

Imaging Wooden Artefacts using Chirp Sources

R. QUINN¹†, J. M. BULL¹ AND J. K. DIX²

¹Department of Geology, University of Southampton, Southampton Oceanography Centre, Empress Dock, European Way, Southampton SO14 3ZH, UK; and

²Department of Oceanography, University of Southampton, Southampton Oceanography Centre, Empress Dock, European Way, Southampton SO14 3ZH, UK

ABSTRACT This paper investigates the potential for imaging submerged and buried wooden artefacts in the marine environment using high-resolution seismic reflection techniques. Models to calculate theoretical reflection coefficients of 11 wood species buried in shallow marine sediments are developed. The models use estimates of acoustic impedance contrasts to predict the strength of reflections resulting from buried wooden artefacts. Traditionally, wooden wrecks are composed of oak, with lesser components of mahogany, pine and elm. Experimental results on wood samples from a sixteenth century oak wreck (the *Mary Rose*) are presented as a control on theory.

Results indicate that wooden wrecks may be readily imaged by a suitable sub-bottom profiler operating under appropriate survey conditions. Particular reference is made to Chirp sonar, which transmits a frequency modulated pulse, providing high-resolution digital seismic data. Chirp data acquired over an eighteenth century buried oak wreck (the *Invincible*, Horsetail, East Solent) is presented. Calculations of reflection coefficients from reflection data acquired over the site support both the theoretically and experimentally derived data. © 1997 John Wiley & Sons, Ltd.

Archaeol. Prospect. 4: 25–35, 1997.

No. of Figures: 7. No. of Tables: 4. No. of References: 21.

Key words: wood; shipwreck; reflection seismology; Chirp.

Introduction

Over the past three decades, marine seismic reflection techniques (echosounders, sidescan sonars and sub-bottom profilers) have been used in the investigation of sites of maritime archaeological interest (McGhee *et al.*, 1968; Frey, 1971; Chauhan and Almeida, 1988; Rao, 1988; Redknapp, 1990; Hobbs *et al.*, 1994). Traditionally,

the application of sub-bottom profiling techniques 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 high-resolution, digital, frequency modulated (FM) sub-bottom profiling system. Chirp has proven itself as a useful surveying tool in disciplines where high vertical resolution is a necessity, e.g. environmental and cable and pipe laying operations (McGee, 1990; Schock and LeBlanc, 1990). The authors believe that Chirp is the first suitable sub-bottom profiling technique required for detailed investigations of maritime archaeological sites.

†Correspondence to: R. Quinn, Department of Geology, University of Southampton, Southampton Oceanography Centre, Empress Dock, European Way, Southampton SO14 3ZH, UK. Tel: (01703) 595073/596608. Fax: (01703) 593052. Email: rjq@mail.soton.ac.uk

Contract grant sponsor: NERC (UK); Contract grant number: GR3/9533.

The seismic reflection method

The success of the seismic reflection method is dependent upon the presence of resolvable acoustic impedance contrasts within the subsurface. Acoustic impedances (the product of density, ρ and compressional wave velocity, V_p) can be used to define the reflection coefficient, V_p , which is a measure of the strength of the reflection:

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

A reflection will occur at a boundary if a contrast exists between the acoustic impedances of the media. The polarity of the reflection coefficient is dependent on whether there is an increase (positive reflection) or decrease (negative reflection) in ρV_p across the interface. In normal subsurface geological situations, values of K_R fall into the range of ± 0.1 (Anstey, 1981), with the majority of the energy being transmitted.

Wood structure and elasticity

The compressional wave velocity in any material is dependent upon the state of isotropy of the material. Conventional seismic theory assumes material isotropy and therefore a single compressional wave velocity. Wood, however, is a composite, anisotropic material (Flinn and Trojan, 1981; Smith, 1986; Weidmann *et al*, 1990), and a single compressional wave velocity does not accurately characterize a wood species. An understanding of this anisotropy is fundamental in calculating compressional wave velocities for wood. The following section briefly examines the nature of wood anisotropy and comments on the variability in the elastic properties of wood.

In order to correlate a given direction in a tree with its macrostructure the following set of axes is defined (Figure 1): the axis parallel to the tree stem is called the longitudinal axis (L), while the axis perpendicular to the annual growth rings is called the radial axis (R). The third axis, the tangential axis (T), is parallel to the growth rings and perpendicular to both the L and R (Hearmon, 1948; Flinn and Trojan, 1981; Smith, 1986; Weidmann *et al*, 1990).

The theory of wood elasticity rests on the assumption that the gross material possesses three mutually perpendicular planes of elastic symmetry (Figure 2), and that it is perfectly elastic and homogeneous (Hearmon, 1948). Wood, however is only an approximation to this ideal material. The longitudinal–tangential surface (generated by a line parallel to the axis of the tree and moving along the growth rings) is not a plane, but roughly cylindrical. The other two planes of elastic symmetry are more truly planar, but even in these some deviations occur due to growth irregularities (Hearmon, 1948).

