Mar. Sci. Tech. Bull. (2022) 11(3): 331-342
e–ISSN: 2147–9666
info@masteb.com

dergipark.org.tr/en/pub/masteb
www.masteb.com
DOI: 10.33714/masteb.1144180

Marine Science and Technology Bulletin

RESEARCH ARTICLE

Mapping and recording of ancient shipwrecks by using marine remote sensing techniques: Case studies from Turkish coasts

Nilhan Kızıldağ[1*]

[1] *Dokuz Eylül University, Institute of Marine Sciences and Technology, Department of Marine Technology, Balçova, 35640, İzmir, Türkiye*

ARTICLE INFO

Article History:
Received: 18.07.2022
Received in revised form: 10.09.2022
Accepted: 13.09.2022
Available online: 20.09.2022

Keywords:
Ancient shipwrecks
Remotely operated vehicle
Side-scan sonar
Sub-bottom profiler
Underwater cultural heritage
Underwater photogrammetry

ABSTRACT

Within the context of the "Shipwreck Inventory Project of Turkey (SHIPT)," numerous acoustic remote sensing and photogrammetric surveys have been carried out along the coast of Turkey with the aim of detecting, mapping and documenting underwater cultural heritage. During the surveys, many ancient shipwreck sites have been discovered thanks to advanced technologies such as high-resolution side-scan sonar (SSS), sub-bottom profiler (SBP), and remotely operated vehicle (ROV). Once acoustic anomalies have been located, shipwreck sites have been verified by ROV and documented by a 3D photogrammetric survey. Analysis of the collected data confirmed that the survey design and data acquisition parameters are the most important criteria for obtaining the best quality image of the shipwrecks. Performing high-resolution remote sensing and photogrammetric survey for shipwrecks using optimal data collection techniques provides rapid results, decreasing time and budget and increasing the quantity of underwater cultural heritage. This paper discusses proper survey stages for the rapid, effective, and high quality detection and recording of shipwrecks using advanced technology. Acoustic images of shipwrecks comparing cargo, period, and form are also introduced in this paper, for the first time, which provides data on interpreting anomalies accurately for further exploration and monitoring surveys.

Please cite this paper as follows:

Kızıldağ, N. (2022). Mapping and recording of ancient shipwrecks by using marine remote sensing techniques: Case studies from Turkish coasts. *Marine Science and Technology Bulletin*, *11*(3), 331-342. https://doi.org/10.33714/masteb.1144180

* Corresponding author
E-mail address: nilhan.kizildag@deu.edu.tr (N. Kızıldağ)

Introduction

Underwater archaeological surveys carried out over the last 60 years demonstrate that the Turkish coasts are very rich in terms of underwater cultural heritage (Pulak, 1998; Ward & Ballard 2004; Bass, 2005; Royal, 2006; Brennan et al., 2012; Özdaş, 2010; Özdaş et al., 2012; Kızıldağ & Özdaş, 2021). Nevertheless, no systematic and long-term exploration had been performed until now, which covers Black Sea, Aegean Sea and Mediterranean Sea. The Shipwreck Inventory Project of Turkey (SHIPT) has been carrying out for years with a primary goal of documenting underwater cultural heritage off Turkish coasts.

Underwater cultural heritage (e.g., shipwrecks, settlement structures and artifacts) contains all traces of human existence having a cultural, historical or archaeological character which have been partially or totally under water (UNESCO, 2001, Article 1). Therefore, the documenting of shipwrecks of different ages and forms provides significant data on ancient shipbuilding, navigation, sea trade routes, sea battles, and transportation of materials. In addition to their cultural value, the wrecks also provide a habitat for the marine ecosystem as they form artificial reefs. Mapping of these resources provides great benefits for developing the Blue Economy.

A large number of shipwrecks, from the Bronze Age to the Ottoman Period, have been discovered and reported during several surveys carried out under SHIPT (Özdaş, 2009, 2010; 2022; Özdaş et al., 2012). Nevertheless, the shipwrecks found in shallow waters are mostly damaged by anchorage, illegal dives and fishing activities. After obtaining advanced remote sensing technology (e.g., SSS, SBP and ROV), SHIPT have focused on open-sea surveys, which allowed us to increase the quantity of the shipwreck sites; access the untouched shipwrecks in good-condition; and the rapid documentation of the sites before destroying.

Compared to conventional scuba diving methods, the use of remote sensing methods provides great advantages to underwater archaeological researches via the recording and monitoring of both shallow and deep water shipwreck sites in a rapid and cost-effective manner (Singh et al., 2000; Quinn et al., 2002; Ward & Ballard 2004; Delaporta et al., 2006; Bingham et al., 2010; Bates et al., 2011; Pacheco-Ruiz et al., 2019; Westley et al., 2019). However, during a marine survey, each manoeuvre of the survey vessel or visual inspection for verifying the acoustic anomalies increases the cost and time of the survey. Using optimum data acquisition techniques and interpreting data accurately are key factors to performing low-cost surveys and providing immediate and accurate results.

The image quality of side-scan sonar varies, depending on data acquisition parameters (frequency, range, etc.), ship velocity and limitations, towfish depth, equipment specifications and settings (resolution related to signal processing technology, transducer design, towfish stabilization, etc.), sea conditions (that affect pitch and roll motion of towfish and produce acoustic noise), features of the seafloor (e.g., sandy substrate, rocky outcrops, marine flora), orientation of the survey line relative to the target, and operator skills and experience (Bates et al., 2011). When detecting shipwrecks, setting survey operation configurations properly and obtaining positional information accurately are the key factors for side-scan sonar imaging. It is important to optimize the data collection parameters to avoid wasting time, causing extra effort, or increasing the costs.

The frequency and the range, as well as ship velocity, must be set according to possible dimensions of objects. Passing with slow speed over a feature provides better resolution in terms of getting more acoustic reflections. However, acquiring data with a high frequency and therefore narrow range (e.g., 50 m) increases the possibility of detecting the target. The sonar towfish altitude above the seafloor is also an important factor in recording a quality image. Getting the towfish closer to the seafloor increases the sweeping area and provides better resolution by reducing signal absorption and acoustic noise in the water column (Lurton, 2010). Since sea conditions affect the pitch and roll motion of sonar towfish, images of targets may be shown distorted. In windy weather, data often contains a great deal of noise, and this frequently causes the target to be hidden.

Once the shipwrecks are detected, the next step is to obtain a high quality optical record of the sites. Using photogrammetric techniques, a highly accurate site map can be built up and maximum information can be obtained (Drap et al., 2015). This allows to produce 1:1 scale photogrammetric models with 3D views of shipwreck sites and to identify the distribution area and quantity of the archaeological material. Another benefit of photogrammetry is to be able to monitor the wreck sites in terms of damage by making comparisons before and after conditions. In addition, underwater photogrammetry provides virtual access to the archaeological sites by both specialists and public (Drap et al., 2015).

This paper presents an effective procedure for underwater archaeological survey in order to (i) record and document the shipwreck sites in high quality, (ii) decrease the cost and time and (iii) increase the quantity of shipwreck. Proper survey stages were discussed for the rapid, effective, and high quality recording of the shipwrecks using advanced technology. Additionally, in this paper, for the first time, a comparison of acoustic images of shipwrecks, which have different cargo (e.g., amphora and stone) and are dated to different periods, were presented.

