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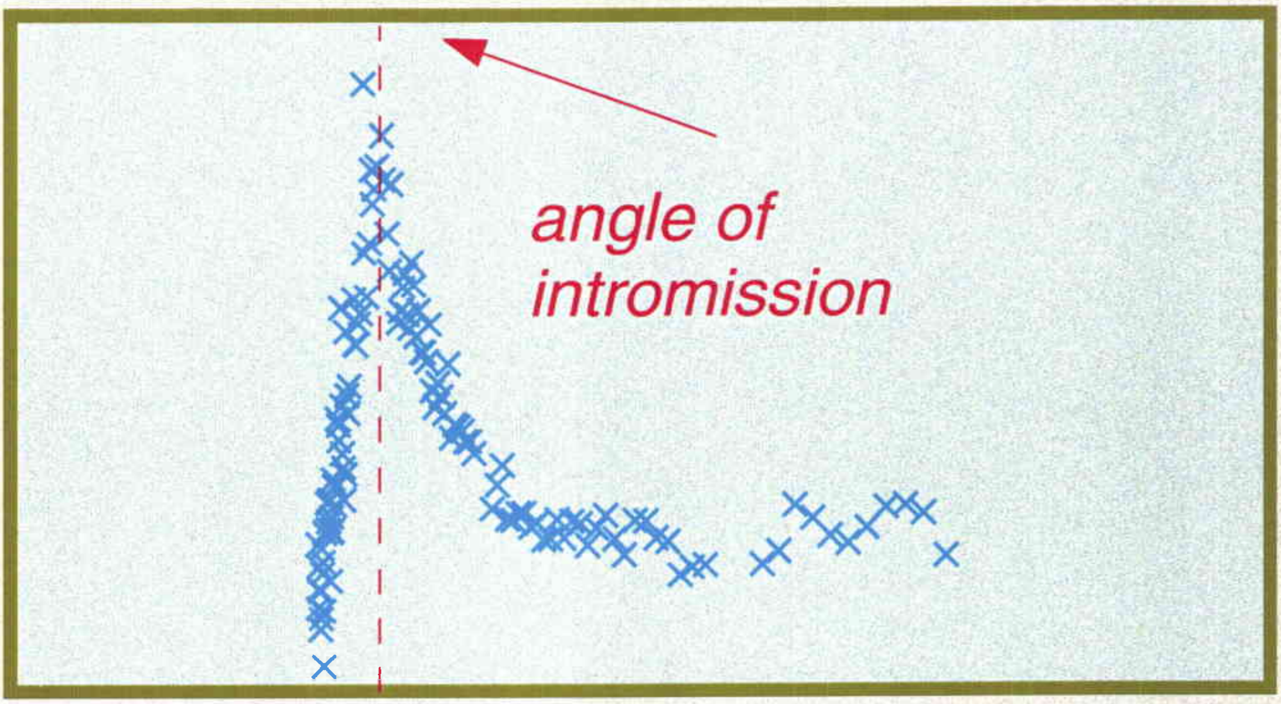
Direct observation of the angle of intromission in marine sediment



Charles Holland
June 2001

NORTH ATLANTIC TREATY ORGANIZATION ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD

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Direct Observation of the Angle of Intromission in Marine Sediments

Charles W. Holland

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Jan L. Spoelstra
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Direct Observation of the Angle of Intromission in Marine Sediments

Charles W. Holland

Executive Summary: Active sonar systems in shallow water must contend with seabed reverberation, which masks the returns from submarines. In order to predict the performance of such systems, databases for seafloor reflection and scattering are required. However, current NATO databases are generally too simple to accurately predict the dependence of sonar performance on frequency or bottom region. In this paper new measurements and interpretation are given that provide scientific advances of importance to the development of future NATO seabed databases.

