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Searching for Ancient Shipwrecks in the Aegean Sea: the Discovery of Chios and Kythnos Hellenistic Wrecks with the Use of Marine Geological-Geophysical Methods

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This paper presents the results of two deep-water archaeological surveys recently conducted in the Aegean Sea, and the advantages of using conventional marine geological techniques in deep-water archaeology. Two Hellenistic wrecks were discovered: one in the Chios-Oinousses strait at 70 m, was a concentration of over 400 amphoras in a 1.5-m-high, high-backscattering, morphological high; the second, west of Kythnos island, at 495 m, consisted of a few amphoras scattered in a 20 × 20-m-wide area. Side-scan sonar was integrated with high-resolution sub-bottom profiling, and the integration of the two data-sets proved to contribute significantly to realistic interpretation of the sonar targets.

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Key words: side-scan sonar, sub-bottom profiling, geological interpretation, ancient wrecks, amphora concentration, sedimentation rate.

Evidence of sailing activity and maritime transportation in the Aegean Sea dates back to at least the Mesolithic or Neolithic Period (10,000–7000 BC), as indicated by the discovery of obsidian from Milos island, Cyclades Archipelago, in Frachthi cave, Argolis, NE Peloponese, and by the first traces of island colonization (McGrail, 2001). Maritime transportation subsequently grew tremendously and became very important for trade activity and product exchange between the main cultural centres in ancient (Classical, Hellenistic, Roman, Byzantine) times (Agouridis, 1997). In the course of time a vast number of vessels have plied the Aegean Sea conveying goods, people and ideas, and it seems reasonable to assume that the frequency of maritime accidents increased in parallel with the growth of maritime activity. The large number of wrecks of various periods discovered to date all over the Aegean Sea verifies this hypothesis.

Many shipwrecks were discovered by divers at relatively shallow depths during the 19th and 20th century. Growing trawling activity at depths up to 600–700 m has very frequently resulted in the recovery of ancient artefacts during the last decades. It is often the case that amphoras and pottery are being caught in the fishing nets of trawls all over the Aegean. Some of them have been delivered to the Ephorate of Underwater Antiquities at Athens, while others not. Apart from amphoras, statues or other objects of high archaeological value have been retrieved from the sea-bed and delivered to the Ephorate. The majority of the known bronze statues have been discovered by fishermen while trawling or sponge-diving.

This fact led the Ephorate of Underwater Antiquities (EUA) of the Greek Ministry of Culture and the Hellenic Centre for Marine Research (HCMR) to join their efforts towards mapping of the Aegean sea-floor, aiming at the discovery of the remnants of our ancient nautical heritage. The collaboration started in 2000 and has resulted to date in the discovery of tens of Classical, Hellenistic, Roman, Byzantine and Post-Byzantine shipwrecks all over the Aegean Sea (Fig. 1). Herewith we present the way that marine geophysical methods and geological-oceanographic interpretation of the

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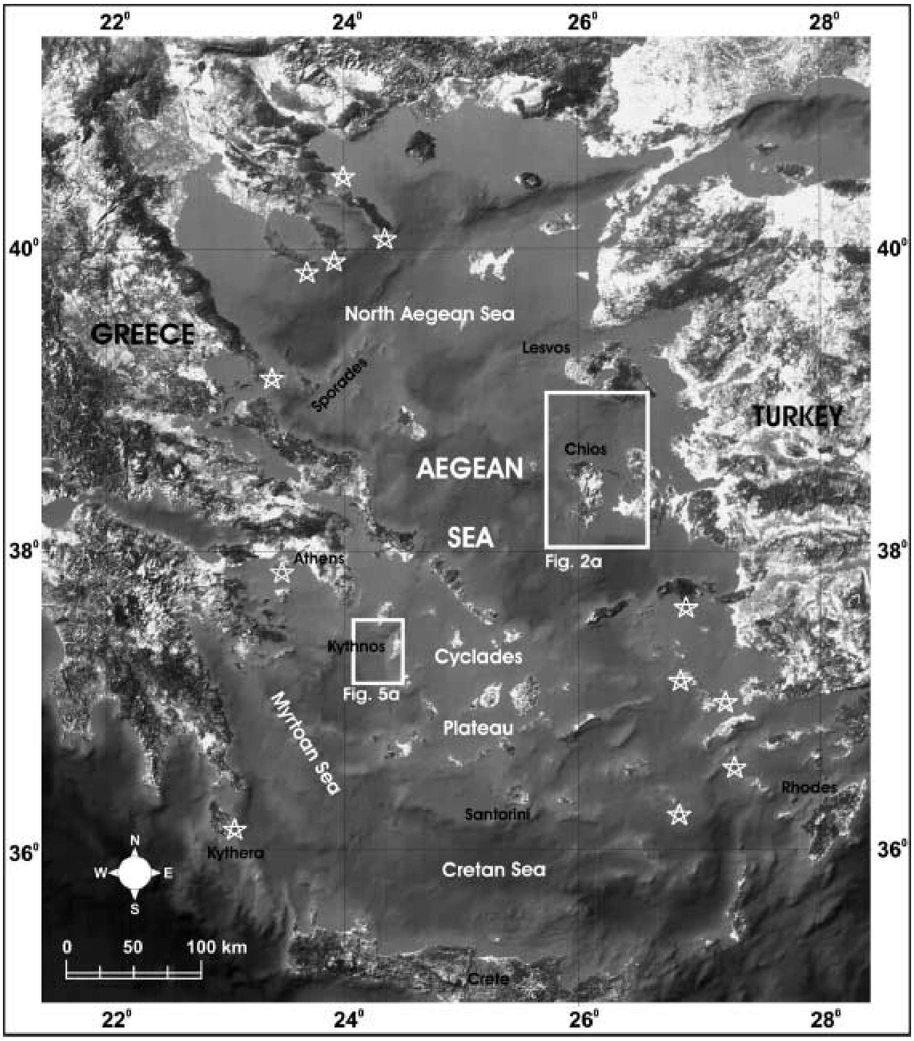

Figure 1. Morphological map of the Aegean region. White stars indicate areas surveyed during the last five years as part of the HCMR-EUA collaboration. White boxes mark the study areas, between Chios and Oinousses islands (Fig. 2a) and west of Kythnos island (Fig. 5a).

geophysical recordings were used for deep-water archaeological research during joint HCMR-EUA cruises, and contributed to the discovery of two Hellenistic wrecks close to Chios and Kythnos islands, in the Aegean Sea (Fig. 1).

Research outline

In the first 3 to 4 years of the joint EUA-HCMR research cruises, the investigation of the sea-bed was mainly based on side-scan sonar prospecting and the interpretation of the sonar images. Remotely operated vehicles (ROVs) and the two-person submersible *Thetis*, operating from the research vessel *Aegaeo*, were used for visual inspection of selected sonar targets. Priority was given to searching at depths exceeding the depth range of scuba diving. Nevertheless, the majority of the 20 wrecks discovered were found accidentally or located following information provided by fishermen and old sponge-divers, at depths shallower than 100 m, close to rocky coasts. Only two out of hundreds of visually-inspected sonar targets were proved to correspond to ancient wrecks.

Remains of ancient shipwrecks on the sea-floor are usually restricted to the cargo of the wrecked vessels instead of the vessel itself. In cases of merchant ships, which are the majority of ancient wrecks found so far, the cargo was composed mainly of amphoras and pottery. In areas of low sedimentation rate the amphoras lie scattered on the sea-bed or form a longitudinal topographic

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high, gently rising above the sea-floor. The latter case reflects the shape and dimensions of the wrecked vessel (Hadjidaki, 1996; Ballard *et al*, 2001). Structures like that are being recorded on the side-scan sonographs as strongly-reflecting targets, very similar to low-relief rocky outcrops. Thus, interpretation of the sonographs alone, without the assistance of data on the nature of the sea-floor's substrate, led more often than not to the misinterpretation of sonar targets. As a result, numerous ROV and submersible dives ended up with the 'discovery' of rocky outcrops on the sea-bed.

In 2004, sub-bottom profiling emerged as a basic tool of the joint research effort of EUA and HCMR. Integration of the sub-bottom profiling data resulted in a major qualitative and quantitative improvement of the effectiveness of the research efforts. The combination of sub-bottom profiling and side-scan sonar data led to a dramatic decrease in the number of 'targets of interest', since strongly-reflecting sonar targets deriving from rocky outcrops were immediately excluded on the basis of the sub-sea-floor data. Consequently, the previously almost purposelessly-consumed ship-time in unsuccessful ROV and submersible dives was drastically eliminated, allowing the systematic survey of larger areas of the sea-floor. This integrated both marine geophysical methods and was followed by the interpretation of the acquired data on the basis of marine geological and oceanographic principles.