The extent to which a specimen departs from the ideal material is dependent on the position of the specimen within the framework of the tree. If the distance of the specimen from the centre of the tree is large in comparison with the sample dimensions, the effect of curvature of the longitudinal–tangential plane is minimal (Hearmon, 1948), and this surface is more truly planar. The values of elastic constants within a single tree can vary by 20 per cent, and specimens from different trees of the same species may differ by a factor of 2:1 (Hearmon, 1948). Throughout

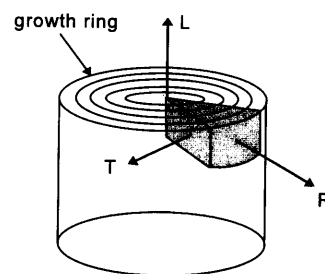


Figure 1. Diagram illustrating the three wood axes: L = longitudinal, R = radial and T = tangential. (Modified from Weidmann *et al*, 1990.)

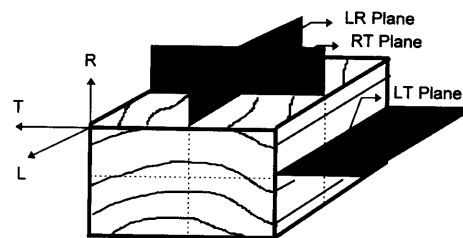


Figure 2. Diagram illustrating the three planes of elastic symmetry in wood: LR = longitudinal–radial plane, RT = radial–tangential plane and LT = longitudinal–tangential plane.

this paper, when calculating compressional wave velocities in wood, the assumption of a planar longitudinal-tangential surface is made.

Compressional wave velocities in wood

The compressional wave velocity in a wood sample is dependent upon the orientation of the incident compressional wave relative to the axes/planes of elastic symmetry. Pure compressional waves are those in which the direction of particle displacement coincides with the direction of wave propagation. Pure compressional waves therefore can occur only in solids in which dimensions in all directions are greater than a wavelength (Cremer *et al*, 1973). Thus, only some seismic waves are pure compressional waves. When dealing with a natural material such as wood, samples are rarely (if ever) of sufficient extent in all directions to support pure compressional waves. This paper treats the wooden specimens as plates (thus mimicking planks of wood as used in ship construction), where at least one sample dimension is smaller than a single wavelength. Figure 3 outlines the three possible end-member cases for a compressional wave incident upon a wood sample. It must be stressed that these are end-member cases, and any intermediate case is possible.

The compressional wave velocity incident on a plate is calculated from:

$$V_P = \sqrt{\frac{E}{\rho(1 - \mu^2)}}, \quad (2)$$

(Cremer *et al*, 1973), where E is the Young's modulus (ratio of stress to strain in the tension

direction), μ is Poisson's ratio (the ratio of lateral extension to longitudinal contraction) and ρ the density.

For the three independent cases outlined in Figure 3, the compressional wave velocities are calculated by:

$$V_L = \sqrt{\frac{E_L}{\rho(1 - \mu_L^2)}} \quad (2a)$$

$$V_R = \sqrt{\frac{E_R}{\rho(1 - \mu_R^2)}} \quad (2b)$$

$$V_T = \sqrt{\frac{E_T}{\rho(1 - \mu_T^2)}} \quad (2c)$$

where the average Poisson Ratio in the direction of applied stress is used. Results of the calculated compressional wave velocities of the 11 wood species are listed in Table 1.

Figure 4 is a log-normal plot of compressional wave velocity against density for the 11 wood species represented in Table 1. The compressional wave velocities along-grain (V_L) are consistently faster than those across-grain (V_R and V_T). Best-fit lines (least-squares method) plotted against the point distribution demonstrate a divergent relationship with decreasing density for along-grain and across-grain values. This relationship indicates that the anisotropy of wood decreases with increasing density.

Experiment on oak samples from the *Mary Rose*

British-built pre-nineteenth century wooden ships were traditionally constructed from oak, with lesser components of mahogany, pine and elm (J. Adams, pers. comm.). In order to validate the theoretically derived compressional wave velocities, a series of experiments were carried out on a suite of oak samples from the hull structure of the *Mary Rose* (King Henry VIII's flagship), which was wrecked off the south coast of England in 1545, and subsequently raised in 1982. The experimental work on the wood

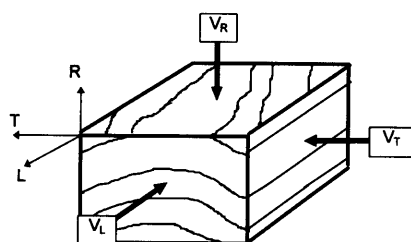


Figure 3. Diagram illustrating the three end-member cases (V_L , V_R and V_T) for a compressional wave incident on a plank of wood.

