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# The *Mary Rose* site—geophysical evidence for palaeo-scour marks

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## Introduction

Since the development-led boom in rescue archaeology in the 1960s and 1970s, the vicissitudes of funding and the growing recognition of the non-renewable nature of the archaeological resource, have prompted much more circumspect attitudes to excavation (Cleere, 1989; Hunter & Ralston, 1993). Hence the justification of decisions to excavate are generally based either on the threat from development or other agency, or the need for research, where excavation is viewed as the best or only way to answer certain questions, or occasionally both. As a result, greater emphasis is now based on desk-top assessments, non-intrusive evaluations such as fieldwalking and geophysical surveys, and on the associated task of building Sites' and Monuments' Records (SMRs) to better quantify and manage the resource.

Over the same period archaeology underwater focused on the development of appropriate excavation and recording methods and the collection of data. Since the mid 1980s, this area of research has moved in a broadly similar direction, concentrating less on the excavation of single sites (often as a reaction to chance discoveries) and more on assessment and recording. An increasing number of projects in coastal regions are more proactive in character, involving regionally co-ordinated surveys. This trend is also reflected in the UK Government's interpretation of current legislation, in particular with respect to historic wrecks, as well as dove-tailing with the recently established database for maritime sites at the National Monuments Record Centre at Swindon, UK.

Over the past 30 years, various marine seismic reflection techniques have been used in the investigation of sites of archaeological interest, (McGhee *et al.*, 1968; Frey, 1971; Chauhan & Almeida, 1988; Rao, 1988; Redknap, 1990). To date, the application of sub-bottom profiling systems to maritime archaeology has been restricted by poor resolution and an inability to image the seabed in very shallow water depths. Recent advances in both acquisition and processing techniques have culminated in the development of a system known as 'Chirp', a digital, frequency-modulated (FM) sub-bottom profiling system.

The principal objectives of this paper are to present the results and associated interpretation of a three-dimensional Chirp sub-bottom survey of the excavated *Mary Rose* site carried out in conjunction with the Mary Rose Trust, and discuss the application of Chirp technology to maritime archaeology. In order to familiarize the reader with the principles of operation

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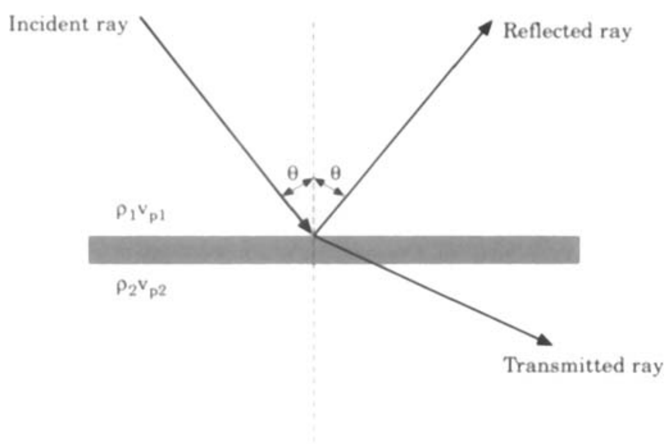


*Figure 1.* Reflection and transmission from a boundary in the sub-surface. A boundary giving rise to a reflection will be marked by an acoustic impedance contrast across it. The incident ray is partitioned into a reflected ray and a transmitted ray. The proportion of incident amplitude that is reflected is controlled by the reflection coefficient. See text and Equation 1 for more details.

of the sub-bottom profiling system, the following two sections concentrate on seismic reflection theory and introduce the aspects of Chirp sonar which set it apart from conventional sub-bottom profiling technology. For those interested, more detailed discussions on the principles of acoustics can be found in many general geophysics texts (including Anstey, 1981; and Sheriff & Geldart, 1995), and the systematics of Chirp design and operation is dealt with more comprehensively in Schock & LeBlanc (1990) and Parent & O'Brien (1993). Furthermore, a *Notes* section is provided at the end of the paper providing definitions for some of the terminology and concepts introduced.

## The seismic reflection method

The seismic reflection method utilizes the propagation of waves through the earth. Seismic reflection profiling is accomplished by transmitting an acoustic signal through the water column into the underlying sediments and measuring the time interval between pulse transmission and the arrival of the reflected signals. Assuming a velocity at which the acoustic signal propagates through the sub-bottom sediments, it is possible to estimate the depth of reflectors. In seismic reflection theory, a material is characterized by its compressional wave velocity ($V_p$) and density ($\rho$). The product $\rho V_p$ is known as the acoustic impedance. If a contrast exists between the acoustic impedance of two materials ($\rho_1 V_{p1}$ and $\rho_2 V_{p2}$), then a reflection occurs at the boundary of the media (Fig. 1). The strength of this reflection is governed by the reflection coefficient, $K_R$, where:

$$K_R = \frac{\rho_2 V_{p2} - \rho_1 V_{p1}}{\rho_2 V_{p2} + \rho_1 V_{p1}} \quad \text{(Equation 1)}$$

This equation means that the higher the contrast between the acoustic impedances of the media, the stronger the reflection from the boundary. Values of $K_R$ range between $-1$ and $+1$. If $K_R = 0$, then the incident compressional wave is entirely transmitted, and no reflection occurs. Conversely, if $K_R = -1$ or $+1$ then complete reflection of the incident wave occurs,