It is widely accepted that remote-sensing techniques are a powerful tool in deep-water archaeological research (Ballard *et al.*, 2000; Papatheodorou *et al.*, 2001; Quinn *et al.*, 2002a; Quinn *et al.*, 2002b; Chalari *et al.*, 2003; Blondel and Pouliquen, 2004; Papatheodorou *et al.*, 2005, Sakellariou *et al.*, 2006), especially at depths beyond the range of scuba-diving. Among other advantages remote-sensing techniques provide the ability to systematically survey large areas and to collect large amounts of data within a relatively short time. Quinn *et al.* (2000) describe adequately the principles of the operation of side-scan sonar, sub-bottom profiler and magnetometer, and the advantages of using geophysical equipment to record submerged and buried archaeological resources. Nevertheless, the majority of the published works refer to the detection of relatively-recent, wooden- or iron-made wrecked ships, the hull of which is rather complete or relatively well-preserved and commonly rises well above the sea-floor (Hobbs *et al.*, 1994; Søreide and Jasinski, 1998; Barto Arnold III *et al.*, 1999), or to the geophysical investigation of already-known submerged archaeological sites (Quinn *et al.*, 1997; Quinn *et al.*, 1998). The present work aims to present in detail the equipment and the methodology used during the survey for ancient, wooden shipwrecks, of which only the cargo, exclusively composed of amphoras and fine ceramics, is preserved at various depths. Instrumentation and settings are thoroughly described. Particular attention has been paid to the rationale behind the interpretation of the side-scan sonar targets and their correlation with the results of the visual verification. The contribution of the sub-bottom profiling data to the geologically-reasonable interpretation of the side-scan sonar recordings is considered to be of great importance, especially in areas with complex sub-sea-floor geological structure. The sedimentation rate around the submerged archaeological sites will be shown to be also a very important factor for the preservation of the wreck's cargo.

Survey rationale and planning

The Chios survey took place in April 2004 (Sakellariou *et al.*, in press). The survey area covered the 1–2 nautical miles (2–3.5 km) wide strait between Chios and Oinousses islands in the eastern Aegean Sea (Fig. 2). Prassonissia islands, two small islets located within the strait leave a less than 1 mile (1.85 km) wide passage available for sailing. This fact, along with the orientation of the strait in N-S direction creates a very dangerous maritime passage for the ancient merchant ships, especially under strong northern winds. The southern part of the strait, of 60–70 m mean depth, was the first to be surveyed. The 7 km^2 (2 km wide by 3.5 km long) area was investigated along north-south survey lines at 150 m spacing.

The Kythnos survey took place in March 2005 as a follow-up of the delivery of a bronze statue to the Ephorate of Underwater Antiquities (Sakellariou *et al.*, 2005). The statue had been recovered by a trawler while fishing at 500 m mean depth, west of Kythnos island. The aim of the survey was to locate the wrecked ship, which would have been carrying the statue. According to the fisherman who delivered the statue, it was supposed to have been caught in the cod net soon after the start of a N-S, 14 mile (26 km) long trawling line. The area chosen to be surveyed first included a 6.5 km (3.5 nautical miles) long and 1.0 km wide stripe (6.5 km^2) covering the northern part of the above-mentioned trawling line. Survey

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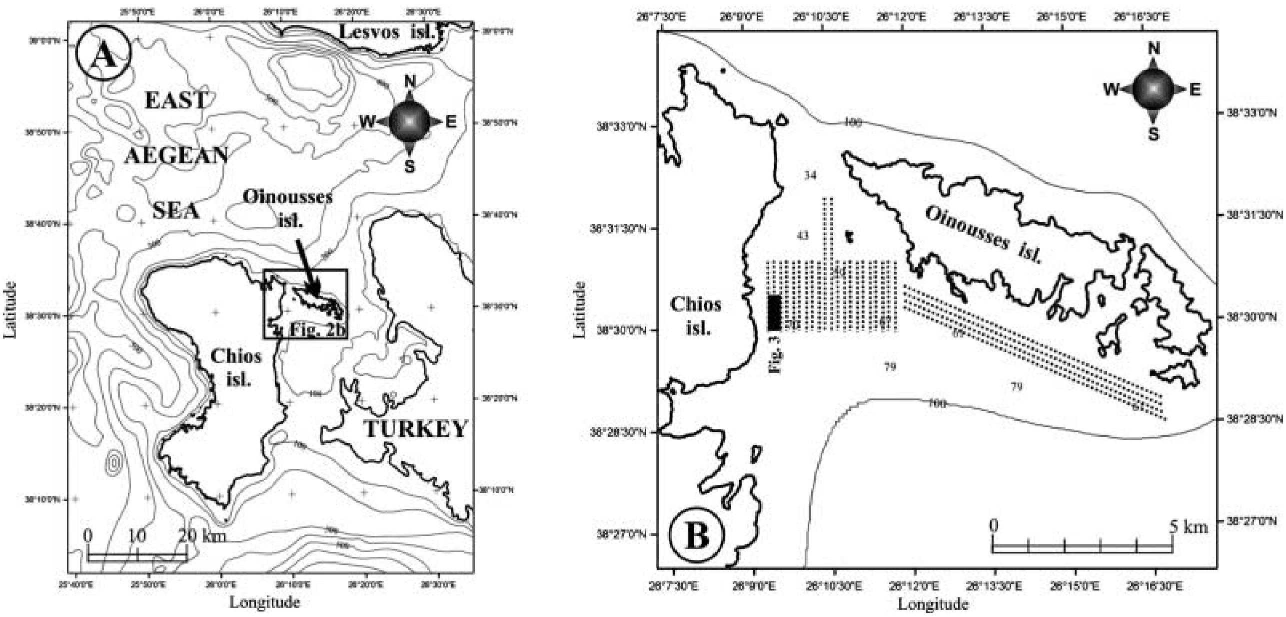

Figure 2. (a) Location map of the study area between Chios and Oinousses islands in the Eastern Aegean Sea. (b) Side-scan sonar and sub-bottom profiling track-lines performed in the Chios-Oinousses strait. The location of the profile shown in Fig. 4 is indicated on the map.

lines were drawn in a N-S direction with 150 m spacing. Both surveys were conducted on board the 61-m-long research vessel *Aegaeo* of the Hellenic Centre for Marine Research. The equipment used during the 2004 Chios and 2005 Kythnos expeditions included marine geophysical instrumentation for the acoustic-seismic investigation of the sea-floor and underwater vehicles for the visual inspection of the selected targets.

Instrumentation and settings

Marine geophysical instrumentation of both surveys incorporated a side-scan sonar system and a 3.5 kHz sub-bottom profiler. The side-scan sonar system was composed of a Geoacoustics Ltd two-channel, dual frequency tow-fish, an electro-hydraulic winch with 1800 m tow-cable and a Geoacoustics side-scan-transceiver. The sonar's tow-fish was being deployed from the A-frame placed at the stern of the vessel. Sonar data were being recorded on paper film by an EPC Model 1048 2-channel analogue recorder—serving also as trigger for the side-scan sonar—and digitally by using Isis Sonar v.6.41 software by Triton Imaging, Inc. The operating frequency during the side-scan sonar survey was 100 kHz and the swath-width about 190 m (95 m per channel) at a shooting rate of 0.125 sec—8 pings per second. By the 150 m spacing of the survey lines we managed to maintain about 25% overlapping of the sonar coverage between the adjacent lines. The vessel's speed was more or less constant at 2.5 knots (1.25 m/sec) and the height of the tow-fish from the sea-floor 10–15 m. Assuming a sound speed of 1500 m/sec in the water, at the shooting rate of 0.125 sec, swath-width of 190 m and vessel-speed of 1.25 m/sec, the sonar system may provide maximum along-track resolution of 15–20 cm and maximum across-track resolution of 20–40 cm. That high resolution along- and across-track fulfils the requirements of the survey, since even a single, isolated amphora is larger than 15 cm in diameter, thus it would be detected by the sonar.

The 3.5 kHz sub-bottom profiler used for the survey was composed by an ORE 4-array transducer tow-fish associated with a Geoacoustics Ltd., Model 5210A geopulse receiver and a Model 5430A geopulse transmitter. The profiler's tow-fish was being hanging from the stern-crane off the port side of the vessel at 2 m below the surface. Sub-bottom profiling data were digitally acquired using Delph Seismic + software, geo-encoded using Delph Map v.2.9.6 software and post-processed using SeismicGIS software of Triton Imaging Inc. Sub-bottom profiling and side-scan sonar survey were conducted synchronously, along the same track-lines. The profiler was operating at a frequency of 3.5 kHz, a shooting rate of 1 sec and pulse duration of 2 ms. The vertical resolution provided

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by the system under that settings was *c*.0.5 m and the along track resolution *c*.1.25 m.

