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Technical Paper

Exploring the Phoenician shipwreck off Xlendi bay, Gozo. A report on methodologies used for the study of a deep-water site

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Abstract

A shipwreck was discovered in deep-water during a systematic side-scan sonar survey conducted in 2007 by Malta's heritage authorities and the University of Malta. Located off the coast of the island of Gozo, Malta, this site was the subject of a series of further in-depth studies that spanned over 10 years. Throughout this period, a number of different technologies were used to explore, record and study the site. This paper provides an overall description, analysis and evaluation of the various technologies and methodologies used to investigate this site.

Keywords: archaic shipwreck, remote sensing, Gozo, Xlendi bay, deep-water shipwreck

1. Introduction

Since 2006 the Superintendence of Cultural Heritage in Malta and the University of Malta have surveyed the coastal waters around the Maltese Islands. Equipment and other logistical support for this survey have been provided by the Aurora Special Purpose Trust, Vulcan Inc. and the University of Malta. The Malta Shipwreck Project conducts a systematic side-scan sonar survey aimed at locating, documenting and recording the submerged cultural assets located within Malta's territorial waters. Results from this ongoing project feed into a programme of protection and management based on a comprehensive knowledge of underwater archaeological sites. Over the years, numerous sites have been located and catalogued, ranging from ancient shipwrecks to the wrecks from the 1950s Cold War period. This long-term project is ongoing and permits Maltese heritage authorities to take informed decisions on the way forward for specific sites.

Although there is a large concentration of submerged cultural heritage located on the seabed off Malta and Gozo, one of the targets located in the course of the survey proved to be remarkable. This is the site of a seventh-century BC shipwreck that contained a cargo best described as 'Phoenician' – the only such shipwreck in the central Mediterranean known to date. Due to its exceptional nature, the site was considered worthy of further in-depth investigations. This paper presents a description, analysis and evaluation of the various technologies and methodologies used over the course of a decade in the study of the site.

2. Area of study

The Malta Shipwreck Survey Project chooses an area for study based on a number of factors, including: budget availability, type of equipment being deployed, and a series of 'probability questions' that help establish the potential for archaeological sites being discovered (Gambin, 2014). One such area was Xlendi Bay, chosen mainly because of known archaeological recoveries in the area and because of peculiar maritime conditions that are prevalent in this particular zone (Gambin, 2002-03; Azzopardi, 2013) (Fig 1). Open to the prevailing northwesterly winds, the sea in this area is easily whipped up with waves rebounding off the high cliffs, causing a very dangerous counter-swell. Moreover, the presence of a headland on the northwestern-most part of the bay brings strong

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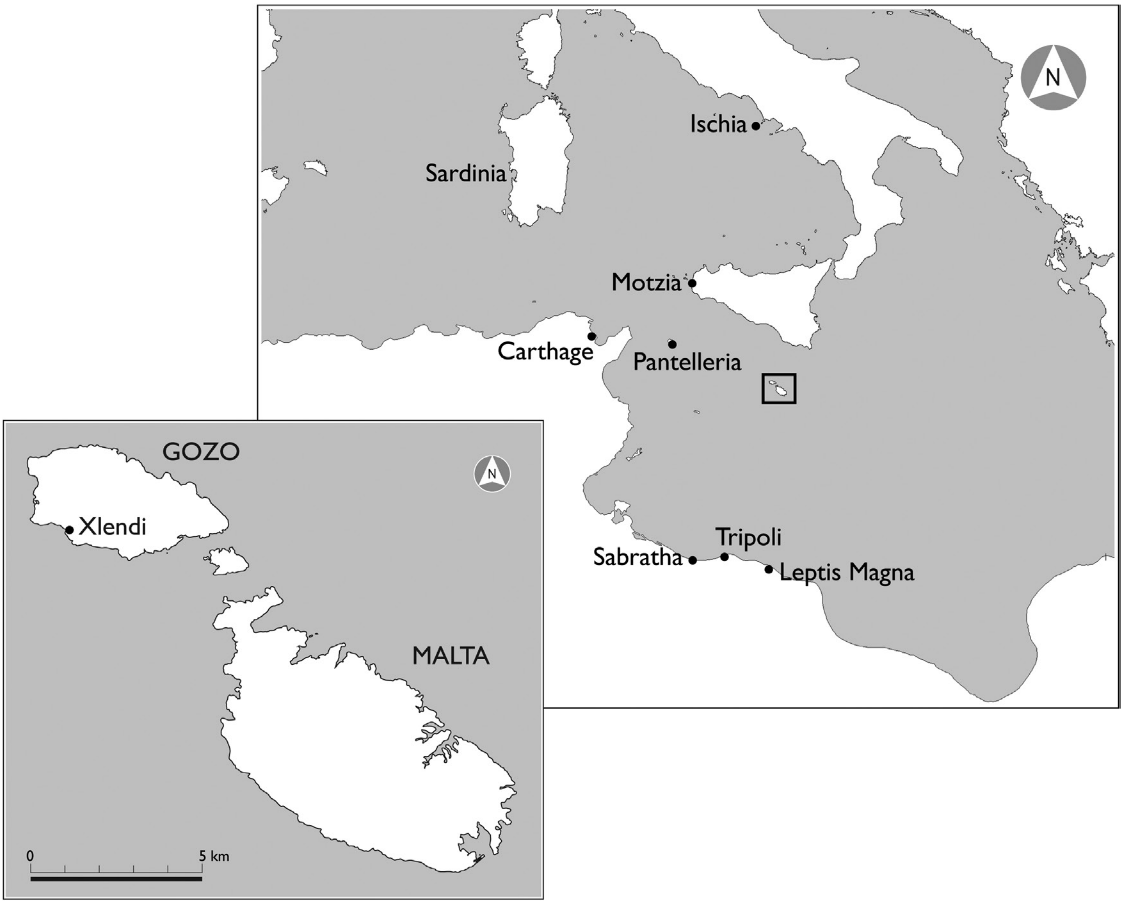

Fig 1: Map showing the location of Xlendi on the island of Gozo, Malta

currents into play, further contributing to a 'confused' sea state. According to local fishermen, such conditions may also prevail when weather conditions are seemingly favourable to navigation. Even for those using motorised boats, the area remains potentially dangerous.

3. Methodology and discovery

In the case of Xlendi Bay, a Klein System 3000 towfish with a dual frequency of 100 kHz/500 kHz was utilised for the survey in 2007. A wide area augmentation system (WAAS) global positioning system (GPS) is integrated into SonarPro, Klein's sonar acquisition software. This ensures that all sonar data are geo-referenced. In order to maximise the resolution offered by this equipment, 12 lines were planned using the navigation elements in the SonarPro software. Lines were set at 160 m intervals, and the sonar was run using a 100 m range giving a swath of 200 m. This approach also provides ample overlap in the subsequent phases of data processing and analysis.

The sonar was towed by a 27-foot aluminium purpose-built survey vessel at a maximum speed of 3 knots, thus keeping water-column noise at a minimum and ensuring the best possible sonar imagery. Lines were run in parallel to the coastline in order to avoid radical changes in the seabed topography that is present under the cliffs. Cable deployment was controlled using a DT Marine hydraulic winch with a combined cable counter/sheave. This system permitted the survey team to maintain the towfish at a relatively constant height of between 15 m and 18 m above the seabed.

Sonar files were recorded in SDF format and backed up at the end of every day at sea. All sonar files were subsequently processed using SonarWiz by Chesapeake Technology. This software permits the production of high-resolution sonar mosaics (Fig 2), as well as comprehensive target analysis and reports. The survey outside of Xlendi Bay produced a number of anomalies and, following the thorough analysis of these, only one of these was considered to be potentially significant. Through WIZMAP, the anomaly was measured at ~11 m by 4 m and was situated at a depth of circa 110 m. The target identification was based on: *(a)* the dissimilarity between the anomaly and the surrounding seabed topography; *(b)* the overall shape and size of the anomaly being similar to that of an ancient shipwreck; and *(c)* the rounded shadows of the individual objects forming part of the anomaly (Fig 3).

