IN SITU MEASUREMENTS OF SEAFLOOR SHEAR-WAVE VELOCITY AND ATTENUATION USING SEISMIC INTERFACE WAVES

L. Dale Bibee

Naval Research Laboratory, Marine Geosciences Division, Stennis Space Center, Mississippi, USA

1. INTRODUCTION

Among the suite of geoacoustic properties of seafloor sediments, the elastic shear wave velocity and the attenuation of shear waves are the most difficult quantities to measure, and consequently the most poorly known. Sampling of sediments with coring techniques produces sample disturbance that can significantly affect the shear wave parameters subsequently measured in a laboratory. This is particularly true of the loosely consolidated sediments that often make up the upper few meters of the seafloor. Therefore, *in situ* measurements are required to obtain unambiguous values for these parameters.

Remote sensing capabilities for determination of compressional wave velocity and attenuation have been highly developed by the petroleum industry. These techniques use towed compressional wave sources and hydrophone receiving arrays to probe the sub-seafloor structure. Because of the partial conversion of the compressional wavefield to shear waves by sub-seafloor interfaces, the shear wave parameters in the bottom can have measurable effects on the compressional wave signals. Therefore, these measurements can place constraints on the shear wave properties [1]. However, these data are difficult to invert for shear wave parameters, and ambiguities in the results may be caused by unresolved complexities of the compressional wave velocity structure. These problems lead us to consider more direct measurement techniques.

Direct measurement of shear parameters requires a shear wave source and receiver placed on or below the seafloor. Barbagelata et al. [2] describe a high frequency probe system that can sample the upper 1-2 m of the sediment column. Deeper penetration requires lower frequency sources and larger source-receiver separations. Some attempts have been made to make measurements using refracted shear body waves [3]. However, the exploitation of seismoacoustic surface waves propagating at the sediment-water interface has been the most common technique used for shear wave parameter determination. Ali and Schmalfeldt [4], Jensen and Schmidt [5]and Snoek[6] presented summaries of the work that has been done in this field. Many experiments have been conducted in water depths at which the seafloor is accessible by divers. However, few measurements have been made in the deep ocean.

Davies[7] used a remote technique in which explosive charges placed on the seafloor were used to generate surface waves which were then sensed by seafloor hydrophones. Whitmarsh and Lilwal[8]concluded that a weight drop technique could produce measurable signals. Sauter et al. [9] used a variation of the explosive source and seafloor receiver technique, but used ocean bottom seismometers (OBS) rather than hydrophones to sense the wavefield. Whitmarsh and Miles [10] reported results from seafloor shot/OBS measurements in the Norwegian Sea.

2. EXPERIMENTAL TECHNIQUE

We have used the technique described by Sauter et al. [9] to investigate the shear wave structure in three different deep-sea environments. This technique uses approximately 20 kg of TNT explosive placed on the seafloor at ambient pressure and detonated with an expendable timer and electric blasting cap (Figure 1). The shot falls freely from the sea-surface. An array of OBS's is deployed to receive the signals from both the surface and body wave paths. The various compressional wave multipath signals propagating through the water column are used to constrain both the source-receiver separation and the source detonation time. For separations of more than a few hundred meters the surface wave modes are clearly separated in time from the higher speed body wave phases. At ranges more than 2-3 km, the signal/noise ratio of the surface wave signal has significantly degraded.

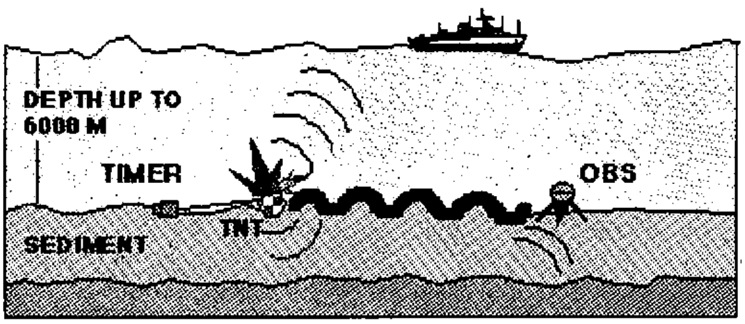

Figure 1. Explosive shots detonated on the seafloor with an expendable timer generate Scholte waves that are recorded on ocean bottom seismometers.