The purpose of using the sub-bottom profiler for this kind of survey is the need for collecting as much information about the natural geological characteristics of the sea-floor and its substrate as possible and not to 'detect' possible wrecks on the recordings of the profiler. The in-depth knowledge of marine geological factors, which form the structure of the sea-floor and its substrate, is of paramount importance and helps greatly when interpreting the side-scan sonar recordings, especially the nature of the sea-bed and the selected targets. For example, small outcrops of rocky basement rising to the sea-bed through the surrounding sediments produce strong reflecting targets on the sonar recordings similar to the ones derived from an ancient shipwreck cargo, forming a short ridge on the sea-bed. In such cases, in the absence of any information on the structure of the substrate, it is always very difficult to interpret correctly the nature of the target. When ROV diving is used to inspect the nature of such kind of strong reflecting, 'highly promising' targets, it often ends up with the discovery of rocky outcrops on the sea-floor. Repeated unsuccessful ROV or submersible dives waste a large amount of money (ship-time) and time, but what is more important is the disappointment and the gradually-growing feeling of purposeless research among the cruise participants.

One ROV and one submersible were used for visually inspecting the selected side-scan sonar targets on the sea-bed and eventually for collecting artefacts. The observation-class *Super Achilles* ROV (Comex, FR) can operate at depths up to 1000 m and is equipped with navigation sonar, two lights, one electric 3-function arm, and a video camera. *Super Achilles* was used mainly for visual ground-truthing of the selected targets. The 2-person, Model Remora-2000, *Thetis* submersible, also manufactured by Comex, can operate at a maximum depth of 610 m. It was mainly used for systematic observation on sites of particular interest as well as for sampling archaeological artefacts like amphoras. It is equipped with omni-directional navigation sonar, two lights, two hydraulic arms of 3- and 5-functions, one suction pump and one high definition video camera.

The Chios survey

Geological setting and sea-floor prospecting

The sea-floor survey area in the strait between Chios and Oinousses islands was, as already mentioned, performed along 22 parallel, 1 mile (1.85 km) long lines, aligned N-S at 150 m spacing (Fig. 2b). Another 4 lines were surveyed parallel to the southern coastline of Oinousses island, in WNW-ESE direction. The 60–70 m deep, flat sea-floor is covered by Holocene silt of variable thickness. The rocky base occurs on the sea-bed of the western and eastern part of the area, close to the nearby rocky coasts of Chios and Oinousses islands. Base outcrops form elongated or shapeless ridges or patches on the sea-floor, either connected to the adjacent rocky coasts or isolated, emerging on the sea-floor through the silty sediments.

The morphology of the rock represents the relief of the area during the last glacial stage, when the sea-level was −120 m (Chappell and Shackleton, 1986; Shackleton, 1987; Fairbanks, 1989). The Holocene sea-level rise led to the flooding of the strait and the deposition of silty sediments, which tend to smooth the pre-Holocene relief. A very pronounced outcrop occurs in the northern part of the area. A low-relief, 50–60 m wide, WSW-ENE, linear base stripe can be followed on the side-scan sonographs from the western to the eastern edge of the surveyed area. Sub-bottom profiling data show the presence of a small fault, running along the southern side of the stripe. The latter represents the uplifting (footwall) block north of the fault trace. South of the fault-line, the thickness of the recent sediments increases rapidly to more than 20–30 m.

Trawling scars are observed on the side-scan recordings only from the central section of the southern part of the area. Thus, possible wrecks located on the sea-floor outside the trawling field may have been preserved unaffected by recent trawling activity. Several tens of targets were recorded on the side-scan sonographs. The majority of them were interpreted as base-rock outcrops, since this interpretation was supported by the sub-bottom profiling data. Other targets were considered of low interest. The sonograph shown in Fig. 3a shows a characteristic image of the sea-floor from the south-western part of the survey area, close to the Chios coast. A very pronounced outcrop of the base rock is recorded on the southern part of the image. This is seen as a strongly-backscattering area displayed in dark grey tones. Variations of the colour tones originate from the rough and irregular relief of the base-rock outcrop, while lighter grey tones may come from small silt or sand pockets on the rock. The section of the 3.5 kHz profile, shown in Fig. 3b, was acquired simultaneously with the sonar record

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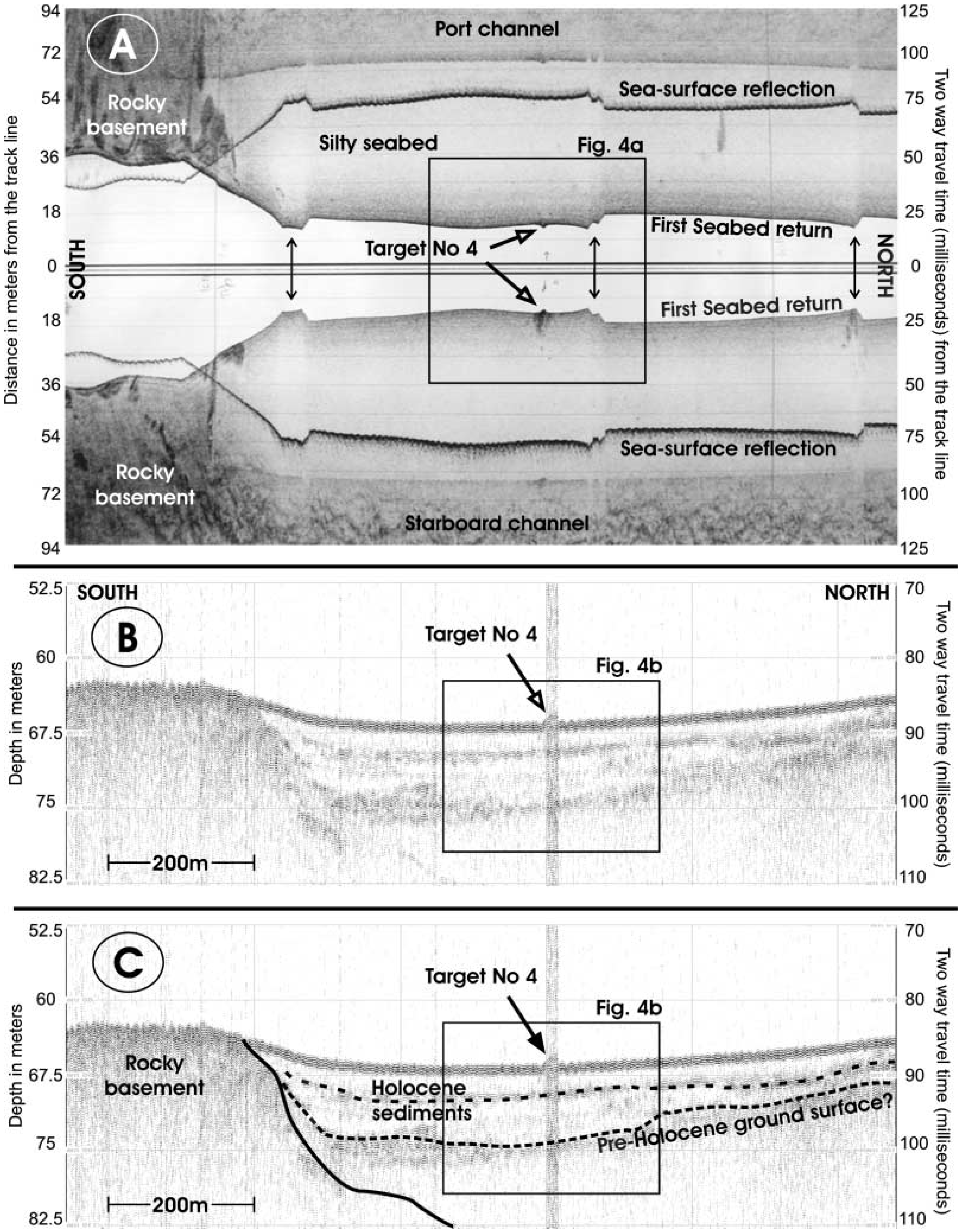

Figure 3. (For caption see following page)

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of Fig. 3a. In the interpretation of this profile (Fig. 3c) it is clearly shown that the highly-backscattering area recorded on the sonar image coincides with the occurrence of the base-rock on the sea-floor.

Weakly-backscattering (light grey tones) sea-floor occurs in the sonographs of Fig. 3a, north of the rock outcrop. Despite the high-amplitude reflection derived from the first return from the sea-surface and the medium-amplitude returns, which occur at the outer part of both channels and originate from the waves of the sea-surface, the sea-floor displays a homogenous acoustic character. This part of the sea-floor is underlain by recent sediments of significant thickness, as shown on the high-resolution profile of Fig. 3b and 3c. Two acoustically-transparent seismic packages separated by a medium-amplitude reflector overly a high-amplitude, morphologically-irregular reflector. The latter forms the roof over the acoustically-opaque base, which represents the rocky substrate. The total thickness of the transparent packages varies between 5–7 m. We interpret them as mainly silt deposits accumulated during the present high sea-level stage. The high-amplitude, irregular reflector below them may well represent the ground-surface of the alluvial plain, which would have connected Chios and Oinousses islands during the last glacial stage, when sea-level was at −120 m (Chappell and Shackleton, 1986; Shackleton, 1987; Fairbanks, 1989). According to the Holocene sea-level-rise curve, the sea should have drowned the present day 70-m-deep survey area some 13–14 ka ago (Perissoratis and Conispoliatis, 2003). Thus, mean accumulation rate of marine sediments during the Holocene in the area may be as high as 0.5 m/ka.