Fig 2: Mosaic of sonar coverage in area of study

Fig 3: Sonar image of shipwreck in 500 kHz

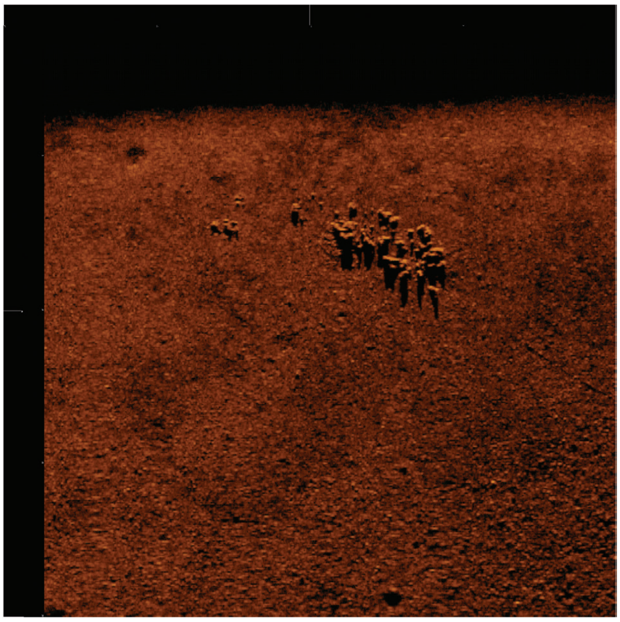

Fig 4: Sonar image of rock formation with similar outline to ancient shipwreck

Given its high potential, a decision was taken to obtain a better resolution sonar image of the target. To accomplish this, the towfish was towed at a speed not exceeding 2 knots and not higher than 3 m off the seabed. Although the high-resolution sonar image strengthened the hypothesis that the target was an ancient shipwreck, some natural seabed features have been known to have similar characteristics to those described earlier (Fig 4). Further data would therefore have to be gathered prior to establishing, beyond any doubt, the exact nature of the target.

3.1. High frequency side-scan sonar survey

In 2008, a decision was taken to further investigate the anomaly using higher frequency side-scan sonar to acquire and produce sonar imagery with a higher resolution. For this phase of the study, a Klein System 3900 towfish with a dual frequency of 455 kHz/ 900 kHz was utilised. Once again, a WAAS GPS ensured that all sonar data were geo-referenced. The two pre-set survey lines ensured that the towfish ran parallel to, and lengthwise of, the anomaly. Using the 900 kHz setting and a 20 m range maximised the resolution offered by the equipment. With such high frequencies, the sonar becomes more susceptible to boat heave and wave action. It was therefore imperative to wait for the calmest possible day in order to execute this survey.

The sonar was towed at a maximum speed of 2 knots and kept no more than 2 m above the seabed. Imagery acquired during this phase permitted further interpretation of this site as an ancient shipwreck. A closer look at the 900 kHz image enabled the identification of objects laid out in three distinct sections. As shown in Fig 5, rectangular objects are present on either extremity of the site, whereas more rounded objects are present in the centre

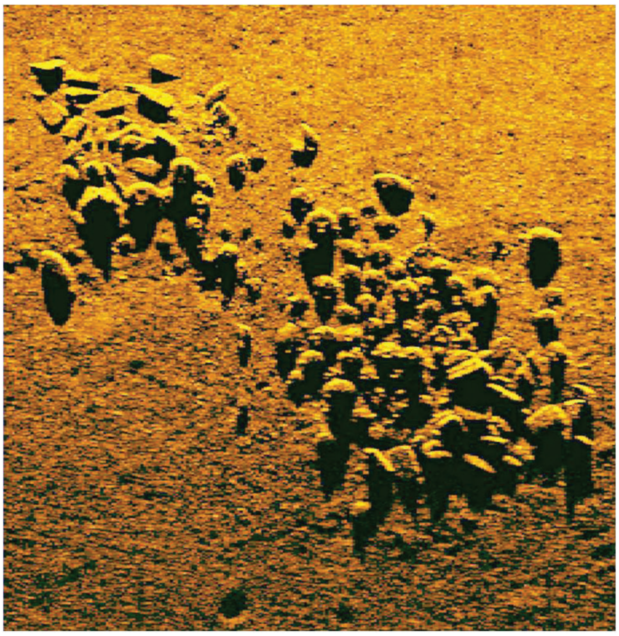

Fig 5: Sonar image of shipwreck in 900 kHz

section. From Fig 5, it is also possible to identify an absence of objects in part of the central area.

3.2. Sub-bottom profiler survey

In the 2008 season, a sub-bottom profiler was also deployed. This was done to eliminate any remaining doubt that the anomaly consisted of a natural rock formation (Sakellariou 2007a; 2007b) and to explore how far the anomaly extended into the seabed. For this phase of the survey, a K-Chirp Model 3310 sub-bottom profiler, fully integrated with a WAAS GPS was deployed. This system uses two 2–8 kHz Chirp transmit transducers for optimal penetration of the seabed.

Four tightly spaced survey lines were planned to run across the target using SonarPro software. The sub-bottom profiler was towed at a maximum speed of 2 knots and at a height of 2 m above the anomaly, ensuring the acquisition of the best possible sub-bottom data, which were subsequently processed in WizMap. The results of the survey clearly indicated a break in sub-bottom sediments, confirming that the anomaly did not form part of the natural seabed topography. Moreover, the four lines completed in 2008 permitted the study of the sub-bottom deposits in cross-section. In some areas below the visible anomaly, sub-bottom data showed a layer of hard sub-strata present in the seabed. Indications were that the anomaly extends ~1.8 m into the sediment (Fig 6).

The hard substrata suggested that objects were likely buried underneath what was detected by the side-scan sonar. However, despite recent advances in