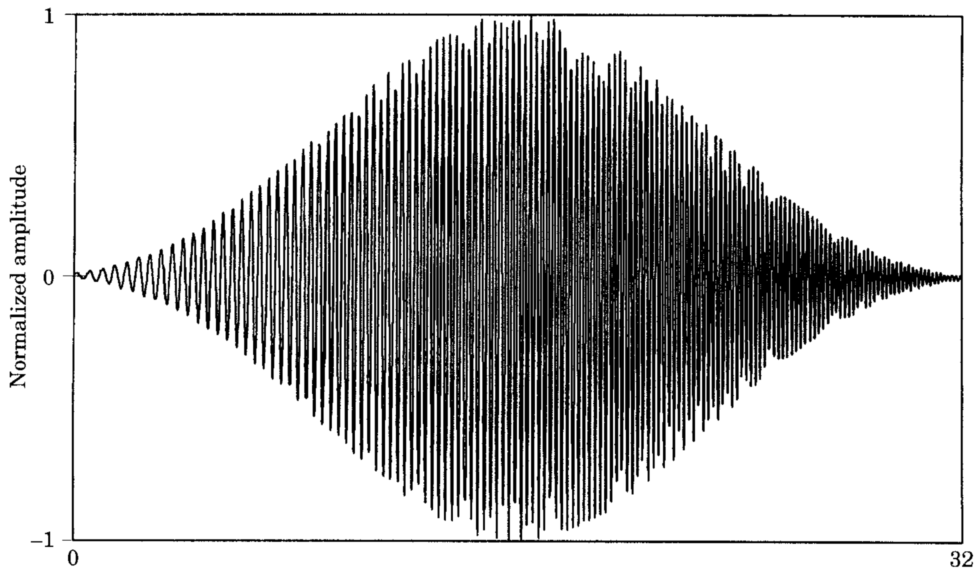


*Figure 2.* An example of a 32 ms frequency-modulated Chirp pulse, sweeping between 2 and 8 kHz (reproduced courtesy of GeoAcoustics Limited, Great Yarmouth, UK). Note the frequency content increases to the right.

and no energy is transmitted across the boundary.

In geological terms, values of $K_R$ tend to fall in the range of $\pm 0{\cdot}1$ (Anstey, 1981) with the majority of the energy being transmitted. Where anthropogenic materials such as wood are brought into contact with unconsolidated marine sediments, values of $K_R$ tend to have a broader range (Quinn *et al.*, 1996). Historically, wooden wrecks are composed of oak, with lesser components of pine, mahogany and elm. Quinn *et al.* (1996) demonstrated that theoretical reflection coefficients between oak and unconsolidated marine sediments range between $-0{\cdot}03$ and $-0{\cdot}63$ (values considerably higher than those found in normal sub-surface geological situations) indicating a high probability of imaging wooden artefacts using an appropriate sub-bottom profiling system.

**Chirp technology**

Perhaps the most important recent development in high-resolution marine geophysics is the advent of powerful and affordable digital electronics and desktop computing facilities. Chirp technology utilizes these developments to aid processing and acquisition techniques to produce high quality, high-resolution sub-bottom images in real time. The most obvious aspects of Chirp sonar that set it apart from conventional systems are the increased vertical resolution[1] of Chirp systems, pulse repeatability and the acquisition of data with a high signal-to-noise ratio[2] (SNR).

Unlike conventional short-pulse, single-frequency systems (e.g. pingers and boomers), the Chirp sonar transmits a linearly swept, frequency modulated (FM) pulse, i.e. the frequency of the pulse changes linearly with time (Fig. 2). In conventional sub-bottom profilers, a trade-off occurs between penetration and vertical resolution. A high frequency source produces high resolution images of the sub-bottom, but penetration is limited. Conversely, low frequency pulses penetrate deeper, but produce less-detailed sections.

Pinger's typically operate in a frequency range of 3 to 12 kHz, corresponding to vertical resolutions of the order 20 cm. The pinger's depth of penetration is very limited however, typically tens of metres in fine muds and only several metres in coarse sediments. Boomers, with a higher energy output, offer higher depths of penetration but vertical resolution is typically limited to 0·5 to 1 m. The Chirp systems wide bandwidth (typically of the order 10 kHz) limits this trade-off between penetration and vertical resolution by transmitting a range of frequencies, thus ensuring optimum penetration *and* resolution. The vertical resolution of the Chirp system is a function of the bandwidth of the transmitted pulse, whereas the resolution of conventional systems in entirely dependent on the pulse length. Therefore relatively low frequency wideband Chirp pulses can be used to achieve high vertical resolution. For example, a Chirp system bandwidth of 10 kHz corresponds to a theoretical vertical resolution of 7·5 cm, assuming a compressional wave velocity of 1500 $ms^{-1}$ (typical velocity value for the water column).

With conventional systems, variations in the amplitude and phase of the transmitted pulse lead to a problem in source repeatability. In the Chirp system, the problem of pulse repeatability is addressed by pre-processing the transmitted pulse, i.e. amplitude and phase weighting is applied to the outgoing Chirp pulse. Source repeatability greatly aids post-processing of the acquired sub-bottom data, as many of the algorithms applied to seismic data are designed around the signature of the transmitted signal.

Seismic data are usually corrupted with various forms of unwanted noise. FM pulse compression in the Chirp system is performed using a matched filter (Schock & LeBlanc, 1990), which correlates the recorded sub-bottom reflections with the transmitted pulse. If any of the recorded signal or noise energy does not match the outgoing Chirp pulse, the matched filter attenuates the unwanted signals thus improving the SNR of the acquired data.

### The *Mary Rose* site

The *Mary Rose*, King Henry VIII's flagship, was built in 1509 and subsequently wrecked on 19 July, 1545. The wreck was rediscovered in the Solent during the late 1960s (Fig. 3), and site excavation culminated with the raising of the hull remains in 1982. Events leading to the location, excavation and subsequent raising of the *Mary Rose* are well documented (McKee, 1982; Rule, 1982; Dobbs 1995). Today, the raised hull structure is on display in Portsmouth Dockyard, while the *Mary Rose* site itself remains one of 42 sites currently designated under the Protection of Wrecks Act, 1973 (Archaeological Diving Unit, 1996). Elements of the wreck remain buried on the seabed and the site is constantly monitored by the Mary Rose Trust.