A strongly backscattering (dark grey) feature, located within the homogenously weakly-reflecting sea-floor of Fig. 3a, is also shown in magnification in Fig. 4a. That feature was selected as first priority target, labelled No 4, and was considered the first one worth visual inspection. On the sonographs, the target itself was interpreted as a 17-m-long by 7–8 m wide and 1.5–2 m high gentle culmination, sitting on a low-backscatter (light grey tone) flat sea-floor. The target was, luckily, located right beneath the tow-fish, thus its relief has been accurately displayed by the first return of the signal from the sea-bed. Precise examination of the high-backscatter target indicates that it is composed of numerous very-strongly-reflecting (black) points, which can be easily recognized at the rim of the target.

The same feature was imaged by the sub-bottom profiler, since it was accidentally located on the vessel's track. On the 3.5 kHz sub-bottom profile (Fig. 3b and 3c, magnified in Fig. 4b) the target was recorded as a 2-m-high gentle mound, lying on the sea-floor. The origin of the noise, which partly masks the record only for the length of the target, is not quite clear. The total thickness of the sedimentary deposits below the target area exceeds 15 m, as shown on the profile. In the substrate of the sea-floor, below target No 4, we recognize a 7-m-thick transparent acoustic package with a low-amplitude reflector within it (Fig. 4b). A high-amplitude, morphologically-irregular reflector marks the bottom of the acoustically-transparent package. We interpret this strong reflector as the exposed land surface of the last low-sea-level stage, as already mentioned. Accordingly, the overlying transparent package represents sedimentary deposits accumulated since the last sea-level rise. Hence, the possibility of target No 4 representing a rock outcrop on the sea-floor was immediately excluded.

Figure 3. (See previous page) (a) Side-scan sonar image (100 kHz frequency, 125 milliseconds key-rate) from Chios-Oinousses strait (see Fig. 2b for location) showing a flat, homogenous, low-backscattering (light grey) sea-floor, covered by silt deposits. The strongly-backscattering (dark grey) area at the left side of the sonograph derives from hard rocks, which outcrop on the sea-floor. Target No 4, in the centre, is a low morphological mound with strong backscatter, located within the weakly-reflecting silty sea-floor. Left (port) and right (starboard) channels and the reflection from sea-surface are indicated on the figure. Thin double arrows indicate step-like features—acquisition artefacts, resulting from tow-cable pulling out. (b) Section of a 3.5 kHz sub-bottom profile acquired at 125 milliseconds key-rate along the central line of the sonograph shown in Fig. 3a. (c) geological interpretation of the 3.5 kHz profile. Depth is given in two-way-travel-time (right) and in metres (left), assuming 1500 m/sec sound velocity. The interpretation of the profile in Fig. 3c shows a 5–7-m-thick acoustically-transparent package, overlying a strong, morphologically-irregular reflector. The latter is assumed to represent the alluvial ground-surface exposed during the last low-sea-level period. The transparent package is thus interpreted as fine-grained, Holocene deposits, accumulated during the last 12,000 years. Note that the Holocene deposits shown on the profile coincide with the weakly-reflecting, flat sea-floor of Fig. 3a. The strongly-reflecting, acoustically-opaque formation at the left part of the profile coincides with the strongly-reflecting area at the left part of the sonograph (Fig. 3a). It forms the geological base below the Holocene deposits and is composed of hard rocks (limestone and schists) like the ones outcropping on the nearby islands. Target No 4 is indicated on the sonographs and the profile. Despite its strongly reflecting character, similar to the one of the geological base rock, it in fact lies on top of the fine-grained Holocene deposits, rather than rising through the sediments, as the base rock does.

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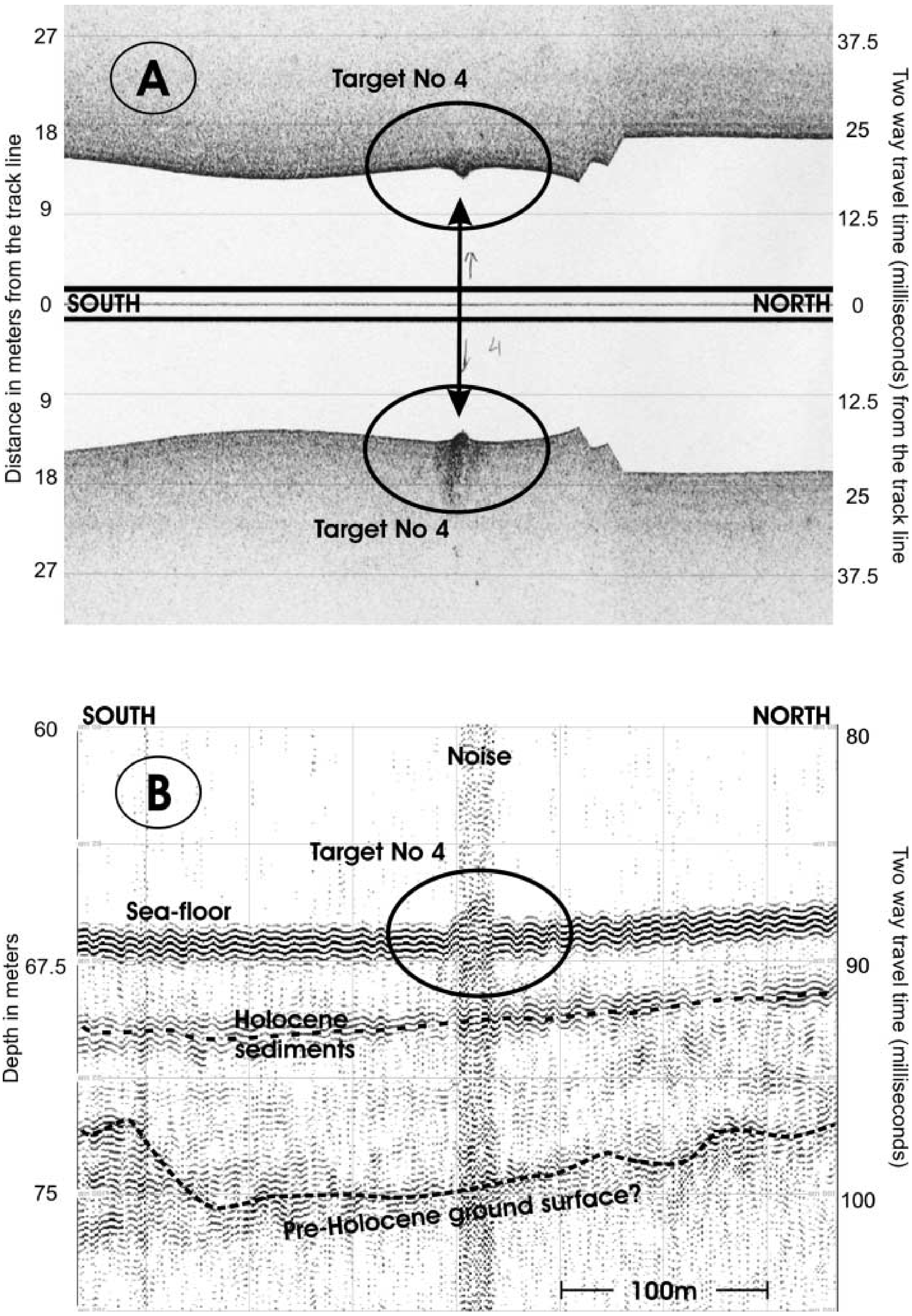

Figure 4. (For caption see following page)