Material and Methods

As a part of SHIPT project, high-resolution remote sensing and photogrammetric data were collected along the coast of Çanakkale and Yalıkavak Peninsula in 2016 and 2018. In particular, Çanakkale has geologically strategic importance in terms of its location on ancient maritime route connecting the Mediterranean Sea with the Black Sea. Although many archaeological investigations have been carried out on land in Çanakkale during the last hundred years, underwater cultural heritage has remained undocumented. For this reason, the first systematic survey has been performed in Çanakkale's coastal waters by using the methods of (a) side-scan sonar (SSS) and (b) sub-bottom profiler (SBP) imaging for detection and documentation of shipwrecks; (c) remotely operated vehicle (ROV) and scuba diver inspection for visual verification and photogrammetric recording of wreck sites (Figure 1).

All data were integrated into the ArcGIS software, and a database was created which is called "Acoustic Database for Underwater Archaeological Sites of Turkey (ADAST)". It contains the sonar images, preliminary interpretation, depth, positional and operational information, underwater photos of targets, as well as marine environmental data (i.e., geological, geomorphological, biological and oceanographic data) of the archaeological sites. ADAST allows to us to classify, compare, and create maps with multiple layers of targets.

Side-Scan Sonar Imaging

During the side-scan sonar survey, multiple records of findings were acquired by using different configurations, which provided the opportunity to determine the best operational techniques for recording shipwrecks. A Klein 3000H model with a dual frequency of 445 kHz/900 kHz SSS was used for imaging seafloor. A low frequency of 445 kHz was used to explore a large-scale area, with the range varied between 100 m and 150 m per sides depending on the site, as the sonar was towed at an average speed of 3 knots. Line intervals were set at 160 m to provide overlap for the mosaic, while the sonar was run using a 100 m range with a swath of 200 m. After detecting and locating the targets, the frequency and the range were adjusted to 900 kHz and 50 m respectively and obtained high-quality images.

Different uses of SSS data acquisition parameters were compared in two sets of images for each wreck site in terms of frequency of the acoustic signal and range scale, to present their effect on the different wreck forms. The altitude of the towfish above the seafloor was approximately 10% of the range. Cable deployment was controlled with an Emce Clw model electrical winch equipped with 600 m armoured cable and a cable counter sheave. The positional data were provided by a JRC model differential global positioning system (DGPS) receiver.

Although target detection and recognition from side-scan data were mostly based on manual interpretation during data collection, all data were integrated into SonarWiz (Chesapeake Technology Inc) software for post-processing stage. Data were processed focusing on gain corrections to remove the variation in brightness. Automatic Gain Control (AGC) was applied to data in order to correct the differences in the amplitude of the signal and normalise the across-track gradient banding in the

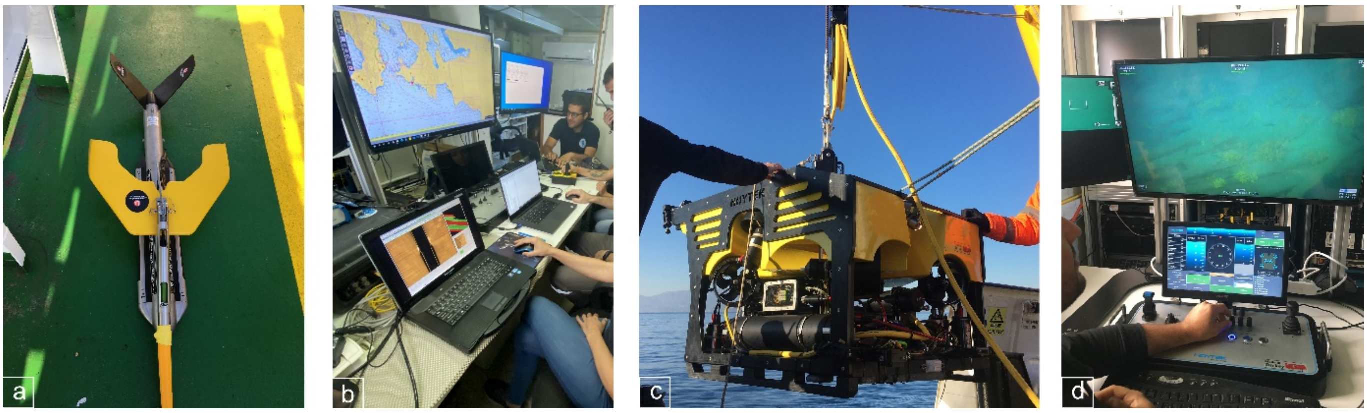

Figure 1. Marine remote sensing survey. (a) SSS towfish; (b) SSS control room; (c) ROV; (d) ROV control panel

imagery. Bottom-tracking corrections were applied and all lines were corrected for slant range to produce mosaic of the seafloor. Shadow lengths of the targets were measured in the target editor to estimate of object heights above the seafloor.

Sub-Bottom Profiler Imaging

Even though the primary goal was detecting and imaging the shipwrecks using side-scan sonar, the sub-bottom profiler imaging was integrated, both to eliminate non-artificial anomalies and to image the vertical profile of the subsurface beneath the shipwrecks. Integration of the sub-bottom profiler data can help in verifying the sonar targets. When a shipwreck is located among rocky outcrops, it can be difficult to distinguish whether the reflection derives from a wreck or a geological feature. On the basis of reflection geometry, the anomalies can be identified in the sub-bottom profiler data: while rocks extend into the deeper layers beneath the seafloor, wrecks generate a chaotic acoustic pattern and weak hyperbola-shaped reflections, forming an acoustically transparent zone underneath.

SBP systems were used to image below the seafloor. EdgeTech 3100-216 portable SBP with 2-16 kHz pulses and Bathy 2010 SyQwest Chirp SBP system with 9 transducers at a frequency of 3,5 kHz were operated. A transmit rate of 4 Hz was used during the survey. Wrecks, partially buried in sediment, require the use of high-resolution sub-bottom profilers to image the stratigraphy beneath the wrecks. Since high-resolution data is important for recognizing archaeological features, the recording speed was kept as low as possible, at a maximum of 3 knots.

Visual Inspection and Photogrammetry

Once targets were located and positions recorded, visual investigation was performed through ROV to identify acoustic anomalies. All targets were confirmed as shipwrecks on the first dive, thanks to the accuracy of the positional data and the software calculations of the sonar towfish location.

During the verification and photogrammetry operations, two ROVs were used. Hoytek 1000m model ROV equipped with BlueView Imaging Sonar (900 kHz) and Hoytek 200m model ROV equipped with Imagenex Imaging Sonar (900 kHz) were deployed. Applied Acoustics Easytrak Alpha model ultra-short baseline (USBL) was used for underwater acoustic positioning. Both ROVs were designed specifically for underwater archaeological surveys by equipping with manipulator, autopilot, HD and still cameras and lighting systems for photogrammetric imaging. The configuration of lights and cameras is crucial to obtain high-quality and clear images. In particular, the lighting is an important factor in photogrammetry. A well-designed lighting system allowed homogeneous exposure for each photo frame and consistency between images avoiding focusing on the particle. Four subsea LED lights (45,000 lumen) were mounted on our ROVs to ensure the optimum lighting.