Figure 2 shows the primary features of the observed signals on a vertical component seismometer. A compressional wave propagating through the water column and upper sediments arrives less than 2 seconds after the shot detonation. In some cases a small amplitude arrival representing energy refracted from high velocity layers below the seafloor precedes the direct water path arrival. At intervals of a few seconds (depending on the water depth), impulsive signals arrive that correspond to ray paths reflecting from the sea-surface and bouncing multiple times in the water column. At later times (typically tens of seconds after the detonation), a dispersed, low-frequency (0.5 - 6 Hz), wave train arrives that represent the surface wave signal (Scholte wave). The low frequency nature of this signal is a result of the shear wave attenuation suppressing the higher frequency signals. The explosive source has a bubble oscillation frequency of more than 100 Hz at the depths for which our data was taken (2600-4700 m). Consequently little of its acoustic energy is radiated at the measurement frequency. A source that produced energy predominantly in the frequency band of interest here could potentially contain a much lower total energy than the explosive and yet deliver similar results.

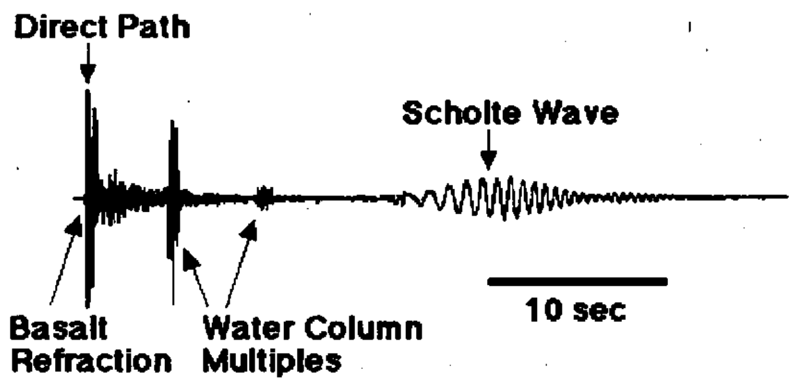

Figure 2. A typical time series recording of a vertical seismometer is shown. A small precursor arrival is a refracted compressional wave traveling though the basaltic basement. It is followed by a direct path compressional wave arrival and a series of water column multiples. The phase of interest here (the Scholte wave) arrives approximately 30 seconds after the detonation. Range to the source is 1000 m.

3. PROCESSING TECHNIQUES

It is the dispersive nature of the Scholte wave that allows the shear wave velocity as a function of depth below the seafloor to be determined. Lower frequency, longer wavelength energy senses material properties at larger depth below the seafloor, and therefore travels faster if the shear wave velocity increases with depth (typically the case). We use the multiple window spectral techniques described by Landisman et al. [11] to generate a matrix of spectral amplitudes as a function of group velocity and frequency (Figure 3). This matrix is often referred to as a Gabor matrix. Loci of high amplitude elements in this matrix define the dispersion curves for the fundamental and higher order modes. A trial and error forward modeling procedure is then used to match the observed dispersion curves with those predicted from a seafloor model. The spectral amplitude of the matrix elements along the dispersion curve contain information about the shear wave attenuation. By examining the relative spectral amplitudes from different source-receiver pairs, the attenuation can be derived.