Prior to the positive identification of the wreck in the late 1960s, a number of geophysical surveys were conducted over the supposed wreck-site in an attempt to locate the exact position of the *Mary Rose* (Rule, 1982). In 1967, an anomaly was recorded in the supposed position of the wreck by John Mills using a combination of dual-channel sidescan sonar and pinger. A year later, John Mills was joined by Professor Harold Edgerton of the Massachusetts Institute of Technology, and a second geophysical survey was conducted over the site, using two pingers operating at frequencies of 5 and 12 kHz. Four anomalies were recognised in close proximity to the supposed site, one of which was interpreted as the buried wreck. The target identified by the sub-bottom profilers provided sufficient impetus for the archaeologists to excavate the site.

During November 1994, 27 years after these initial geophysical surveys, the

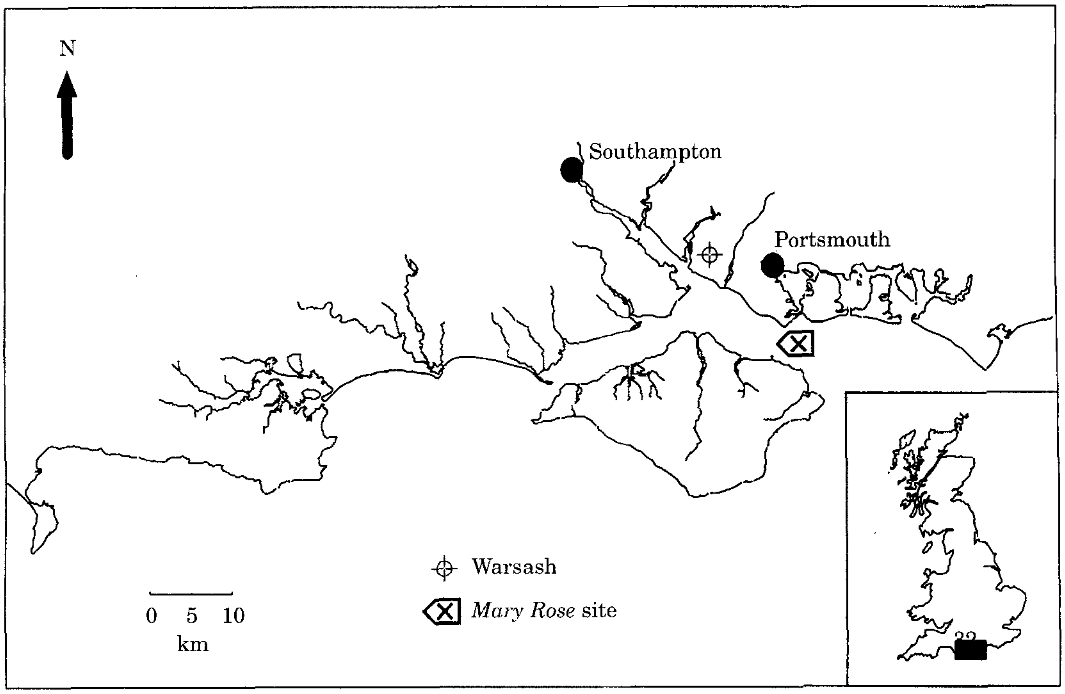


*Figure 3.* Location map of the *Mary Rose* site located at Spithead, East Solent. The location of the differential GPS land receiver station at Warsash is indicated.

authors surveyed the excavated *Mary Rose* site using a Chirp system. The aim of the survey was to investigate the site for remaining wreck structure, to put the excavated site into a sedimentological context with the advantage of detailed site knowledge supplied by the Mary Rose Trust and to assess the applicability of the Chirp system to marine archaeology.

## Survey equipment and methodology

The geophysical survey was conducted on 22 November 1994 aboard the research vessel *Mary Lisa*, utilizing a 2 to 8 kHz swept frequency Chirp system. Throughout the survey, a 32 ms pulse length and a system transmit rate of four pulses per second was used in the acquisition of digital sub-bottom data. Survey navigation, with an accuracy of ± 1 m, was provided by a differential global positioning system (DGPS).

A pseudo three-dimensional survey, of 10 m line spacing, was conducted over the site (Fig. 4), covering an area of approximately 350 × 250 m centred on the excavation hole. Eleven east–west and 18 north–south lines were acquired, totalling over 6 km of Chirp data. The survey grid was designed to provide close three-dimensional cover in order to image potential remaining wreck artefacts. Tight three-dimensional coverage ensured any artefact material recognised in the east–west sub-bottom profiles could be readily tied in with the north-south lines.

## Data processing

Sub-bottom profilers are capable of recording acquired data in digital format, and can be subsequently processed to increase the SNR in order to aid data interpretation. This post-processing can be purely cosmetic in terms of improving the