ROV technology provided opportunity to generate photomosaics by taking thousands of photos on the wreck sites time and depth-independently, which improved quality of 3D models. The height of the ROV was kept at approximately 2 meters above the remains by using auto-altitude configuration. Minimum overlap of 50% between the images was provided for full coverage. The number of photos varied depending on the size of the site.

Using photogrammetric techniques, highly accurate site maps have been built up and maximum information has been obtained. 1:1 scale photogrammetric models with 3D views of shipwreck sites were produced and the distribution area and quantity of the archaeological material was identified. 3D models were generated using Agisoft Photoscan software. Thus, preliminary site maps of the shipwrecks were obtained using photogrammetry.

Results

Five shipwreck sites located on the western Turkish coast were presented in this paper (Table 1, Figure 2). The shipwreck sites were located at depths between 22 and 50 m, differing in terms of cargo, form, and age. The study area displays a mixed seafloor structure consisting of muddy and sandy sediments, various benthic habitats dominated by *Posidonia oceanica*.

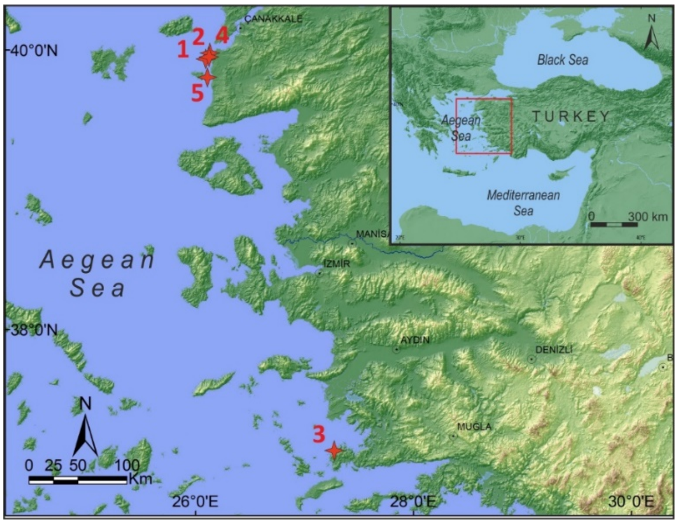

Figure 2. Location map of the shipwreck sites

Table 1. List of shipwreck sites located by acoustic remote sensing methods

Site Name	Cw	Date	Dm (m)	H (m)	Dp (m)	Ds (m)	Visible Artifacts	Condition
Wreck Site-1	Amphora cargo	4th-3rd c. BC	18 × 9	0.6	27	2300	100	Well-preserved
Wreck Site-2	Amphora cargo	5th-6th c. AD	14 × 9	0.6	25	1500	95	Well-preserved
Wreck Site-3	Amphora cargo	1st c. BC	20 × 8	1.4	50	620	350	Well-preserved
Wreck Site-4	Stone cargo	18th c. AD	19 × 8	1.5	22	1700	2000	Well-preserved
Wreck Site-5	Warship	18th-19th c. AD	38 × 20	1.6	25	2500		Heavily damaged

Note: Cw: Classification of wreck; Dm: Dimension; H: Height; Dp: Depth; Ds: Distance to shore. Artifact identification and dating by Harun Özdaş.

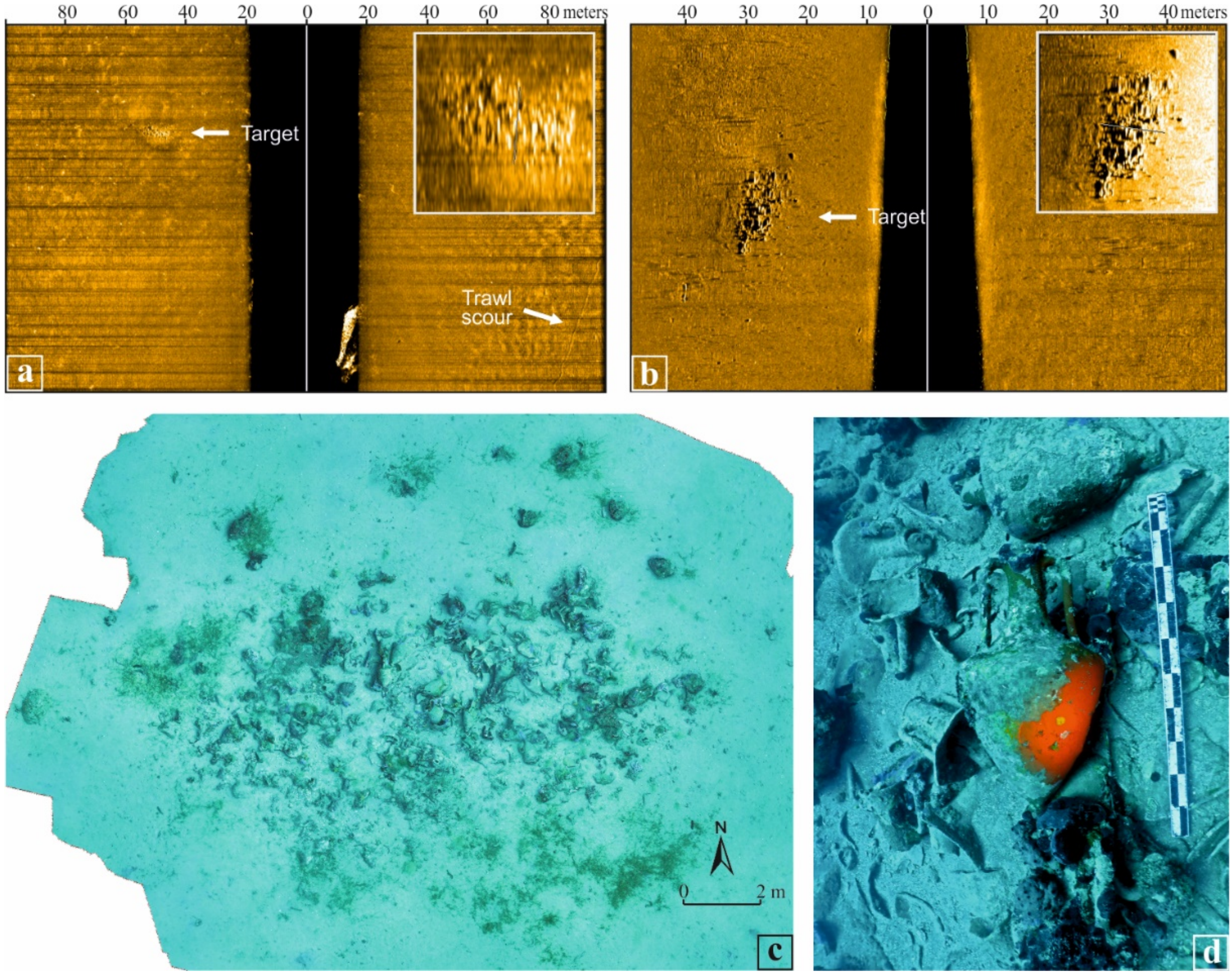

Figure 3. Wreck Site-1: (a) low frequency side-scan sonar image, (b) high frequency side-scan sonar image obtained using optimal data acquisition parameters, (c) photogrammetric image of wreck site showing the amphora pile, (d) an amphora among the cargo

Wreck Site-1

During the systematic side-scan sonar mapping off Çanakkale coasts, a target was detected at a depth of 27 m, at a fair distance from shore (2.3 km) on the flat and sandy seafloor, covering an area of 18 m × 9 m. (Figure 3, Table 1). An E-W-directed oval-shaped target was imaged transmitting a low frequency signal (445 kHz) at a range of 100 m (200 m swath range) and at a velocity of 3.5 knots (Figure 3a). A high-resolution image could be acquired at a high frequency of 900 kHz and 50 m range, at a velocity of 3 knots (Figure 3b). This remarkable target clearly corresponded to the shape of a shipwreck.