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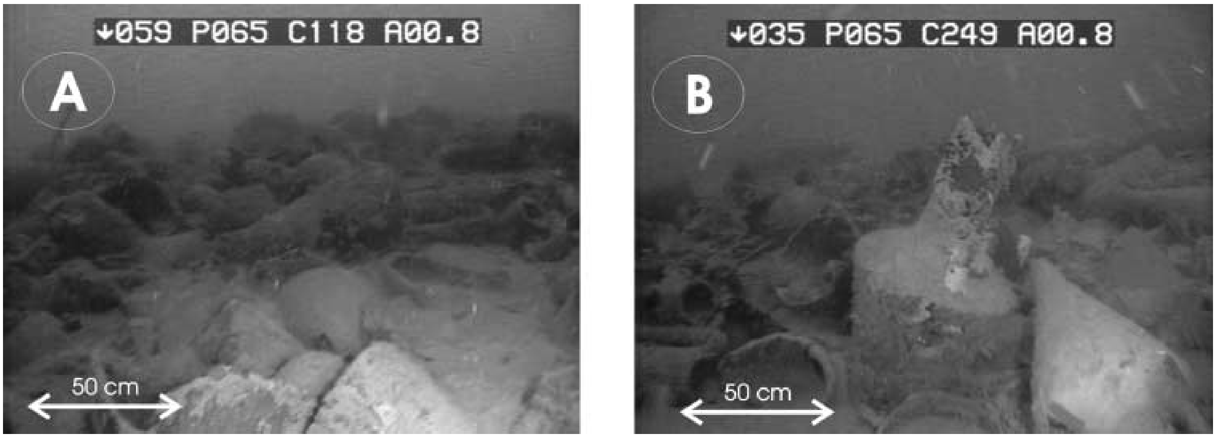

Figure 5. a & b. Video images taken from ROV *Super Achilles* from Target No 4 at 70 m. The target constitutes a 17-m-long by 6-m-wide by 1.5-m-high concentration of a few hundred Chios and Samos(?) type amphoras of the late-4th or early-3rd century BC. Approximate scale-bar drawn on both images is reliable only for the foreground of the picture.

Target visual inspection

Target No 4 was the first one to be visually inspected. The observation class ROV *Super Achilles* dived first to the target on Sunday 4 April 2004 at 10:00 am. Very soon the ROV's sonar located the target and after a few minutes it became clear that the low mound on the sea-floor was a concentration of ancient amphoras (Fig. 5). Over 400 amphoras, belonging to two main types—Chian and an as-yet unidentified type, originating probably from an adjacent production centre, and pottery, made up the cargo of the ancient ship, which wrecked round the mid-4th century BC (Kourkoumelis *et al.*, forthcoming). The overall shape and dimension of the amphora concentration verified the interpretation of the target from the side-scan sonar and sub-bottom profiler recordings. The main body of the strongly-backscattering sonar target represents the core of the amphora concentration, which rises up to 1.5–2 m above the surrounding flat sea-floor. The black dots, which exist around the main target, represent strong point-reflections originating from individual amphoras which lie scattered on the sea-floor around the main concentration.

Kythnos survey

The surveyed area is located in the north-eastern part of the Myrtoan Sea, on the gently-dipping western slope between the Cyclades shallow plateau and the 1100-m-deep Myrtoan basin (Fig. 6 left). The sea-floor of the surveyed area extends at depths between 460–530 m. The survey west of Kythnos islands was conducted along 6 parallel, 3.5 mile (6.5 km) long lines at 150 m spacing, aligned in a N-S direction (Figs 6b). The area chosen covered the northernmost section of the trawling line along which the bronze statue was recovered in September 2004. Although the horizontal distance between the trawling tools on the sea-floor does not exceed *c*.200 m, we decided to survey a 1000-m-wide zone along the inferred trawling line (Fig. 6b). The methodology followed and the settings used were as described above. Vessel's speed was at 2.5 knots and cable lay-out varied between 1250–1500 m depending on the depth of the sea-floor and the speed of the vessel. Accordingly the sonar tow-fish was at 1200–1430 m horizontal distance behind the vessel.

Environmental and geological site conditions

The sedimentation rate is a very important geological factor for the preservation of a possible ancient wreck or its remains on the sea-floor. High sedimentation rate may result in full burial of the wreck within a short time, making it thus undetectable from the side-scan sonar. Very low sedimentation rate tends to leave any possible

Figure 4. (See previous page) (a) Close-up of Target No 4 shown in the sonograph in Fig. 3a. and on the 3.5 kHz profile of Figs 3b and 3c. The elongated shape and the strongly-reflecting character of the low-relief ridge-like feature are clearly shown. The target was accidentally located on the ship's route and this was the reason it was imaged by both channels of the sonar and by the sub-bottom profiler. (b) In this profile the target is acquired as a 1.5-m-high object, which lies on the acoustically-transparent, fine-grain, Holocene deposits and does not connect to any hard bedrock below the sea-floor. Consequently, a possible rise of the geological base at the site of Target No 4 is excluded.

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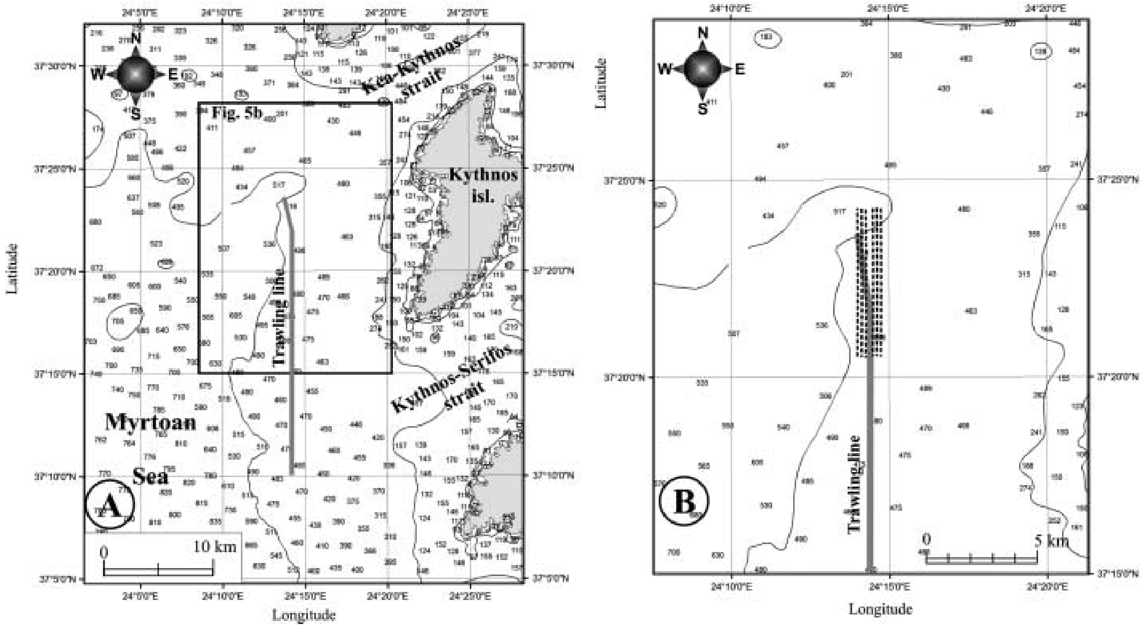

Figure 6. (a) Location of the study area west of Kythnos island, in the northeastern Myrtoan Sea. (b) Track lines (150 m spacing, 3.5 miles/6.5 km long) along which the side-scan sonar and sub-bottom profiling survey was performed in the area west of Kythnos island. The trace of the trawling line, along which the bronze statue was retrieved, is shown in both maps.

wreck free on the sea-floor, but also exposed to corrosion and activities such as fishing and trawling.

Sedimentation rate in the Aegean Sea varies significantly, following the rough large-scale morphology of the sea-floor. High sedimentation rates (0.3–1.0 m/kyr) occur in deep basins, which are characterized by enhanced tectonic subsidence and are located close to large landmasses, like the North Aegean Trough basins (Roussakis *et al.*, 2005) and the Gulf of Corinth (Moretti *et al.*, 2004). Low sedimentation rates have been observed in deep basins like the Cretan basin in the South Aegean or in shallow plateaus like the Cyclades plateau, which are not affected by the deposition of suspended material transported by rivers. Nevertheless, in all the above cases, the sedimentation rate may vary between a few centimetres to a few tens of centimetres per 1000 years. Gravity cores recovered from the Cretan Sea indicate a sedimentation rate of about 10 cm/kyrs (Aksu *et al.*, 1995), while one core from the Myrtoan basin, close to the Kythnos survey area, revealed very similar values for the last 18,000 yrs (Geraga *et al.*, 2000).

Figure 7 shows a characteristic 3.5 kHz sub-bottom profile acquired from the survey area. The substrate of the sea-floor is composed of transparent acoustic packages separated by medium- and low-amplitude reflectors, running parallel to the sea-floor. The transparent packages may represent fine-grain deposits, predominantly silt or clay, while the medium- and low-amplitude reflectors may derive from coarser-grain deposits. The seismic stratigraphy of the sea-floor's substrate implies continuous sedimentation for at least the upper 25–30 milliseconds (at least 15–20 m) below the sea-floor. No hard base was observed on any of the acquired seismic profiles in the survey area. The shallowest medium amplitude reflector lies at 6–8 milliseconds (4–6 m) below the sea-floor. This reflector may have derived by a distinct layer deposited at the base of Holocene, when the sea-level started to rise after the last glacial maximum some 18,000 yrs ago (Chappell and Shackleton, 1986; Shackleton, 1987; Fairbanks, 1989). In that case, mean sedimentation rate in the survey area could be as high as 20–30 cm/kyrs for the Holocene interval. In the absence of gravity cores and consequently of any ground-truthing of this seismic profile, it is not possible to have an accurate value of the sedimentation rate in the survey area. So, we follow the results presented in Geraga *et al.* (2000), assuming that sedimentation rate may well be as high as 10 cm/1000yrs.