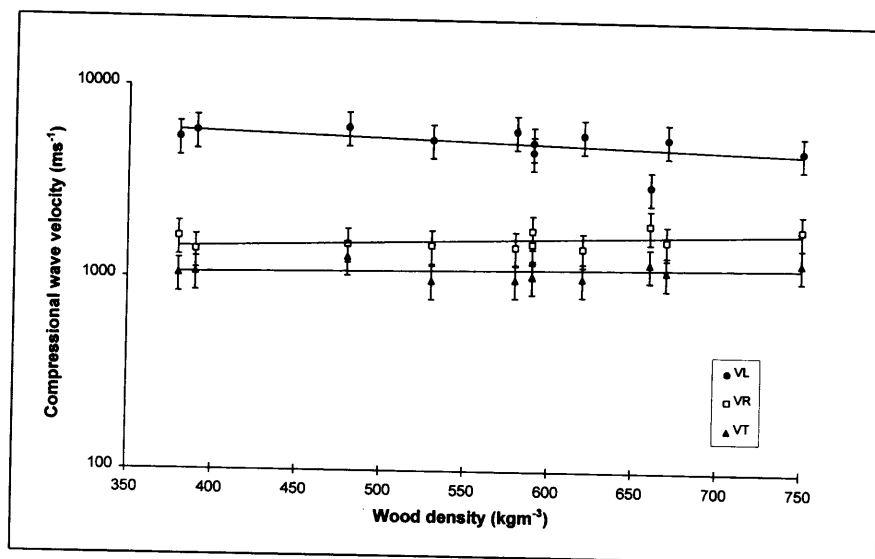


Figure 4. A plot of compressional wave velocity against density for the 11 wood species of Table 1. Errors of 20 per cent on individual species values are used, as indicated by Hearmon (1948).

samples was conducted in conjunction with the Institute of Sound and Vibration Research at the University of Southampton. Two experimental configurations were used. The first set of experiments were designed around a 1.82 m oak beam taken from the hull of the wreck. Owing to sample dimensions, only the compressional wave velocity in the longitudinal direction (V_L) was measured. The second set of experiments were conducted on a series of incrementally cored samples (5 mm diameter) taken from the outer portions of timbers, which were in direct contact with the burial sediments.

Figure 5 shows the experimental configuration for the beam experiment. In order to ensure

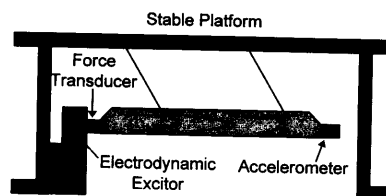


Figure 5. Schematic of the experimental configuration for the estimation of V_L from the oak sample taken from the hull structure of the *Mary Rose* (see text for more details).

good contact between the wood and the force transducer, the beam was suspended from a stable platform by means of angled cables. At the opposite end of the sample, an accelerometer was attached via a self-tapping screw,

Table 1. Table of wood density, Young's modulus (E), Poisson's ratio (μ), and the compressional wave velocities calculated from equation (2a-c) for the 11 wood species. (The density, Young's modulus and Poisson's ratio data is from Hearmon, 1948)

Wood species	Density (kg m^{-3})	E_L (GN m^{-2})	E_R (GN m^{-2})	E_T (GN m^{-2})	μ_L	μ_R	μ_T	V_L (m s^{-1})	V_R (m s^{-1})	V_T (m s^{-1})
Ash	670	15.8	1.51	0.80	0.49	0.38	0.20	5570	1620	1120
Beech	750	13.7	2.24	1.14	0.48	0.41	0.20	4870	1890	1260
Birch	620	16.3	1.11	0.62	0.46	0.41	0.20	5780	1470	1020
Maple	590	10.0	1.52	0.87	0.48	0.46	0.22	4690	1810	1250
Mahogany	530	12.4	0.97	0.48	0.43	0.43	0.22	5360	1500	980
Oak	660	5.3	2.14	0.97	0.42	0.39	0.19	3120	1960	1230
Walnut	590	11.2	1.19	0.63	0.56	0.39	0.20	5260	1540	1050
Poplar	380	9.7	0.89	0.41	0.36	0.36	0.17	5420	1640	1050
Douglas fir	480	15.7	1.06	0.78	0.37	0.21	0.19	6160	1520	1300
Scots pine	580	16.3	1.10	0.57	0.47	0.36	0.16	6010	1480	1000
Spruce	390	10.7	0.71	0.43	0.45	0.27	0.17	5870	1400	1070

ensuring minimal structural damage to the beam. Throughout the experiment, the sample was kept in a plastic coating to ensure minimal moisture loss, and was insulated from direct contact with the cables by means of heavy cotton padding.