The visual inspection verified the presence of an amphora pile, which represents the cargo of a ship dated to the early Hellenistic period. The detailed study of the photogrammetry allowed to estimate the total number of amphorae visible on the seafloor. Over 100 amphorae were defined, largely in good condition, most of them on the surface and some partially buried in the sediment (Figure 3c, d).

Wreck Site-2

The second sonar target was detected 1.5 km off the coast of Çanakkale, at a depth of 25 m, with a frequency of 445 kHz and a range of 150 m (Figure 4a, Table 1). Setting the frequency at 900 kHz and the range at 50 m, a clear image of the target was obtained, even though the velocity of the ship was kept to a minimum 3.6 knots due to the strong current (Figure 4b). Based on the shape, dimension, and the acoustic signature, the sonar image was interpreted with each single reflection most likely deriving from a single amphora. In addition, bright reflections from the surrounding seafloor of the target may indicate a scour pit formed by the bottom currents around a possible shipwreck.

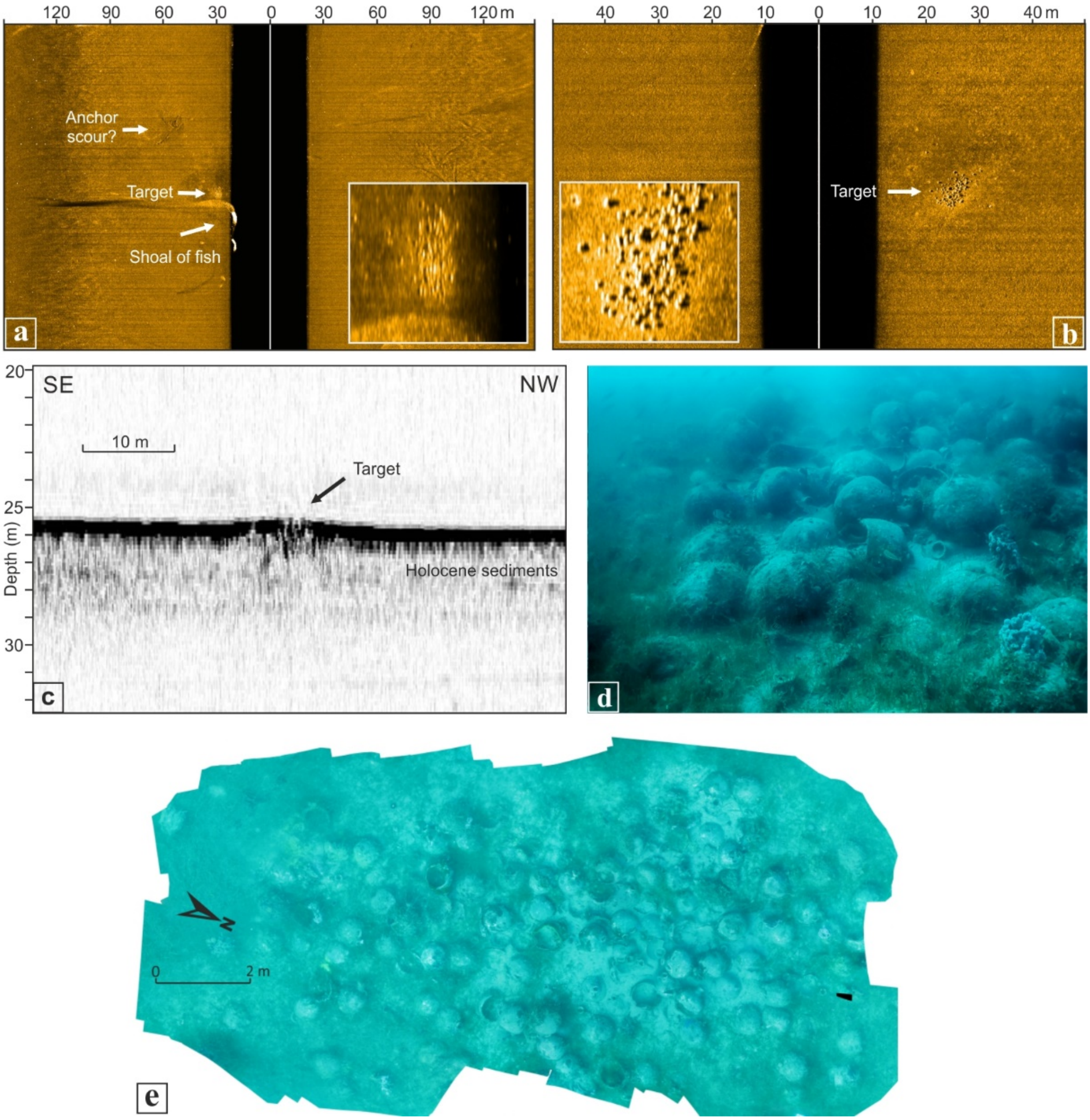

Figure 4. Wreck Site-2: (a) low frequency side-scan sonar image of the target that is partly covered by a shoal of fish, (b) high frequency side-scan sonar image, (c) chirp sub-bottom seismic profile over the shipwreck displaying the chaotic reflections underneath and general stratigraphical structure. The site is underlain by at least 3-4 m of Holocene sediments (d) amphora cargo, (e) photogrammetric image

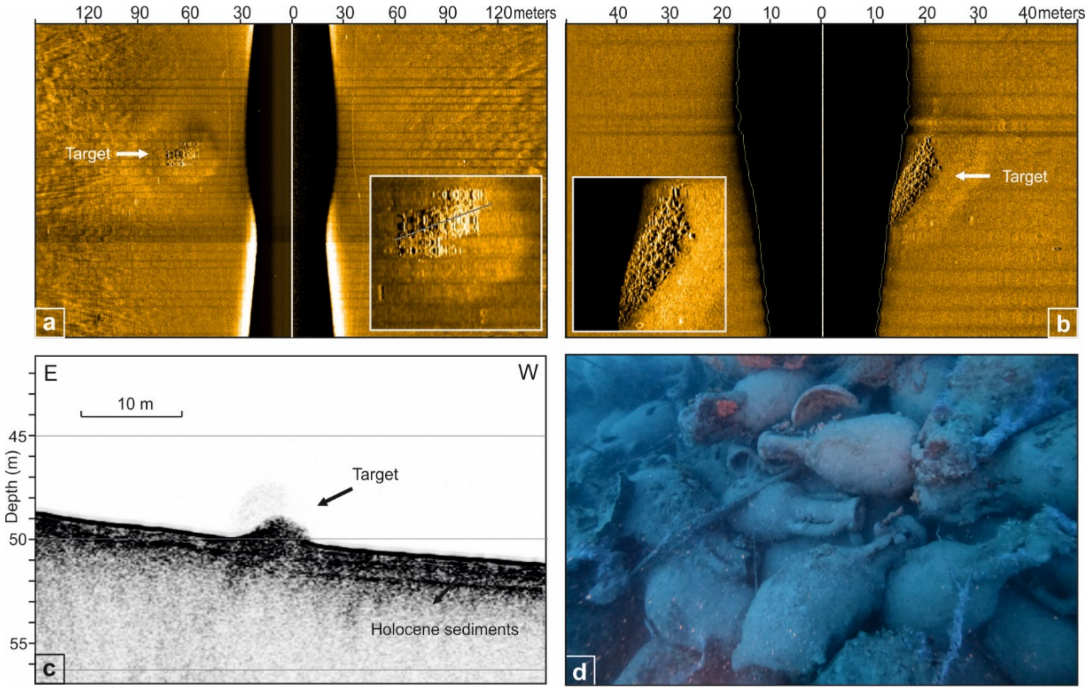

Figure 5. Wreck Site-3: (a) low frequency side-scan sonar image, (b) high frequency side-scan sonar image, (c) chirp sub-bottom seismic profile over the shipwreck displaying the height of the mound and general stratigraphical structure, (d) amphora cargo