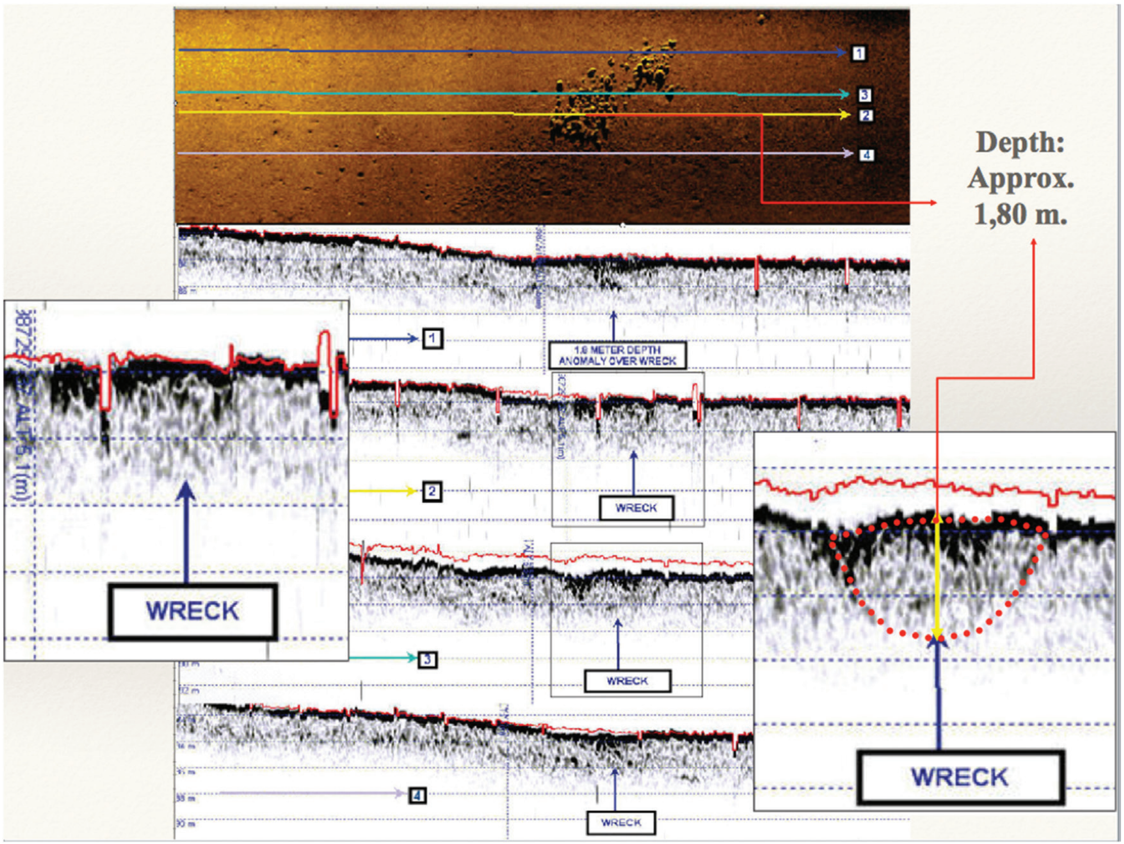

Fig 6: Sub-bottom data showing cross sections of shipwreck

the use of sub bottom profilers on archaeological sites, acquired data do not permit secure identification on the form of buried objects but can shed light on their size. In the case of Xlendi, however, it was not possible to distinguish individual objects such as amphorae, probably due to their compactness and proximity to each other. Moreover, organic materials such as water-logged wood are not identifiable in the sub-bottom data (Søreide 2011: 130). Therefore, the results from the sub-bottom survey could, at best, be considered as having indicative value on the potential for further archaeological deposits present in the sediments.

3.3. Remote operated vehicle (ROV) survey

In 2008/2009, ROV surveys were planned and executed. The main aims of these surveys were: *(a)* to establish definitively the nature of the anomaly; *(b)* to obtain video and photographic data of the anomaly; and *(c)* to create a photomosaic of the anomaly. In order to achieve this, a small observation class Seaeye Falcon ROV was utilised. This ROV carried a high-resolution fixed focus colour camera with a resolution 480 TVL and a sensitivity of 0.2 LUX at f1.4, and a half-inch charge-coupled device (CCD) image sensor. This camera could be tilted remotely ±90 degrees. Illumination was provided by two dimmable 75 W lighting units. A separate Kongsberg 5M Pixel Digital Stills Camera complete with a synchronised flashgun was also mounted on the ROV. Changing of the orientation of the stills camera from oblique to vertical could only be done with the ROV on the surface and thus required its recovery to do so.

The ROV was also equipped with an Imagenex 881A Multi Frequency Imaging Sonar (multi-frequency, fully tuneable imaging transducer and software). This sonar has default frequency settings of 310 kHz, 675 kHz and 1 MHz, and can be deployed in 360° polar, sector and side-scan modes. For the purpose of this phase of the survey, the sonar was used solely to locate the anomaly. The ROV was deployed from the same 27-ft aluminium purpose-built survey vessel as used previously, which was fitted with a TrackLink 1500 Series ultra-short base line (USBL) acoustic tracking system by LinkQuest Inc. Despite this system facilitating the manual station-keeping over the site, the surface vessel was not constantly stable, which in turn de-stabilised the ROV. All tether management for this phase of the survey was done manually.

Several minutes of video footage were recorded during the two days spent on the site. Phase one consisted of the acquisition of 180 oblique photographs for generic and detailed views of the site. This primary visual record permitted the final confirmation that the anomaly was indeed an ancient shipwreck. It established that the shipwreck consisted of a mixed cargo that included western Phoenician and Thyrennian amphorae, worked blocks and other varieties of ceramic containers datable to ~700 BC (Sourisseau et al., 2014). Photographs from this phase of the ROV survey allowed the identification of semi-buried ceramic and stone objects protruding from the seabed (Fig 7). These photographs corroborate the indications of buried objects first observed in the sub-bottom data.

A further 110 vertical photographs for the creation of a photomosaic were obtained by 'flying' the ROV over the site six times. However, the lack of both a stable surface vessel and accurate navigation software meant that the lines were determined manually and through observation. In order to develop the photomosaic, the vertical photographs were processed using Autopanopro, a photograph stitching software produced by Kolor. Initially photographs would be processed by lines and, once each of the separate lines were readied, these were merged to form the final image (Fig 8).

Fig 7: Elements from the second layer of cargo protruding from the seabed

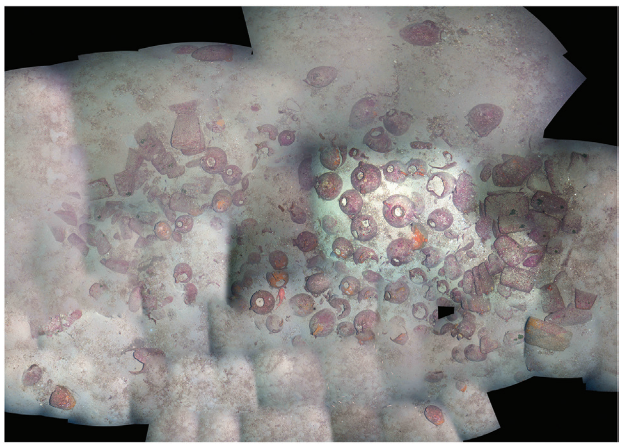

Fig 8: Photomosaic of shipwreck completed in 2010

The combined stills camera and strobe proved useful for the acquisition of good quality stills photography, but the lack of suitable lighting made the video footage unusable for anything other than general observation. The major difficulty was the manual station-keeping of the small surface vessel. Constant movements and adjustments were sometimes transmitted through the umbilical, subsequently destabilising the ROV. Despite the aforementioned shortcomings, it was still possible to create a basic but informative photomosaic of the overall photographic view of the entire site, which could be used to plan any future archaeological work.

3.4. 2014 data acquisition and processing

A grant application was accepted on the basis of the datasets gathered between 2007 and 2008, and the funds obtained were used for an ultra-high resolution survey of the site. Furthermore, the possible recovery of sample objects would contribute to a better understanding of the site, such as: *(a)* enabling a closer look at objects to establish exact typologies; *(b)* sampling objects and sediments for lipid analysis, DNA studies and pollen studies, as well as petrological studies; and *(c)* high-resolution recording of recovered objects in 3D for future use in photogrammetric models.

Under the ambit of the GROPLAN Project, Comex deployed the Minibex – a light and highly manoeuvrable 30 m vessel fitted with a dynamic positioning (DP) system. The DP system permits the vessel to remain stationary above a fixed seabed reference point, thus providing a stable environment from which to deploy and operate submersible assets. The *Super Achille* is a light observation-class ROV fitted with a tether management system that was deployed from the Minibex. Its payload consisted of a complex system of cameras, including: one pan and tilt camera for piloting; a high-definition (HD) camera/video recorder for videography; and a reflex digital camera with flashes for stills photography. Lighting is provided by four halogen lights. The ROV also carries a three-way working arm and a Tritech panoramic sonar.

The *Remora 2000* is a two-person manned submersible with a fully autonomous operational duration of up to 5 hr. Its payload includes a high-resolution 725 kHz scanning sonar, an echosounder and two Cybernetix SAMM hydraulic manipulators (one 5-way and the other 3-way). For the purpose of this survey, the *Remora 2000* was set up with the ROV3D system and four high-power Hydrargyrum medium-arc iodide (HMI) lights with appropriate diffusers (Fig 9). This lighting is a crucial part of the photogrammetric process. It must meet two criteria: homogeneity of exposure for each image, and consistency between images. In order to maximise light quality, the lights are fixed on the submarine as far from the camera as possible.