Two experimental methods were used to produce independent values for the compressional wave velocity of the beam in the longitudinal direction.

- (i) *The phase-delay method.* The phase at both ends of the beam was measured via the force transducer and the accelerometer, and the variation in phase ($\Delta\phi$) was recorded with change in frequency (Δf). The compressional wave velocity was then calculated from:

$$V_p = \frac{\Delta\omega\Delta x}{\Delta\phi}, \quad (3)$$

where $\Delta\omega = 2\pi\Delta f$, Δx is the beam-length and $\Delta\phi$ is the phase delay.

- (ii) *The cross-correlation method.* A compressional wave was transmitted down the length of the beam by the force transducer. The transmitted wave was measured initially at the force transducer and again at the accelerometer, and the resulting spectra were cross-correlated. The correlation peak

gave the transit time for the compressional wave to travel the beam-length. The compressional wave velocity was calculated by dividing the length of the sample (Δx) by the transit time (t):

$$V_p = \frac{\Delta x}{t}. \quad (4)$$

Graphical representation of the experimental results on the oak beam are shown in Figure 6. The linear relationship demonstrated between phase and frequency in Figure 6a indicates that no interference from bending waves was introduced into the experiment and that the propagating compressional wave is frequency independent, thus validating the experimental methods used.

The second set of experiments measured the force (F) exerted on the cored oak samples by an accelerometer within a frequency range of 0–6.4 kHz. An estimate of the Young's modulus (E) was calculated from the relationship:

$$E = \frac{F}{A}, \quad (5)$$

where A is the cross-sectional area (πr^2). The compressional wave velocity of each cored sample was subsequently calculated from:

$$V_p = \sqrt{\frac{E}{\rho}}. \quad (6)$$

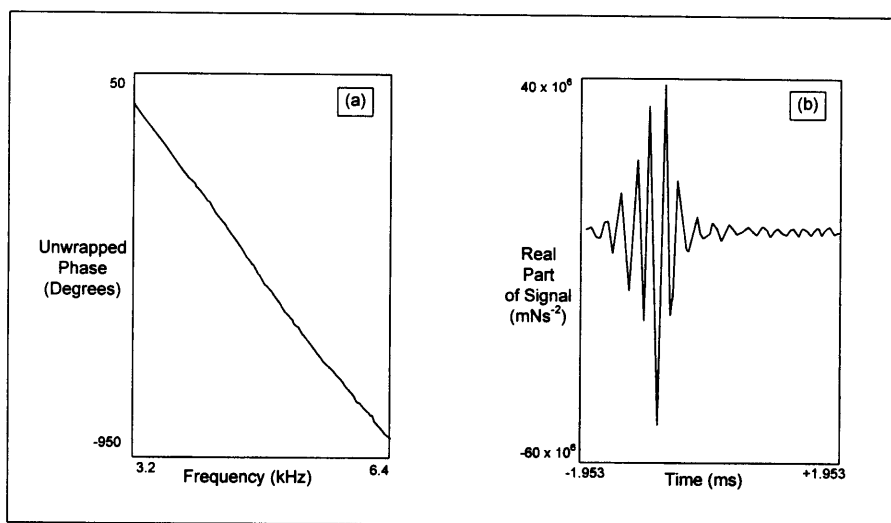


Figure 6. Graphical representation of the experimental results on the oak beam experiments: (a) results from the phase-delay method; (b) results from the cross-correlation method.

Table 2. Table summarizing the compressional wave velocities calculated for oak from theory and experiment

Calculation method	V_L (m s ⁻¹)	V_R (m s ⁻¹)	V_T (m s ⁻¹)
Theoretical	3120 (± 20 per cent)	1960 (± 20 per cent)	1230 (± 20 per cent)
Experimental phase delay	2370 (± 15 per cent)	—	—
Experimental cross-correlation	2300 (± 15 per cent)	—	—

Table 3. Table of typical density and velocity values for unconsolidated marine sediments (after Orsi and Dunn, 1991)

Lithology	Density (kg m ⁻³)	Compressional wave velocity (m s ⁻¹)
Sand	2100	1734
Sand-silt-clay	1740	1575
Clay	1450	1496

Comparison of theoretical and experimental results

Table 2 summarizes the theoretically derived oak values and experimental results for the oak beam. The data series agree within error limits, thus validating the theoretically derived compressional wave velocities. Differences in velocity values may be explained by the large variations in elastic properties between individual wood specimens. Experimental work on the cored samples from the outer 5 cm of timbers from the *Mary Rose* (all values lie around 1000 m s⁻¹) demonstrate that oak samples that have been in close proximal contact with the marine environment are degraded and possess more isotropic elastic properties. This structural degradation is limited to the outer few centimetres of the specimens, whereas the inner wood of the beam is structurally sound and demonstrates no appreciable degradation in relation to the theoretically derived compressional wave velocity.