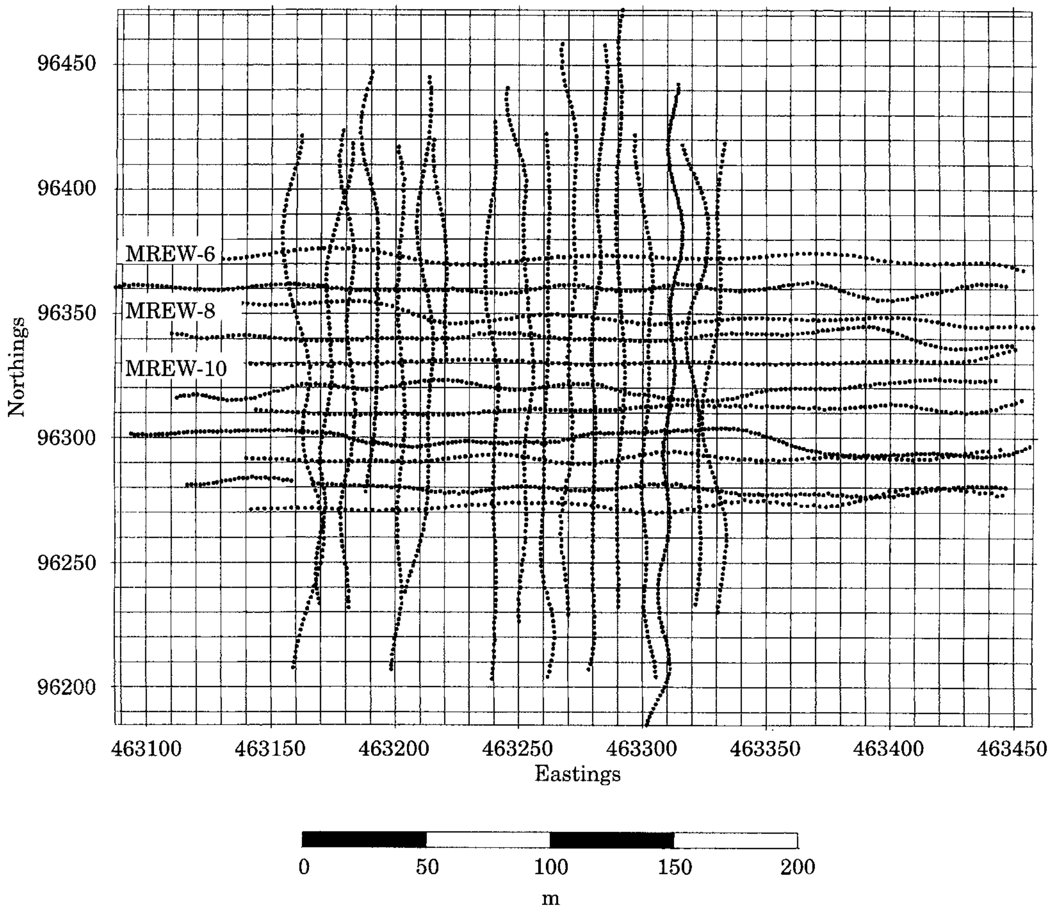


*Figure 4.* Shotpoint map of the three-dimensional Chirp survey of the *Mary Rose* site, Spithead, East Solent. The labelled lines are referenced in the text.

type of display (e.g. colour or grey-scale as opposed to black and white), or much more fundamental as is described below. The most widely accepted digital data format for the acquisition of sub-bottom data is SEG-Y format (the Society of Exploration Geophysicists—Y format), and recording in this format ensures that the data can be read by any seismic processing software (as developed by the exploration industry). The principal aim of seismic processing is to manipulate the acquired data in order to resemble as closely as possible the sub-surface stratigraphy and to aid data interpretation.

The Chirp data was correlated with the known 2–8 kHz source sweep in real-time during acquisition. Each survey line is corrected for tidal variations over the survey period, and subsequently converted to a time-equivalent ordnance datum. Further processing of the correlated Chirp data was completed using ProMAX™ software mounted on a Unix workstation. The processing sequence included true amplitude recovery[3], bandpass filtering[4], FX deconvolution[5] and the application of a dynamic signal-to-noise (S/N) filter (Fig. 5).

The first three algorithms in the processing sequence are standard seismic processing applications (Hatton *et al.* 1986;

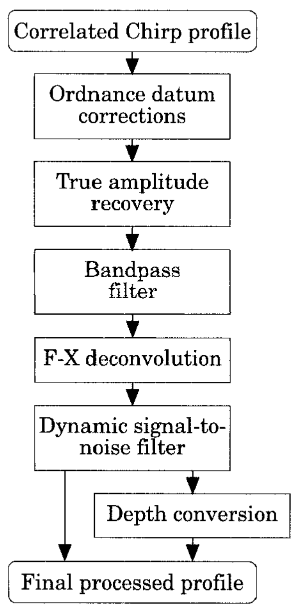


*Figure 5.* Flowchart of the sequence used in the seismic processing of the correlated Chirp data.

Yilmaz, 1987). The application of the dynamic S/N filter as a final step is less standard, and is particularly suitable to Chirp data as it eliminates the need for a conventional 'late-stage' time-variant bandpass filter which is exceedingly difficult to design due to the short data window (average 25 ms).

The dynamic S/N filter is applied to enhance the lateral coherency (or resolution) of the data by weighting each frequency by a function derived from the local signal-to-noise ratio. Dynamic S/N filtering differs from conventional coherency-enhancing methods as the standard methods include a portion of neighbouring traces through an addition process, which inherently leads to some form of lateral smearing (ProMAX User Manual, 1993). In this case, however, although the filter is derived from surrounding traces, it is applied to each trace in turn as an amplitude-only convolutional filter.

**Results and interpretation**

Examples of two post-processed sub-bottom profiles are displayed in Figs 6 and 7. Figure 6 is a section of the east–west Chirp sub-bottom profile MREW-10 (Fig. 4) showing a cross-section of the present day morphology of the excavation hole. From divers logs of the site (Adams, 1988) and the aqcuired Chirp sections, the local geology is interpreted as horizontal/sub-horizontal intercalated muds, clays and sands overlying bedrock of varying topography.

The most striking feature recognised in the sub-bottom profiles over the entire site is the discrete bright-spot (high amplitude reflector) observed in MREW-8 (Fig. 7). A second such discrete anomalous reflector is observed approximately 30 m to the south of the two lines. These brightspot reflectors are unconformable with the local geology, where the horizontal/sub-horizontal soft-sediments horizons terminate abruptly adjacent to the high-amplitude reflectors. The base of the anomalies form erosive surfaces, clearly post-dating the local stratigraphy. Examination of Fig. 7 indicates the majority of the incident energy is reflected at this horizon, indicating a very high acoustic impedance contrast between the comprising material and the surrounding sediments.