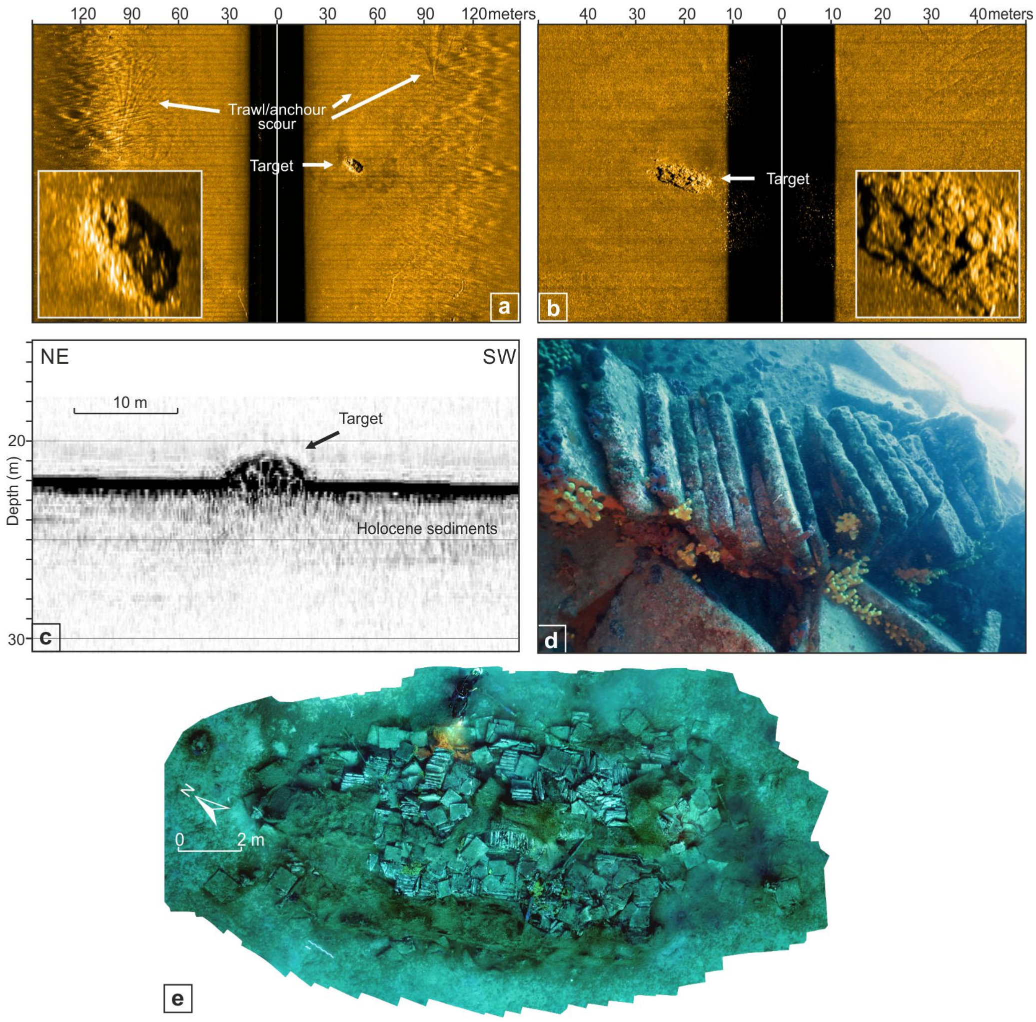

Figure 6. Wreck Site-4: (a) low frequency side-scan sonar image, (b) high frequency side-scan sonar image, (c) chirp sub-bottom seismic profile over the shipwreck displaying the height of the mound and general stratigraphical structure, (d) a stone pile from cargo, (e) photogrammetric image

Sub-bottom profiler data assisted with a more precise interpretation: the anomaly was compatible with an artificial feature (Figure 4c). A transparent zone appeared under the target and chaotic reflections were observed. Data indicated that the seafloor topography is generally flat. Throughout the profile, weak parallel acoustic reflectors were observed in the sub-surface underneath the Holocene sediments.

The visual inspection confirmed that the oval-shaped target is consistent with a shipwreck, which is dated to Late Roman period. The photogrammetric study provided information on the amphora distribution and condition, as well as the total number of visible artifacts (Figure 4e). The cargo is scattered in an area 14 m long and 9 m wide, consists of at least 100 Late Roman 2 (LR2) amphorae, which are mostly in good-condition (Figure 4e). Only one amphora layer with a height of the 0.6 m was visible on the seabed, however at least one more layer is buried in the sediment (Figure 4e). Marine flora growth can be observed over the remains, densely covering the amphorae.

Wreck Site-3

An amphora shipwreck close to Yalıkavak, Bodrum, was imaged by SSS, which was documented by Institute of Nautical Archaeology in 1990s (Figure 5a, b, Table 1). The NE-SW-directed shipwreck covers an area of 20 m × 8 m, at a depth of 50 m. The oval-shaped target lies on a flat and sandy seafloor.

SBP imaging helped us to determine the height of the wreck to be at least 1.4 m (Figure 5c). The stratigraphy under the wreck was interpreted as a 1-2 m thick layer of Holocene sediment overlying a relatively strong high-amplitude parallel reflector.

ROV inspection verified that well-preserved shipwreck consists of mostly intact more than 350 Lamboglia 2 type amphoras, dated to 1st century BC (Figure 5d). The absence of damage must be associated with its location in a modern harbour that protected from illegal trawling and diving activities.

Wreck Site-4

During the side-scan sonar survey another target was detected 1.7 km north of the Site 1 and 2.0 km offshore, at a depth of 22 m (Figure 6, Table 1). The target emerged as a rectangular bright reflection in the first image, at a frequency of 445 kHz and a range of 150 m (Figure 6a). A more detailed image was obtained by one more pass over the target at a high frequency and a 60 m range (Figure 6b). The acoustic signature was slightly different from the signatures produced by wreck sites 1-3. The minimum survey speed could be 3.5 knots due to strong wind and current that often prevented steering the boat on the survey line. The target covers an area 19 m long and 8 m wide.

The sub-bottom profiler record displayed a different shape and acoustic over the flat seafloor (Figure 6c). The target represents a distinctive mound shape with a height of at least 1.5 m, underlain by sediment that is several meters thick. Some continuous-to-discontinuous weak sub-bottom reflectors were observed.