These results correlate strongly with the findings of Wilson *et al* (1993) who studied the degradation of oak from ships wrecked in the Indian Ocean (over the period 1629 to 1886) using geochemical techniques. These authors concluded that the degradation of outer wood samples (those in close contact with the marine environment) is due to loss of carbohydrates, whereas the inner wood of the timbers is protected from this loss and remains structurally sound. Furthermore, the authors concluded that

inner wood samples are relatively undegraded when compared with modern oak and there appears to be no correlation between the age of wood and the degree of degradation.

Reflection coefficients of wood samples from the marine environment

In order to assess the probability of imaging buried wooden artefacts, a series of K_R calculations (equation 1) were made using the densities and velocities of wood ($\rho_2 V_{p2}$) listed in Table 1 and published density and velocity information of unconsolidated marine sediments ($\rho_1 V_{p1}$) listed in Table 3. Results of the calculated reflection coefficients between the two media are listed in Table 4.

The resulting reflection coefficients range between -0.8 and $+0.27$, whereas the majority of the K_R values lie between -0.2 and -0.8 , i.e. K_R values of wood buried in unconsolidated marine sediments are generally large and negative. The magnitudes of the reflection coefficients indicate that reflected disturbances possess 20–80 per cent of the incident amplitude and suggest that wooden artefacts will be readily imaged by a suitable seismic reflection system. Anstey (1981) states that values of $K_R = \pm 0.3$ are unusual in the earth because it is rare that such contrasting materials should be brought into contact. Clearly, however, in the realm of maritime archaeology, such high order reflection coefficients are the norm rather than the exception.

Chirp technology and acquired data

For the benefit of readers who are unfamiliar with basic underwater surveying methodology, a short glossary of the acoustic techniques described in this paper is appended. Recent

advances in both acquisition and processing techniques have culminated in the development of a system known as 'Chirp', a high-resolution, digital, frequency-modulated (FM) sub-bottom profiling system (Schock and LeBlanc, 1990; Parent and O'Brien, 1993) for operation in the marine environment. The most important feature that sets Chirp profilers apart from conventional profilers (such as boomers and pingers) is Chirp's ability to transmit a swept frequency source, thus greatly increasing the vertical resolution of the system. The resolution is a function of the bandwidth of the transmitted pulse, whereas the resolution of conventional systems is entirely dependent on the pulse length (Parent and O'Brien, 1993). Therefore, relatively low frequency wideband Chirp pulses can be used to achieve high vertical resolution. For example, a Chirp source bandwidth of 10 kHz corresponds to a theoretical resolution of 7.5 cm, assuming a compressional wave velocity of 1500 m s^{-1} (typical velocity for the water column).

Having established theoretically and experimentally that it is possible to image buried wooden artefacts in the marine environment, the authors surveyed a site of maritime archaeological interest using a combined array of a dual frequency side-scan sonar mounted on a Chirp towed transducer system. The *Invincible* site (Horsetail, East Solent, UK) was chosen as a test site because it offered the opportunity to acquire data over an eighteenth century oak wreck partially buried by unconsolidated sediments. The *Invincible* (originally *L'Invincible*), a 74 gun third rate, was captured from the French in 1747 and wrecked in 1758. The site of her loss, relocated in 1979, has been partially excavated and a large number of objects have been raised and conserved (Lavery, 1988).

The geophysical survey was conducted utilizing a 100 kHz side-scan sonar combined with a 2 to 8 kHz swept frequency Chirp system in an average water depth of 6 m. Throughout the survey, a transmit rate of four pulses per second was used in the acquisition of digital side-scan and sub-bottom data. Navigation data, with an accuracy of $\pm 1 \text{ m}$, was provided by a differential global positioning system (DGPS).

Figure 7 is a composite image of one line-acquired over the site. It is evident from the

Table 4. Table summarizing the reflection coefficients calculated for the 11 wood species of Table 1 buried in the unconsolidated marine sediments, the properties of which are listed in Table 3. The K_R values in brackets are unlikely to be imaged by reflection seismology because the contrast in acoustic impedances are too low to give rise to a distinct reflection