In order to examine the spatial relationship between the excavation hole and the brightspots referred to above, two-dimensional contour maps of the interpreted horizons were produced. Figure 8a is a contour plot of the sea-floor, produced by digitizing the seabed on each sub-bottom profile and interpolating across the entire survey area. The most obvious feature on the contour plot is the excavation hole located at the centre of the grid, measuring an average of 50 m × 20 m. A similar method was used in the spatial mapping of the brightspots. The maximum interpolated amplitude value was extracted from each trace in a 15 to 19 ms time window (thus encompassing the anomalies), normalized and subsequently interpolated across the survey area to produce

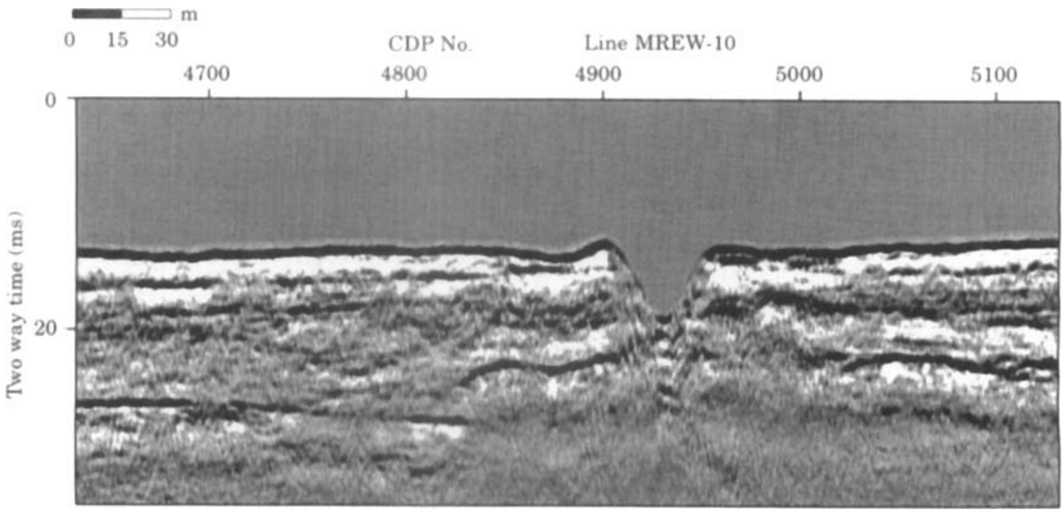


*Figure 6.* Processed portion of east–west orientated Chirp sub-bottom profile (acquired using a GeoAcoustics model 136A towed transducer system) MREW-10 showing a cross-section of the present day morphology of the excavation hole.

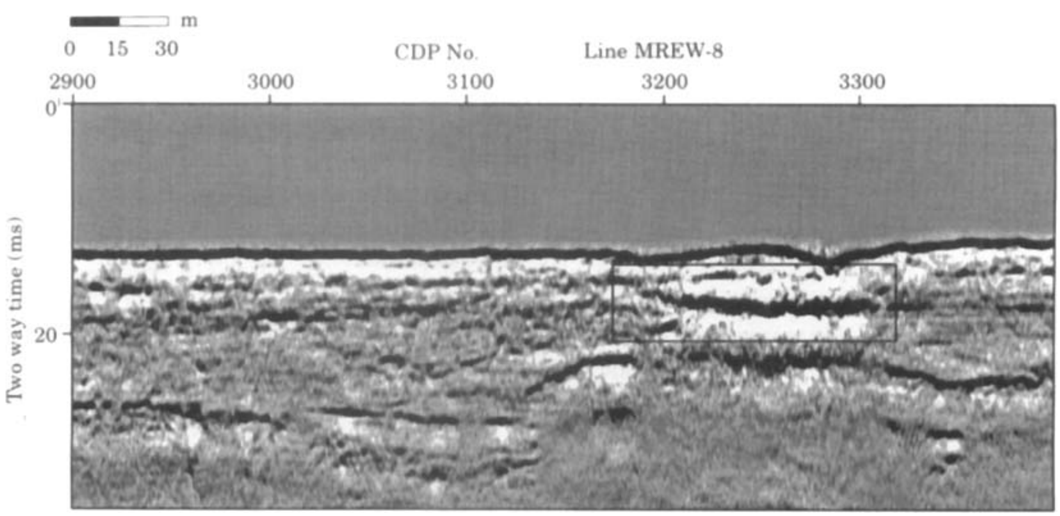


*Figure 7.* Processed portion of the Chirp sub-bottom profile MREW-8, displaying one of the 'brightspot' anomalies (highlighted by the black box). The anomaly is characterized by a discrete high amplitude reflector of length 60 m.

the contour plot of Fig. 8b in which two east–west trending amplitude 'highs' are seen towards the western flank of the survey grid. The sub-parallel anomalies are approximately 50 m in length, while the northern feature (with a maximum width of 20 m) is approximately 5 m wider than the southern anomaly. The base of these erosive features varies between 4·5 and 6 m below the seabed, while relief is limited to approximately 1·5 m.

Caston (1979) identified wreck-associated scour features from sonographs acquired in the outer part of the Thames