The 2014 survey had two goals: measuring the entire visible seabed where the wreck is located, and extracting known artefacts from the site. Both these objectives required documenting the site's position in space as well as that of the individual objects within it, so that they could then be accurately recreated at various post-fieldwork stages. In order to achieve this, optical sensors were used. The ROV3D is a very high-resolution optical trifocal survey system developed by Comex for the production of very high-resolution 3D data. It is composed of one high-resolution, full-frame camera synchronised at 2 Hz, and two low-resolution

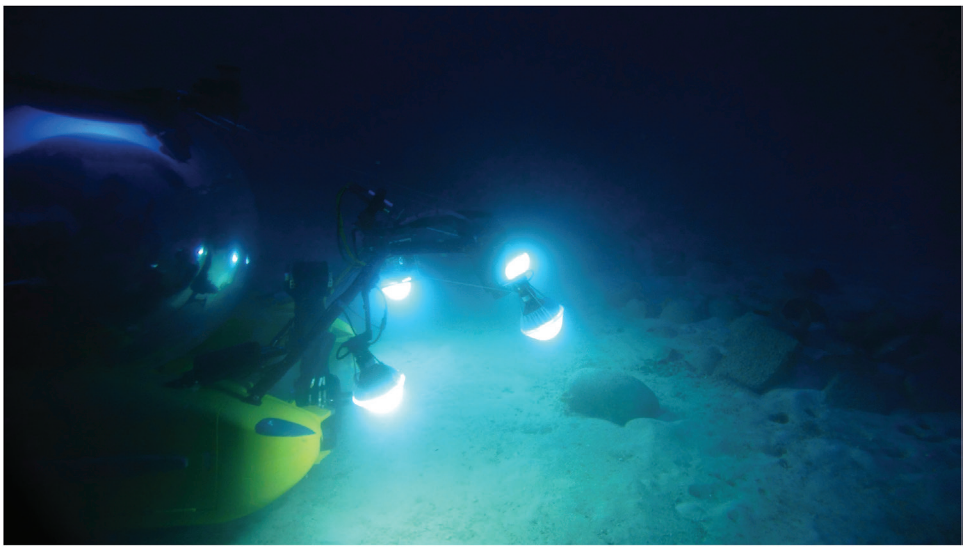

Fig 9: The trifocal system mounted on the REMORA 2000

cameras synchronised at 10 Hz. The ROV3D's navigation system, based on a real-time odometry process, gives the operator real-time positioning of the vehicle (Drap et al., 2015). This system expedited the photogrammetric process in a non-intrusive manner.

The ROV3D system used in 2014 was mounted on the *Remora 2000*. A connection was established between three cameras and a computer fixed externally on the submarine, with the pilot inside in order to facilitate full control (Drap et al., 2015). This system permitted the synchronised acquisition of high- and low-resolution images by video cameras forming a trifocal system. However, it required the three cameras to be independently mounted in separate waterproof housings, and so two separate calibration phases were necessary. The first was carried out on each camera/housing pair in order to compute intrinsic parameters. The second one was done to determine the relative position of the three cameras that were securely mounted on a rigid platform. It was important that this calibration was done before each mission as it affects the scale of the final 3D model. Performing the calibration permitted the acquisition of a 3D model at the right scale, without any interaction on the site.

The trifocal system had two different aims: the real-time computation of system pose, and the 3D reconstruction of the zone of seabed visible from the cameras. The submarine pilot guided the vessel using a dedicated application that displayed the position of the submersible in real time. A remote video connection also enabled the operator to see the images captured in real time by the cameras. Using the available data, the ROV3D operator could assist the pilot to ensure complete coverage of the zone to be surveyed. The pose was estimated based on the movement of the vehicle between two consecutive frames. A system developed specifically for this project was used for computing visual odometry in real time and producing 3D on-the-fly along with a sparse cloud of 3D points (Nawaf et al., 2016; Nawaf et al., 2017).

With the system set on a vertical axis, the *Remora 2000* proceeded to execute eight transect lines on an east–west access (lengthwise across the entire shipwreck). A further six transects were executed on a north–south axis (across the width of the shipwreck). The total survey time was just under 1.5 hr. The *Remora 2000* was re-deployed for phase two of the photogrammetric survey, this time with the cameras deployed obliquely at an angle of 22.5°. For this part of the survey, 10 transect lines on the east–west access and a further 8 transects were executed on the north–south axis. A final transect was done in order to combine an isolated object located ~6 m from the north-west boundary of the shipwreck. This phase took just under 1 hr to complete. A total of 2831 full-frame/high-resolution and 28 310 HD photographs were taken. Following the completion of the survey's data-acquisition phase, a further two dives were carried out so that the site could be inspected at closer quarters by the archaeologists in the team.

To achieve the second goal, the high-resolution images had to be processed to produce a dense model, scaled and created on real baseline distances. Specialised software was developed by the Laboratoire des Sciences de l'Information et des Systèmes, Centre National de la Recherche Scientifique. This software permitted the bridging of the original visual odometry software to commercial software such as Agisoft's Photoscan (Drap et al., 2015). This was done so as to use Photoscan's densification capabilities. This first step produced a dense point cloud and a set of oriented high-resolution photographs that accurately represented the entire site. In turn, this was used for the production of a high-resolution orthophoto of the site (1 pixel per mm) as well as accurate 3D models. Using the high-resolution orthophoto (Fig 10), each visible artefact was given a digital label with a unique object number.

The manned submersible proved to be an invaluable tool for data acquisition. Besides being able to carry the specialised payload described earlier, it also provided an extremely stable platform from which the imagery could be obtained. It permitted the field archaeologists to visit and experience the site first hand for over 2 hours at a stretch. Due to the proximity and clarity afforded by the manned submersible, it allowed the archaeologists to clearly identify and select objects for recovery.

3.5. Model precision

When computing orientation in real time, having to assume small baseline distances prohibits accurate results for the entire set of images. In fact, the main problem is limiting common points to only 4 or 6 images, i.e. 2 or 3 consecutive stereo pairs. Although the visual odometry method presented here is sufficient to ensure the complete coverage of the site in real time, it does not provide enough precision for the final model. This is especially the case for the goal of automatic recognition of each artefact in order to evaluate its variance with the theoretical model.

Therefore, a second step was implemented where the homologous points were extracted and matched for all images, and a global bundle adjustment was performed to ensure the best possible

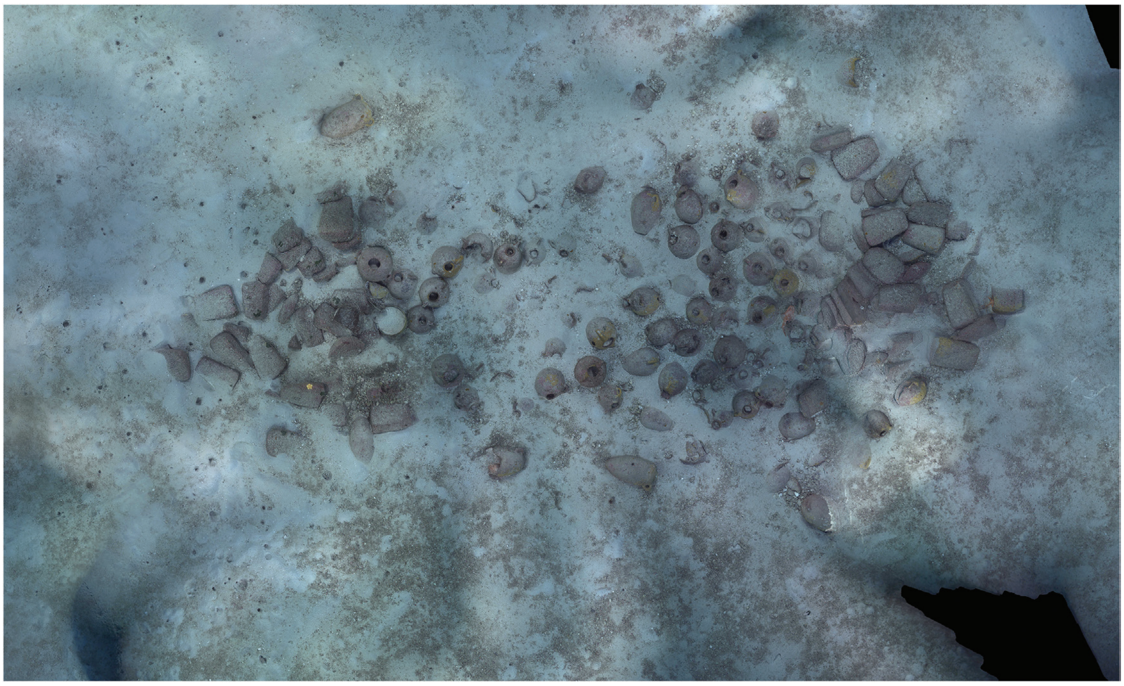

Fig 10: High resolution orthophoto produced in 2014

orientation. This was done whilst taking into account the constraints related to the set of three fixed and calibrated cameras.

