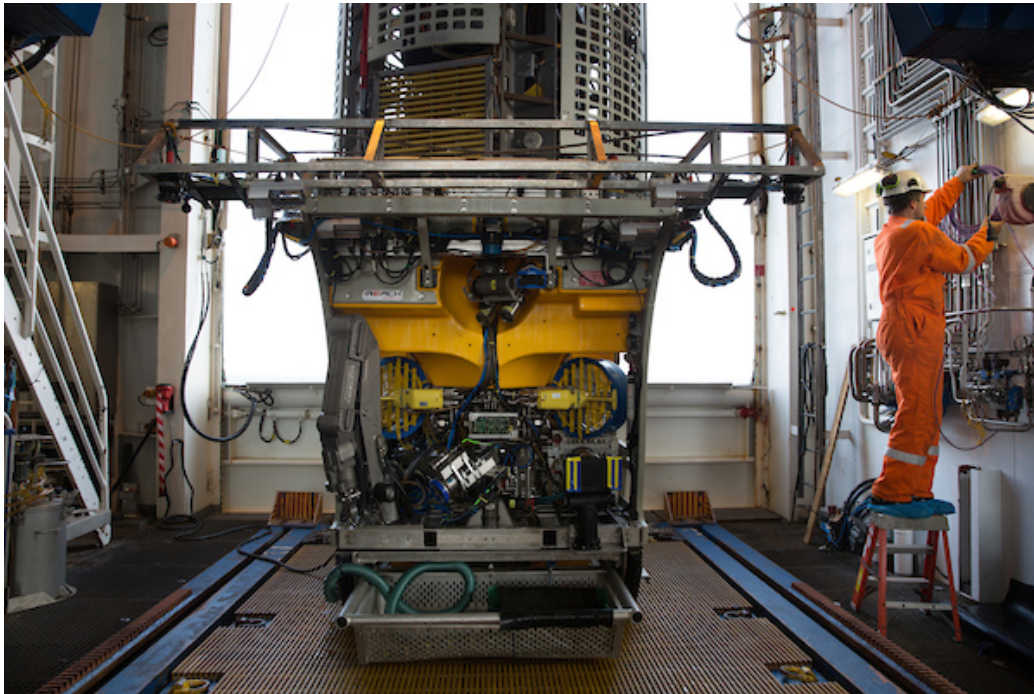


Figure 5: Image showing the Shilling Robotics HD work-class remote operated vehicle (WROV) being prepared on deck by the engineers for one of many shipwreck survey dives. Photograph Jodi Hilton.

213 ensures that the camera's exposure time is exactly matched to the output
 214 from the light-emitting diode (LED) strobe lights. Typical exposure times
 215 for the images gathered during trials were in the region of 1-2msec (see Figure
 216 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.

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

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

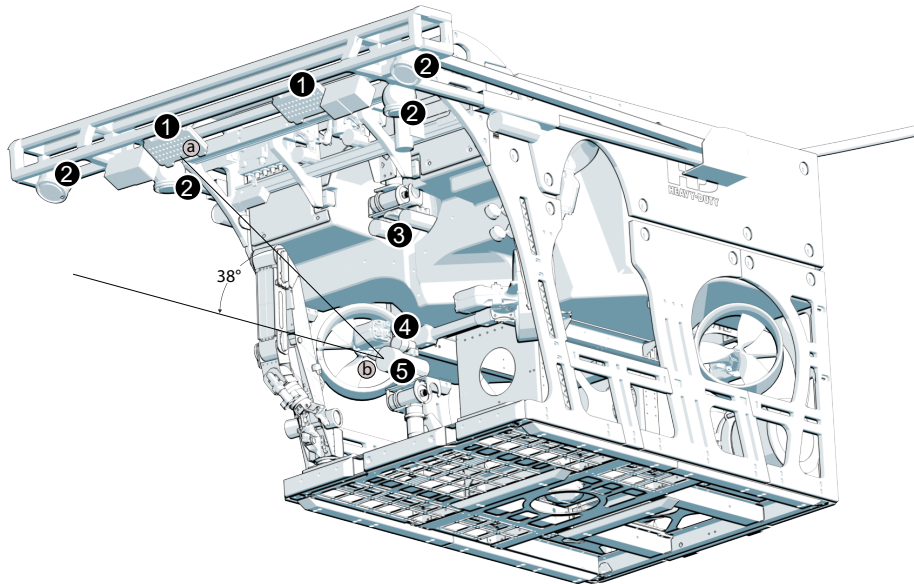


Figure 7: Image showing the standard configuration of lights and cameras for deep sea archaeological photogrammetric survey mounted on the Shilling WROV. (1)LED-based strobe lights (Aphos 32), which when triggered by the stills Cathx camera illuminate the scene to capture high resolution photogrammetric 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.

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

235 Analogous to spray painting an object, to capture the wreck the WROV
236 is piloted through a course that collects images of every part of the struc-
237 ture. This was achieved by first flying the WROV around the perimeter of
238 the wreck as close to the seabed as possible. The cameras were mounted low
239 down on the WROV so these images provided views into the wreck struc-
240 ture and upwards to capture the under surfaces of projecting timbers. This
241 was then repeated at higher levels and completed with vertical flyovers look-
242 ing down. Staying within maximum camera-to-subject distance, (partially
243 dependent on visibility and projecting hazards, meant that the number of
244 circuits required to obtain complete coverage was depending on the size of
245 the site (Figure 8c).

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

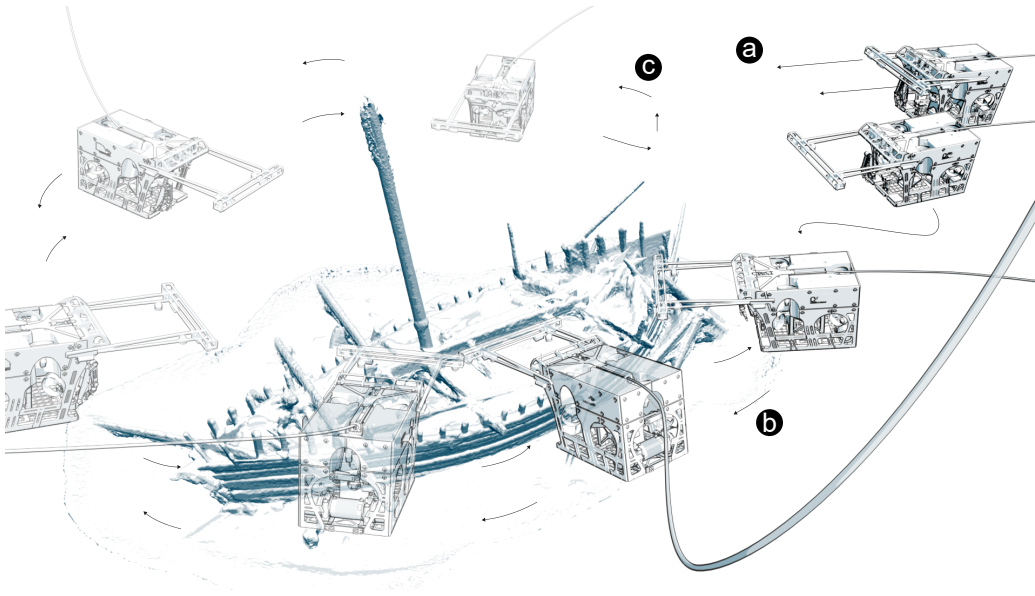


Figure 8: Image showing the survey methodology used to generate underwater photogrammetry using the Shilling WROV. (a, b) The WROV reaches the target and deploys the lighting rig to achieve optimum light diffusion and avoid shadow contamination. (c) Triggered from the surface the stills Cathx camera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

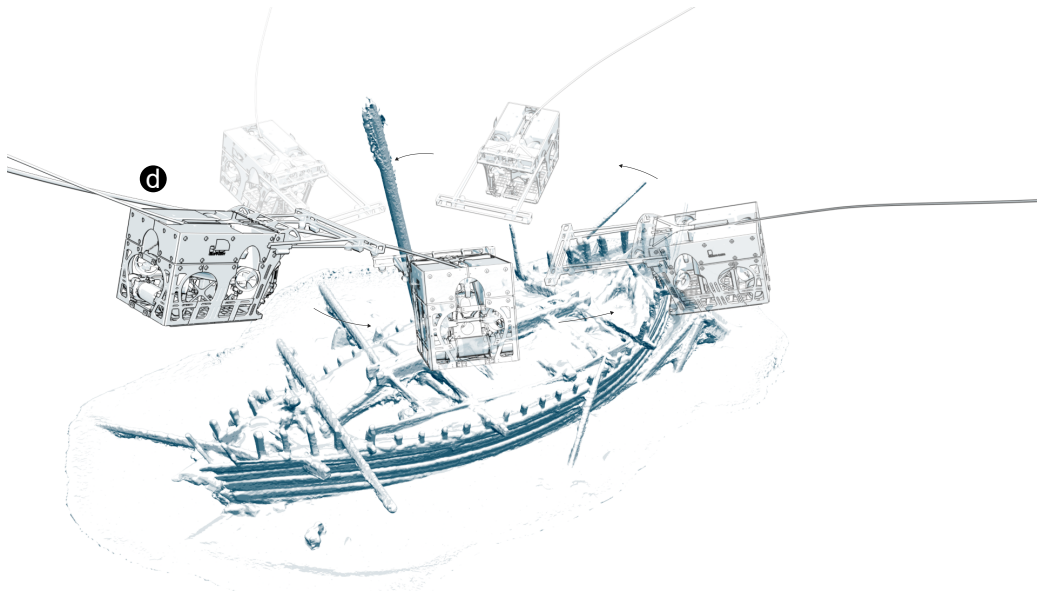


Figure 9: Photogrammetric survey, second phase (d) Once the outside of the shipwreck has been captured the WROV pilot then positions the WROV over the shipwreck to obtain vertical and oblique views the upper and internal structure and, in the case of this Roman wreck the upstanding mast, moving from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

252 3.1.2. SROV Surveyor Interceptor

253 Complementary to the WROV the project also benefited from the use of a
254 revolutionary vehicle designed for high speed survey the *Surveyor Interceptor*
255 was in many ways the project's most important tool, carrying all the required
256 geophysical systems as well as cameras and laser bathymetry. It was the
257 principal tool for the collection of high-resolution geophysical data in 2016-
258 17 and for relocating features and anomalies located in 2015.

259 The *Surveyor Interceptor* (SROV) (Figure 10) presents a very different
260 configuration than its work class counterpart. It is designed to cruise in
261 forward motion close to the seabed, following predefined transects. As the
262 SROV 'flies' over the target, two Edgetech hydrophones collect sidescan sonar
263 data (Figure 11: 1), two dual head EM2040 multibeam echosounders (Figure
264 11: 4) collect bathymetric data down to 10cm resolution, an Edgetech 2205
265 bottle with a DW-106 transducer collects seismic data with a pulse of 1.5-
266 10KHz at 12 ms with a 3.5KHz frequency and three Cathx cameras (Figure
267 11: 2) collect high-resolution imagery supplemented by the strobes (Figure
268 11: 5) and laser bathymetry (Figure 11: 3) to scale the photogrammetric
269 models.