Recent measurements of seabed reflection have shown an effect predicted by models but not previously observed. The measurements show that at a certain angle (called the angle of intromission) there is nearly complete transmission of energy into the seabed. The measurement of this angle is important for two reasons first, it validates seabed reflection models and second it provides a novel method for obtaining seafloor geoacoustic properties. The measurements demonstrate that in many shallow water areas, the upper sedimentary strata are nearly acoustically invisible and act as a lens, effectively changing the angle of incidence on the acoustically significant layers. The implication is that sediments <u>below</u> the first layer will largely control the acoustic reflectivity and scattering characteristics, i.e., will strongly influence sonar performance.

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Direct Observation of the Angle of Intromission in Marine Sediments

Charles W. Holland

Abstract: High porosity marine sediments like silty clays have the curious property that the speed of sound through its bulk medium is lower than that of the interstitial pore fluid. When a high porosity sediment is at the water sediment interface, classical theory predicts that there is an angle at which the reflection coefficient is zero, and there is total transmission of sound into the seafloor. This angle is called the angle of intromission and has not been directly observed at the seafloor to the author's knowledge. Data from a new measurement technique show this phenomenon with remarkable clarity. Measurements of the angle of intromission in the coastal region of Italy indicate that the properties of the surficial high porosity sediments are surprisingly constant over large areas. A simple, but robust inversion method is shown for which the sediment sound speed and density can be directly obtained.

Keywords:

Contents

1 Introduction

Sound propagation and reverberation in coastal areas is often controlled by the properties of the seabed. A common sediment type in shallow water is silty-clay that typically originates from terrestrial sources. Silty-clay and other high-porosity sediment types can have a profound influence on sound propagation (e.g., Eller and Gershfeld, 1985). These sediments exhibit densities greater than, but sound speeds less than water. Classical theory predicts for this sediment that at a certain angle, the reflection coefficient goes to zero, and there is complete transmission of sound into the seafloor. In practice, not all of the energy is completely transmitted, because of sediment attenuation.

The bottom reflection loss ($-20*\log_{10}(|\boldsymbol{R}|)$, where $\boldsymbol{R}$ is the Rayleigh reflection coefficient) for a silty-clay sediment is shown in Fig. 1. The angle of near complete transmission, called angle of intromission, is apparent at 16°.

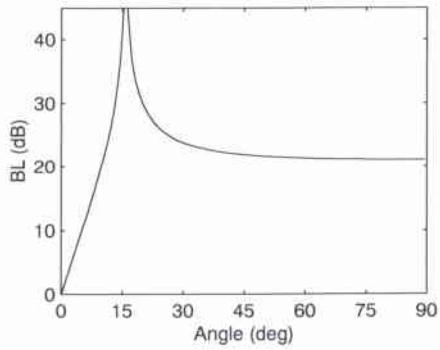


Figure 1 *Theoretical reflection loss for a seabed whose sound speed is smaller than that of the water.*

A number of investigators have reported on measurements showing effects of these high porosity sediments. For example, Christensen *et al.* (1975) using SUS charges in the deep ocean observed that the reflected arrival in the time series data was small enough to be "not discernable" between grazing angles of 13-21°[1]. The angle of intromission presumably fell in that range but could not be clearly identified. Other researchers using

[1] Christensen *et al.* indicate that the angle of intromission is 10°, however, this is inconsistent with the observed 13-21° angular range. Furthermore a 10° angle of intromission is also inconsistent with their estimate of a sound speed ratio of 0.974 (from the travel time difference analysis) which gives an estimated angle of intromission of about 14-16° using a reasonable density ratio range of 1.3 –1.4 g/cc.

similar measurement techniques in deep water have processed the data for the reflection coefficient (e.g., Chapman, 1983) but without direct observation of the intromission phenomenon. Shallow water propagation measurements (e.g., Rubano, 1985 and Hermand, 1999) have evidenced the effects of from the low sound speeds of silty-clay, however, it appears that no direct measurements of the seabed angle of intromission have been published. The difficulty in direct observation of the intromission angle is the presence of ubiquitous sub-bottom higher speed layers, or sound speed gradients which tend to "fill in" the reflection coefficient so that the intromission phenomenon is obscured.