Visual inspection confirmed that it was a well-preserved cargo consisting of a large pile of thin stones. Through the production of a photomosaic, more than 2000 concreted stones were visible (Figure 6d, e). The flat ashlar stones have a maximum length of 80 cm, width of 80 cm, and thickness of 5 cm. In addition to the main cargo, pottery fragments, metal rigging, and a number of iron nails were observed. Some wooden components of the hull can be seen but are mostly buried. A sample was taken from the planking for radiocarbon analysis. The results suggest with 95.4% probability that the ship was built at the end of the 18th century AD. A large portion of the wreck is covered by fishing-net with dense marine growth, which makes investigation difficult. Thanks to photogrammetric survey a 3D image could be obtained, which resulting from the alignment of more than 900 images (Figure 6e).

A number of trawling scars were recorded with side-scan sonar on the surrounding seafloor, which indicate intensive fishing activity in the region.

Wreck Site-5

Another shipwreck was imaged near Bozcaada, 2.5 km offshore at a depth of 25 m. This distinctive target appeared oval-shaped, corresponding to a ship form, lying in a flat, sandy seafloor scattering within an area of approximately 38 m x 20 m (Figure 7, Table 1). A deep scour trail was observed through the side-scan sonar records, passing over the target, which caused serious damage on the east side.

On the sub-bottom profiler record, an acoustic gap was observed in the underlying stratigraphic layer, which was likely caused by a reflected or absorbed acoustic signal due to a denser artificial feature (Figure 7c). The height of the target has been determined to be at least 1.6 m. The general stratigraphy inferred from the sub-bottom data was interpreted as a 3.5-4 m thick layer of Holocene sediment overlying a relatively strong high-amplitude parallel reflector.

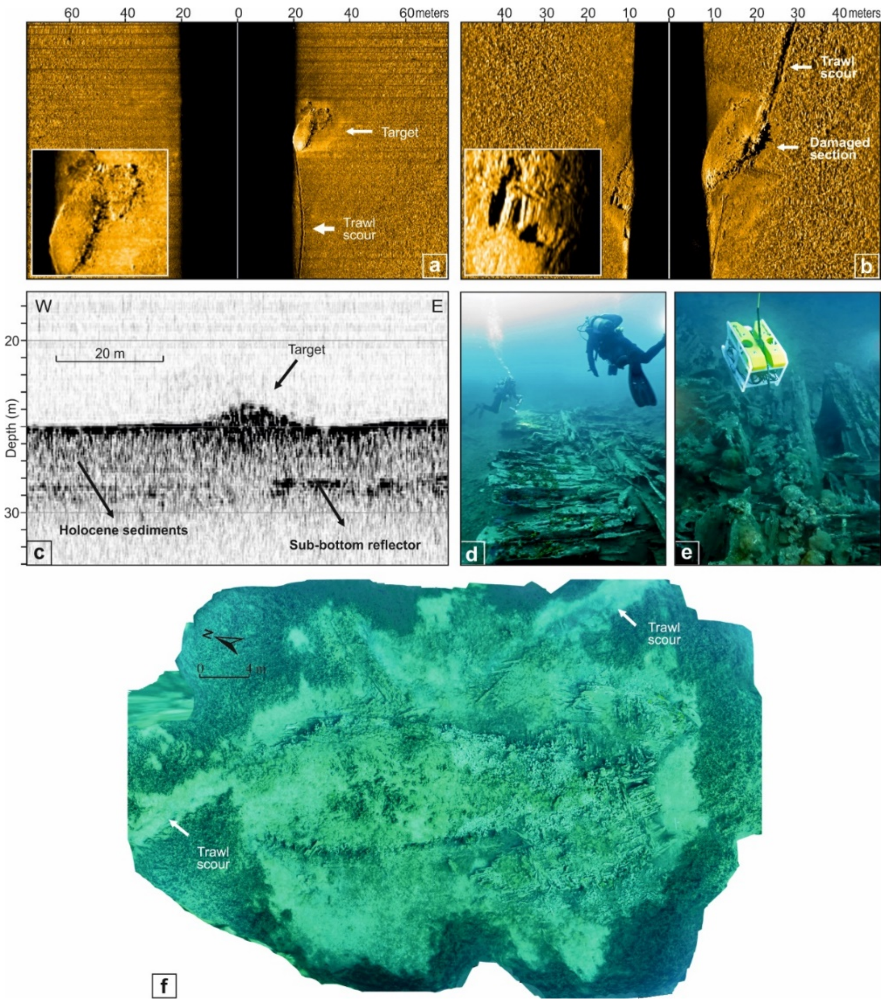

Figure 7. Wreck Site-5: (a) low frequency side-scan sonar image of target that lies on sandy seafloor surrounded by *Posidonia oceanica*, (b) high frequency side-scan sonar image displaying deep trawl scour in detail, (c) chirp sub-bottom seismic profile over the shipwreck displaying the acoustic gap and general stratigraphical structure, (d) underwater photo of the hull component, (e) ROV operation on the wreck site, (f) photogrammetric image

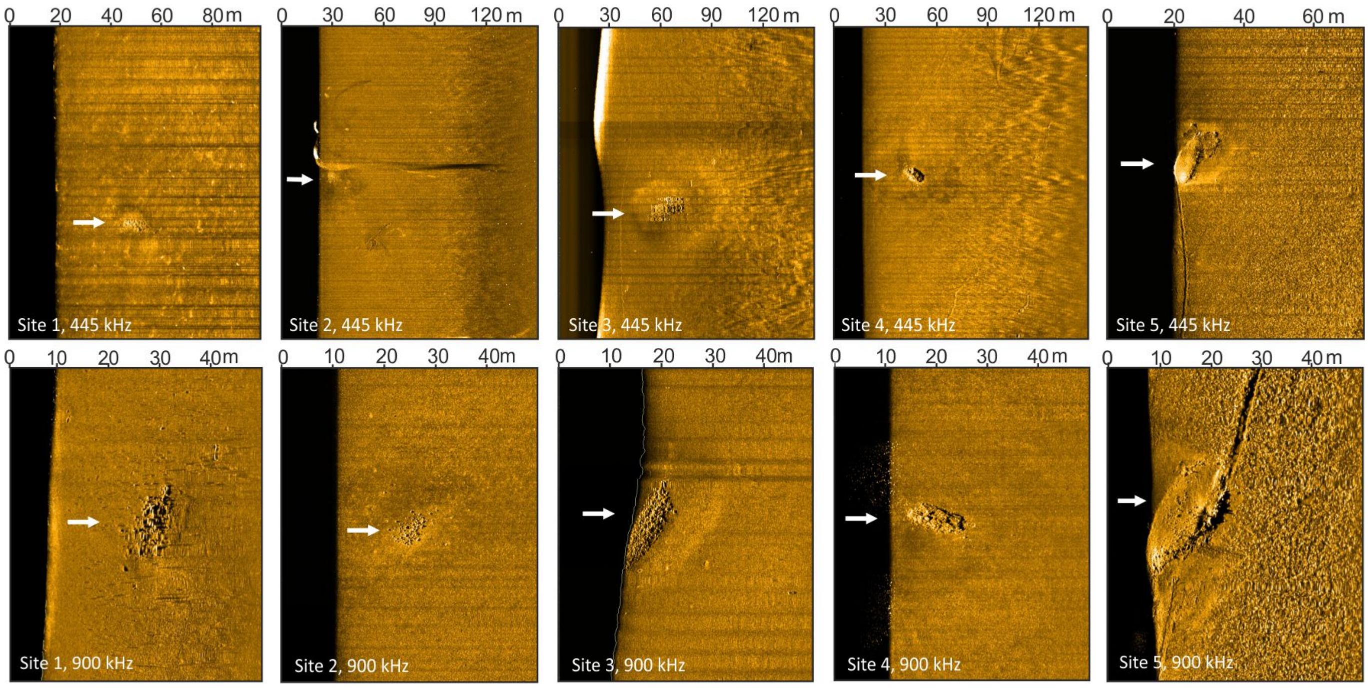

Figure 8. Comparative side-scan sonar images of shipwrecks (upper line displays low frequency images and lower line displays high frequency images)