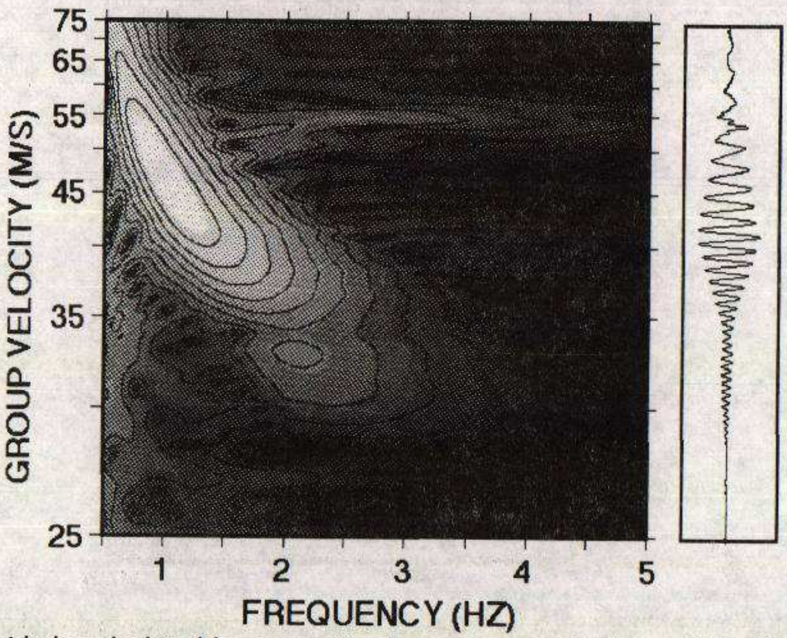

Figure 3. A Gabor matrix is calculated by computing frequency spectra in a sliding time window of the seismogram. The time delay of the center of the window corresponds to a particular group velocity. The vertical axis is labeled in velocity (m/s) but is linear in slowness (s/m) so that particular features in the spectra correspond directly to the adjacent seismogram.

The results that are presented in this paper are computed with this somewhat crude inversion procedure. We expect to refine these results in the future with more sophisticated techniques including joint inversion with phase velocity information, linearized inversion theory, and automated waveform inversion using matched field techniques [12]. While these techniques will generate higher resolution, bounded solutions, we expect the general features of the solutions to change little.

4. RESULTS OF RECENT MEASUREMENTS

From 1990 to 1992, we have conducted three deep-water experiments that resulted in Scholte wave data. The locations of these experiments are shown in Figure 4. Site A was located in an abyssal hill terrain approximately 500 km west of Pt. Conception, California where the water depth is approximately 4700 m. Site B was located at the base of the Oregon continental slope on the distal edge of the Astoria deep-sea fan. The water depth there is approximately 2600 m. Site C is in a sediment pond at the base of the slope defining the western edge of the Southern California borderland terrain, and is within a few miles of the site where the data reported by Sauter et al. [9] were taken. Water depth at this site is approximately 3800 m. In all cases, the current sedimentary regime is thought to be low-energy, and not highly dynamic. Therefore, one would expect the physical properties of the sediments would be rather uniform in lateral extent. With the exception of site B where significant terriginous input to the sediment column is expected, similar shear parameters might also be expected for the sediment column in the different areas.

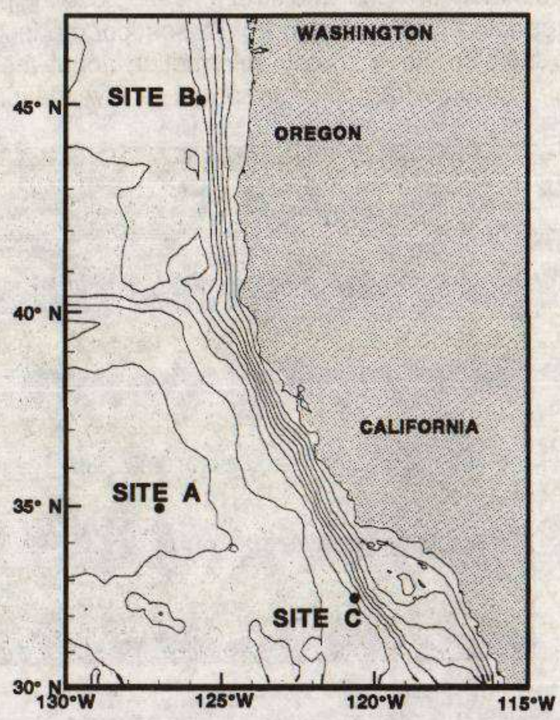

Figure 4. The locations of three sites for which Scholte wave data have been collected.

Contrary to these expectations, both the site-to-site variability and the variability within one of the sites is large. This variability can be seen in the raw data. Figure 5 displays seismograms at the same source-receiver separation from the three sites. The relative shear speeds control the time delay of the Scholte waveforms. Clearly site B exhibits the highest shear speeds followed by site A and then site C. Figure 6 shows the velocity profiles generated by matching group velocity dispersion curves in the three areas. The higher speeds observed at site B are understandable because of the terriginous (sand) component of the sediment added by the Astoria fan sedimentation. However, sites A and C both are expected to be controlled by pelagic sedimentation, and the reasons for the variation are unknown.