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



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

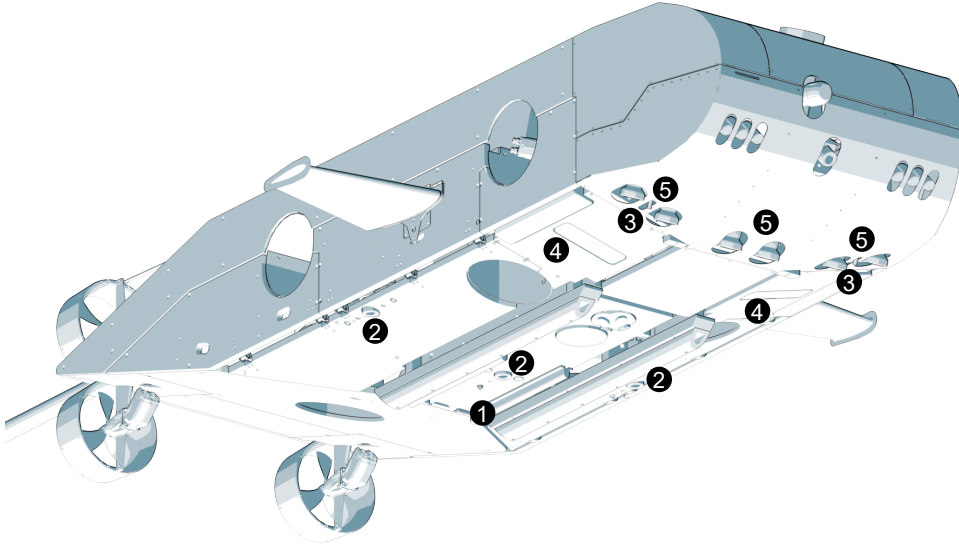


Figure 11: The standard configuration of equipment mounted on the SROV to capture photogrammetric and geophysical data. (1) Edgetech hydrophones. (2) UHD Cathx camera, the main tool for capturing photogrammetric data. (3) Green laser bathymetry system, one of the methods of scaling the photogrammetric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

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

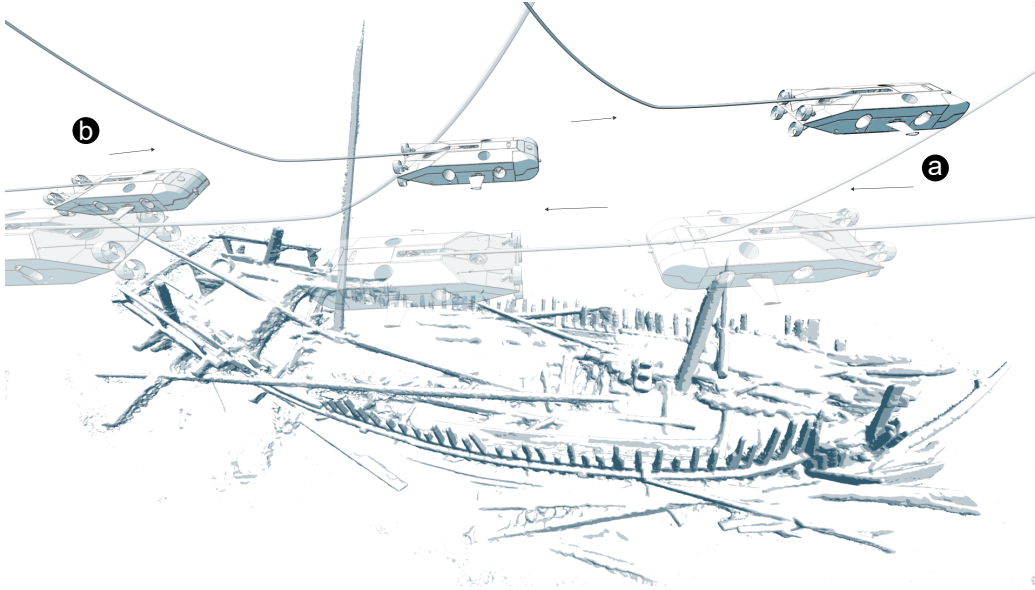


Figure 12: Figure showing the general methodology used to survey deep sea archaeological sites in the Black Sea using the SROV. (a) The SROV makes an initial fly-over, in which it will capture optical and acoustic data simultaneously. (b) adjacent passes will ensure overlap of data and full coverage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

279 3.2. *Geolocation and scaling*

280 Ideally the resolution of a digital model generated from photogramme-
281 try should be complemented by similarly accurate scaling. In shipbuilding,
282 ‘scantlings’ dimensions of key structural elements, as well as the relationships
283 between them, can be diagnostic of period and/or type. Even where this is
284 possible some fundamental dimensions are necessary for even the most basic
285 site records. Scaling underwater can be achieved in a number of ways. The

286 most common one is by capturing in the scene an object of known dimen-
287 sions (Rule, 1995). In our case a 50x50x50cm cube was placed within one of
288 the selected shipwrecks and captured from every possible angle (Figure 13).
289 Within Agisoft PhotoScan Pro (1,3,3 build 4827) the cube was assigned the
290 known dimensions allowing the software to translate this scale to the entire
291 model.

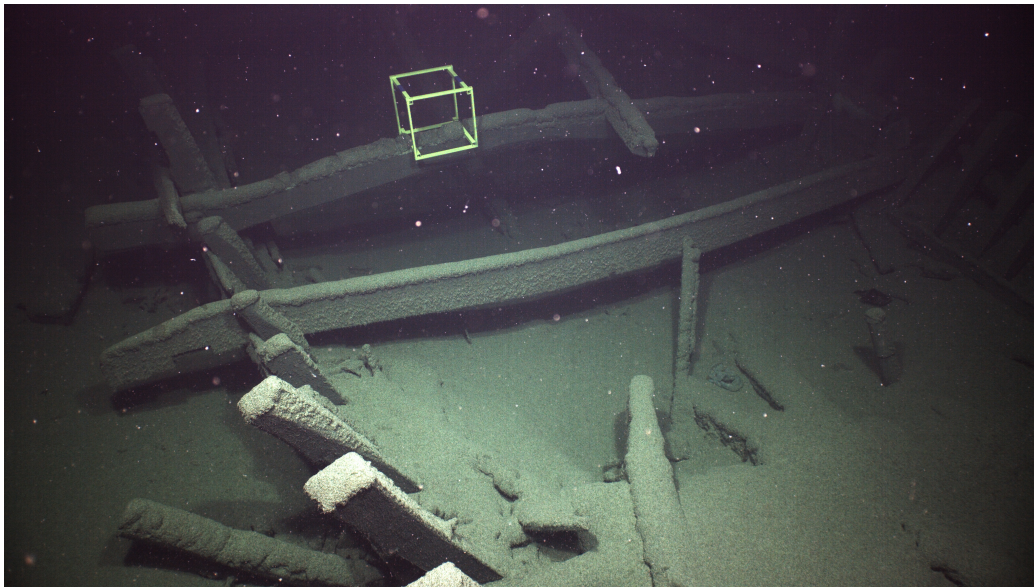


Figure 13: Figure showing the 50x50x50cm cube after it was placed by the WROV on a visible location on top of the timber structure of one of the Roman shipwreck sites studied. Image the authors.

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

296 A second method used ~~in archaeology is~~ was through comparing the re-

297 sults of the point cloud produced from the photogrammetric survey with one
298 generated and scaled by a different method such as swath bathymetry or
299 laser scanning. This has the advantages of not only scaling and geolocating
300 the photogrammetric model, but also ~~to assess~~ of assessing the accuracy of
301 the models by comparing both point clouds. This method is preferred as it
302 allows for a more comprehensive comparison of the site. However, as most
303 of the comparison is done manually, the resolution of the ~~bathymetry survey~~
304 reference point cloud needs to be high enough to show features that can be
305 unequivocally matched with those shown photogrammetrically.

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

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

313 3.2.1. Deep sea camera geolocation.

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

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

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

332 The cameras mounted on the ROVs platforms are subject to a dimen-
333 sional control survey (Dimcon) where their recorded offset is relative to the
334 ‘Sprint’ centre and are measured using a total station or alternatively a pho-
335 togrammetric survey prior to diving. The later method producing very good
336 results within a millimeter accuracy (Figure 14). These relative camera off-
337 sets are then input into the Qinsy interface which assigns the values the
338 navigation data and thus exporting the absolute positioning through the
339 Cathx interface.

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

347 systems (GIS) subsequently.

348 *3.3. Rapid cluster processing*

349 As the images were captured, both by the SROV and by the ROV, these
350 were uploaded through fibre optics onto the ship's mainframe server. This
351 made such media readily available to all of the members of the archaeolog-
352 ical processing team who then fed these to a number of processing clusters
353 available throughout the network. Two Dell Precision Tower 7810 were used
354 as the main processing nodes. The CPU processing power came from the 16
355 cores (2 x Intel(R) Xeon(R) CPU E5-2699 v3 @ 2.30 Ghz) with additional
356 192 GB of RAM, whilst the GPU processing was supplied by an NVIDIA
357 Quadro6000 graphics card for each workstation. Additional support nodes
358 were created within the ship's server by using networked virtual environ-
359 ments and thus adding thee extra nodes for data processing speed. These
360 virtual machines were customisable and where launched in five simultaneous
361 instances of 19 cores (2 x Intel(R) Xeon(R) CPU E5-2699 v3 @ 2.30 Ghz)
362 and 96 GB of RAM each.

363 **4. Quantifying archaeological intervention**

364 Photogrammetry was implemented to record the impact of the archaeo-
365 logical excavations carried out on a number of selected shipwrecks. Sediment
366 accumulation on the sites after their sinking meant that diagnostic features,
367 such as the shape and position of the steering assemblages, their fastenings
368 and tool marks, the shape of the the rudder blades together with the remains
369 of *in situ* material culture, such as elements of the cargo and crew personal

370 belongings, were obscured by burial and may need to be exposed for further
371 study.

372 4.1. The Early 4th Century BC shipwreck

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

378 First, a general survey of the shipwreck was made using the techniques de-
379 scribed above (Figure 15), thus achieving a high-resolution, pre-disturbance,
380 photogrammetric record. Excavation was then carried out using a water
381 induction dredge powered by the WROV hydraulic systems and controlled
382 through a Schilling *Titan4* kinesthetic feedback robotic manipulator. The ex-
383 posure of the archaeological remains were then resurveyed using photogram-
384 metry. Both pre- and post-excavation phases were documented producing
385 photogrammetric datasets to which the archaeological impact assessment
386 was done using GIS root mean squared (RMS) superficial spatial analyti-
387 cal functions to understand and quantify the impact of the archaeological
388 excavations (Figure 16). This method has been also been successfully trial
389 and tested during the Black Sea MAP excavations of the prehistoric settle-
390 ment of Ropotamo in 2016 (Pacheco-Ruiz et al., 2018).

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

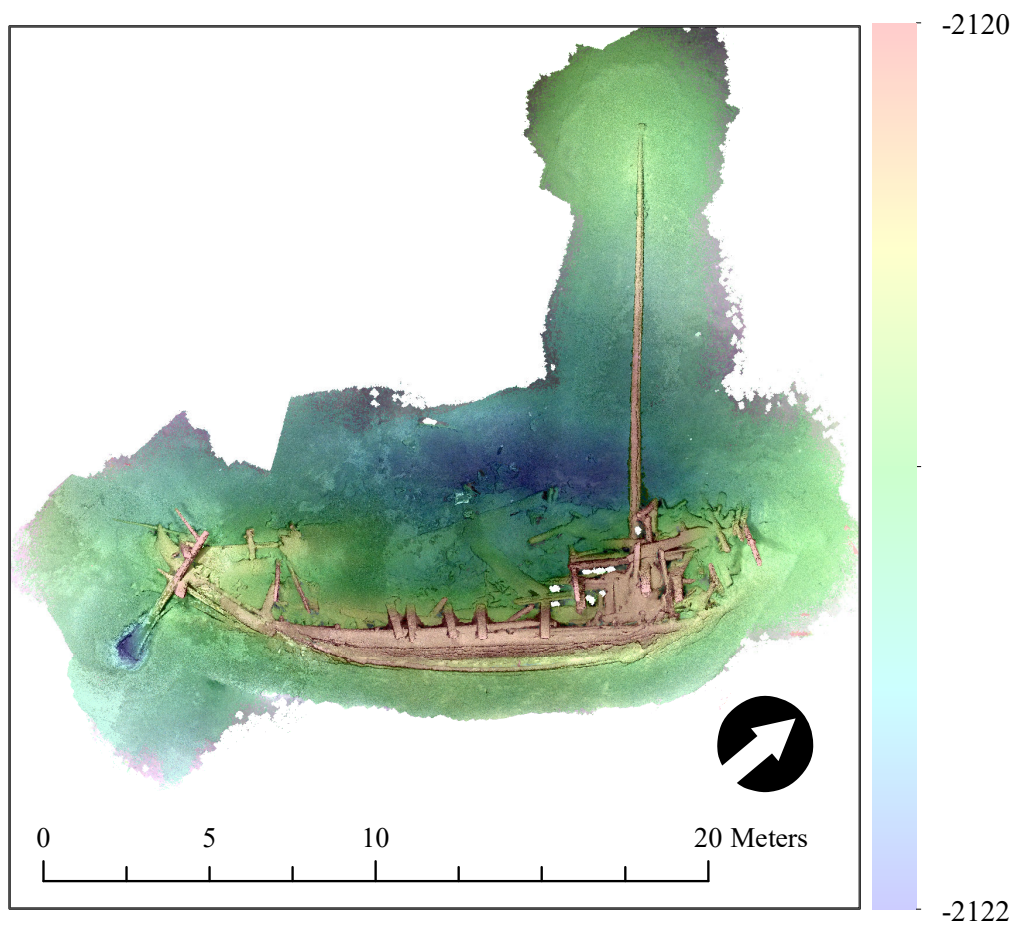


Figure 15: Photogrammetric site plan of an Early 4th Century BC shipwreck represented as a DEM from the photogrammetric model and the orthomosaic, resulting from the alignment of more than 2000 images. Image the authors.