Figure 8a shows the mosaic of the six side-scan sonar lines which were acquired in the study area. A 7-km-long by 1-km-wide area has been almost entirely covered, using total swath of 185 m for every acquired line. Fig. 8b shows a 500 × 500-m-wide

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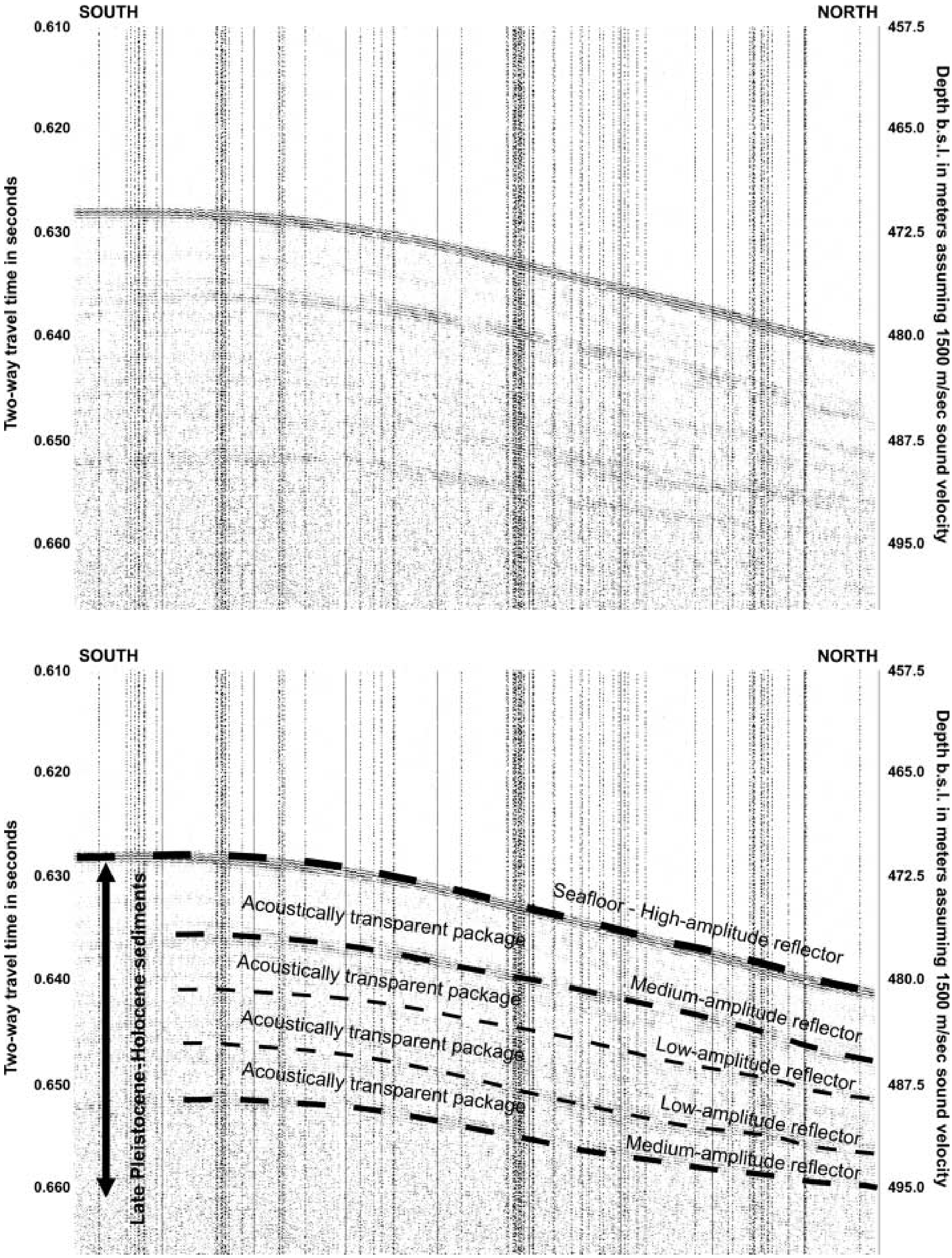

Figure 7. Section of a representative 3.5-kHz sub-bottom profile acquired at 1000 milliseconds in the study area west of Kythnos island (upper) and geological interpretation of the 3.5-kHz profile (lower). Depth is given in two-way-travel-time (left) and in metres (right), assuming 1500 m/sec sound velocity. The interpretation of the profile shows a seismic-sedimentary stratigraphic succession of acoustically-transparent packages and medium- or low-amplitude reflectors of minimum total thickness of 15 m. Hard base rock was not observed in the study area.

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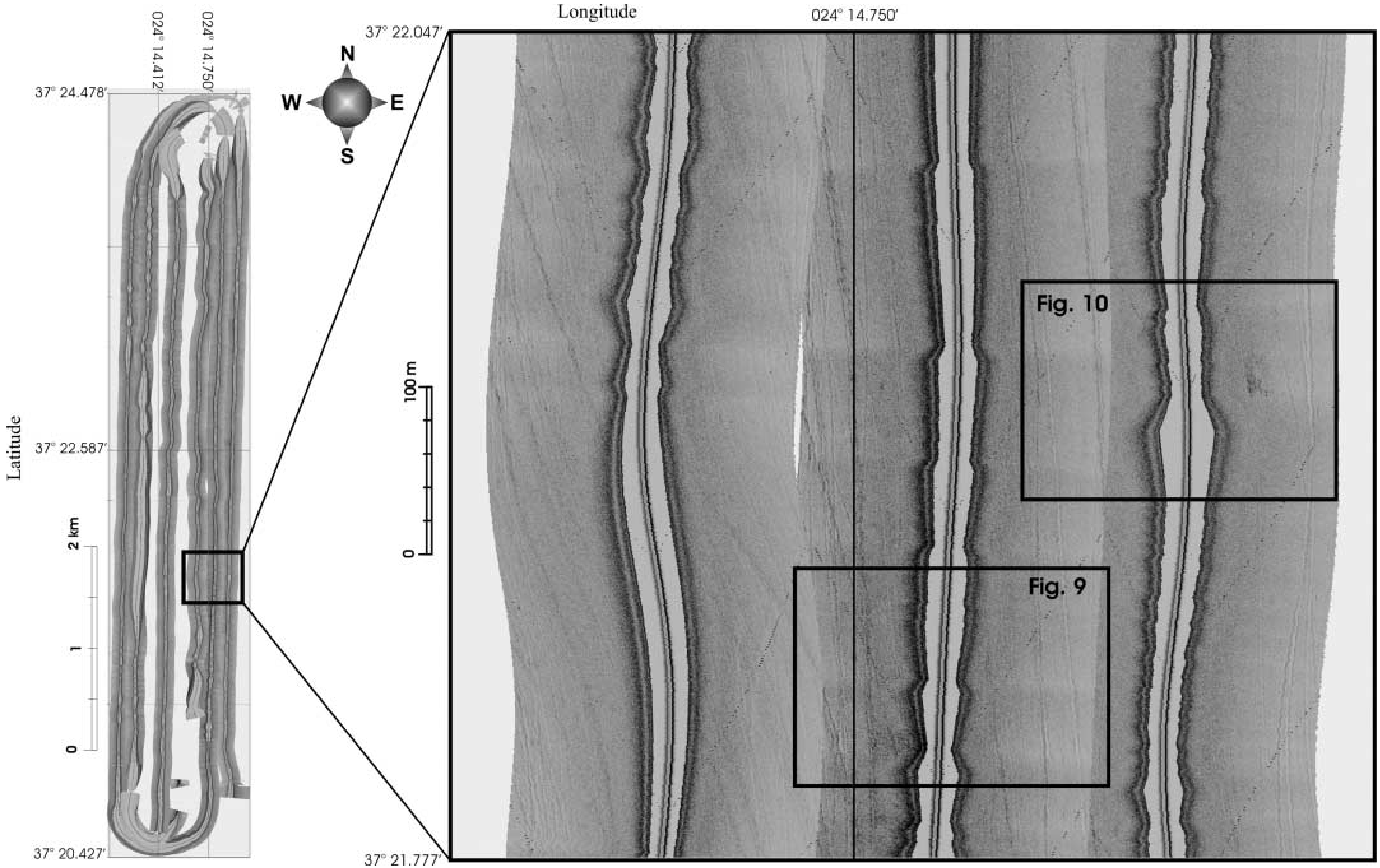

Figure 8. Left: mosaic of the side-scan sonar lines acquired in the study area west of Kythnos island (no slant-range correction applied). Right: zoom of part of the mosaic, showing three successive sonar lines, acquired at 125 milliseconds key-rate, 185 m total swath each line. Traces of trawling are obvious on the weakly-backscattering, homogenous sea-floor. Trawling scars run NNW-SSE or N-S. The location of Figs 9 and 10 are indicated.