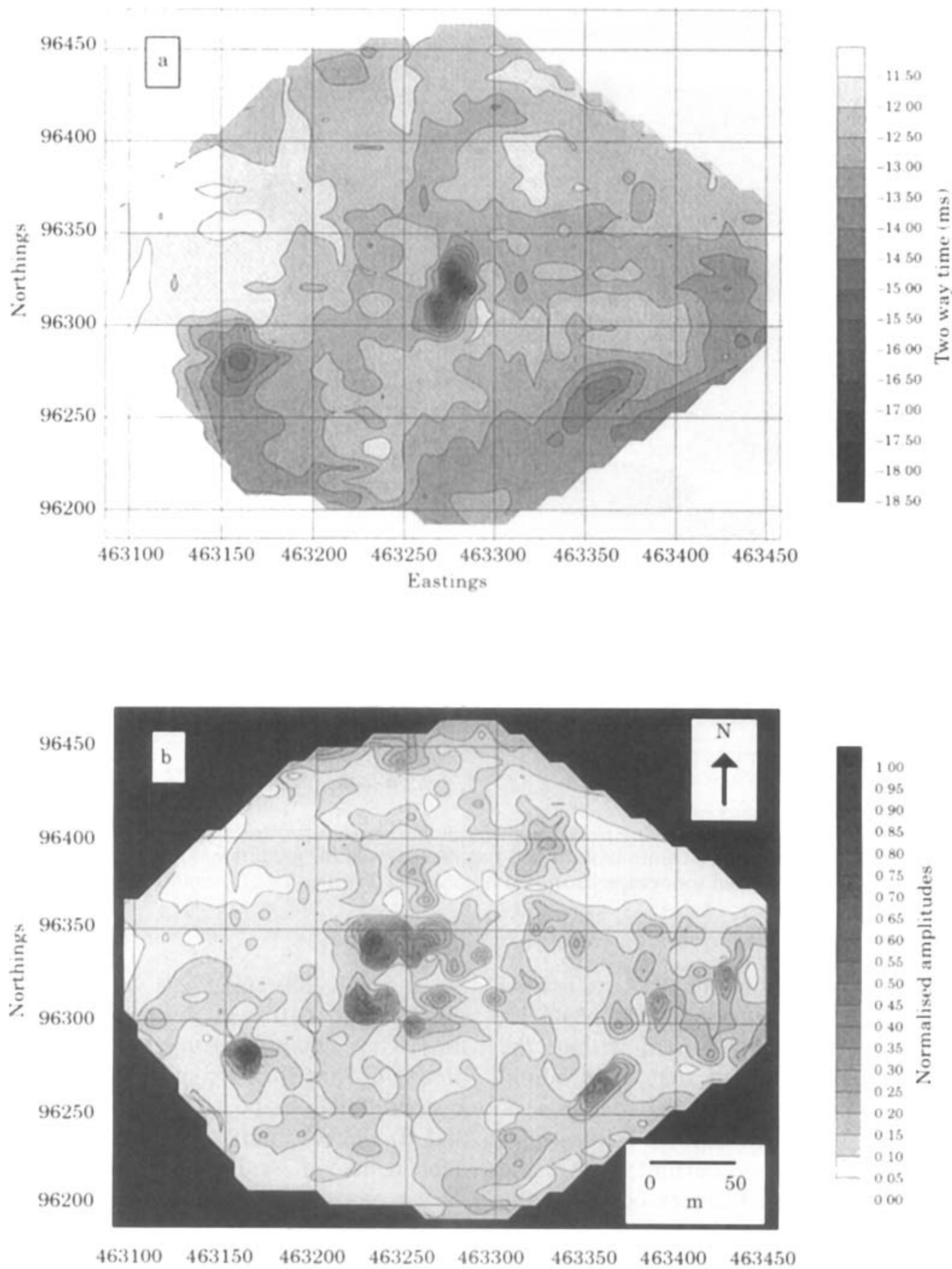


*Figure 8.* (a) A two-dimensional time contour plot of the sea-floor over the *Mary Rose* site. Topographic lows are shown as black, and highs as light-grey. (b) A two-dimensional contoured amplitude map of the 15–19 ms time horizon. The normalised amplitude scale is from light-grey (minima) to black (maxima).

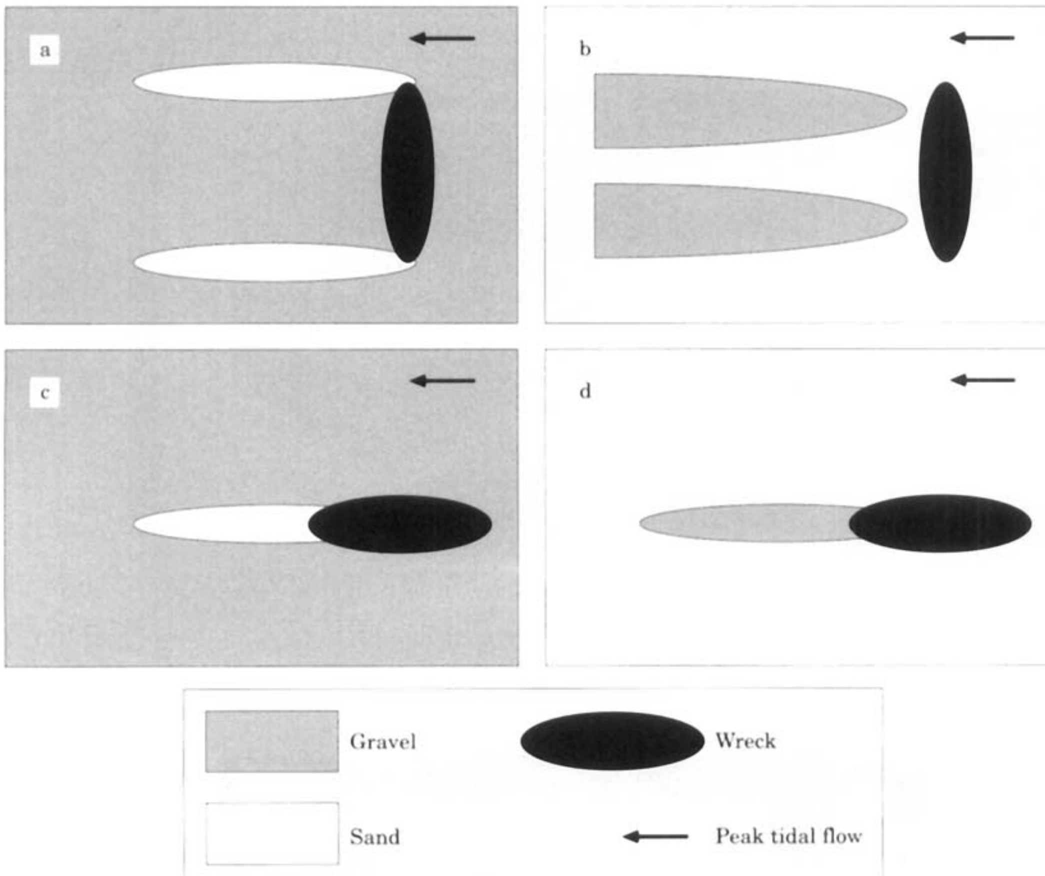


*Figure 9.* Diagrammatic representation of the end-member cases of the gradational series of longitudinal wreck marks observed from sonographs acquired in the outer Thames Estuary (modified from Caston, 1979).