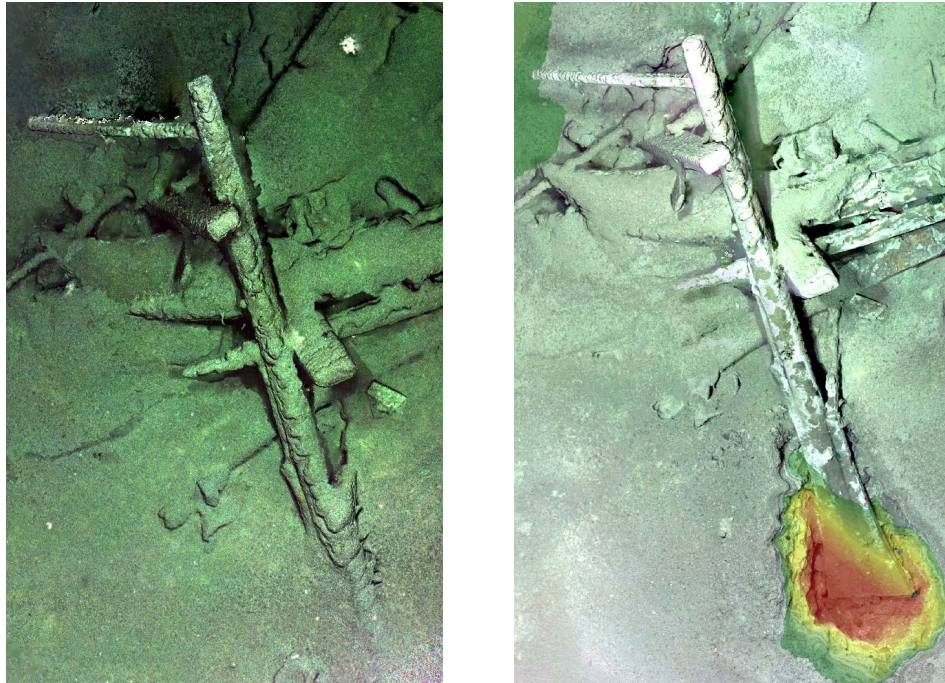


Figure 16: Comparative images showing both phases of the deep sea archaeological excavation of the rudder assembly and its recording. Left: the pre-disturbance survey. Right: the rudder assembly after the intervention using RMS comparison. All heights are zeroed to the seabed surrounding the wreck. Images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

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

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



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

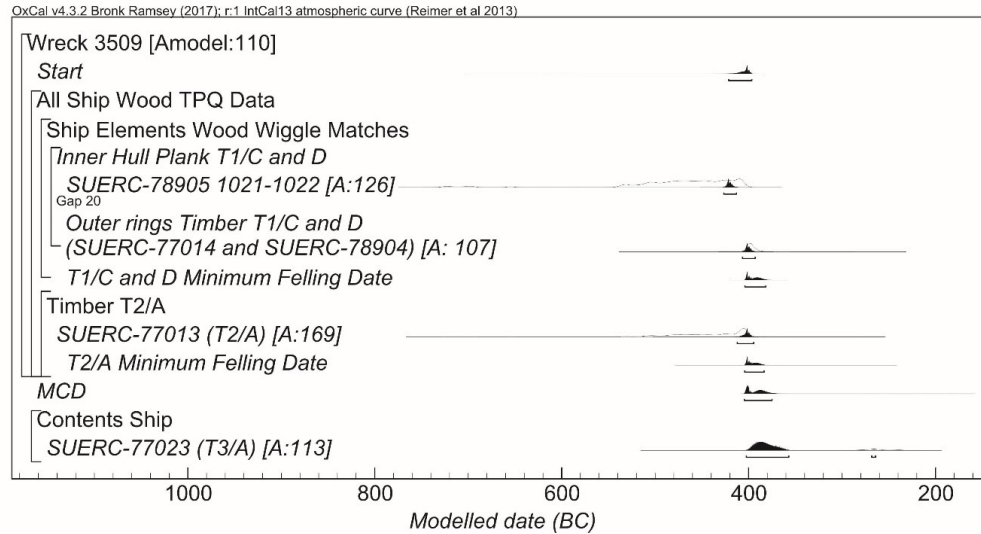


Figure 18: Phase model for the Early 4th Century BC shipwreck.

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

433 of the cameras and lighting array used. Additional time taken to refine the
434 model post-cruise is less cost-dependent. In this case accurate 3D data of
435 well-preserved hulls is demonstrably useful in various ways including hull
436 reconstruction and performance analysis.

437 6. Adding to the database

438 Among the 65 wrecks discovered between 2015 and 2017 are some of the
439 best preserved examples of naval and merchant vessels from the periods of
440 Greek, Roman, Byzantine, Italian Medieval and Ottoman seafaring. ~~In their~~
441 ~~investigation the role of high resolution 3D recording is vital not only~~

442 Surprisingly, there is relatively little known of Black Sea Seafaring even
443 in periods when powerful empires controlled the majority of the traffic. To
444 obtain this many well-preserved wrecks, even if a tiny sample of those that
445 must exist, nevertheless provides a substantial injection of hard data to
446 complement written history. The immediate benefit is a substantial increase
447 in our knowledge and understanding of seafaring and maritime traffic in
448 the Black Sea at both local and regional scales and across sequential cultural
449 periods. Individual shipwrecks are often described as ‘preservation by record time
450 capsules’ but also for providing the basis for subsequent analysis. For example,
451 current research involves hull reconstruction and can be fascinating as
452 individual discoveries. As Muckelroy pointed out, ships often represent a
453 pre-industrial society’s most complex technology (Muckelroy, 1978, 3). As
454 such they offer high resolution views of their parent societies. Even better
455 however, is a series of shipwrecks, for this constitutes longitudinal data
456 providing insights into technological development, trade, warfare and strategies

457 of competition and control that punctuated the cycles of human affairs,
458 what the analiste historian Fernand Braudel described as the *Duree Moyene*
459 (Braudel, 1972).

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

482 make their detection more successful in areas of lower sedimentation on the
483 shelf or further offshore within the deep sea.

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

500 7. Access to the Deep Sea

501 The results achieved in the 2016 and 2017 seasons exceeded expectations
502 in the sense that it was assumed that much of the processing would be car-
503 ried out post-cruise but already in 2016 it was possible to keep pace with
504 the surveys to the extent of having a model of proven fidelity within hours
505 of the survey. In 2017, as we refined our procedure of image capture and

506 post processing, it was usual to have aligned the images (the crucial part of
507 the photogrammetric process), before the WROV had left the site. Subse-
508 quent generation of point cloud, mesh and then rendering (and in 2017 the
509 3D printing of scaled models) could be done at leisure, though still usually
510 completed within 24 hours.

511 During the early development of maritime archaeology there was some
512 discussion about the necessity for archaeologists to dive where the site being
513 investigated was in the diving range. The longstanding consensus (shared
514 by the present authors) is that this is desirable whenever possible. The
515 immediacy of being on the site confers considerable advantages (Adams and
516 Rönby, 2013, 86). However, for sites beyond the diving range submersibles
517 are the only way in which an archaeologist can ‘be’ on site and then it is
518 debatable to what degree this confers benefits over and above experiencing
519 the site from the control van of an ROV. A sense of immediacy there certainly
520 is and one gets a far better appreciation of scale and of site topography and
521 relief for example by comparison to the flattening effect of seeing even hi-res
522 images on screen. This may speed up the process of understanding the site
523 considerably although this is to some extent offset by the advantages an ROV
524 has in both endurance and accessibility. Recent development of UHD video
525 and now the use of photogrammetry as reported in this paper go some way to
526 bringing the researcher to the site or rather the site to the researcher. Being
527 able to explore a detailed 3D model of the shipwreck, either as a 3D print
528 or through a virtual reality (VR) platform allows consideration of enigmatic
529 aspects, almost always resulting in recognition of features not appreciated
530 or understood at first sight even when watching UHD video footage. In one

531 case, on close inspection of a 3D photogrammetric model of a wreck that
532 was relatively broken up and which had initially defied identification, it was
533 realised to be Roman, something that might never have happened had the
534 record of the site only been conventional video.

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

541 ~~Access to the Deep Sea~~ The other major factor is the ways in which these
542 technologies and methodologies enable the research aims, methods and re-
543 sults to reach a wider audience through various experiential modes of ex-
544 tended reality (XR), namely Virtual Reality (VR), Mixed Reality (MR) and
545 Augmented Reality (AR) platforms (Figures 19). ~~These~~ In the experience
546 provided this is similar to Telepresence, pioneered by Dr Robert Ballard,
547 where seabed video was transmitted via satellite direct into schools in real
548 time throughout North America (Brennan et al., 2018). This was both innovative
549 and imaginative and in principle this has never been surpassed, though these
550 days the down link can be streamed to the internet and data can be accessed
551 by associated scientists ashore. Black Sea MAP considered Telepresence
552 but for logistic reasons chose to bring the students to the ships and to use
553 the aforementioned digital platforms (developed since Telepresence was first
554 used) as they are becoming part of the routine fabric of extending knowl-
555 edge in museums, schools, web portals and all digital interactive platforms.

556 ~~The~~ Once the digital content has been created the potential audience is huge
557 and depending on design, the experience is more interactive and open-ended,
558 albeit without the immediacy of Telepresence. Some of the most exciting
559 potential of digital modelling and reconstruction is related to the time depth
560 of archaeological sites in general and shipwrecks in particular which are
561 wonderful vehicles for experiential approaches ~~,-offering- that will enable~~
562 the viewer/wearer/player ~~the opportunity~~ to explore time and processes of
563 change as well as space, landscape, structure and things.