Wood species	K_R (V_L in sand)	K_R (V_R in sand)	K_R (V_T in sand)	K_R (V_L in sand - silt-clay)	K_R (V_T in sand - silt-clay)	K_R (V_L in clay)	K_R (V_R in clay)	K_R (V_T in clay)
Ash	[+0.012]	-0.541	-0.658	+0.153	-0.433	-0.570	+0.265	-0.333
Beech	[+0.002]	-0.440	-0.588	+0.143	-0.318	-0.487	+0.255	-0.210
Birch	[-0.008]	-0.600	-0.704	+0.133	-0.501	-0.625	+0.246	-0.408
Maple	-0.136	-0.546	-0.663	[+0.005]	-0.439	-0.576	+0.121	-0.340
Mahogany	-0.124	-0.642	-0.750	[+0.018]	-0.550	-0.681	+0.134	-0.464
Oak	-0.278	-0.476	-0.635	-0.142	-0.359	-0.543	-0.026	-0.253
Walnut	-0.080	-0.601	-0.709	+0.062	-0.502	-0.631	+0.177	-0.410
Poplar	-0.277	-0.708	-0.802	-0.142	-0.629	-0.746	-0.026	-0.554
Douglas fir	-0.104	-0.666	-0.707	+0.038	-0.629	-0.629	+0.154	-0.497
Scots pine	-0.022	-0.618	-0.725	+0.120	-0.523	-0.651	+0.233	-0.433
Spruce	-0.228	-0.739	-0.794	-0.090	-0.668	-0.736	+0.027	-0.598
								-0.677

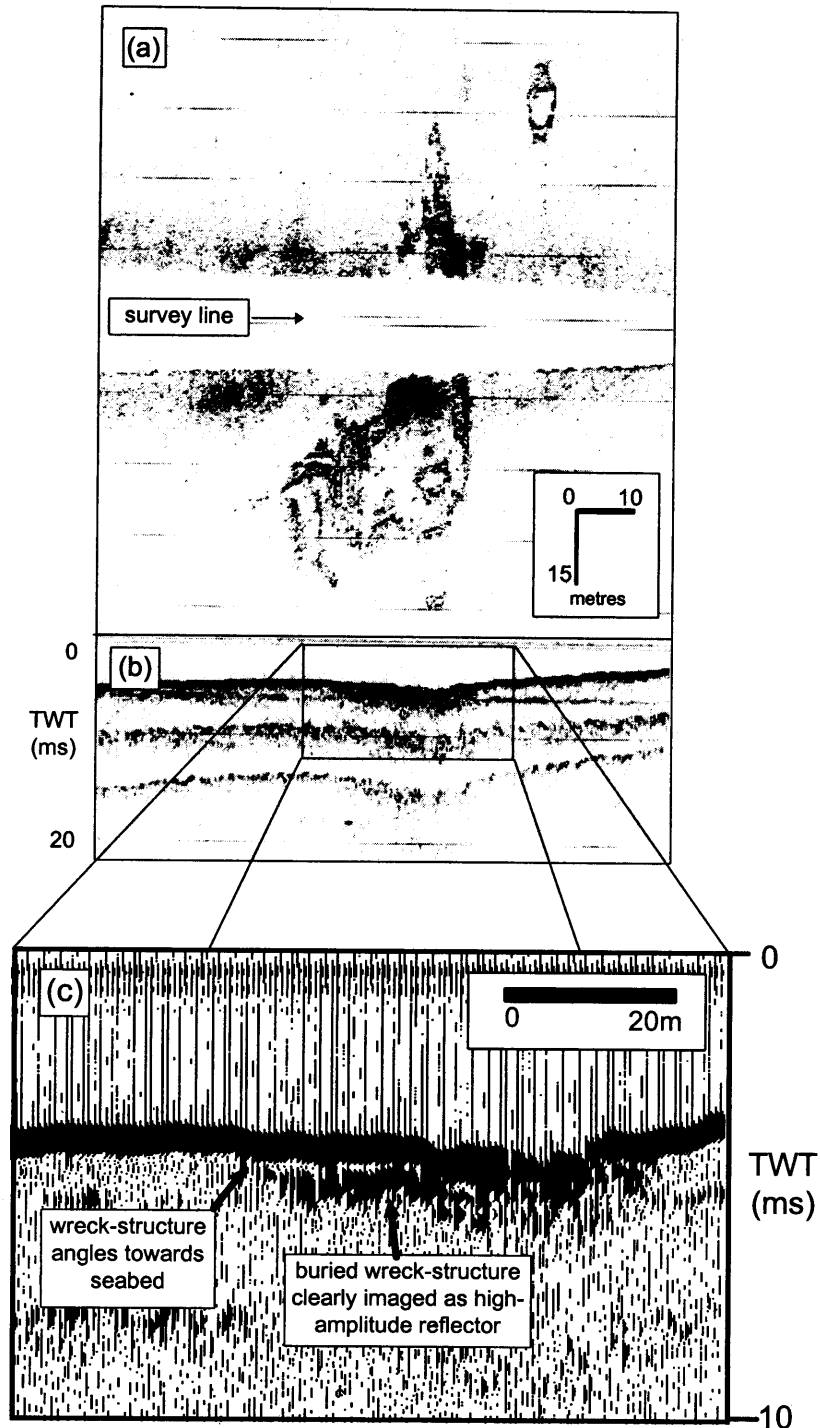


Figure 7. Composite image of the *Invincible* site, Horsetail, East Solent, UK. (a) A dual channel 100 kHz sonograph of the wreck, acquired using a GeoAcoustics dual frequency side-scan sonar. (b) The corresponding correlated Chirp profile, acquired using a GeoAcoustics Model 136A towed transducer system. (c) An enlarged bandpass filtered section of (b). These data were acquired over the centre of the semi-buried wreck, surveying from the buried port-side of the *Invincible* to the exposed starboard-side (left-to-right in the above diagram). The buried oak wreck structure is clearly imaged as a high amplitude reflector in section (c).

side-scan image that a large portion of the wreck was exposed on the seabed at the time of survey. The filtered profile of section (c) clearly images the buried portside of the wooden wreck, providing proof that reflection seismology can image buried wooden artefacts.