The 3D model was obtained using visual odometry and traditional bundle adjustment. This method takes into account all the possible observations of the 3D points, and reveals the presence of residues of ~5 mm on the (X,Y) plane (which is lateral to the motion) and within 1cm range depth-wise (camera direction) on sequences with more than 1000 images. In fact, these data vary in function depending on the quality of the surveyed terrain. When the seafloor is sandy and low textured, the matched points are fewer and of lower quality. In the areas where the amphorae are found, detected feature points are greater in number, their quality is better and the residues between models is less pronounced.

The overall 3D model is scaled by introducing a stereo base of 0.297 m (value obtained after the triple calibration, done before the mission in shallow water) as a constraint in the bundle adjustment. In the end, more than 2000 stereo-pair poses were refined by this constraint so that the residues were less than 1 mm. This approach permitted control of the final precision model without any contact with the seabed, and instead using only accurate extrinsic calibration of the trifocal sensor, which had to be done before each survey campaign.

In order to facilitate the study of the cargo, it was necessary to create accurate 3D models of known objects. This was achieved by scanning the individual objects raised in 2014, which were then assimilated into theoretical 3D models. In turn, software was used for a two-phased recognition process: *(a)* artefact detection, and *(b)* pose estimation of each artefact in order to compute the exact dimension and localisation. Amphorae detection was done in 2D using the full orthophoto. The deep-learning approach yielded a positive result rate of 98 % (Pasquet et al., 2017). Moreover, this process permitted the extraction of the relevant parts of the 3D model where the artefact was located. A 3D matching approach was subsequently used to compute the position, orientation and dimension of the known artefact. Assuming that the buried cargo consists entirely of amphorae, this system can recreate an ‘archaeologist’s impression’ of the entire cargo (Fig 11). The main difficulty with this approach is that it is based on the assumption

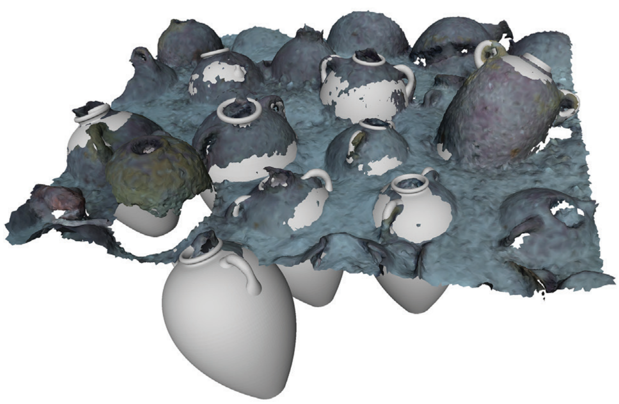

Fig 11: Amphorae reconstruction using the known typology and theoretical 3D model after detection and computation

that the artefact projected into the seabed exists in its entirety and that the visible part of the cargo is replicated below the seabed.

3.6. Object recovery

Following the completion and verification of the photogrammetric survey, a number of sample objects were selected for recovery. Selection was based on: whether the objects provided a representative sample of the cargo; the ease of recovery; and if the recovery could be achieved with the least possible disturbance to the site. Given the distinct nature of the cargo, the recovered samples were chosen to provide a better understanding of the shipwreck, its cargo and what they may eventually reveal about archaic trade in the central Mediterranean. The following four objects were chosen for recovery: *(a)* a saddle quern base; *(b)* an ovoid amphora; *(c)* a flat-bottomed amphora; and *(d)* an urn.

Object recovery was undertaken using the manned submersible. For the quern, a looped cable connected to the vessel's crane was lowered by the ROV. The loop was placed near the object and subsequently tightened carefully by the manipulator arm of the submersible. Once secured, the crane proceeded to lift the quern through the water column to a depth of 25 m where it was met by divers using standard SCUBA equipment. The divers secured the object in a large bag, which ensured the safe recovery from the surface onto the vessel.

A different approach was used for the amphorae and urn. A stainless-steel recovery tool was lowered by the ROV, and the submersible's manipulator ensured that the tool was secured without any undue pressure on the object. Once secured, the manipulator attached the crane's cable to the tool, thus making recovery possible. Again, divers secured the object at a depth of 25 m. This process was repeated for each of the three ceramic artefacts. Once on board, all four objects were placed in saltwater in pre-prepared tubs. At the end of the fieldwork, objects were transported to the University of Malta where they underwent full conservation. Objects were subsequently drawn, photographed and scanned.

The process of object recovery with the combined use of the ROV and manned submersible proved somewhat cumbersome and time-consuming because of a lack of dexterity. An entire working day (10 hr) was spent recovering the four objects. Adding to the overall time was the fact that objects had to be raised individually using the vessel's crane. The presence of a basket on the seabed would have permitted the recovery of multiple objects.

4. 2016/2017 fieldwork

The GROPLAN project catered for one exploratory fieldwork season. Reinforced by the results produced in 2014, a decision was taken to plan further fieldwork on the site. For example, the high-resolution imagery enabled the identification of various important ceramic typologies that were previously indistinguishable in data obtained prior to the GROPLAN Project. The main objectives of the 2016/2017 seasons were:

- continued systematic recovery of objects from the shipwreck; and
- ongoing recording of the site using 3D photogrammetry.

Restricted funding prevented the use of Comex or a vessel with similar capabilities, and the only realistic alternative was the deployment of divers. The depth of the site precluded standard SCUBA equipment. An option of using open-circuit (OC) mixed gas divers was explored but discarded in favour of closed-circuit rebreather (CCR) divers. This decision was based on the premise that CCR systems offered the following advantages over OC: *(a)* more efficient maintenance and preparation times; *(b)* lower costs of consumables; *(c)* better decompression efficiency; and *(d)* improved dive duration and bailout capabilities (Parrish and Pyle, 2002). The purpose of this section is to provide those unfamiliar with CCR diving with background information on the complexity of organising such expeditions.

4.1. Operations

At the start of each working day, the project director and dive safety officer briefed all individuals on the tasks planned for the day. Each day, three dive teams descended to work on the site. The first to descend was the videography team that consisted of three divers plus one safety diver. This team was then followed by two consecutive teams, each consisting of two divers plus one safety diver (see Table 1). This sequence was kept to ensure that: *(a)* the seabed would be undisturbed by the movement of sediments and objects, thus ensuring optimal visibility for the video recording; and *(b)* the site was accurately recorded after every disturbance caused by the other two teams.

Once in the water, all divers descended to 6 m to conduct standard safety checks. Upon successful completion of these checks, divers descended down the shotline to the site. The rate of descent varied depending upon what was being carried by the dive team. Besides executing a controlled descent to avoid sharp rises in the partial pressure of oxygen,

Table 1: Make-up of teams as deployed for various tasks

Team	Personnel	Tasks
1	One camera operator, two light operators and one safety diver	Video capture for 3D photogrammetry
2	Two workers and one safety diver	Excavation, object recovery and general duties
3	Two workers and one safety diver	Excavation, object recovery and general duties

another protocol adhered to by the teams was to descend at the rate of the slowest diver. The dive plan consisted of a maximum bottom time of 20 min, divided into 8 min to descend and 12 min on site. The surface timekeeper indicated to teams 2 and 3 when it was their turn to enter the water and start their dives, with dive teams passing each other at the shotline to eventually reconvene on the last decompression stop, set at a depth of 6 m. At various stages of decompression, back-up divers using standard SCUBA equipment descended to check on the CCR divers and relieve them of equipment such as cameras and lights. The total run time of the CCR dives was ~180 min, of which 160 min were spent in decompression. In conclusion, each diver utilised a total of ~5 hr in order to spend 12 min on the site. The 2 hr above time in the water were utilised for the preparation of the unit, pre-dive checks and post-dive procedures.

4.2. 2016/2017 documentation

Data capture for 3D photogrammetry modelling requires careful planning to ensure the highest quality images with satisfactory overlap of recognisable features in the images (Yamafune et al., 2017). Underwater photogrammetry for archaeological purposes has generally been executed using still photography (McCarthy and Benjamin, 2014), because it is convenient for depths that permit long periods on the seabed and sites for which repeat dives do not cause excessive decompression schedules.