564 ~~The methodology discussed here is a further step along the path towards~~
565 ~~sustainable investigation and management of cultural heritage in deep water,~~
566 ~~wherever it lies.-~~

567 8. Recording a finite resource under threat

568 As well as the immediate research benefits of such discoveries, these sur-
569 veys comprise the first step in preservation by record, but will also lead to
570 preservation by law as well. The coordinates of each find as well as the
571 surveys are lodged with the Bulgarian authorities and with the Centre for
572 Underwater Archaeology at Sozopol. Bulgaria has a more integrated sys-
573 tem of marine management than many other countries. It was the second
574 State to ratify the UNESCO *Convention on the Protection of the Underwater*
575 *Cultural Heritage* (2001) and the heritage authorities have sight of relevant
576 permit applications in all marine zones. Deep water shipwreck sites of out-
577 standing archaeological importance are therefore probably safer in Bulgarian
578 waters than almost anywhere else. This is important due to the fact that
579 these technologies are available anyone with the financial resources to de-

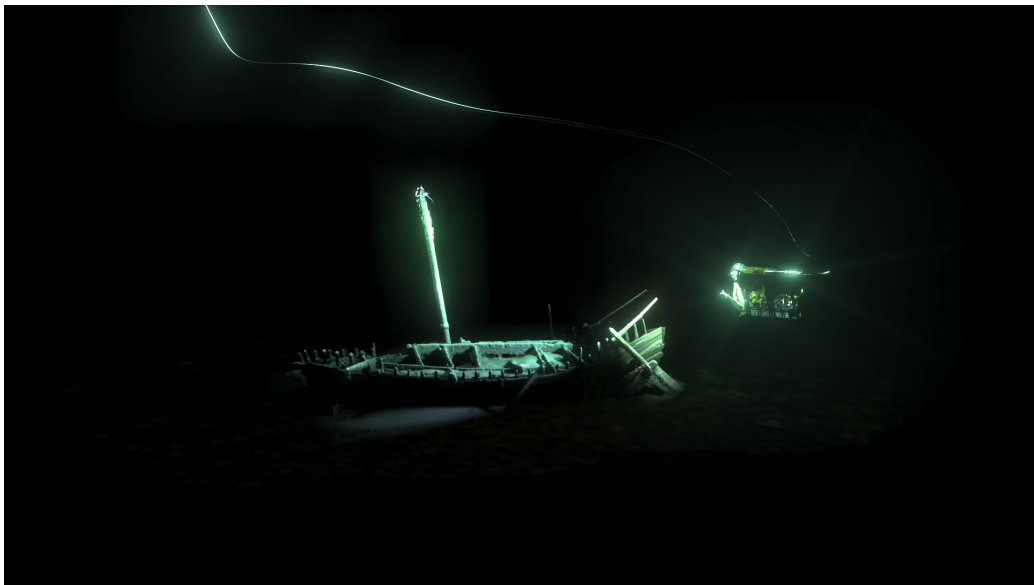
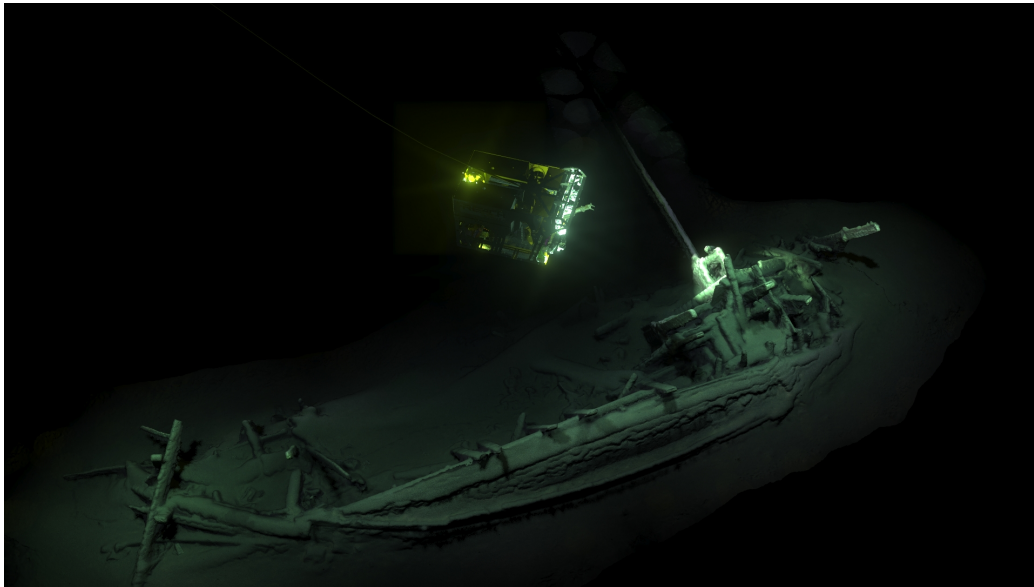


Figure 19: 3D representations of two of the ancient Black Sea shipwrecks based on underwater photogrammetry as a way of transmitting the experiencing of underwater sites to a wider audience. Upper: The Early 4th Century BC shipwreck discussed in this paper. Lower: A 1st/2nd Century AD Roman wreck also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

580 ploy them. While those sectors are principally the military and industry, the
581 latter includes private ventures that are either blatant treasure hunting or
582 ill-disguised forms of the same.

583 Industrial threat is another factor, ever-present but often invisible. Development
584 is one of the most potent threats to underwater cultural heritage near shore
585 but trawling has potentially disastrous impacts on historic wrecks in offshore
586 fishing grounds. The impacts of trawling on both submerged heritage and
587 on benthic communities has been a source of concern at least since the 1980s
588 (Betts, 2000), and more recently (Brennan et al., 2016).

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

598 **9. Conclusion**

599 There have been considerable advances in our capability to discover,
600 record and in some case excavate, robotically in deep water. Accurate and
601 fast data acquisition using ROVs is now possible in the deep sea, with com-
602 putational capacity now able to rapidly process large datasets to provide
603 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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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 4th 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

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 Quater-

7 nary, and when eustatic sea levels were low, the Black Sea became isolated
8 from the Mediterranean and global ocean system (Badertscher et al., 2011;
9 Özdoğan, 2011). The timing of these periods, the nature of the basin, changes
10 in salinity and lake levels, and the subsequent process of transgression have
11 been fiercely debated (Ryan et al., 1997; Hiscott et al., 2007; Yanko-Hombach
12 et al., 2007; Yanko-hombach et al., 2011; Yanko-Hombach et al., 2017; Leri-
13 colais et al., 2009, 2011; Lericolais, 2017; Soulet et al., 2011; Yanchilina et al.,
14 2017). Archaeological questions relate to the fact that land exposed during
15 periods of lower lake levels would certainly have been exploited by human
16 groups and just as certainly lost again as the water level rose and reconnected
17 with the global ocean reservoir via the Sea of Marmara and the Bosphorus
18 Strait, Sea of Marmara, Strait of the Dardanelles and the Aegean Sea region
19 of the Mediterranean.

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

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

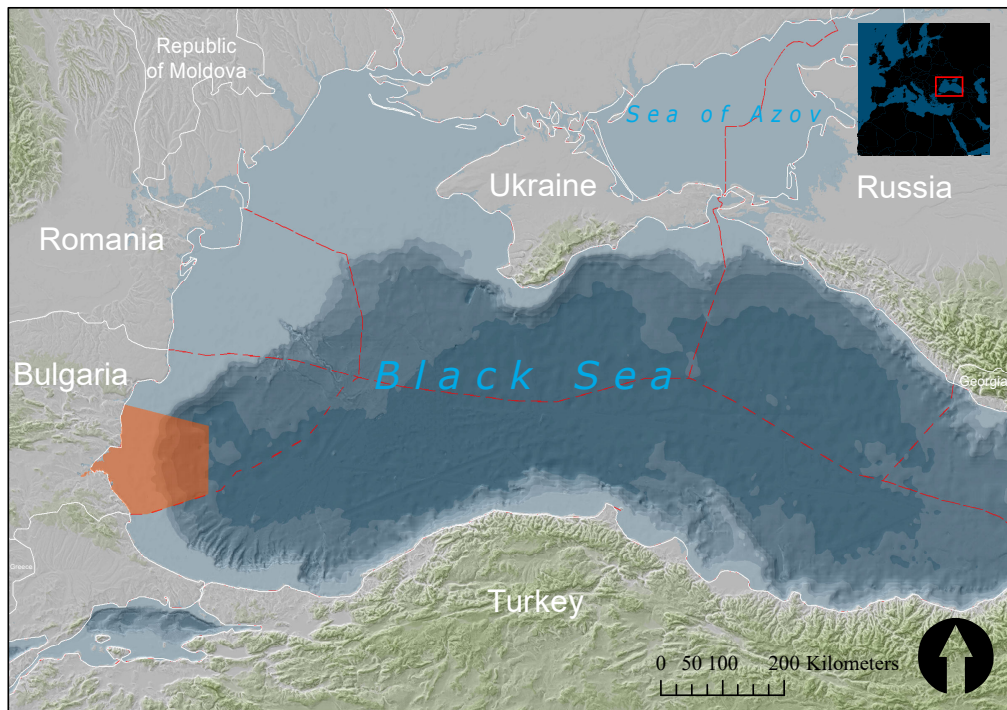


Figure 1: Map of the Black Sea showing the area of study (and permit of work of the Black Sea MAP) of this paper in orange and with red dotted lines, the EEZ of each of the Black Sea's countries. Data GEBCO and GSHHG.

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 km² 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 19th 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;

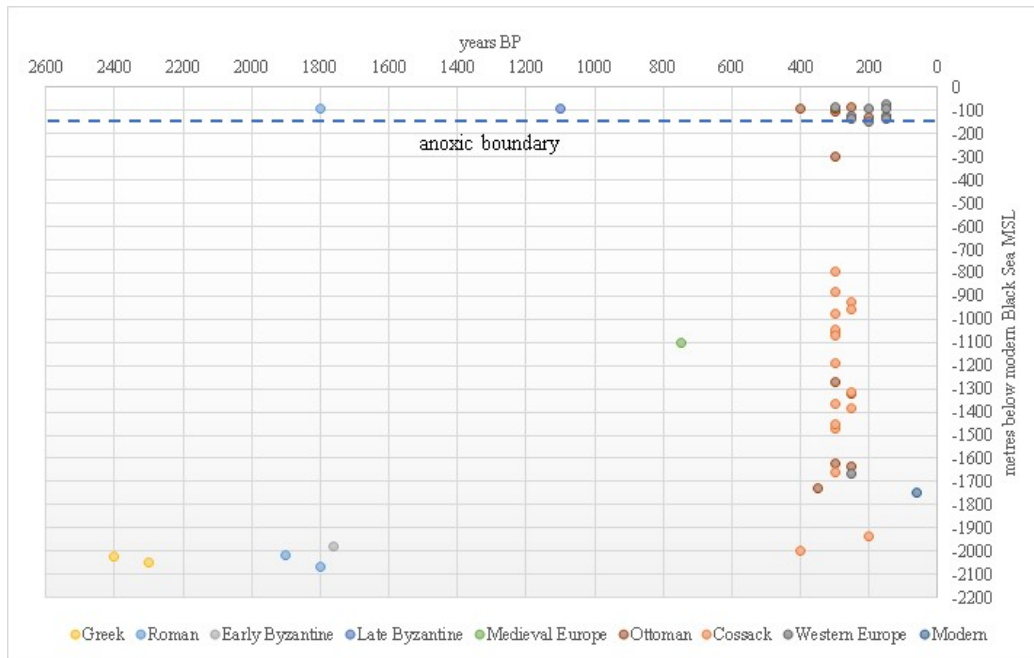


Figure 2: Graph showing the relationship between the chronology and depth of the shipwrecks discovered and recorded by Black Sea MAP. Those found below the anoxic horizon (c. 150m) presented extraordinary level of preservation.

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

58 **2. Archaeological imperatives**

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

72 This is why archaeology as a discipline, both on land and under water,
73 has been an early adopter of every newly developed means of recording and
74 representation and why in many cases it has contributed to the develop-
75 ment of such techniques. The rapidity with which new methods were tried
76 underwater was due to the initiative of various practitioners who were well
77 aware that meeting their archaeological obligations depended on the degree
78 to which they could meet the challenges imposed by the underwater environ-
79 ment. It is not within the scope of this paper to discuss these challenges in
80 detail or to provide a detailed history of the discipline but some of the key

81 developments that underpin current practice are worth reviewing.

82 The underwater excavation that arguable marks the beginning of a pro-
83 fessional maritime archaeology in which ethics as well as the methodology
84 of archaeology were embedded in the trajectory of research, from the devel-
85 opment of research questions through to publication and display, was that
86 carried out at Cape Gelidonya, Turkey, in 1960 (Bass, 1966; Bass et al.,
87 1967). One of the contrasts between this project and those that preceded it
88 was the greater proportion of time devoted to careful observation and record-
89 ing relative to that spent excavating and raising material (Bass et al., 1967).
90 The project established a standard that other projects then attempted to
91 meet, something of a challenge in the more turbid waters in other parts of
92 the world.

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

106 1982, 92, 102 and Kelland, 1994).