A reflection coefficient of the wreck (oak buried in unconsolidated marine sediments) was subsequently calculated to compare with the theoretically derived K_R values listed in Table 4. Following Anstey (1977), Warner (1990) and Spence *et al* (1995), reflection coefficients of the sea-floor ($K_{R(sf)}$) and the oak wreck ($K_{R(wreck)}$) were calculated from the Chirp data using the following relationships:

$$K_{R(sf)} = \frac{TWT_m}{TWT_p} \frac{A_m}{A_p}, \quad (7)$$

and

$$K_{R(wreck)} = K_{R(sf)} \frac{TWT_{wreck}}{TWT_p} \frac{A_{wreck}}{A_p}, \quad (8)$$

where A_p , A_m , A_{wreck} represent the amplitudes of the primary sea-floor reflector, the first multiple and the wreck reflector, and TWT_p , TWT_m and TWT_{wreck} represent the two-way travel times to the primary sea-floor reflector, the first multiple and the wreck structure. A full explanation of the method for calculating reflection coefficients from Chirp data is outside the scope of this paper, however, the results are presented:

$$K_{R(sf)} = +0.43$$

$$K_{R(wreck)} = -0.27$$

A comparison of the reflection coefficient of the wreck calculated from the Chirp data (-0.27) with those values predicted from theory in Table 4 (range: -0.03 to -0.64) indicates that the reflection coefficient calculated from the digital sub-bottom data falls centrally within the range predicted by the modelling, thus validating the theoretical and experimental work outlined above.

Conclusions

- (i) The anisotropy of wood decreases with increasing density, with compressional

wave velocities parallel to the wood grain (V_L) being consistently faster than those across grain (V_R and V_T).

- (ii) Burial in marine sediments causes changes in the physical and elastic properties of the outer few centimetres of wood samples, causing outer wood to behave more isotropically. In contrast, inner wood displays little degradation in structural coherency. Elastic and physical properties remain relatively constant.
- (iii) Variations in reflection coefficients of wood buried in unconsolidated sediments ($+0.27$ to -0.79) are dependent upon the wood species, sediment type and burial and exposure histories.
- (iv) Reflection coefficients resulting from wood buried in unconsolidated marine sediments are typically large and negative. Reflection coefficients calculated for oak (historically the most common ship-building material) buried in sediments range between -0.03 and -0.64 .

Theoretical, experimental and acquired sub-bottom data presented in this paper clearly indicate that wooden artefacts buried in unconsolidated marine sediments can be readily imaged by seismic reflection techniques. Owing to the nature of seismic data acquisition, the ability to image wooden artefacts is dependent not only upon the acoustic impedance contrast that exists between the artefact and the burial sediment, but also upon the size of the target. This size restriction is a direct function of the acquisition parameters of the sub-bottom system. In practical terms, an artefact's dimensions must be greater than 1 m in the horizontal plane and greater than 15 cm in the vertical in order to be imaged by a Chirp system utilizing a 2–8 kHz source at a system transmit rate of 4 pulses per second in water depths of less than 30 m.

Figure 7 and the associated reflection coefficients calculated from the sub-bottom profile, strongly support the authors' belief that Chirp systems (combined with accurate navigation systems and sound survey methods) presently offer the most appropriate technology for non-invasive, high-resolution investigations of sites of maritime archaeological interest.

Acknowledgements

The authors wish to thank the following: Chris Dobbs and Alex Hildred at the Mary Rose Trust for their input and for the donation of the oak samples from the *Mary Rose* for experimental use; Dr Tony Briscoe and Dr Roger Pinnington at the Institute of Sound and Vibration Research (University of Southampton) who undertook the wood experiments; Jon Adams and Professor David Peacock from the Archaeology Department, University of Southampton for their continued support. This research is funded by NERC Grant GR3/9533.

Glossary

Sub-bottom profiler

Sub-bottom profilers utilize a source that generates acoustic waves which are capable of penetrating the seabed. These waves then reflect off boundaries or objects within the subsurface (see *The seismic reflection method* section in the main text) and are detected by an acoustic receiver (or hydrophone) mounted in close proximity to the source. The generated data set is then processed to give a cross-section in the direction of movement of the survey vessel in two-way travel time (the time taken for the pulse to travel from the source to the reflector and back to the receiver).