A new experimental and layer stripping processing technique allow measurement of the reflection coefficient at the boundary of the water-sediment interface. This permits direct observations of the angle of intromission. The observation of the intromission angle provides a unique "window" (or perhaps more appropriately a "lens" since the sound speed contrast introduces refraction) with which to study sediment geoacoustics. Following the presentation of the measurements, a simple but robust geoacoustic inversion technique is presented whereby the sediment sound speed and density are estimated unambiguously. These estimates are confirmed by independent "ground truth" measurements.

2
Reflection measurements

The reflection measurement technique uses a broadband source (Boomer) and a single hydrophone. Details of the measurement technique and processing technique is described in detail in Holland and Osler (2000). Figure 2 shows the reflection loss measurements for the upper sedimentary layer in the Malta Plateau at a water depth of 101 m. The salient feature of the reflection data is the presence of the angle of intromission at about 15°.

One of the remarkable aspects of this kind of sediment is the nearly complete acoustic transparency. Even up to 5 kHz, the data (not shown) indicate that above 10° grazing angle 99% of the energy is transmitted into the seafloor. At the angle of intromission, 99.95% is transmitted. The implication is that the sediments below the first layer will largely control the reflection and scattering characteristics. The silty-clay layer acts largely as a lens, modifying the angle of incidence on the sub-bottom strata.

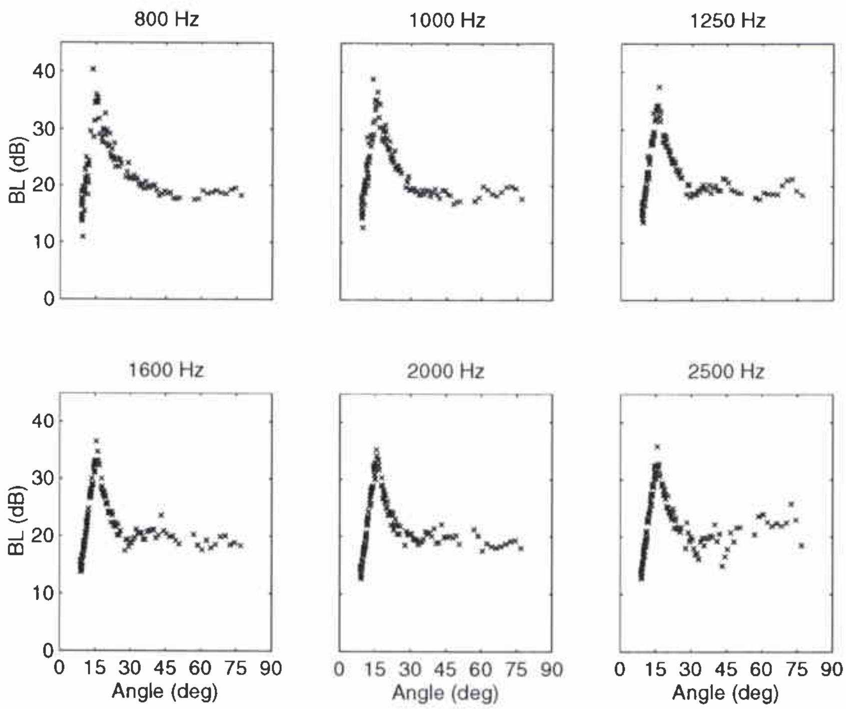


Figure 2 *Bottom reflection loss from first sediment layer on the Malta Plateau. The salient feature in the data is the peak at 15 degrees corresponding to the angle of intromission.*

Another remarkable aspect of these data is the similarity to sites on the Tuscany shelf more than 900 km away. Figure 3 shows 2000 Hz measurements in the Malta Plateau (red) and in the Tuscany shelf area (blue and green). It appears that the surficial sediments in both areas are almost identical. This is surprising given the notorious geoacoustic variability that characterizes shallow water sediments and the distinct riverine environments feeding both regions. The silty clay sediment properties likewise appear to be quite uniform across the entire Malta Plateau.