107 On this and many other projects, the limitations of conventional tech-
108 niques highlighted the need for accurate, rapid methods for recording com-
109 plex three-dimensional structures and the 3D locations of artefacts and other
110 objects of significance. At that time however, most underwater recording was
111 a series of 2D techniques combined in such a way as to enable 3D projec-
112 tions; it was difficult and slow. Structural recording relied primarily on tape
113 measures and on other mechanical means of measuring distances and angles.
114 Photography was used to record features and aspects of archaeological prac-
115 tice but in a period before digital photography, reliable results were hard to
116 obtain, particularly in turbid water and low light, without expensive wide
117 angle lenses and powerful strobes, not to mention knowledge and skill. Some
118 experiments were made with orthomosaics (Stewart, 1991) and photogram-
119 metry (Green, 2016, 99-122; Rule, 1989 and Baker, 2014) but at that time
120 software and computational capacity restricted the progress that was possi-
121 ble.

122 The development of digital photography coupled with faster processors
123 and greater data storage capacity began to have a significant effect on record-
124 ing practice in the 1990s. On the Skerki Bank of the Central Mediterranean
125 in 1997, black and white digital photomosaics of six deep water shipwrecks
126 were produced on board the research vessel during the three weeks of the
127 cruise (Ballard et al., 2000; Singh et al., 2000). Following the cruise the mo-
128 saics were draped over the digital elevation models (DEMs) of the sites to
129 produce an accurate 3D survey of the entire site and every visible artefacts
130 (McCann and Oleson, 2004). Although entirely digital, this process was still

131 time-consuming. However, in 2005 similar techniques were applied to a Clas-
132 sical period wreck in Chios, Greece. A colour mosaic integrated with a DEM
133 was produced, this time within 24 hours (Foley et al., 2009).

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

141 The Mars Project in Sweden, a project to record the wreck of the warship
142 *Mars* (75m deep) lost in 1564, saw the production of a substantial 3D model
143 of the remains using Agisoft Photoscan. The model was produced from tens
144 of thousands of diver-based images taken with 24mpx cameras and built over
145 three seasons of work from 2011 by Ingmar Lundgren (Eriksson and Rönnby,
146 2017).

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

150 **3. Remote operated vehicle (ROV) generated photogrammetry**

151 Survey work of any sort at these depths requires robotics and this in turn
152 requires vessels large enough to deploy them. Since 2003 a successful part-
153 nership between academia and industry has facilitated several projects using
154 advanced offshore systems. This was initially created through a partnership

155 between the Swedish offshore survey company MMT (Marin Mätteknik) and
156 the Maritime Archaeology Research Institute at Södertörn (MARIS) Univer-
157 sity, Sweden, later joined by the Centre for Maritime Archaeology (CMA),
158 Southampton. With funding in place for archaeology in the Black Sea, a
159 core partnership was established with the Centre for Underwater Archaeol-
160 ogy (CUA), Sozopol in Bulgaria and the University of Connecticut, USA.

161 Two vessels on long-term charter to MMT and their industrial partners
162 Reach Subsea were used to locate and record the newly discovered ship-
163 wrecks in the Bulgarian Black Sea: *Stril Explorer* in 2016 (Figure 3a) and
164 *Havila Subsea* in 2017 (Figure 3b). Both are DP2-rated Multi Purpose Sup-
165 port Vessels (MPSVs) used for high precision tasks and surveys within the
166 offshore industry. The methodology and equipment applied was the same
167 on both vessels barring some improvements on the camera systems made in
168 2017, when it was decided to use a wider angle lens for the acquisition of
169 photogrammetric data. Irrespective of these changes the methods described
170 are applicable to the surveys carried out on both vessels (Figure 4).

171 3.1. Camera and lights setup

172 3.1.1. WROV

173 Two work-class remote operated vehicles (WROVs) (from Kyst Design in
174 2016 and HD Shilling Robotics in 2017: (Figure 5), on the basis of their quo-
175 tidian use in industrial tasks and their success rate suggested these tools
176 to be ideal for underwater archaeological surveys using photogrammetric
177 techniques. The principal camera used in the pursuit of high resolution
178 three-dimensional modelling was the wide angle Cathx A1000 Ivanoff cam-
179 era 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

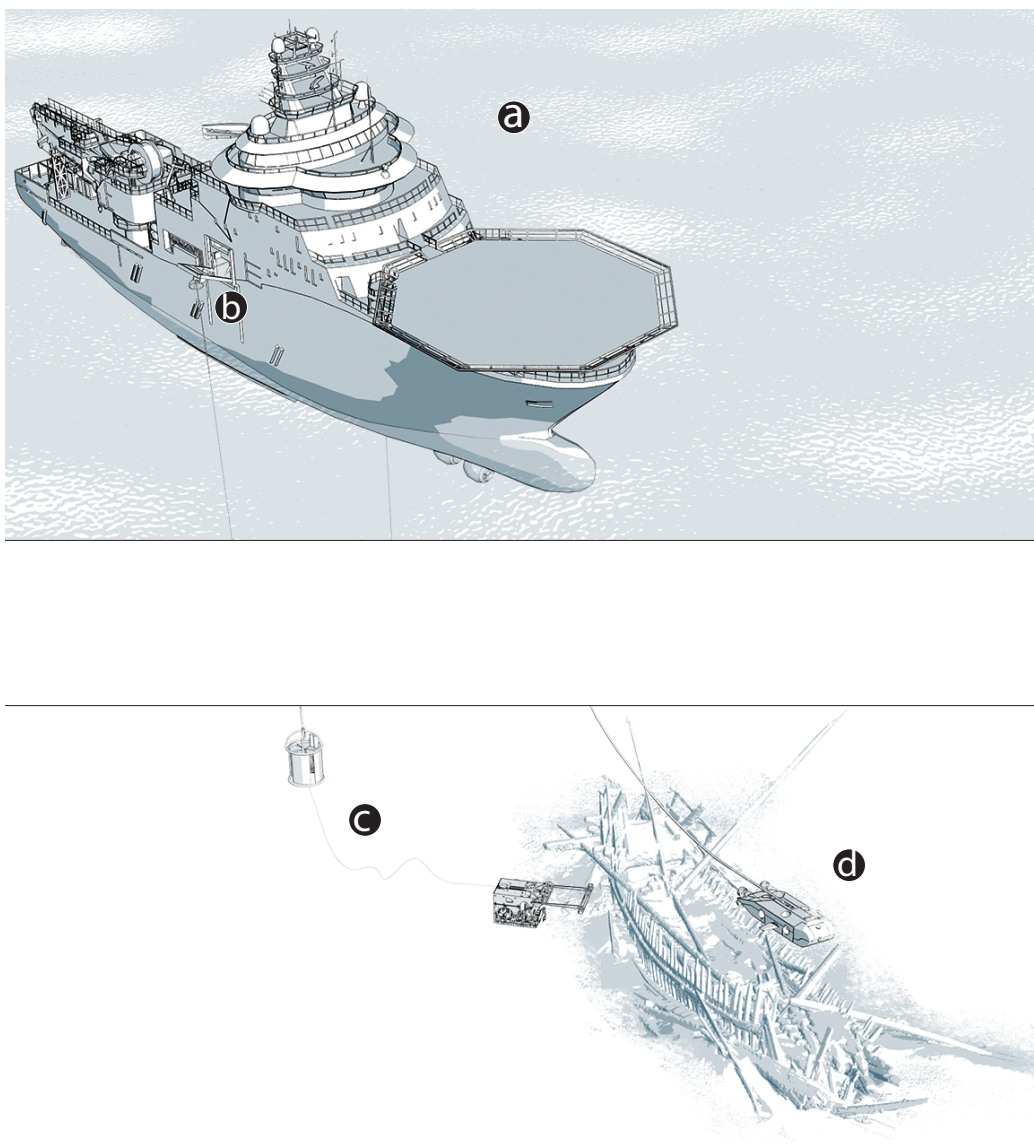


Figure 4: Schematic showing the deployment of the work-class remote operated vehicle (WROV) and the *Surveyor Interceptor* (SROV) to record underwater archaeological sites. (a) *MPSV* Havila Subsea holds position using her dynamic positioning system (DP)2 systems. (b) remote operated vehicles (ROVs) 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.

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

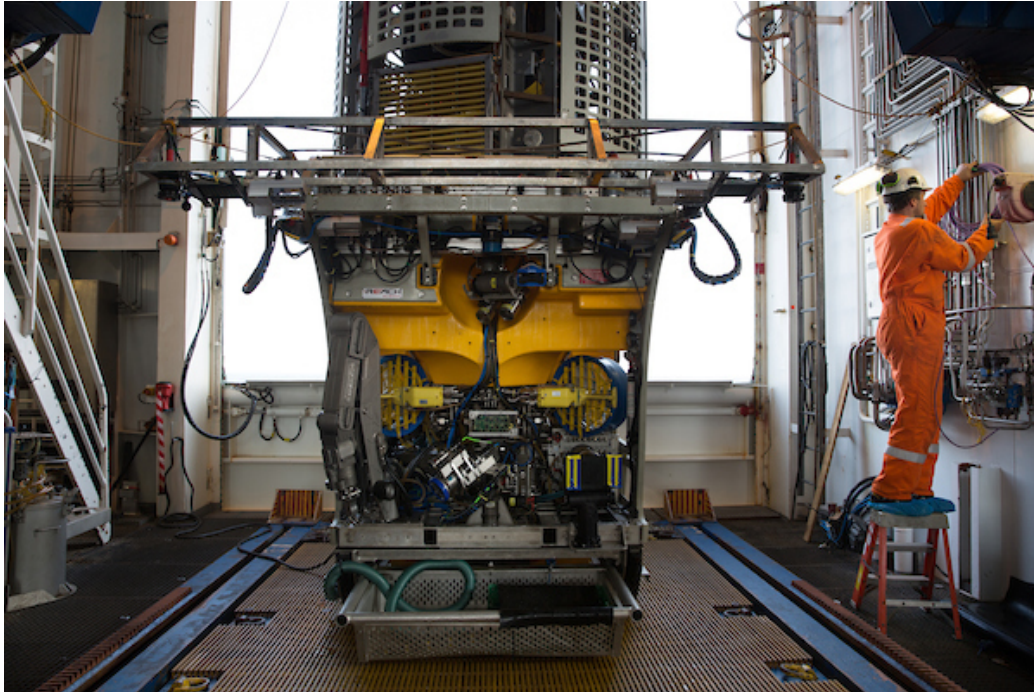


Figure 5: Image showing the Shilling Robotics HD work-class remote operated vehicle (WROV) being prepared on deck by the engineers for one of many shipwreck survey dives. Photograph Jodi Hilton.

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

189 If the camera is attached to a vehicle travelling at 1 Knot (0.51m/sec),
 190 then an exposure time of 30msec will equate to the vehicle having moved
 191 1.53cm during the image capture. To avoid this problem, Cathx has taken
 192 the approach of using cameras with fast, high-end lenses, in conjunction with
 193 high lumen output lights. The cameras directly control the lights, and this
 194 ensures that the camera's exposure time is exactly matched to the output
 195 from the light-emitting diode (LED) strobe lights. Typical exposure times
 196 for the images gathered during trials were in the region of 1-2msec (see Figure
 197 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.

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

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

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

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

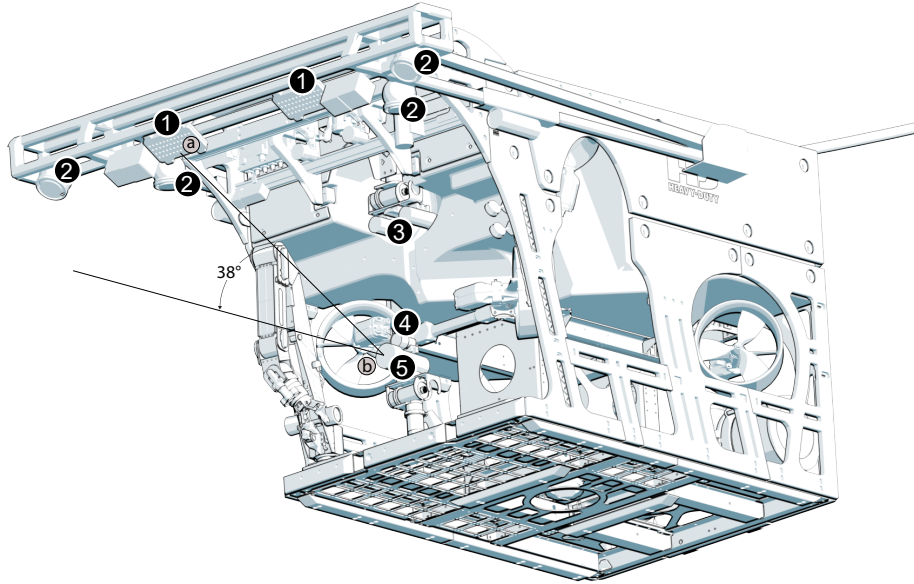


Figure 7: Image showing the standard configuration of lights and cameras for deep sea archaeological photogrammetric survey mounted on the Shilling WROV. (1)LED-based strobe lights (Aphos 32), which when triggered by the stills Cathx camera illuminate the scene to capture high resolution photogrammetric 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).