Due to the depth of the site and the very limited working time (12 min) on the bottom, it was not possible to take a full set of still photographs of the site for photogrammetric purposes. It was therefore decided to utilise video as the primary data capture method for this particular site. 3D photogrammetry based on HD videos captured by a team of divers is a relatively new methodology that provides a quick and cost-effective way to document a wreck site, especially at extreme depths. Test runs in shallow water were executed to ensure that an area measuring 15 m by 6 m could be covered in 12 min or less. All tests were successful. Precise preparations prior to all dives were imperative in order to be absolutely certain that mishaps such as moisture droplets, low battery or a lack of data storage do not occur.

Video was captured with a Sony A7SII full-frame camera fitted with a Vario-Tessar FE 4/16-35 ZA OSS 16 mm rectilinear wide-angle lens. These were loaded into a Nauticam NA-A7 housing with two attached Keldan 130 W lights producing 13 000 lms each. In 2016, additional lighting was provided by two divers, one carrying a 300 W Northern Light Scuba Supernova producing 30 000 lms and the other a prototype 1000 W Northern Light Scuba Supernova producing 100 000 lms. In 2017, the latter was replaced by two EasyDive Revolution lights producing 13 000 lms each. This added illumination proved crucial for two reasons: (a) it provided ample lighting in an otherwise very dark environment; and (b) it led to more accurate and realistic 3D models.

The three divers swam abreast with those holding the lights, making sure that they did not create strong shadows or enter the field of view (Fig 12). The cameraman used recognisable features to maintain the swimline, with the other two basing their direction and positioning on the movements of the cameraman. Swimming in unison and maintaining steady buoyancy throughout this operation were crucial to ensure consistent and optimal results (Fig 13, Fig 14). A safety diver (to ensure that the dive plan and parameters were respected) continually followed the three swimmers.

Two essential elements when working on underwater sites are speed with which data can be captured, coupled with the ability to record the complex surfaces of a wreck (Yamafune et al., 2017). Each dive produced ~12 min of HD video, from which two images per second were extracted using the video image capture software FrameShots. The circa 1440 photographs were then uploaded to Agisoft's PhotoScan and RealityCapture for processing. A low-resolution version of the model was produced almost immediately after each dive, and used to ensure that the alignment and coverage were complete and the model correct. The low-resolution model was also used to plan the dives. High-resolution versions of the models were then processed and data exported in different formats in order to suit several purposes. Deliverables included 2D orthophotos, point clouds, 3D meshes as well as VR applications. The 2D orthophotos were subsequently processed and optimised using the aforementioned control methods developed after the 2014 season (Fig 15).

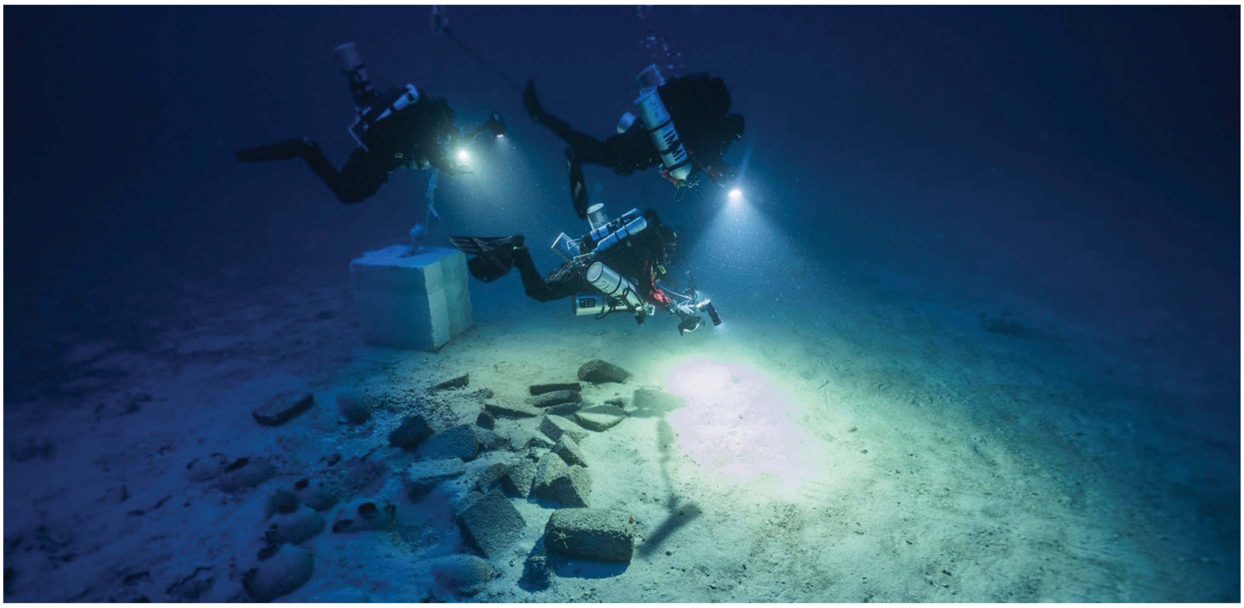

Fig 12: Three divers executing swim-lines over the site (D. Gration)

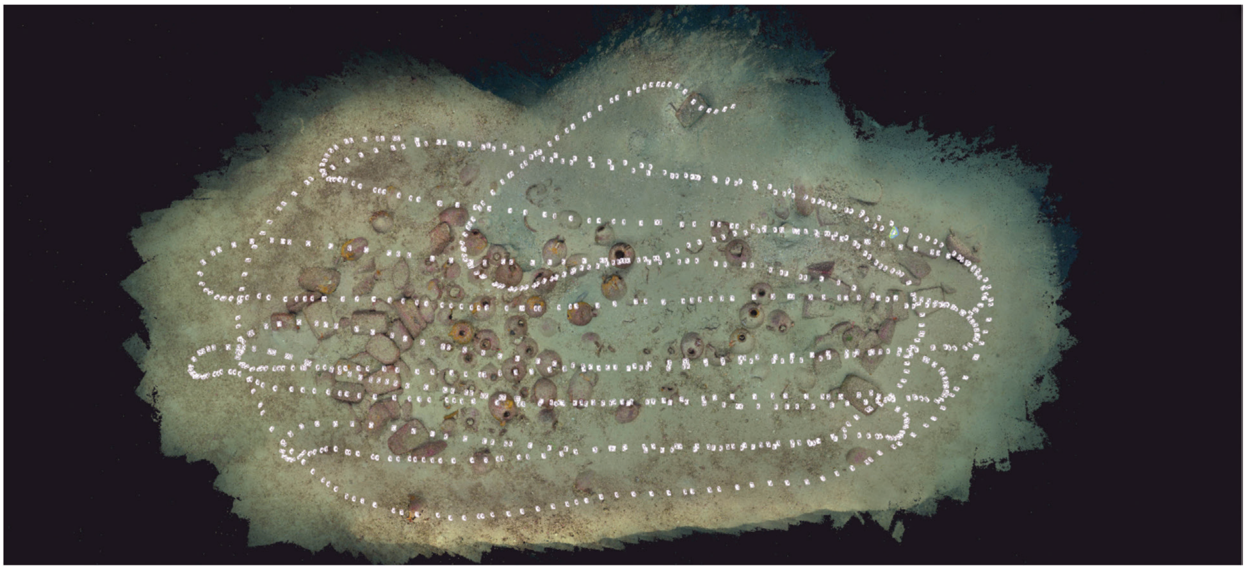

Fig 13: An example of swim lines undertaken by underwater cameraman for the acquisition of video footage for the production of the photogrammetric model

The use of HD video for primary data acquisition provides an extremely time-economical system to record deep-water sites without compromising the quality of acquired data. It also facilitated the production of quick, accurate and high-resolution photogrammetric models after every intervention on the site.