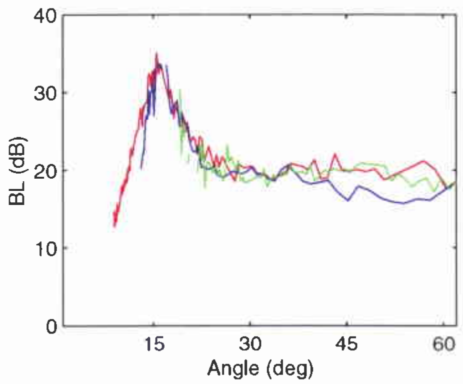


Figure 3 *Comparison of measured reflection coefficient at 2000 Hz in the Malta Plateau (red) and at two sites in the North Elba area (blue, green) at 102 m water depth .*

3
Geoacoustic inversion using the angle of intromission

The angle of intromission presents an opportunity to probe the sediment geoacoustic properties. In this section a simple, but robust geoacoustic inversion scheme is described, then applied to the data. The resulting geoacoustic properties are compared with ground truth.

The angle of intromission, δ, is a function of the ratio of the bulk density, ρ, and velocity, c, contrasts at the interface and is given by:

$$\cos\delta = \left(1-(\rho_1 c_1/\rho_2 c_2)^2\right)^{1/2}\left(1-(\rho_1/\rho_2)^2\right)^{-1/2} \tag{1}$$

where the subscript refers to layer number. By measuring the reflection coefficient, we can easily extract two parameters, the angle of intromission, δ, and the normal incidence pressure reflection coefficient v. Those two parameters (along with ρ_1 and c_1 in the water) are sufficient to unambiguously obtain the sediment density and sound speed from the following equations[2]

$$\rho_2 = \rho_1\left(1-4\upsilon/(\cos\delta(1+\upsilon))^2\right)^{-1/2} \tag{2}$$

$$c_2 = \rho_1 c_1/\rho_2\ (1+\upsilon)/(1-\upsilon) \tag{3}$$

Figure 4 shows the relationship between the measured parameters δ and v and the extracted sediment properties ρ_2 and c_2. The solid and dashed lines show the sensitivity of the sediment properties to changes in δ and v respectively. The salient aspect of the figure is that the sediment properties are very sensitive to the two measured parameters. Note that the sound speed is most sensitive to δ. Conversely, δ is nearly independent of sediment density (which can be seen by inspection of Eq 1).

[2] Another inversion possibility would be to link density and sound speed together through an empirical relation (e.g., Bachman(1985)), and thus only need to measure either θi or υ. However, there is enough variability in these relationships that render such an approach inferior to that proposed above (Eqns 2,3).