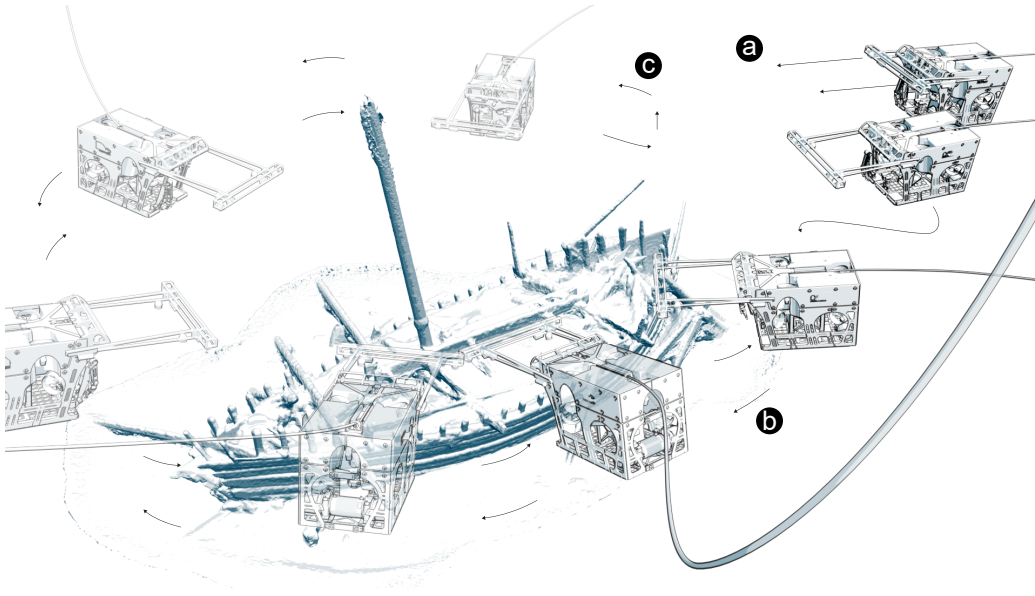


Figure 8: Image showing the survey methodology used to generate underwater photogrammetry using the Shilling WROV. (a, b) The WROV reaches the target and deploys the lighting rig to achieve optimum light diffusion and avoid shadow contamination. (c) Triggered from the surface the stills Cathx camera 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).

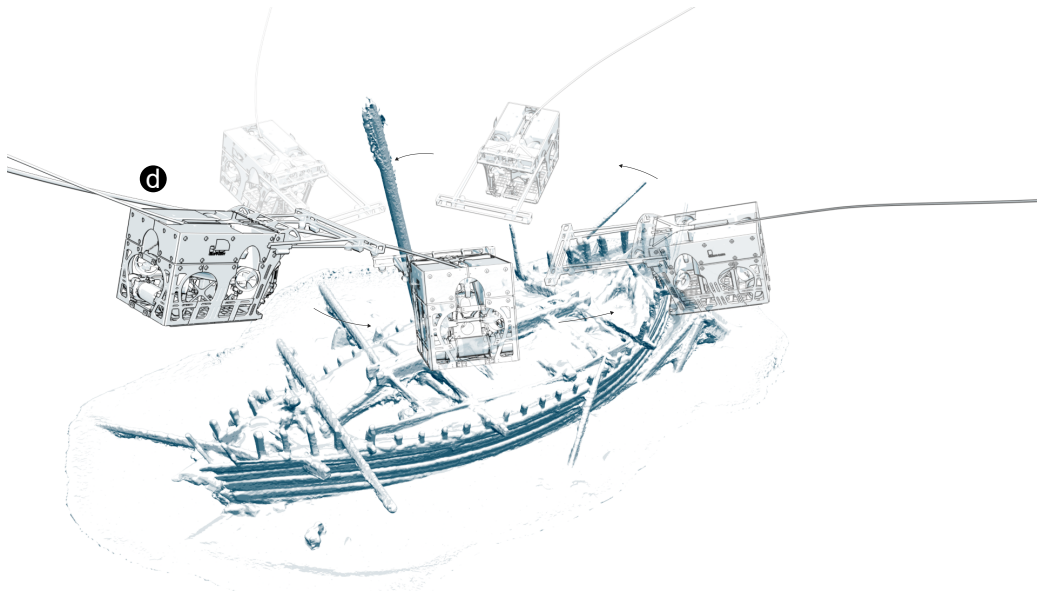


Figure 9: Photogrammetric survey, second phase (d) Once the outside of the shipwreck has been captured the WROV pilot then positions the WROV over the shipwreck to obtain vertical and oblique views the upper and internal structure and, in the case of this Roman wreck the upstanding mast, moving from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

233 3.1.2. SROV Surveyor Interceptor

234 Complementary to the WROV the project also benefited from the use of a
235 revolutionary vehicle designed for high speed survey the *Surveyor Interceptor*
236 was in many ways the project's most important tool, carrying all the required
237 geophysical systems as well as cameras and laser bathymetry. It was the
238 principal tool for the collection of high-resolution geophysical data in 2016-
239 17 and for relocating features and anomalies located in 2015.

240 The *Surveyor Interceptor (SROV)* (Figure 10) presents a very different
241 configuration than its work class counterpart. It is designed to cruise in
242 forward motion close to the seabed, following predefined transects. As the
243 SROV 'flies' over the target, two Edgetech hydrophones collect sidescan sonar
244 data (Figure 11: 1), two dual head EM2040 multibeam echosounders (Figure
245 11: 4) collect bathymetric data down to 10cm resolution, an Edgetech 2205
246 bottle with a DW-106 transducer collects seismic data with a pulse of 1.5-
247 10KHz at 12 ms with a 3.5Khtz frequency and three Cathx cameras (Figure
248 11: 2) collect high-resolution imagery supplemented by the strobes (Figure
249 11: 5) and laser bathymetry (Figure 11: 3) to scale the photogrammetric
250 models.

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



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

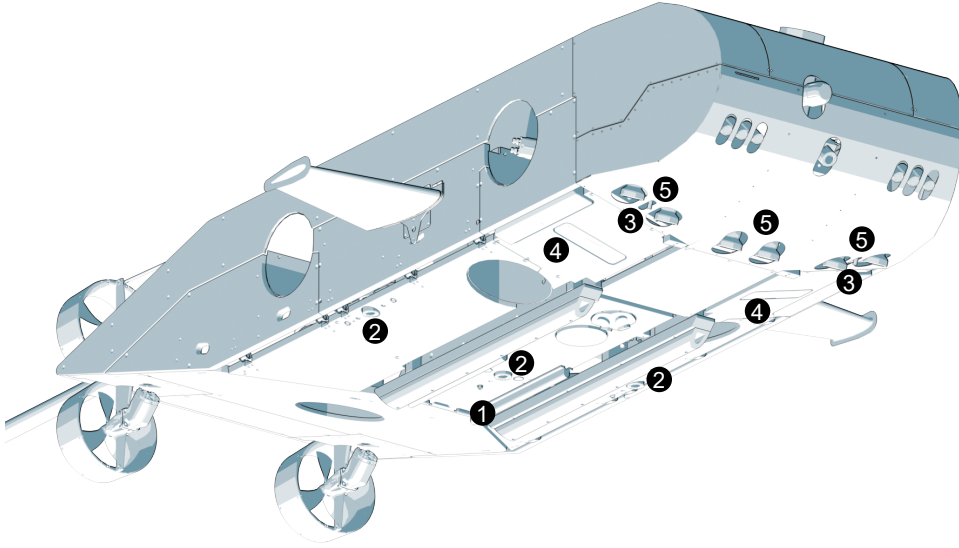


Figure 11: The standard configuration of equipment mounted on the SROV to capture photogrammetric and geophysical data. (1) Edgetech hydrophones. (2) UHD Cathx camera, the main tool for capturing photogrammetric data. (3) Green laser bathymetry system, one of the methods of scaling the photogrammetric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

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

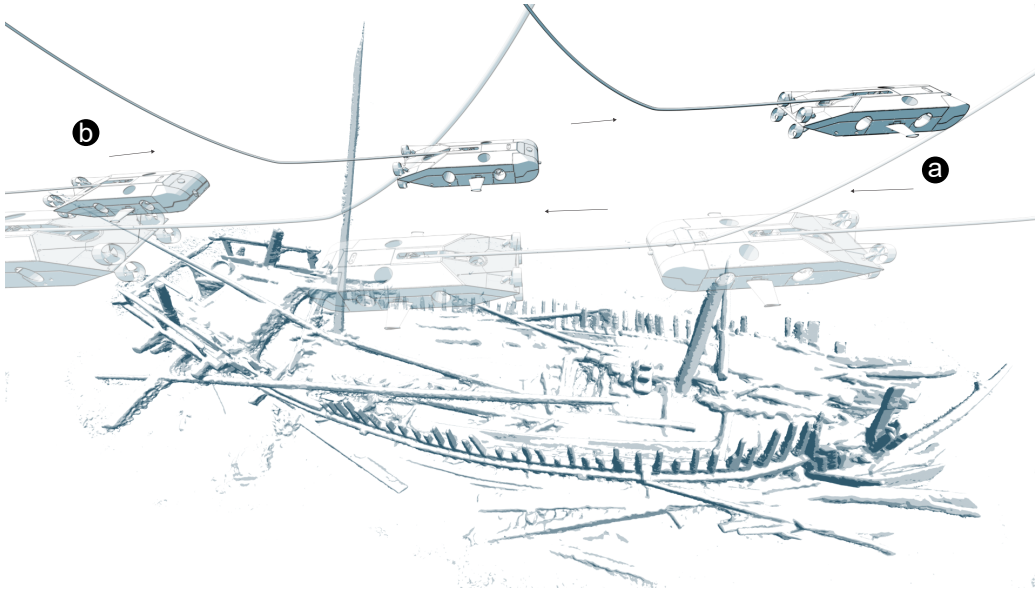


Figure 12: Figure showing the general methodology used to survey deep sea archaeological sites in the Black Sea using the SROV. (a) The SROV makes an initial fly-over, in which it will capture optical and acoustic data simultaneously. (b) adjacent passes will ensure overlap of data and full coverage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

260 3.2. Geolocation and scaling

261 Ideally the resolution of a digital model generated from photogramme-
 262 try should be complemented by similarly accurate scaling. In shipbuilding,
 263 ‘scantlings’ dimensions of key structural elements, as well as the relationships
 264 between them, can be diagnostic of period and/or type. Even where this is
 265 possible some fundamental dimensions are necessary for even the most basic
 266 site records. Scaling underwater can be achieved in a number of ways. The

267 most common one is by capturing in the scene an object of known dimen-
268 sions (Rule, 1995). In our case a 50x50x50cm cube was placed within one of
269 the selected shipwrecks and captured from every possible angle (Figure 13).
270 Within Agisoft PhotoScan Pro (1,3,3 build 4827) the cube was assigned the
271 known dimensions allowing the software to translate this scale to the entire
272 model.