The target was visually investigated by both divers and ROV and interpreted to be a warship from Ottoman period (Figure 7d, e). Partially-buried and heavily damaged hull timbers were observed. The wooden elements were in poor-condition and covered by marine growth, which made it difficult to identify their function. ROV survey provided a detailed photogrammetric model of the shipwreck, which consists of 1430 photographs (Figure 7f).

Discussion

In this paper, an effective procedure was presented that streamlines optimal remote sensing survey methods to detect underwater archaeological sites and obtain high-quality images of their current conditions. Remote sensing methods provide a lot of advantages that extend the survey area and time when compared with conventional scuba diving documentation. Determining the optimal survey design and defining the proper data acquisition parameters decreases the cost and time and increases the quantity of shipwreck that can be surveyed, at the same time providing high-quality data. Since deciding which targets require visual inspection is critical, as mistakes may result in extra effort, the capability and experience of the operator is also significant in the detection of shipwrecks and the acquisition of high-quality data.

Side-scan sonar surveys carried out along the coast of Turkish coasts have revealed some considerations when imaging the shipwreck sites. For instance, since biodiversity at the wreck sites is high, one must take into consideration that the remains may be covered by groups of fish. Moreover, the orientation of the survey line relative to the target also has an effect on obtaining a quality image. Furthermore, when an acoustic positioning system (ultra-short base line, USBL) is lacking, the velocity and the direction of the current should always be taken into consideration. In areas with currents, towfish may drift to the starboard or port side of the ship, not in line with the ship. In such areas, running parallel with the direction of the current makes it easier to accurately locate the position of the target, and therefore reduces the need for visual inspection. Setting the range scale and the run direction according to the target, velocity, and altitude of the towfish are important factors in acquiring maximum high-resolution data. In summary, data acquisition strategy and operator experience in the interpretation of anomalies are crucial components to obtaining optimal archaeological results rapidly and cost-effectively.

The integration of sub-bottom profiler and side scan sonar data verifies that a sub-bottom profiler can contribute to the elimination of non-artificial targets. This technique also provides information about geological structures and sedimentological data at the shipwreck site. In this study, sub-bottom records indicated that the region was affected primarily by a high amount of sediment accumulation, which would also affect the shipwreck sites.

ROV survey confirmed that photogrammetric imaging is rapid and accurate method for documenting of shipwreck sites when ROV is specially designed to generate photomosaics. A scuba diver can only work on the shipwreck less than 1 hour per day, while ROV can obtain images from the site without time constrains. Both recording hundreds of photos and using autopilot navigation of ROV instead of diver-operated record allowed to produce high-accuracy 3D models of the sites.

The results also verify the benefit of high-resolution side-scan sonar imaging, when properly performed, to identify and quantify damage to shipwreck sites. Side-scan sonar allowed us to image the trail of trawling nets both on the shipwreck and in its vicinity.

The comparative images of five ancient shipwrecks in terms of the variety of ships' cargo, age, and form are presented in this paper, which provide information for further sonar surveys aiming to detect shipwrecks. Four shipwrecks were cargo ships that carried amphorae and stone, dated to the early Hellenistic period (4th to early 3rd century BC, Site 1) (Prummel, 2003); to the Roman period (1st century BC, Site 3) (Boersma et al., 1986); to the late Roman period (5th-6th century AD, Site 2) (Opait, 2004); and to the Ottoman period (18th century AD, Site 4); while the other one was a warship from Ottoman period (18th-19th century AD, Site 5) (Bingeman et al., 2000; Zorlu 2008), which had wooden hull components relatively well preserved. Thus, we have the opportunity to compare the side-scan sonar images of the shipwrecks in terms of (i) cargo remains vs. wood remains; (ii) amphora cargo vs. stone cargo; (iii) early Hellenistic period vs. late Roman period. Sonar contacts of wrecks consisting of a one-layer amphora pile show similarities in terms of their shape and dimension, reflecting very similar acoustic characteristics (i.e., weak backscatter) (Figure 8).

The stone-carrying shipwreck reflects a different image from the others, due to its compact structure. Target 5 could easily be recognized as possible shipwreck, unlike the others, due to its relatively well-preserved shape, dimensions, and distinctive shadow. Varying sonar images compiled from different shipwrecks have the potential to provide data that will allow researchers to recognize anomalies in further surveys.

The sonar images and photomosaics of Site 1 and Site 2 demonstrate that only one amphora layer in each shipwreck remained visible on seafloor, even though Site 1 is a thousand years older than Site 2. This can be explained by oceanographic events and the geological environment. In general, a scour effect is observed in shipwreck sites, formed by bottom currents (Ballard et al., 2002; Quinn, 2006). This effect may give rise to the top layer being exposed instead of being completely buried.

Conclusion

The results have demonstrated that when proper survey strategy and equipment configuration are designed, high-resolution remote sensing survey is quite useful to rapidly and cost-effectively locate and record underwater cultural heritage. In particular, the critical techniques necessary for optimal side-scan sonar data acquisition in order to both explore potential archaeological sites and obtain high-quality images for the evaluation of the current conditions of the shipwrecks were described in detail in this study. This effective survey procedure and the comparative acoustic images can also provide a basis for further underwater archaeological investigations to be designed to locate, record, and monitor underwater cultural heritage.

This study emphasizes the necessity of rapid documentation and therefore the use of advanced technology, with effective survey design achieved by using proper equipment and data acquisition parameters, as well as careful interpretation. The sonar survey results demonstrate that the procedure for optimal data acquisition and analysis should be well understood by researchers, in order to discern potential shipwrecks from among other geological features on the seafloor. This increases the quantity of underwater cultural heritage that can be surveyed and reduces the time and budget of survey.

Acknowledgements

Data were obtained from the database of SHIPT project, which is supported by the Republic of Turkey's Presidency of Strategy and Budget (Project no. 2014H040080). Permission for the survey was granted by the Republic of Turkey's Ministry of Culture and Tourism. The author would like to give special thanks to the Harun Özdaş, director of SHIPT project. Thanks also to the representative of the Ministry, Hüseyin Vural, Emre Savaş and İhsan Tercan; team members, İrfan Yıldız, Samet Harmandar, Orhan Atkın, Özkan Özel and the other members who helped with data collection; and, also to Captain Mustafa Cengiz and the crew of *R/V K. Piri Reis* and *STS Bodrum* for their contributions during field work.