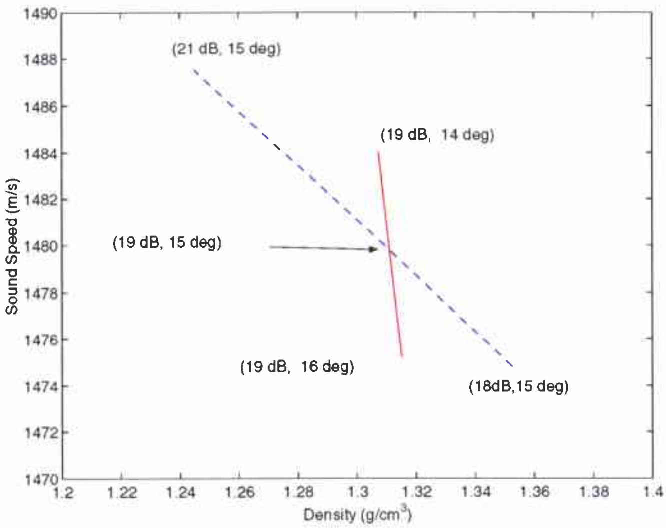


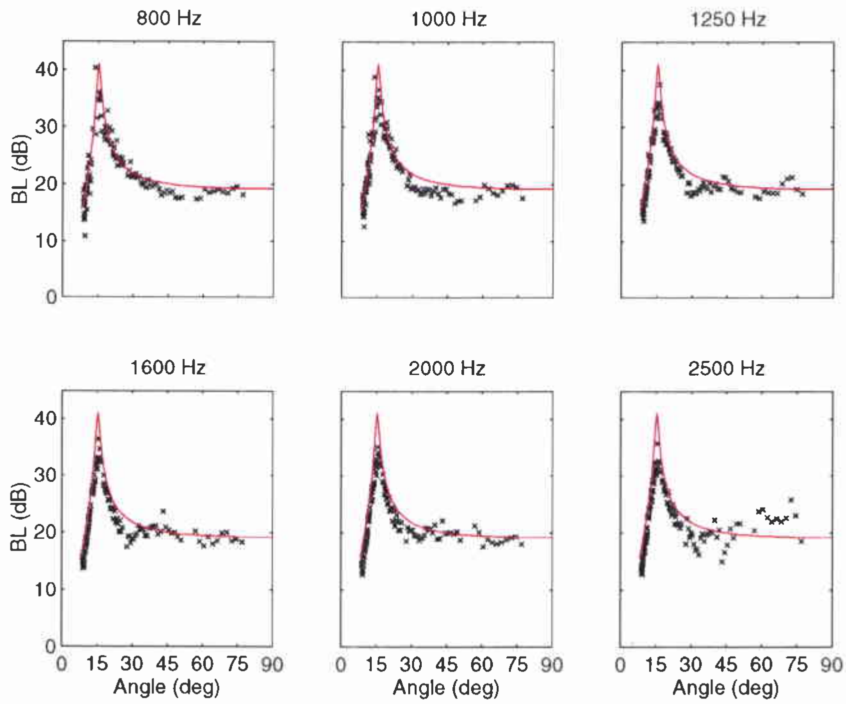
*Figure 4 The relationship between 20*log_{10} ν, δ and the sediment properties.*

It would be desirable to also estimate the sediment attenuation from the measurements. In a homogeneous medium, the magnitude of the reflection coefficient at δ could be used to estimate sediment attenuation. However, $|R(\delta)|$ is also controlled by micro-scale layering, scattering from volume inhomogeneities, and scattering from interface roughness[3]. Since these effects almost certainly dominate $|R(\delta)|$ (and are unknown), we do not attempt to extract the attenuation coefficient. However, fitting an effective attenuation to the data can provide an upper bound to the intrinsic sediment absorption.

[3] There are yet other practical difficulties with trying to extract information at the angle of intromission. One is that it requires infinitely fine angular resolution. Yet another practical difficulty is that for the small attenuations associated with these kinds of sediments requires a very wide dynamic range in the data acquisition system in addition to a high source level and low noise.

4 Geoacoustic inversion results and ground truthing

By picking off the angle of intromission and the normal incidence reflection coefficient from the data of 15°and 19 dB respectively, Eqns (2,3) immediately give the silty clay sound speed and density of 1480 m/s and 1.32 g/cc[4]. Model-to-data comparisons using those inputs (and a fitted effective attenuation of 0.07 dB/m/kHz) are shown in Fig. 5. The slight frequency dependence and the fluctuations around the model results are indicative of the presence of ultra fine-scale layering, volume inhomogeneities, and/or surface roughness[5]. The effective attenuation value is useful in defining the absolute upper bound for intrinsic attenuation, which for this sediment type is expected to be one order of magnitude smaller than 0.07 dB/m/kHz.



[4] The bottom water sound speed and density are 1511 m/s and 1.029 g/cc, respectively.

[5] Sidescan and bottom video recordings show that the seafloor is very flat and featureless except for holes from biologics. It is hypothesized that the fluctuations in the reflectivity data are caused by ultra fine-scale layering and volume inhomogeneities.

Figure 5 Measured bottom reflection loss (x) from the first layer of sediment with the model results from the geoacoustic inversion (red line).

4.1 Ground truthing using wide angle reflection data

The time domain data provide the opportunity to "ground-truth" the sound speed estimates from the geoacoustic inversion scheme. The Bryan (1980) technique was used as described in Holland and Osler (2000).