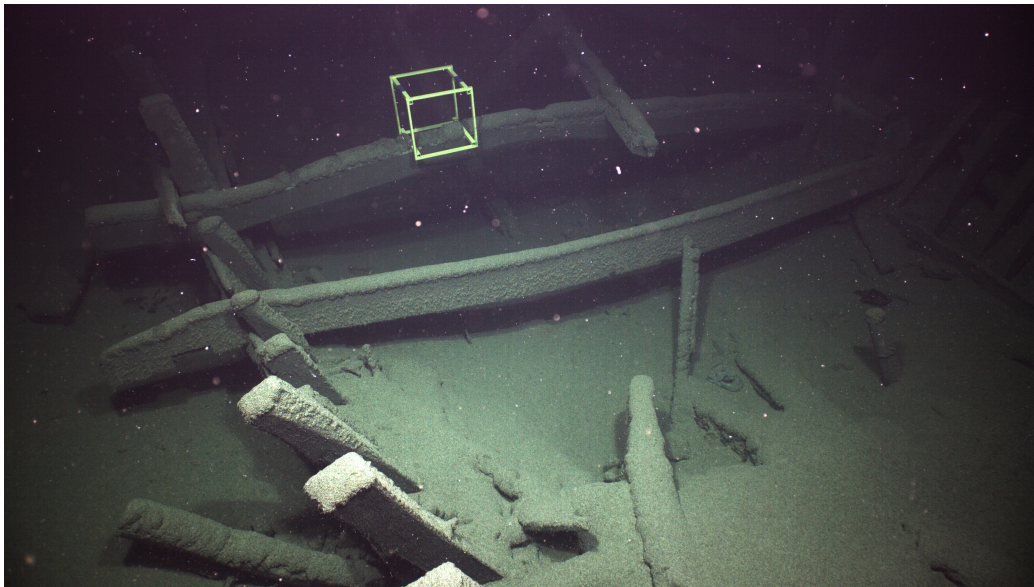


Figure 13: Figure showing the 50x50x50cm cube after it was placed by the WROV on a visible location on top of the timber structure of one of the Roman shipwreck sites studied. Image the authors.

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

277 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'

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

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

313 The cameras mounted on the ROVs platforms are subject to a dimen-
314 sional control survey (Dimcon) where their recorded offset is relative to the
315 ‘Sprint’ centre and are measured using a total station or alternatively a pho-
316 togrammetric survey prior to diving. The later method producing very good
317 results within a millimeter accuracy (Figure 14). These relative camera off-
318 sets are then input into the Qinsy interface which assigns the values the
319 navigation data and thus exporting the absolute positioning through the
320 Cathx interface.

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

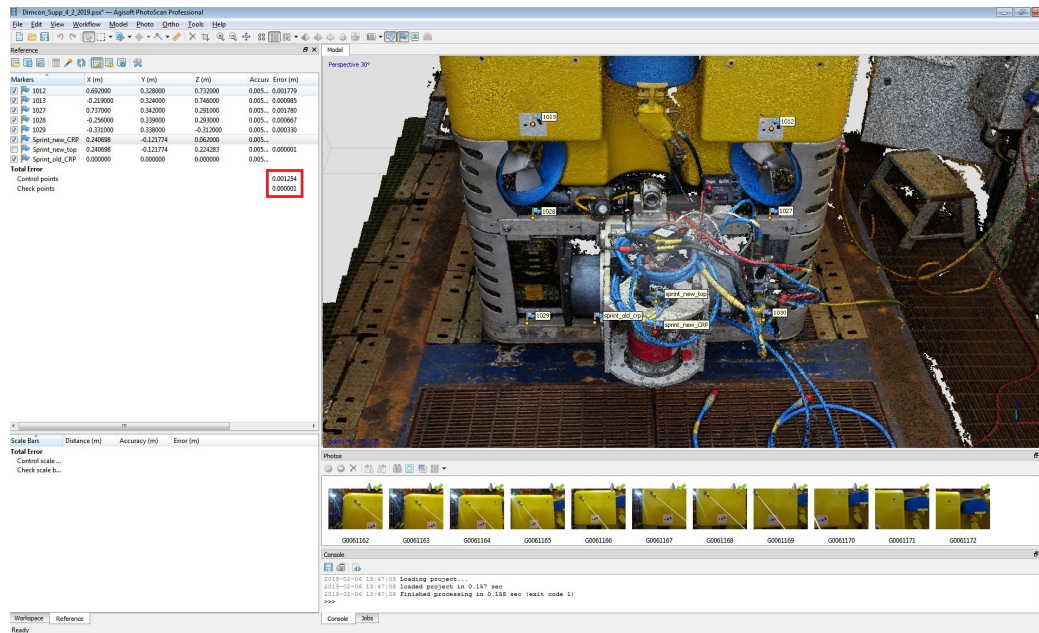


Figure 14: Results of the Dimcon of the Sprint INS mounted aft of the WROV using Agisoft Photo Scan software. The red rectangle shows the error of the photogrammetric model in metres. Image the authors.

328 systems (GIS) subsequently.

329 *3.3. Rapid cluster processing*

330 As the images were captured, both by the SROV and by the ROV, these
331 were uploaded through fibre optics onto the ship's mainframe server. This
332 made such media readily available to all of the members of the archaeolog-
333 ical processing team who then fed these to a number of processing clusters
334 available throughout the network. Two Dell Precision Tower 7810 were used
335 as the main processing nodes. The CPU processing power came from the 16
336 cores (2 x Intel(R) Xeon(R) CPU E5-2699 v3 @ 2.30 Ghz) with additional
337 192 GB of RAM, whilst the GPU processing was supplied by an NVIDIA
338 Quadro6000 graphics card for each workstation. Additional support nodes
339 were created within the ship's server by using networked virtual environ-
340 ments and thus adding thee extra nodes for data processing speed. These
341 virtual machines were customisable and where launched in five simultaneous
342 instances of 19 cores (2 x Intel(R) Xeon(R) CPU E5-2699 v3 @ 2.30 Ghz)
343 and 96 GB of RAM each.

344 **4. Quantifying archaeological intervention**

345 Photogrammetry was implemented to record the impact of the archaeo-
346 logical excavations carried out on a number of selected shipwrecks. Sediment
347 accumulation on the sites after their sinking meant that diagnostic features,
348 such as the shape and position of the steering assemblages, their fastenings
349 and tool marks, the shape of the the rudder blades together with the remains
350 of *in situ* material culture, such as elements of the cargo and crew personal

351 belongings, were obscured by burial and may need to be exposed for further
352 study.

353 4.1. The Early 4th Century BC shipwreck

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

359 First, a general survey of the shipwreck was made using the techniques de-
360 scribed above (Figure 15), thus achieving a high-resolution, pre-disturbance,
361 photogrammetric record. Excavation was then carried out using a water
362 induction dredge powered by the WROV hydraulic systems and controlled
363 through a Schilling *Titan4* kinesthetic feedback robotic manipulator. The ex-
364 posure of the archaeological remains were then resurveyed using photogram-
365 metry. Both pre- and post-excavation phases were documented producing
366 photogrammetric datasets to which the archaeological impact assessment
367 was done using GIS root mean squared (RMS) superficial spatial analyti-
368 cal functions to understand and quantify the impact of the archaeological
369 excavations (Figure 16). This method has been also been successfully trial
370 and tested during the Black Sea MAP excavations of the prehistoric settle-
371 ment of Ropotamo in 2016 (Pacheco-Ruiz et al., 2018).

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

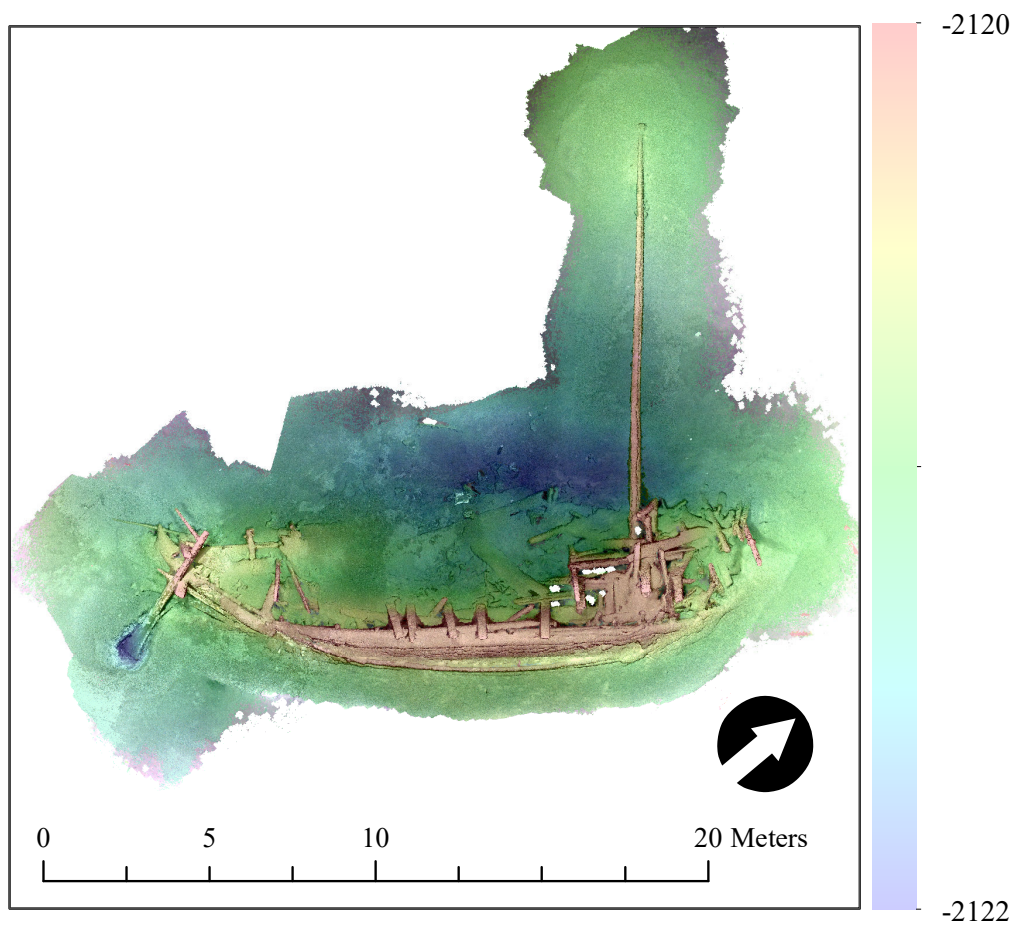


Figure 15: Photogrammetric site plan of an Early 4th Century BC shipwreck represented as a DEM from the photogrammetric model and the orthomosaic, resulting from the alignment of more than 2000 images. Image the authors.