Side-scan sonar

The acoustic pulse from the side-scan sonar is transmitted and received from a single stream-lined towfish deployed at distance from the survey vessel. These devices have both port and starboard transducers that generate pulses with large vertical beam angles (typically 150°) and narrow horizontal beam angles (0.25–0.75°). The vertical beam is typically angled at 15° down from the horizontal, so that the majority of the source energy is directed towards the sea-floor. The generated data set is an apparent three-dimensional acoustic image of the sea-floor. The area of the seabed imaged is dependent upon the slant range coverage, with typical systems

having ranges between 50 m channel⁻¹ and 600 m channel⁻¹ (i.e. 100 m and 120 m total swath width).

References

- Anstey, N. A. (1977). *Seismic Interpretation: the Physical Aspects*. Boston: International Human Rights Development Corporation.
- Anstey, N. A. (1981). *Seismic Prospecting Instruments*, Vol. 1, 2nd edn, *Signal Characteristics and Instrument Specifications*. Berlin: Gebreuder-Borntraeger.
- Chauhan, O. S. and Almeida, F. (1988). Geophysical methods as a tool to explore submerged marine archaeological sites. In Rao, S. R. (editor), *Marine Archaeology of Indian Ocean Countries*, (Goa, India: National Institute of Oceanography). 3–5.
- Cremer, L., Heckl, M. and Ungar, E. E. (1973). *Structure-borne Sound: Structural Vibrations and Sound Radiation at Audio Frequencies*, 2nd edn. Berlin: Springer-Verlag.
- Flinn, R. A. and Trojan, P. K. (1981). *Engineering Materials and Their Applications*, 2nd edn. Houghton and Mifflin.
- Frey, D. (1971). Sub-bottom survey of Porto Longo Harbour, Peloponnesus, Greece. *Nautical Archaeology* 1: 170–175.
- Hearmon, R. F. S. (1948). *The Elasticity of Wood and Plywood*. London: HMSO.
- Hobbs, C. H., III, Blanton, D. B., Gammisch, R. A. and Broadwater, J. (1994). A Marine Archaeological Reconnaissance Using Side-Scan Sonar, Jamestown Island, Virginia, U.S.A. *Journal of Coastal Research* 10(2): 351–359.
- Lavery, B. (1988). *The Royal Navys First Invincible. The Ship, the Wreck and the Recovery*. Invincible Conservations Ltd.
- McGee, T. M. (1990). The use of marine seismic profiling for environmental assessment. *Geophysical Prospecting* 38: 861–880.
- McGhee, M. S., Luyendyk, B. P. and Boegman, D. E. (1968). Location of an ancient Roman shipwreck by modern acoustic techniques — a critical look at marine technology. *Marine Technology Society 4th Annual Conference*, Washington, DC.
- Orsi, T. H. and Dunn, D. A. (1991). Correlations between sound velocity and related properties of glacio marine sediments: Barents Sea. *Geo-Marine Letters* 11: 79–83.
- Parent, M. D. and O'Brien, T. F. (1993). Linear-swept FM (Chirp) sonar seafloor imaging system. *Sea Technology* 34: 49–55.
- Rao, T. C. S. (1988). Geophysical techniques to locate pre-historic sites and artefacts on the continental shelf. In Rao, S. R. (editor), *Marine Archaeology of Indian Ocean Countries* (Goa, India: National Institute of Oceanography) 73–77.

- Redknap, M. (1990). Surveying for underwater archaeological sites: signs in sands. *The Hydrographic Journal* 58: 11–16.
- Schock, S. G. and LeBlanc, L. R. (1990). Chirp sonar: a new technology for sub-bottom profiling. *Sea Technology* 31: 35–39.
- Smith, W. F. (1986). *Principles of Material Science and Engineering*. McGraw-Hill.
- Spence, G. D., Minshull, T. A. and Fink, C. (1995). Seismic studies of methane gas hydrate, offshore Vancouver Island. In Carson, B., Westbrook, G. K., Musgrave, R. J. and Suess, E. (editors), *Proceedings of the Ocean Drilling Program, Scientific Results* 146(1): 163–174.
- Warner, M. R. (1990). Absolute reflection coefficients from deep seismic reflections. *Tectonophysics* 173: 15–23.
- Weidmann, G., Lewis, L. and Reid, R. (1990). *Structural Materials, Materials in Action Series*. London: Butterworth Scientific Ltd.
- Wilson, M. A., Godfrey, I. M., Hanna, J. V., Quezada, R. A. and Finnie, K. M. (1993). The degradation of wood in old Indian Ocean shipwrecks. *Organic Geochemistry* 20(5): 599–610.