Wide-angle reflection data and the associated hyperbolic picks (red dashed lines) are shown in Fig. 6. Figure 7 provides the resulting interval velocity associated with main reflecting horizons (solid blue line). The average sound speed in the top 10 m is 1490 m/s. Using the 1.5 m/s sound speed gradient observed in the core data (see Fig. 8) the interface sound speed of 1482.5 m/s agrees extremely well with the intromission inversion of 1480 m/s.

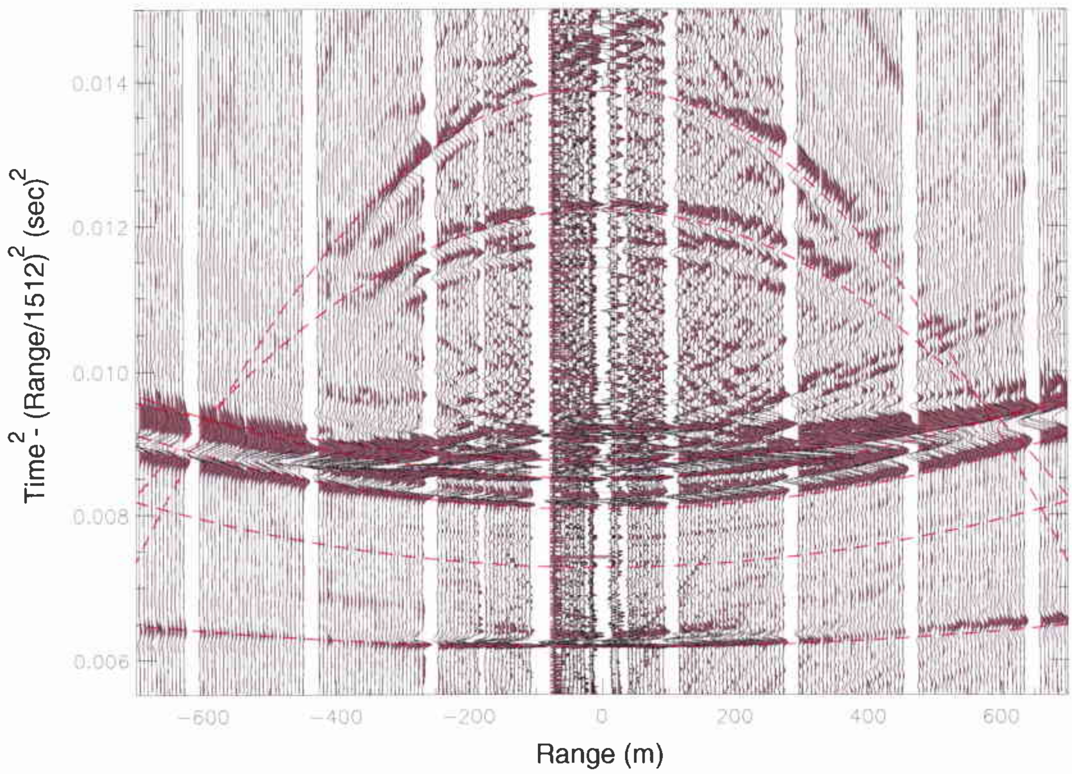


Figure 6 *Time domain data with horizon picks (dashed red hyperbolae). The reflection from the silty-clay interface is the first arrival (at about 0.006 s^2). Note the decrease in amplitude and change of phase due to the angle of intromission at about 440 m range, corresponding to 15 degrees.*

Another way to estimate the gradient in the upper 10 m is to use even weak reflecting horizons. A very weak horizon was found at 5.1 m sub-bottom and the solution obtained including that pick is shown in Fig. 7 in the red dashed line. The average sound speed over the first 5 m was 1485 m/s, giving 1481 m/s at the water-sediment interface, essentially again identical to the value obtained from the angle of intromission analysis.