4.3. Object recovery

One of the main objectives of the 2016–17 seasons was the continued systematic recovery of objects that would contribute to a better understanding of the shipwreck. Objects chosen for recovery included: *(a)* typologies not recovered in 2014; *(b)* typologies similar to those recovered in 2014 (for comparative purposes); *(c)* a handstone; and *(d)* fragments that were clearly in secondary positions. A lifting basket was designed with netted sides, so as to minimise impacts on the objects during recovery (Fig 16). A lifting mechanism for the basket was controlled from the surface. The basket was lowered as close to the site as possible and subsequently moved into place by divers (Fig 16).

The sediment composition within which the shipwreck is situated is formed of a combination of very compacted sandy mud, shells, loose coral concretions and stones. Hand-fanning was used to remove sediments surrounding the objects, so that the objects could be extracted and transported by

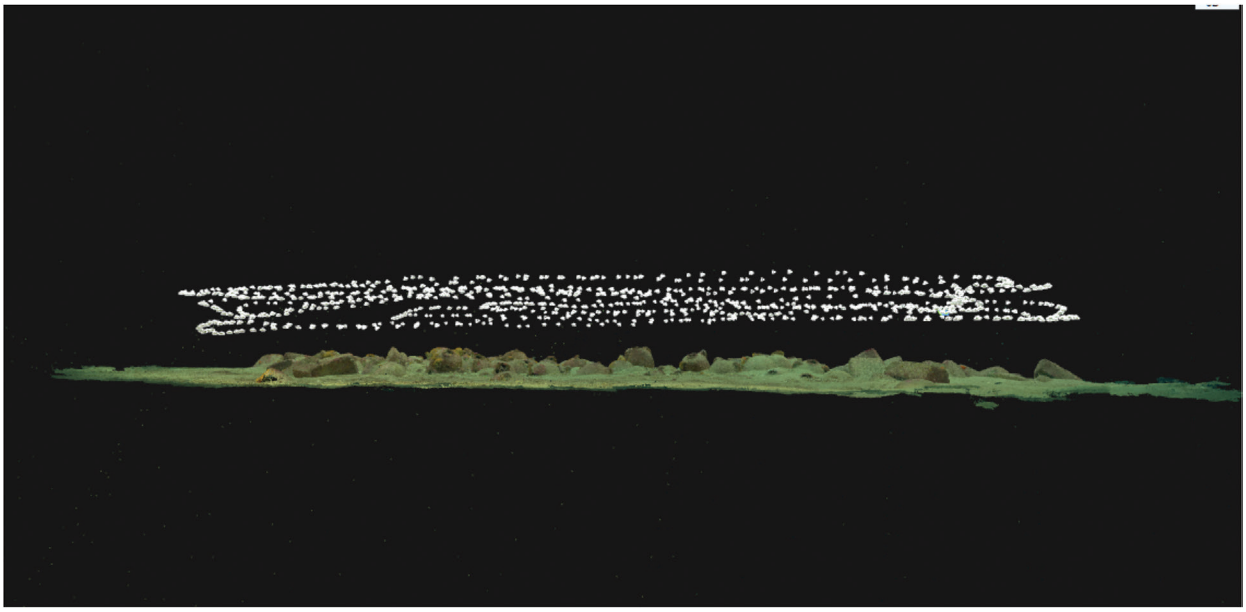

Fig 14: A different view of Fig 13 that illustrates the consistent height off the site maintained by cameraman during the data acquisition phase

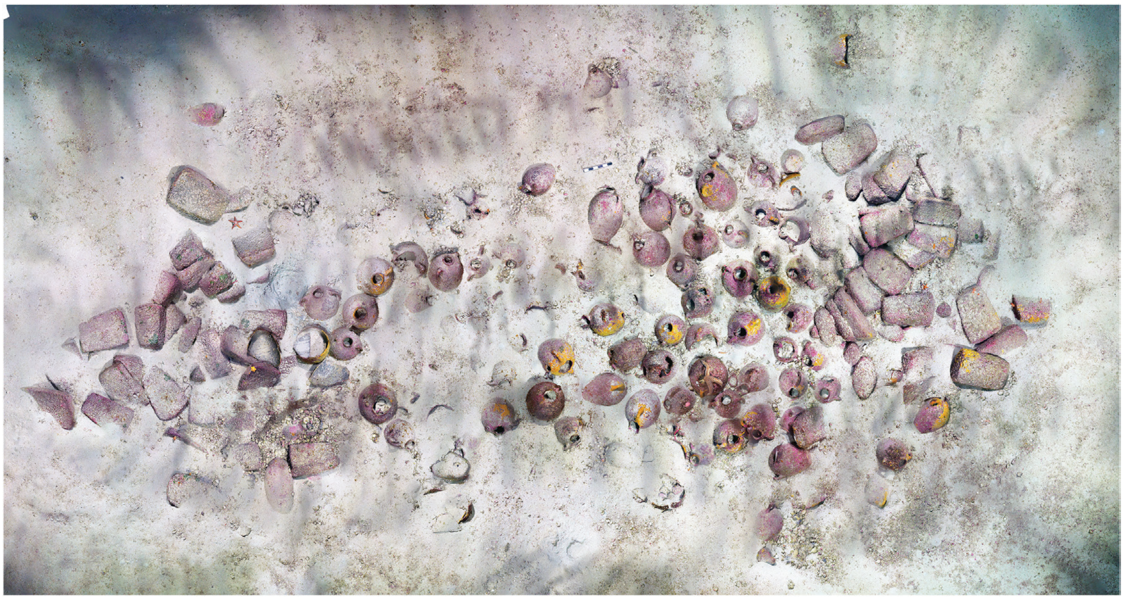

Fig 15: Orthophoto obtained from the 2016 photogrammetric survey

the divers to the lifting basket. As a safety precaution, the basket was raised at the end of diving operations with a swimmer on the surface to ensure the smooth transfer of the objects onto the vessel. A total of eight whole objects (seven ceramic and one stone) and three fragmented objects (all ceramic) were raised between 2016 and 2017 (see Table 2).

5. Discussion

Since the earliest discoveries of deep-water shipwrecks in the 1950s, there has been a steady increase in the quantity and frequency of projects carried out on deep-water archaeological sites throughout the world (Søreide, 2011). The Mediterranean has witnessed some revolutionary undertakings specifically aimed at studying ancient shipwrecks. Between 1989 and 2003 for example, the Woods Hole Oceanographic Institution (WHOI) conducted a series of studies on shipwrecks at a depth of 800 m at Skerki Bank in the central Mediterranean. The project was aimed at using submersibles deployed with state-of-the-art sensors and other equipment for in-depth recording of shipwrecks and object recovery (Ballard et al., 2000). Due to the extreme depths of these projects, all work was executed remotely without the intervention of divers. Other techniques, involving ROVs, were

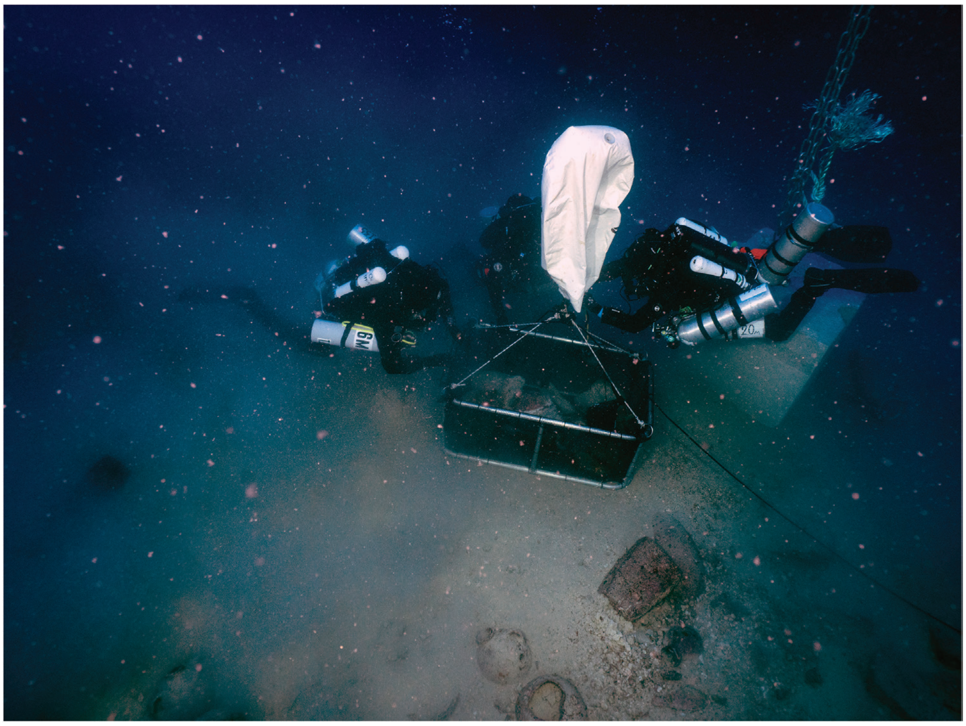

Fig 16: Divers in the process of recovering excavated objects (D. Gration)