Figure 6 shows two different curves for site A. Although the experiment encompassed an area of only 2 km square, inversions from different paths within that area showed variability in shear velocity greater than 50% [13],[14]. In contrast, site C showed almost no variability. Although we have no direct sampling of site A, we expect the sediment lithology to be uniform over the area covered by our experiment. We speculate that diagenetic changes in the sediment, possibly associated with off-ridge hydrothermally driven fluid circulation, are responsible for the observed variation.

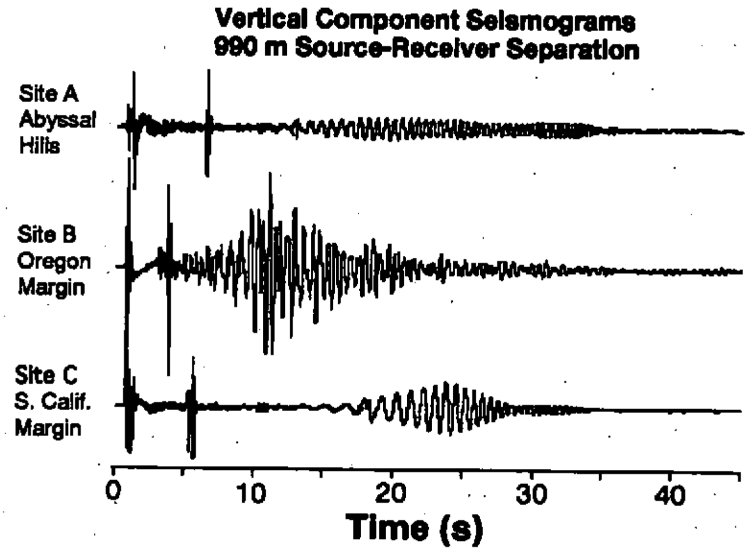

Figure 5. Vertical component seismograms from an explosive bottom shot at 990 m range is shown for each of the three sites. Clearly the Scholte wave speeds are highest at site B and lowest at site C.

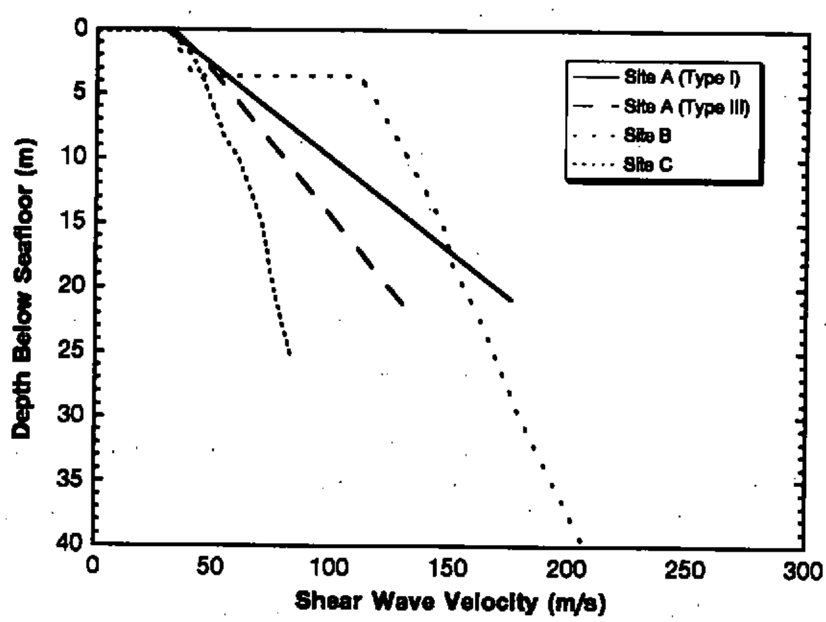

Figure 6. Shear-wave velocity curves are plotted as functions of depth below the seafloor. Site B has a thin (3 m) layer of muds overlying higher velocity material that probably contains sand. Site C was adjacent to DSDP Site 469 which cored hemi-pelagic clays in the upper 40 meters of the sediments. Two curves taken from Schreiner et al. [14] are shown for site A. The seismograms from that site fell into four general classes each with a distinctive velocity profile.