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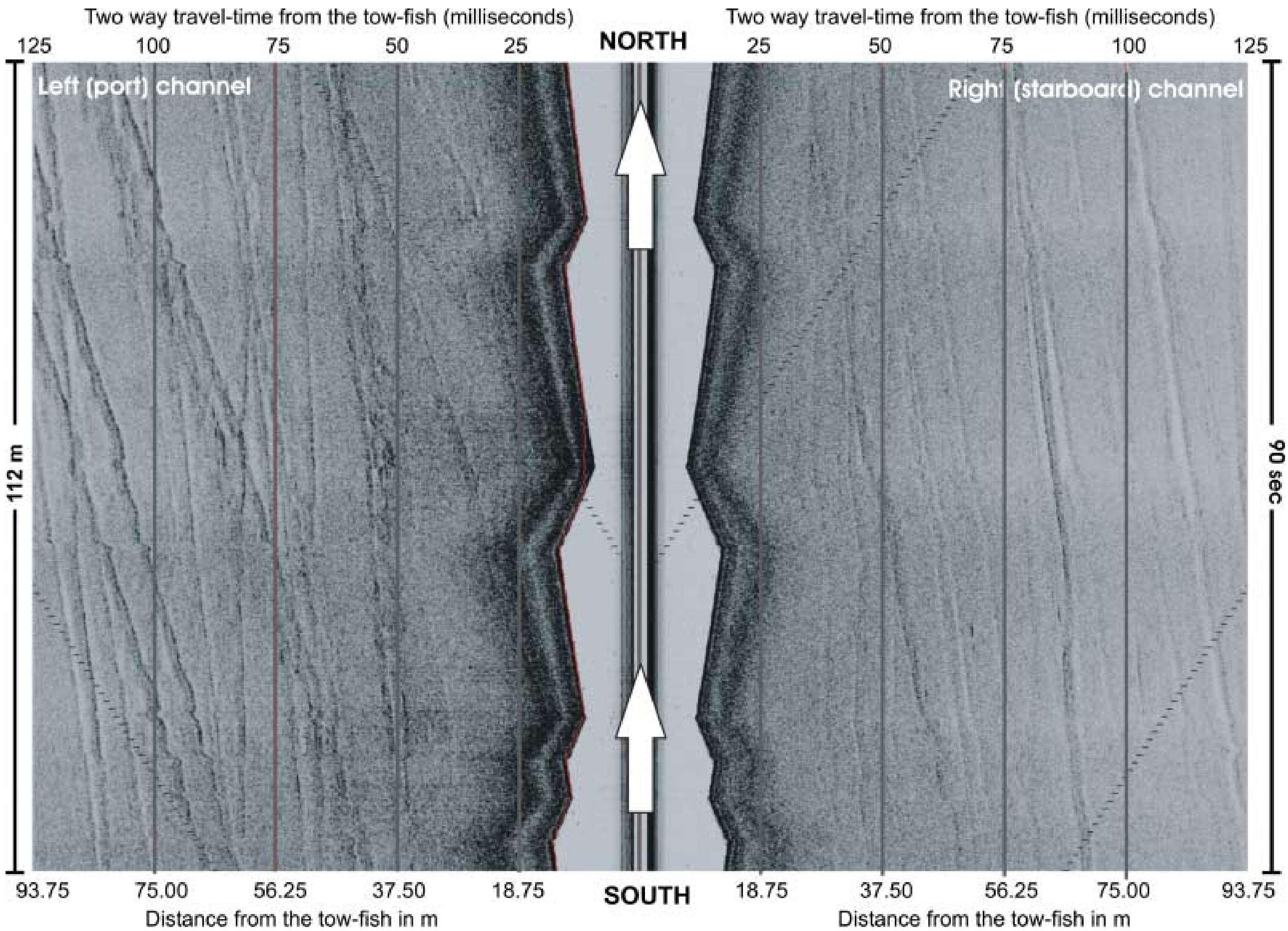

Figure 9. Side-scan sonar image (100 kHz frequency, 125 milliseconds key-rate) from the study area west of Kythnos island (see Fig. 8 right for location) showing a flat, homogenous, weakly-reflecting (light grey) sea-floor, covered by fine-grain deposits. Heavy black and white lines running NNW-SSE (top left to bottom right) are metre-wide furrows, created on the sea-floor by the dragging of the cod doors while trawling. The study area is located within an intensively-fished trawling-field. The direction of the trawling scars coincides with the direction of the northern section of the trawling line shown in Fig. 6.

area, covered by three successive parallel lines at 150-m spacing. This mosaic section displays a characteristic large-scale image of the sea-floor character. Low backscattering indicates that fine-grain sedimentary deposits (silt-mud) cover the sea-bed. Numerous, continuous trawling scars, aligned in a N-S to NNW-SSE direction, are very prominent on the sonograph and verify that the survey area belongs to an exhaustively-trawled field. The trawling scars are impressive in the sonograph Fig. 9. They are acquired as linear structures characterized by an anechoic (white) median line associated with strongly-backscattering (dark grey) lineaments on both sides. The observed trawling scars are continuous, linear furrows, several tens of centimetres deep and about 1–2 m wide, which develop when the two otter-boards of the trawl are being dragged on the muddy sea-floor.

In the sonograph in Fig. 10 the density of the trawling scars is significantly lower, compared to Fig. 9, leaving the low-backscattering, muddy sea-floor relatively free of the characteristic furrows, so that the strongly-reverberating feature within the white box is easily recognizable. That feature, labelled Target No 1, consists of a number of high-amplitude, point-like reflections, scattered on the sea-floor in an area of 20 × 20 m. As shown in Fig. 11a, the main body of the target displays higher backscatter (darker colour) than the surrounding sea-floor, indicating a slight change of the nature of the sea-bed. A NNW-SSE-trending trawling scar forms the western limit of the target. In the light of the data for the shallow sub-sea-floor structure, provided by the high resolution profiling (Fig. 7), the recorded target was not likely to have derived from any rocky outcrop on the sea-floor.

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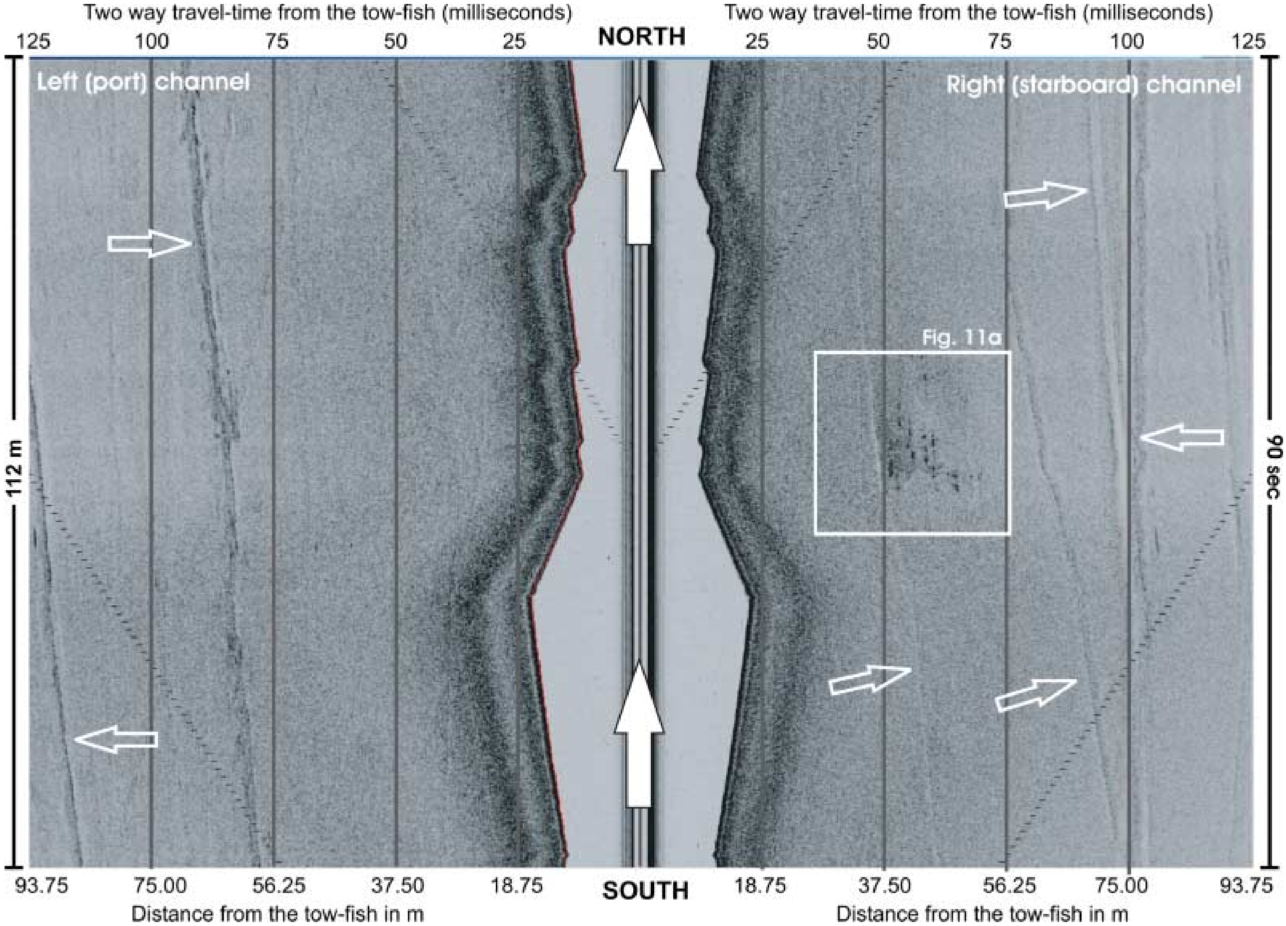