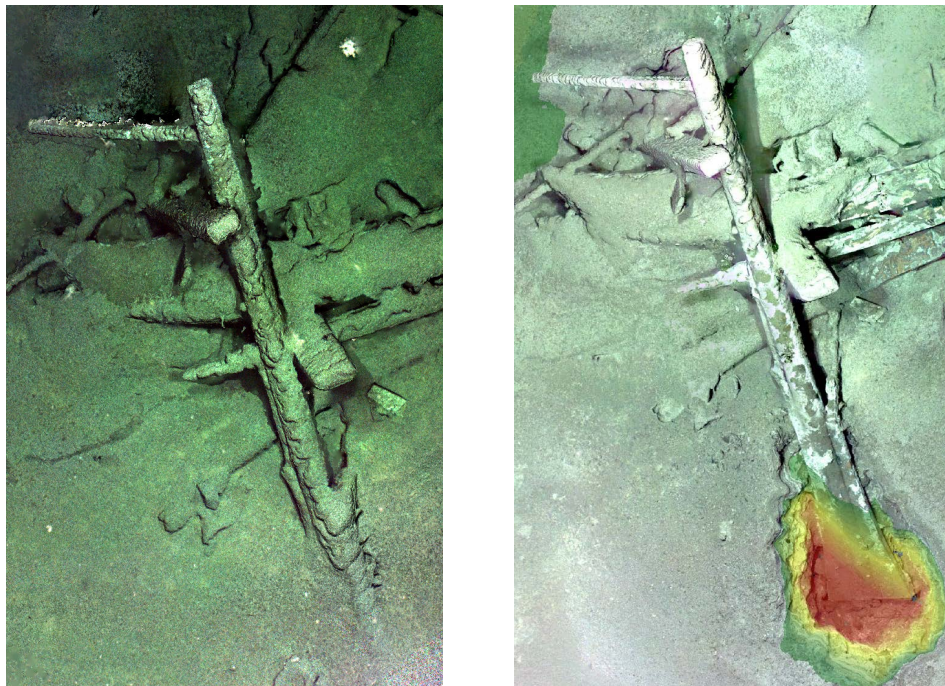


Figure 16: Comparative images showing both phases of the deep sea archaeological excavation of the rudder assembly and its recording. Left: the pre-disturbance survey. Right: the rudder assembly after the intervention using RMS comparison. All heights are zeroed to the seabed surrounding the wreck. Images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

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

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



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

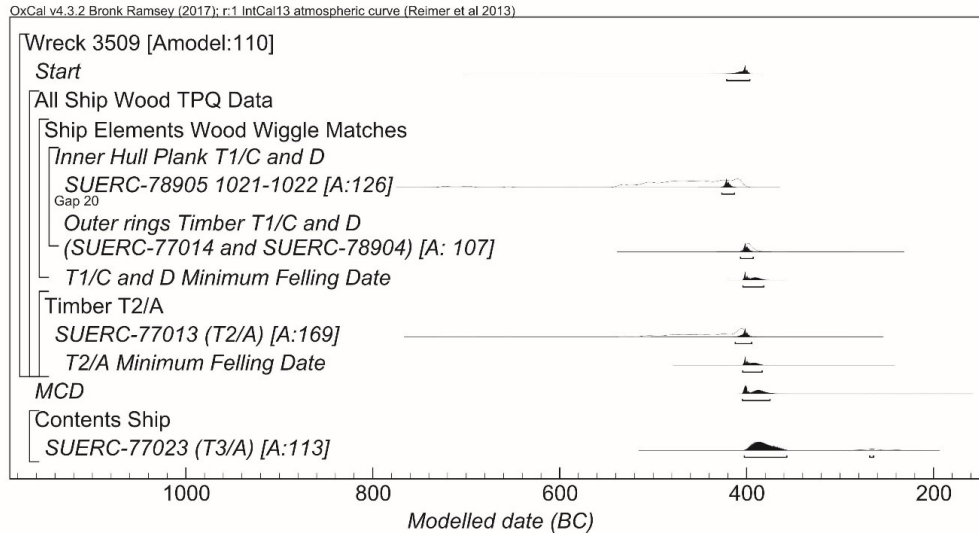


Figure 18: Phase model for the Early 4th Century BC shipwreck.

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

414 of the cameras and lighting array used. Additional time taken to refine the
415 model post-cruise is less cost-dependent. In this case accurate 3D data of
416 well-preserved hulls is demonstrably useful in various ways including hull
417 reconstruction and performance analysis.

418 6. Adding to the database

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

422 Surprisingly, there is relatively little known of Black Sea Seafaring even
423 in periods when powerful empires controlled the majority of the traffic. To
424 obtain this many well-preserved wrecks, even if a tiny sample of those that
425 must exist, nevertheless provides a substantial injection of hard data to com-
426 plement written history. The immediate benefit is a substantial increase in
427 our knowledge and understanding of seafaring and maritime traffic in the
428 Black Sea at both local and regional scales and across sequential cultural
429 periods. Individual shipwrecks are often described as ‘time capsules’ and can
430 be fascinating as individual discoveries. As Muckelroy pointed out, ships of-
431 ten represent a pre-industrial society’s most complex technology (Muckelroy,
432 1978, 3). As such they offer high resolution views of their parent societies.
433 Even better however, is a series of shipwrecks, for this constitutes longitu-
434 dinal data providing insights into technological development, trade, warfare
435 and strategies of competition and control that punctuated the cycles of hu-
436 man affairs, what the analiste historian Fernand Braudel described as the
437 *Duree Moyene* (Braudel, 1972).

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

462 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 Rönby, 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

487 3D printing of scaled models) could be done at leisure, though still usually
488 completed within 24 hours.

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

512 record of the site only been conventional video.

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

519 The other major factor is the ways in which these technologies and method-
520 ologies enable the research aims, methods and results to reach a wider au-
521 dience through various experiential modes of extended reality (XR), namely
522 Virtual Reality (VR), Mixed Reality (MR) and Augmented Reality (AR)
523 platforms (Figures 19). In the experience provided this is similar to Telep-
524 resence, pioneered by Dr Robert Ballard, where seabed video was transmit-
525 ted via satellite direct into schools in real time throughout North America
526 (Brennan et al., 2018). This was both innovative and imaginative and in
527 principle this has never been surpassed, though these days the down link can
528 be streamed to the internet and data can be accessed by associated scien-
529 tists ashore. Black Sea MAP considered Telepresence but for logistic reasons
530 chose to bring the students to the ships and to use the aforementioned digital
531 platforms (developed since Telepresence was first used) as they are becoming
532 part of the routine fabric of extending knowledge in museums, schools, web
533 portals and all digital interactive platforms. Once the digital content has
534 been created the potential audience is huge and depending on design, the ex-
535 perience is more interactive and open-ended, albeit without the immediacy
536 of Telepresence. Some of the most exciting potential of digital modelling and

537 reconstruction is related to the time depth of archaeological sites in general
538 and shipwrecks in particular which are wonderful vehicles for experiential
539 approaches that will enable the viewer/wearer/player to explore time and
540 processes of change as well as space, landscape, structure and things.

541 **8. Recording a finite resource under threat**

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

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

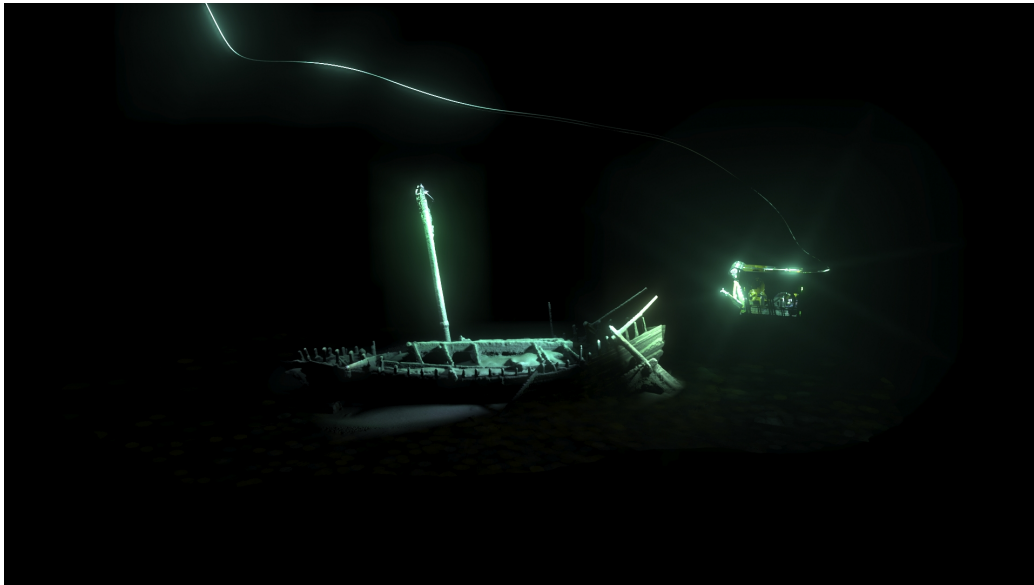
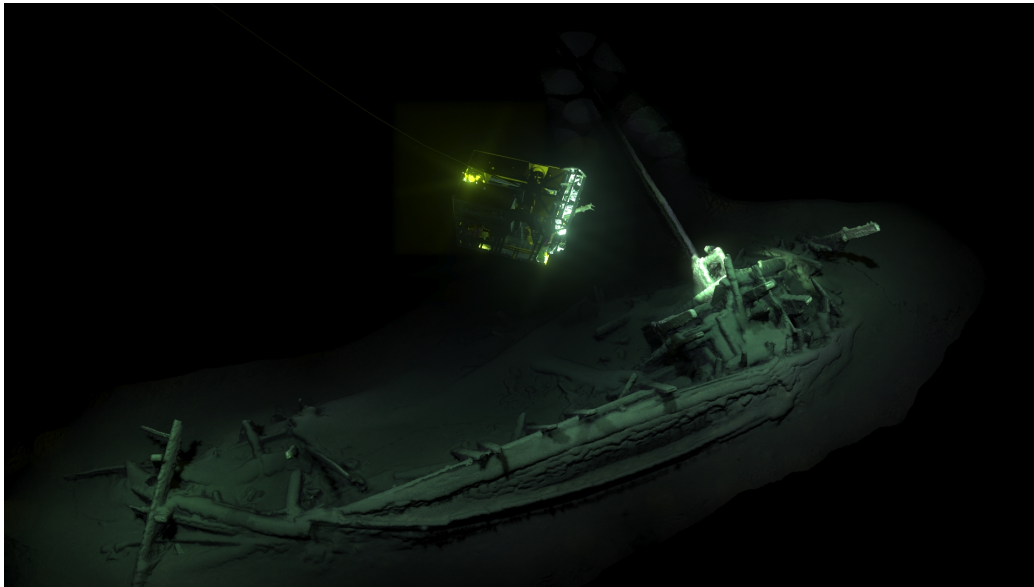


Figure 19: 3D representations of two of the ancient Black Sea shipwrecks based on underwater photogrammetry as a way of transmitting the experiencing of underwater sites to a wider audience. Upper: The Early 4th Century BC shipwreck discussed in this paper. Lower: A 1st/2nd Century AD Roman wreck also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

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

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

572 **9. Conclusion**

573 There have been considerable advances in our capability to discover,
574 record and in some case excavate, robotically in deep water. Accurate and
575 fast data acquisition using ROVs is now possible in the deep sea, with com-
576 putational capacity now able to rapidly process large datasets to provide
577 comprehensive models in the field. The combination of WROV and SROV
578 platforms also means that a wide range of complementary survey techniques
579 can be used over these sites, enabling photogrammetric models to be accu-
580 rately scaled and positioned. These models provide researchers without ac-
581 cess to the deep sea the ability to make new discoveries about early seafaring,
582 shipbuilding and performance of ancient vessels as well as the long-debated
583 nature of their appearance. The use of photogrammetry has also allowed the
584 dissemination of these discoveries to be made to the general public, with ma-

585 jor news outlets throughout 2017-19 showcasing these discoveries and making
586 extensive use of the resultant rendered images.

587 Unfortunately the technologies employed in the activities on deep water
588 wreck sites are not always driven by research questions or conducted accord-
589 ing to internationally accepted best practice. It is hoped that projects such
590 as the Black Sea MAP and the methodologies discussed here constitute a fur-
591 ther step along the path towards sustainable investigation and management
592 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	$\delta^{13}\text{C}$ (‰)	Calibrated Date	Modelled date
SUERC-77014	Starboard side hull plank T1(D) <i>Pinus</i> sp. <i>sylvestris</i> group, rings 1 to 4 (1001-1004) from outer edge	2310 \pm 24	-26.7	410-260 cal. BC (95.4%)	410-390 cal. BC (95.4%)
SUERC-78904	Starboard side hull plank T1(C) <i>Pinus</i> sp. <i>sylvestris</i> group, rings 1 to 2 (1001-1002) from outer edge	2357 \pm 24	-22.2	510-380 cal. BC (95.4%)	410-390 cal. BC (95.4%)
Combined SUERC-77014 and SUERC-78904 (2334 \pm 17)				410-380 cal. BC (95.4%)	410-390 cal. BC (95.4%)
SUERC-78853	Starboard side hull plank T1(C) <i>Pinus</i> sp. <i>sylvestris</i> group, rings 11 to 12 (1011-1012)	2277 \pm 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) <i>Pinus</i> sp. <i>sylvestris</i> group, rings 21 to 22 (1021-1022)	2397 \pm 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). <i>Pinus</i> sp. <i>sylvestris</i> group, rings 1 to 5 (1001-1005) from outer edge	2374 \pm 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) <i>Fagus</i> sp., sapwood present	2293 \pm 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%)

OxCal¹ 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);
};

```