Estuary. These erosional marks are associated with scour around wreck obstacles lying on, or partially buried within, the seabed. Caston showed that longitudinal wreck marks extend parallel to the peak tidal flow on the downstream (stronger of the peak ebb or flood current) side of the wreck. Where such features occur on the upstream side of the wreck they are much smaller in dimension. The occurrence of single or double wreck marks was shown to reflect the orientation of the wreck with respect to the peak tidal current flow. The most common type of wreck mark observed consists of twin scour shadows emanating from wrecks lying broadside to the current flow (Fig. 9a and b). The shortest and narrowest scour features are those that emanate from wrecks aligned precisely along the current, thus presenting a streamlined shape to the flow (Fig. 9c and d). Wreck mark morphology is also dependent on seabed lithology; wreck marks on a sand floor consist of broad, shallow troughs whereas those on gravel floors are narrower and less extensive (Fig. 9). A modern example of wreck marks is shown in the sonograph of Fig. 10. The unequal development of the wreck marks in each direction is due to the oblique alignment of the wreck relative to the peak tidal flow (from left to right).

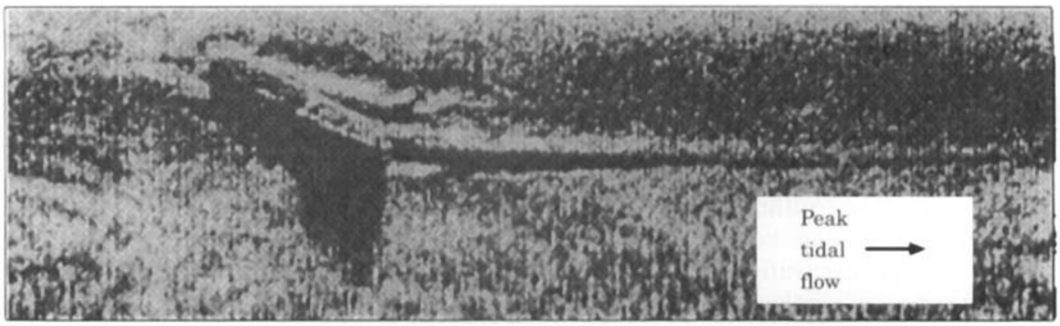


*Figure 10.* Sonograph showing a wreck (55 m long and a maximum of 14 m high) with scour hollows emanating from the bow and stern of the wreck (modified from Belderson *et al.*, 1982). The unequal development of the wreck marks is due to the oblique alignment of the wreck relative to the peak tidal flow.

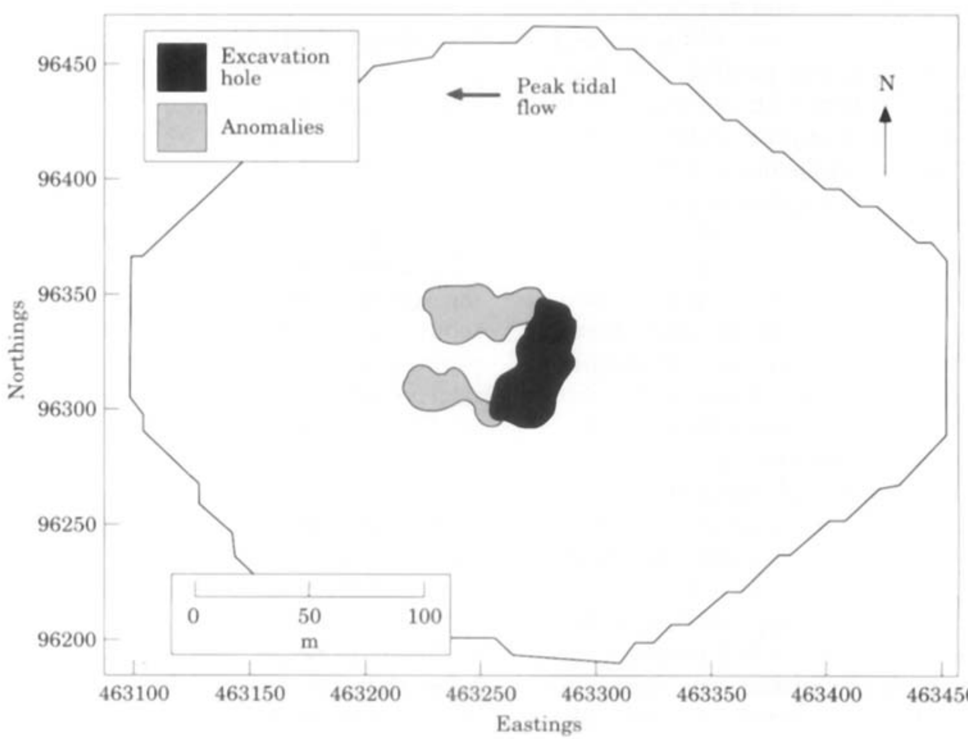


*Figure 11.* Composite map of the *Mary Rose* site displaying the position of the excavation hole (black) overlain on the spatial extent of the anomalies (grey) from Fig. 9.