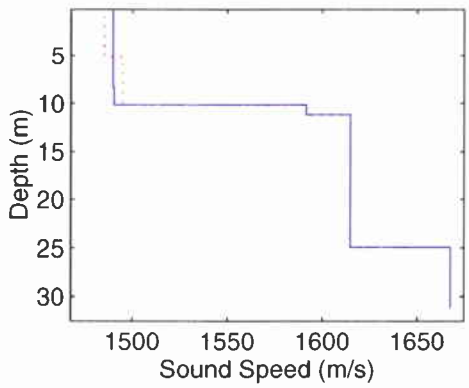


Figure 7 *Sediment sound speed from time domain analysis. The solid blue line represents interval velocities from the main reflecting horizons, the red dashed line includes a very weak layer at 4.9 m sub-bottom in order to obtain a better estimate the sound speed at the water-sediment interface.*

4.2 Ground truthing from core data

The core data are not of sufficient quality to provide as solid confirmation as the time-domain analysis showed above, however, there is evidence worthy of note.

Core data (see Fig. 8) from this site had calibration problems. Insufficient water above the core was available for proper calibration, in addition, there was a multipath problem in the measurement system. Although the absolute values of the sound speed are not known, the data indicate the presence of a sound speed gradient, estimated at 1.5 s^{-1} (as shown in the dotted black line).

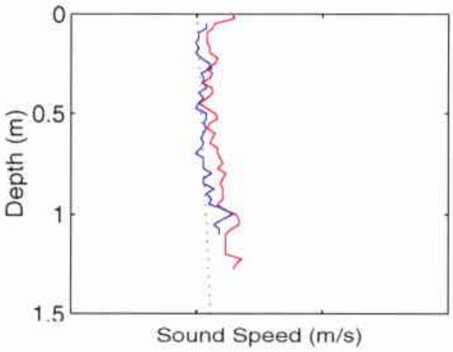


Figure 8 *Corrected measurements (red and blue) from two gravity cores. The tick marks are 10 m/s and the dashed line is a fit to the data with a gradient of 1.5 s⁻¹.*

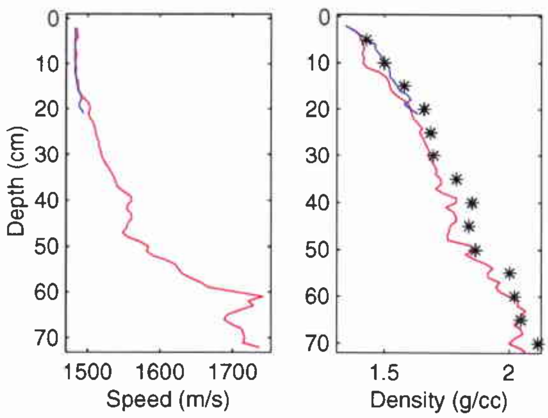


Figure 9 *Core analyses (solid lines) at Site 10 from the multi-sensor core logger. The asterisks were measured using standard laboratory methods as a cross-check. The cores were separated by approximately 130 m.*

Figure 9 shows the nearest (10 miles away) high quality core data. The sound speed and density from this core data are 1483 m/s and 1.346 g/cc at the top of the core (2 cm depth). These values are in excellent agreement with the geoacoustic inversion results of 1480 m/s and 1.32 g/cc. Despite the spatial separation between this core and the acoustic measurements, there is evidence that the interface properties are uniform across scales of the entire plateau.

5
Summary and conclusions

In summary, the phenomenon of the intromission angle, long inferred by indirect measurements was shown by direct measurements. Initial indications are that the associated high-porosity sediments blanketing shallow water regions around the coastal region of Italy are surprisingly homogeneous vis-à-vis spatial variability of the sediment properties.

The measurement of this phenomenon opens several doors for probing the sediment geoacoustics. A simple method was demonstrated by which to recover the sediment sound speed and bulk density. Conducting this inversion over various frequency bands could be a powerful tool for examining frequency dependence of the material properties. Also, the unique "window" provided by the angle of intromission is an opportunity to measure ultra fine-scale geoacoustic fluctuations that are ordinarily impossible to measure via reflectivity but whose effects become measurable at the angle of intromission.

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