Compliance With Ethical Standards

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

References

Ballard, R. D., Lawrence, E., Stager, D. M., Yoerger, D., Mindell, D., Whitcomb, L. L., Singh, H., & Piechota, D. (2002). Iron Age shipwrecks in deep water off Ashkelon, Israel. *American Journal of Archaeology, 106*(2), 151–168.

Bass, G. F. (Ed.) (2005). *Beneath the seven seas: Adventures with the Institute of Nautical Archaeology*. Thames & Hudson.

Bates, C. R., Lawrence, M., Dean, M., & Robertson, P. (2011). Geophysical methods for wreck-site monitoring: The rapid archaeological site surveying and evaluation (RASSE) programme. *International Journal of Nautical Archaeology, 40*(2), 404-416. https://doi.org/10.1111/j.1095-9270.2010.00298.x

Bingeman, J. N., Bethel, J. P., Goodwin, P., & Mack, A. T. (2000). Copper and other sheathing in the Royal Navy. *International Journal of Nautical Archaeology, 29*(2), 218-229. https://doi.org/10.1111/j.1095-9270.2000.tb01453.x

Bingham, B., Foley, B., Singh, H., Camilli, R., DellaPorta, K., Eustice, R., Mallios, A., Mindell, D., Roman, C., & Sakellariou, D. (2010). Robotic tools for deep water archaeology: Surveying an ancient shipwreck with an autonomous underwater vehicle. *Journal of Field Robotics, 27*(6), 702–711. https://doi.org/10.1002/rob.20350

Boersma, J., Yntema, D., & van der Werff, J. (1986). Excavations in the House of the Porch (V. ii. 4–5) at Ostia. *BABESCH - Annual Papers on Mediterranean Archaeology, 61*, 77-138. https://doi.org/10.2143/BAB.61.0.2012598

Brennan, M. L., Ballard, R. D., Roman, C., Bell, K. L., Buxton, B., Coleman, D. F.,Inglis, G., Köyğasıoğlu, O., & Turanlı, T. (2012). Evaluation of the modern submarine landscape off southwestern Turkey through the documentation of ancient shipwreck sites. *Continental*

Shelf Research, 43, 55-70. https://doi.org/10.1016/j.csr.2012.04.017

Delaporta, K., Jasinski, M. E., & Søreide, F. (2006). The Greek-Norwegian deep-water archaeological survey. *International Journal of Nautical Archaeology, 35*(1), 79-87. https://doi.org/10.1111/j.1095-9270.2006.00090.x

Drap, P., Merad, D., Hijazi, B., Gaoua, L., Nawaf, M. M., Saccone, M., Chemisky, B., Seinturier, J., Sourisseau, J. -C., Gambin, T., & Castro, F. (2015). Underwater photogrammetry and object modeling: A case study of Xlendi Wreck in Malta. *Sensors, 15*(12), 30351-30384. https://doi.org/10.3390/s151229802

Kızıldağ, N., & Özdaş, H. (2021). Relative sea-level changes along the Fethiye coast (SW Turkey) based on recent archaeological data. *Geoarchaeology, 36*(3), 474-489. https://doi.org/10.1002/gea.21841

Lurton, X. (2010). *An introduction to underwater acoustics: Principles and applications.* Springer Science & Business Media.

Opait, A. (2004). The eastern Mediterranean amphorae in the province of Scythia, pp. 293–308. In: Eiring, J., & Lund, J. (Eds.), *Transport amphorae and trade in the eastern Mediterranean: Acts of the international colloquium at the Danish Institute at Athens.* Aarhus University Press.

Özdaş, H. (2009). Ege Bölgesi sualtı araştırması 2007 yılı çalışmaları. *Araştırma Sonuçları Toplantısı, 26,* 249-258.

Özdaş, H. (2010). Ege-Akdeniz Bölgesi sualtı araştırması 2008 yılı çalışmaları. *Araştırma Sonuçları Toplantısı, 27,* 433-452.

Özdaş, H. (2022). *Karaburun Roma Dönemi Rodos Batığı: Ön inceleme sonuçları* [Karaburun Roman Period Rhodian Shipwreck: Preliminary results]. *Türk Arkeoloji ve Etnografya Dergisi, 83,* 11-31.

Özdaş, H., Kızıldağ, N., & Okan, E. (2012). Ege-Akdeniz bölgesi sualtı araştırması 2010 yılı çalışmaları. *Araştırma Sonuçları Toplantısı, 29*, 267-280.

Pacheco-Ruiz, R., Adams, J., Pedrotti, F., Grant, M., Holmlund, J., & Bailey, C. (2019). Deep sea archaeological survey in the Black Sea–Robotic documentation of 2,500 years of human seafaring. *Deep Sea Research Part I: Oceanographic Research Papers, 152*, 103087. https://doi.org/10.1016/j.dsr.2019.103087

Prummel, W. (2003). Animal remains from the Hellenistic town of New Halos in the Almirós plain, Thessaly. In: Kotjabopoulou, E., Hamilakis, Y., Halstead, P., Gamble, C., & Elefanti, P. (Eds.), *Zooarchaeology in Greece: Recent advances* (pp. 153-159). British School at Athens.

Pulak, C. (1998). 1996 Sualtı araştırması. *Araştırma Sonuçları Toplantısı, 15*(1), 307–322.

Quinn, R. (2006). The role of scour in shipwreck site formation processes and the preservation of wreck-associated scour signatures in the sedimentary record – evidence from seabed and sub-surface data. *Journal of Archaeological Science, 33*(10), 1419-1432. https://doi.org/10.1016/j.jas.2006.01.011

Quinn, R., Breen, C., Forsythe, W., Barton, K., Rooney, S., & O'Hara, D. (2002). Integrated geophysical surveys of the French Frigate *La Surveillante* (1797), Bantry Bay, Co. Cork, Ireland. *Journal of Archaeological Science, 29*(4), 413-422. https://doi.org/10.1006/jasc.2002.0732

Royal, J. (2006). The 2005 remote-sensing survey of the south-eastern Bozburun Peninsula, Turkey: Shipwreck discoveries and their analyses. *International Journal of Nautical Archaeology, 35*(2), 195–217. https://doi.org/10.1111/j.1095-9270.2006.00112.x

Singh, H., Adams, J., Mindell, D., & Foley, B. (2000). Imaging underwater for archaeology. *Journal of Field Archaeology, 27*(3), 319-328. https://doi.org/10.2307/530446

UNESCO. (2001). *Convention on the Protection of the Underwater Cultural Heritage 2001.* Retrieved on March 2022, from http://portal.unesco.org/en/ev.php-URL_ID=13520&URL_DO=DO_TOPIC&URL_SECTION=201.html

Ward, C., & Ballard, R. D. (2004). Deep-water archaeological survey in the Black Sea: 2000 season. *International Journal of Nautical Archaeology, 33*(1), 2-13. https://doi.org/10.1111/j.1095-9270.2004.00002.x

Westley, K., Plets, R., Quinn, R., McGonigle, C., Sacchetti, F., Dale, M., McNeary, R., & Clements, A. (2019). Optimising protocols for high-definition imaging of historic shipwrecks using multibeam echosounder. *Archaeological and Anthropological Sciences, 11*(7), 3629-3645. https://doi.org/10.1007/s12520-019-00831-6

Zorlu, T. (2008). *Innovation and Empire in Turkey: Sultan Selim III and the modernisation of the Ottoman navy.* IB Tauris Academic Studies.