Figure 11 is a composite map of the *Mary Rose* site, where the position of the excavation hole (former position of the *Mary Rose)* is laid over the east–west trending anomalies described above. The present-day peak tidal flow over the site (275 to 279°, Mary Rose Trust, pers. comm.) is also indicated. When the *Mary Rose* sank in 1545, the hull lay heeled on its starboard side in the seabed at an angle of 60° from the vertical (Rule, 1982). The nature of the obstruction the hull presented to easterly and westerly tidal flows was therefore very different. East–west currents passed over and around the irregular surfaces of the castling and decks, while those flowing west to east would have been deflected by the smoother form of the hull. The authors propose that the anomalies recognised on the western margin of the excavation hole are the manifestation of palaeo-scour features formed around the wreck of the *Mary Rose* soon after she was sunk.

Caston (1979) further demonstrated that longitudinal wreck marks are shallow (typically 1·5 m to 2 m) relative to their widths and lengths and may be curved near to the wreck but the distal portion is always straight and parallel. This description is consistent with observations from the sub-bottom profiles (where maximum relief on the anomalies is 1·5 m) and the shape of the anomalies in plan view (Fig. 11). When Fig. 11 is viewed alongside Figs 9 and 10, good correlation is noted in the spatial relationship between the anomalies and excavation hole of the *Mary Rose* site, and the scour marks and the position of the wrecks from Figs 9 and 10. The dimensions and erosive base of the anomalies are also consistent with wreck-associated scour features. Additional supporting evidence for this interpretation comes from the morphology of the wreck marks in relation to the seabed lithology over the site. Caston (1979) states that wreck mark morphology is dependent upon seabed lithology, where scour features formed on sandy floors around wrecks consist of longitudinally extensive, broad, shallow troughs as opposed to narrower, deeper and less extensive features on gravel floors (Fig. 9). The outline of the interpreted wreck marks on Fig. 11 indicate these scour features are broad in comparison to the dimensions of the excavation hole. The Tudor seabed on the *Mary Rose* site was a mix of clays and sands (Adams, 1988), and a comparison of Fig. 11 with Fig. 9b indicates a similar geometry between the position of the wreck and the morphology of the wreck marks formed on a sandy floor.

The presence of these longitudinal scour features was previously unrecognised on the *Mary Rose* site. Large segments of the hull superstructure and the stern and bow-castles of the wreck eroded subsequent to sinking. The authors propose that a proportion of this material survives as wreck fragments in the scour pits to the west of the excavation. In the years after sinking, the hull structure standing above the seabed in the water column gradually eroded and collapsed, so constituting progressively less of an obstruction to tidal flow (Rule, 1982). Hence, any depressions caused by the scouring action gradually filled in, sealing and preserving any timber elements and other objects deposited within. The resulting fill in the scour pits is therefore a stratigraphic record of this interrelated process and indicates a direct relationship between the morphology of the seabed obstruction and its associated scour features. Furthermore, the authors propose that the strong reflection from the interpreted wreck marks is due to the contrast between the fill material (a combination of oak wreck fragments and coarse grained sedimentary material deposited within these pits due to preferential deposition in topographic lows on the seabed) and the surrounding unconsolidated sediments.

These proposals indicate the authors' belief that the *Mary Rose* site has had a highly variable depositional history. This ranged from a highly dynamic erosive environment subsequent to the initial wrecking, followed by a period of relatively high deposition rates in the scour pits once the wreck structure had degraded to a level concordant with the seabed, to a more acquiescent period subsequent to the deposition of a 'hard shelly layer '(Rule, 1982) which sealed the Tudor levels over the site in the late 17th or early 18th century.

Recognition and preservation of longitudinal scour features in the sedimentary record conveys important implications for the maritime archaeologist and the surveying geophysicist. For the archaeologist, the buried longitudinal scour pits may be high profile target sites where fragmented material from a degraded wreck is deposited and preserved. The scours may also contain important evidence for the archaeologist regarding the nature and chronology of wreck degradation within a dynamic environment. For the surveying geophysicist, the sheer dimensions of these material traps imply they may be more easily recognised on the sub-bottom profile than the actual target wreck. In extreme cases, where a wooden wreck is so completely degraded that the majority of the superstructure is fragmented, the wreck may not provide the concentration of coherent material required to produce a strong reflection, but material in associated scour pits may.

## Conclusions

The Chirp profiles of the excavated *Mary Rose* site have imaged structures previously unknown on site, interpreted as infilled longitudinal scour features associated with the sinking and subsequent degradation of the *Mary Rose* in a dynamic tidal environment. The authors propose that the fill material includes wreck fragments from the superstructure of the *Mary Rose* and coarse grained sediment preferentially deposited in scour hollows on the portside of the ship.

The preservation of longitudinal palaeoscour features has important implications for both the maritime archaeologist and the geophysical surveyor. Information regarding the degradation and preservation of a wreck may be gleaned from the morphology and systematic excavation of these material traps. The dimensions of the filled scour marks indicate these features may be more easily recognised on sub-bottom profiles than the partially degraded wrecks that were originally responsible for their formation.

The Chirp profiling technique has proven itself as a rapid, non-invasive investigative technique for sites of maritime archaeological interest, and is therefore of particular utility in the protection and management of submerged archaeological material. Rather than merely providing a technique for locating sites, high-resolution sub-bottom data can provide information regarding the nature and chronology of wreck degradation and a more accurate definition of the extent of a site.

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## Notes

[1] *Vertical resolution*: The minimum distance between two distinguishable adjacent reflectors.

[2] *Signal-to-noise ratio*: The term signal is used to describe any event from which we require information, everything else in the seismic record may be attributed to noise. Seismic data quality is defined by its signal-to-noise ratio (SNR), i.e. the ratio of signal energy to noise energy in the acquired data. Good quality data will therefore have a high SNR.

[3] *True amplitude recovery*: Applies a single time-variant function to the sub-bottom data to compensate for loss of amplitude due to wavefront spreading.
[4] *Bandpass filter*: This is applied to seismic data in order to suppress low- and high-frequency noise.
[5] *Deconvolution*: This is the process of undoing one or more filters which are considered to have had an undesirable effect on the data. The successful application of deconvolution frequently increases the resolution of seismic data.

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