Figure 10. Side-scan sonar image (100 kHz frequency, 125 milliseconds key-rate, 125 milliseconds/94 m swath per channel) from the study area west of Kythnos island (see Fig. 8 right for location) showing a flat, homogenous, weakly-reflecting (light grey) sea-floor, covered by fine-grain deposits. Large white arrows pointing north show the ship's direction. Left (port) and right (starboard) channels are marked. Distance from the tow-fish is given in metres and in time (seconds) at the lower and upper edge of the sonograph. Total length of sonograph in N-S direction is 90 seconds (*c*.112 m). Total width is 250 milliseconds (*c*.190 m). Trawling scars are indicated by small white arrows. The white box marks a concentration of high-amplitude, point-like reflections, scattered on the sea-floor in an area of 10 × 15 m. Magnification of this target is shown in Fig. 11a. Note that the target is limited to the west by a trawling scar.

Thus, the strong, point-like reflections and the moderately-reflecting main body of the target should derive from any kind of small objects, lying on the sea-floor or at a shallow depth below it.

Target visual inspection

Target No 1 was the first one to be visually inspected. The two-person submersible *Thetis* dived first to the target on Wednesday 16 March 2005 at 14:30, with one of the authors (P. M.) as passenger-archaeologist. Fig. 11b presents the result of the visual inspection of the target. Several tens of ancient amphoras were lying on the sea-floor, semi-buried within the mud. Some of the amphoras have been shifted by several metres, leaving on the soft sea-floor a shallow furrow behind them. Shifting of the amphoras may be attributed to trawling activity in the area, and it may occur when the half-buried amphoras are caught by the cod-net of the trawl.

The visually observed distribution of the amphoras on the sea-floor allows a re-interpretation of the shape and the acoustic character of target No 1, which is shown on the sonographs in Figs 10 and 11a. Each single, point-like, strong reflection of the target is very likely to have derived from each single amphora which rises above the sea-floor. The resolution provided by the side-scan sonar system under the settings described above supports this interpretation. Moreover, the moderately-

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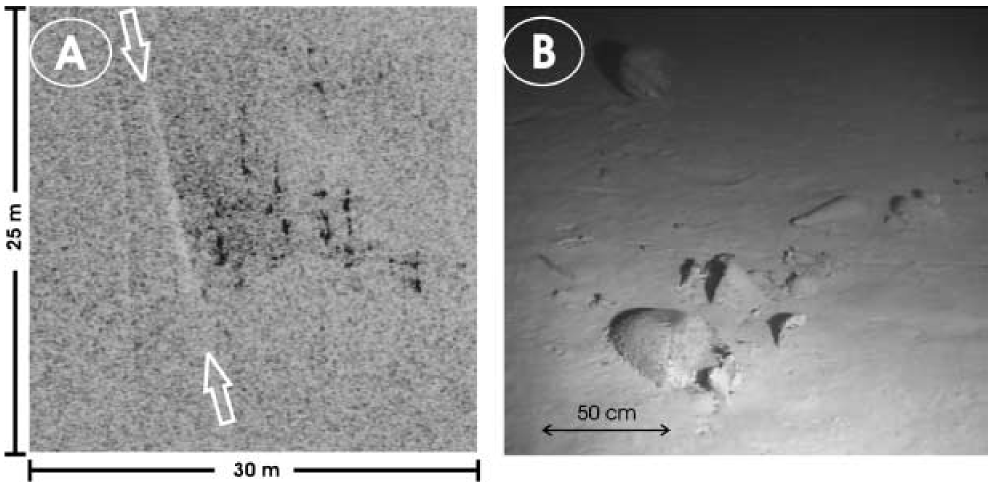

Figure 11. (a) Close-up of Target No 1, shown in Fig. 10. The target consists of a few tens of point-like, high-amplitude reflections, scattered in an area 10 × 15 m. The surrounding sea-floor is characterized by low backscatter (light grey) while the main body of the target is marked by darker grey tones, which indicate higher backscatter. (b) Photograph taken by *Thetis* submersible from Target No 1 at 495 m. Approximate scale-bar drawn on the photo is reliable only for the foreground. Visual inspection of the target revealed the presence of a concentration of a few tens of Chios- and Samos(?)-type amphoras of the early to mid-3rd century BC. Note that the distribution of the amphoras on the sea-floor coincides with the distribution of the point-like reflections of Target No 1, indicating that each reflection has derived from a single amphora.

backscattering main body of the target may indicate the presence of more remains (amphoras or other) of the wrecked vessel, which may be covered by the accumulated mud and lie at a very shallow depth below the present sea-floor.

A second, combined dive of *Thetis* and the *Super Achilles* ROV resulted in the sampling of two amphoras (Sakellariou *et al.*, 2005). Examination indicated that the cargo of the wrecked ship was similar to the Chios-Oinousses wreck consignments—Chian amphoras, a type similar to the unidentified one, and pottery, dating to the late-4th century BC. Following Geraga *et al.* (2000) and assuming constant sedimentation rate during the Holocene, about 20–30 cm of mud deposits should have accumulated on the sea-floor of the survey area in the last 2.4 kyrs, since the sinking of the discovered wreck. Taking also in account that the wrecked ship should have originally sunk by several tens of centimetres within the soft mud of the sea-floor, we consider as highly possible that more objects from the ancient vessel may have been preserved, being presently covered by a thin mud drape.

Conclusions and discussion

Remote-sensing techniques are a powerful tool for deep-water archaeological research, especially for the detection of archaeological sites beyond diving depths. Conventional marine geophysical methods of sea-floor survey, including side-scan sonar imaging and sub-bottom profiling, provide valuable information on the character of the sea-floor and its substrate. Nevertheless, their use becomes all the more effective when the principles of oceanography and marine geology are being followed during the interpretation of the geophysical recordings.

Thus, conclusions on the nature of side-scan sonar targets, drawn solely from the interpretation of the recorded sonographs and the acoustic characteristics of the targets, may be erroneous or may be in direct discrepancy with the geological structure of the surveyed area. The integration of sub-bottom geophysical profiling data provides valuable information on the geological structure of the sea-floor's shallow substrate. Even if sub-bottom profiling is not directly suitable for the detection of submerged antiquities, the knowledge of the shallow sub-seafloor structure constitutes an almost absolute prerequisite for a geologically-reasonable interpretation of the side-scan sonar images.

The methodology followed, and the interpretation of the geophysical recordings which are presented here, and led to the discovery of the Chios and Kythnos Hellenistic wrecks at 70 m and 495 m depth respectively, demonstrate the effectiveness of the integrated use of side-scan sonar and sub-bottom profiler in searching for ancient wrecks.

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Amphoras and pottery constitute the remains of both wrecks on the sea-floor. In the case of the Chios wreck, over 400 concentrated artefacts form a longitudinal body of high reflectivity, which rises by 1.5–2 m above the surrounding flat, muddy sea-floor. Loose amphoras, scattered over a 20 × 20-m-wide area, represent the remains of Kythnos wreck and were recorded as strongly-reflecting points. Both wrecks were found in areas where the sea-floor is underlain by thick sedimentary sequences, as nicely shown on the sub-bottom profiler recordings. In the absence of the sub-seafloor data, both targets could be easily misinterpreted as possible outcrops of the rocky substrate or loose rocks on the sea-floor respectively, especially because such structures occur in close proximity to both sites.

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