Table 2: A list of objects recovered between 2014 and 2017

Object	Code	Typology	Year recovered	Comments
Amphora	A079	ZITA	2014	Contained some ceramic fragments inside
Amphora	A045	Ramon 2.1.1.1	2014	
Urn	C002	Unidentified	2014	Contained some ceramic fragments inside
Quern	M058	Saddle quern	2014	Base
Olla	A012	Unidentified	2016	
Amphora	A015	Ramon 2.1.1.1	2016	Large fragments making up an entire amphora
Handstone	M010	Saddle quern	2016	
Jug	C001	Phoenician aryballos	2016	
Amphora	A010	Ramon 2.1.1.1	2017	Large fragments making up an entire amphora
Amphora	A019	Ramon 2.1.1.1	2017	Large fragments making up an entire amphora
Amphora	A040	ZITA	2017	
Amphora	A070	ZITA	2017	
Amphora	A071	Greek type	2017	
Amphora	A074	ZITA	2017	
Amphora	A075	ZITA	2017	
Olla	A099	Unidentified	2017	Contained some ceramic fragments inside

successfully developed for deep-water excavations of a shipwreck from the 4th century AD situated in 90 m of water off the island of Levanzo, Sicily. Although reachable to CCR technical divers, the availability of a purpose-built research vessel and a specialised ROV enabled the project directors to work remotely during the two excavation seasons on this site (Royal and Tusa, 2012). Likewise, the Grand Ribaud F shipwreck was recorded and studied at a depth of 61 m using the combined efforts of a manned submersible and an ROV (Long and Delauze, 2000). What these and other deep-water archaeological projects have in common is that they were all serviced by large support vessels.

Other underwater projects at depths beyond 50 m, such as the excavation of the Ouest-Embiez 1 shipwreck in France, were executed on air with similarly limited bottom times to those of Xlendi

Table 3: Comparative dive parameters for the Antikythera and Xlendi projects (The Antikythera dive parameters were kindly supplied by Dr B Foley, one of the project directors.)

	Antikythera	Xlendi
Depth of main operations	51 m	110 m
Gas mix used (He/O_2)	16/40	8/70
Gradient factor		50/85
Bottom time	45 min	12 min
Run time	120 min	160 min
Maximum consecutive dive days	4	3
Bail out cylinders carried by divers	2 (other bail outs on ascent line)	4 (spare cylinder with 100 % O_2 at 6 m)

(Bernard et al., 2007). The Ouest-Embiez 1 excavation demonstrated that limitations on bottom time do not compromise scientific standards. Also of note is the fact that the investment of time and effort into the deep-water excavations at Ouest-Embiez 1 by divers produced valuable archaeological results (Fontaine and Foy, 2007). However, the only other project that is comparable to Xlendi is one currently underway on the Antikythera shipwreck.[†] CCR divers are working at depths of up to 51 m using a water dredge (powered by a submersible pump) to excavate small areas of the site. All operations are conducted from a relatively small dive platform – similar to that used in Xlendi in 2017. However, the depth of the Anikythera shipwreck permits longer bottom times, shorter run times and more repeat dives to maximum depth (see Table 3).

The initial seasons dedicated to the study of Xlendi provided the added value of 'preliminary data' to longer-term project planning. Combined sonar images, sub-bottom surveys and ROV material provided a data platform on which crucial decisions could be taken. First and foremost, data acquired between 2007 and 2008 helped identify the site as an archaic shipwreck and thus highlight its rarity and importance, pointing to a need for in-depth studies beyond what had already been achieved. This statement is made on the following basis:

1) **Rarity**: a recent study on Phoenician shipwrecks datable to 8th–6th century BC identified no more than 6 sites in the entire Mediterranean – 2 in ~400 m of water off Israel (Ballard et al., 2002), 3 in shallow waters of the Spanish coast and 1 located off France (Abdelhamid, 2015);
2) **Importance**: the well-preserved cargo that is currently visible can, if studied holistically, contribute to a much-needed and improved understanding of trade networks and exchange mechanisms of the Archaic Mediterranean (Gras, 1997).

Therefore, on the basis of rarity and importance, it was decided that any interventions after 2008 would also include the recovery of objects.

[†] Details of this project can be accessed via: https://antikythera.whoi.edu/

The intensive use of various technologies and techniques on this one particular site between 2007 and 2008 provided an opportunity to garner information that is proving to be indispensable to the current phases of the project. For example, the results from the sub-bottom survey, combined with photographic evidence, provide an informed sense of what to expect when full excavation gets underway. In turn, such knowledge will influence planning for post-excavation works such as first-aid and longer-term conservation, recording, sampling and storage. Additionally, the first photomosaic provided the basis on which objects could be quantified and assigned digital labels.

The 2014 season provided site-specific information for the use of a manned submersible and an ROV to methodically record the site to the highest scientific standard, as well as for the recovery of objects. Through the use of such tools, no divers were exposed to arduous technical decompression dives required to work at such depth. Moreover, working remotely gave the known benefit of additional time on the site – a manned submersible is limited to the duration of its batteries whereas an ROV may be used on a 24-hr basis.

There were two main disadvantages encountered when using such equipment. Firstly, there are the costs involved: manned submersibles and ROVs with certain capabilities can only be deployed from purpose-built vessels with specialist crews. These come at a daily cost that is usually prohibitive for archaeological projects whose limited funding do not normally permit long-term access to large survey vessels (Søreide, 2011). Secondly, direct human interaction with the archaeology of an underwater site facilitates a degree of acuity, dexterity and immediate decision-making that are, to date, sharper than those obtainable through the sole use of robotics (Broadwater, 2002).

The drive to find a diver-based solution was also cost driven, because a fully equipped research vessel may cost anything between 25 000 to 50 000 euros per day. An entire three-week diving mission (2017) cost a fraction of having a specialised vessel (with submersible and ROV) on site – the cost difference ratio between the 2014 and the 2017 seasons was of 10:1. Although very challenging, scientific diving can be executed safely at depth with meticulous planning and discipline (Kesling, 2016). Having direct contact with the site allowed the team to apply a more flexible approach when it came to site recording and object recovery. Moreover, certain details on particular objects became discernible and permitted re-interpretations based on comparisons between direct observations and past records. Admittedly, there were limitations to using divers on archaeological sites at such depths. These include: *(a)* the lack of trained archaeologists certified for CCR diving at depths beyond 50 m; *(b)* the difficulty of finding certified CCR divers with the predisposition to execute work to established scientific standards; *(c)* the limited amount of time divers can spend on the site itself; and *(d)* the taxing nature of repeat dives to 110 m.

6. Conclusion

At Xlendi, the first two seasons of diver deployment were approached with a degree of extra caution. This was the first time that an archaeological project has been carried out exclusively by divers at 110 m, thus making such a conservative approach justifiable. Besides the potential for additional archaeological knowledge and data to the corpus of information that will become available to researchers, it is also reasonable to assume that the continuation of this project will also contribute to the development of approaches, techniques and methodologies to be used by CCR divers on sites at depths of around 100 m. It is envisaged that over the coming years, equipment designed and developed specifically for this project will made available. These include a low-cost observation camera, an underwater laser scanner and a bespoke dredge that is able to function reliably in 13 atm. The combination of this equipment with knowledge garnered from the 2016–17 field seasons will facilitate the long-term and systematic excavation of the site.

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