5. NEW EXPERIMENTAL TECHNIQUES

In theory, the Gabor matrix computed above should contain maxima associated not only with the fundamental mode Scholte waves, but also with the higher order modes. The delineation of these modes would be extremely useful since, unlike the fundamental modes, their wave functions do not decay away from the interface in a simple exponential function. They may have maxima at depth rather than at the interface and thus are more sensitive to deeper structure. The resolving power of fundamental mode data decreases rapidly when the depth exceeds the wavelength of shear waves in the media. The joint inversion of fundamental and higher mode data can result in higher resolution estimates at larger depths. In practice, the higher modes are difficult to define with the data. The horizontal component seismometers in the OBS may be more sensitive to the higher order modes than the vertical component sensors. However, the coupling of seafloor horizontal sensors to the sediment is clearly more difficult than that of the vertical sensors [15], and the horizontal seismometers receive more signal from converted shear body waves that are propagating vertically in the sediments.

It is possible that higher order modes may be defined more clearly by placing the sensor below the seafloor. Figure 7 shows the numerical prediction of the Scholte wave modes as functions of depth below the seafloor. The SAFARI algorithm [16] was used to generate the seismograms. The late arriving fundamental mode clearly peaks at the seafloor and decays rapidly with depth. The higher order modes are less affected by sensor depth. Figure 8 shows Gabor matrices computed for one sensor at the seafloor and another sensor buried 20 m deep. The theoretical dispersion curves are also shown. The fundamental mode is clearly suppressed for the buried sensor. The second overtone is more clearly defined on the buried sensor, but definition of the first overtone is improved only for frequencies below 3 Hz. Additional improvement of the higher modes could probably be achieved with a buried source as well as a buried receiver.

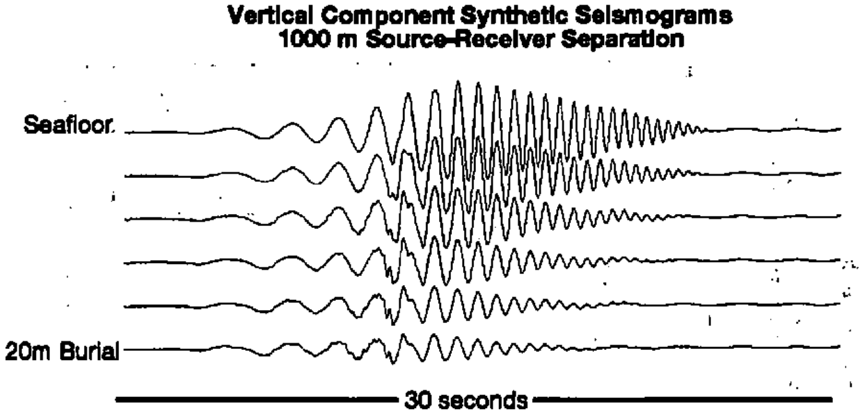

Figure 7. SAFARI numerical predictions of the Scholte modes for vertical seismometers at the seafloor and at 4 m increments of burial depth. The source remains at the seafloor. The higher frequency fundamental mode signal decreases rapidly with depth and the higher order modes become more significant.

At the Naval Research Laboratory, an effort is underway to develop penetrator systems that will allow inexpensive implantation of seismic sensors below the seafloor at full ocean depth. One system uses a modified sediment coring scenario to push a sensor package into the seafloor using a heavy weight stand. The weight and core pipe is then removed, leaving the sensor package and seafloor recorder behind. A second system uses a seafloor, sea water hydraulic pump to drive a small drill motor at the bottom end of a sensor package. The sensor package is suspended from the seafloor package by an electrical and hydraulic umbilical cable and allowed to drill itself into the sediments. A penetration depth of 100 m is targeted for this system in contrast to 10-20 m depths anticipated for the weight driven system. Both systems are undergoing engineering tests; the weight driven system has successfully achieved 8 m penetration. These systems will provide the capability for extending the resolution and depth capability of seismoacoustic Scholte wave inversions.

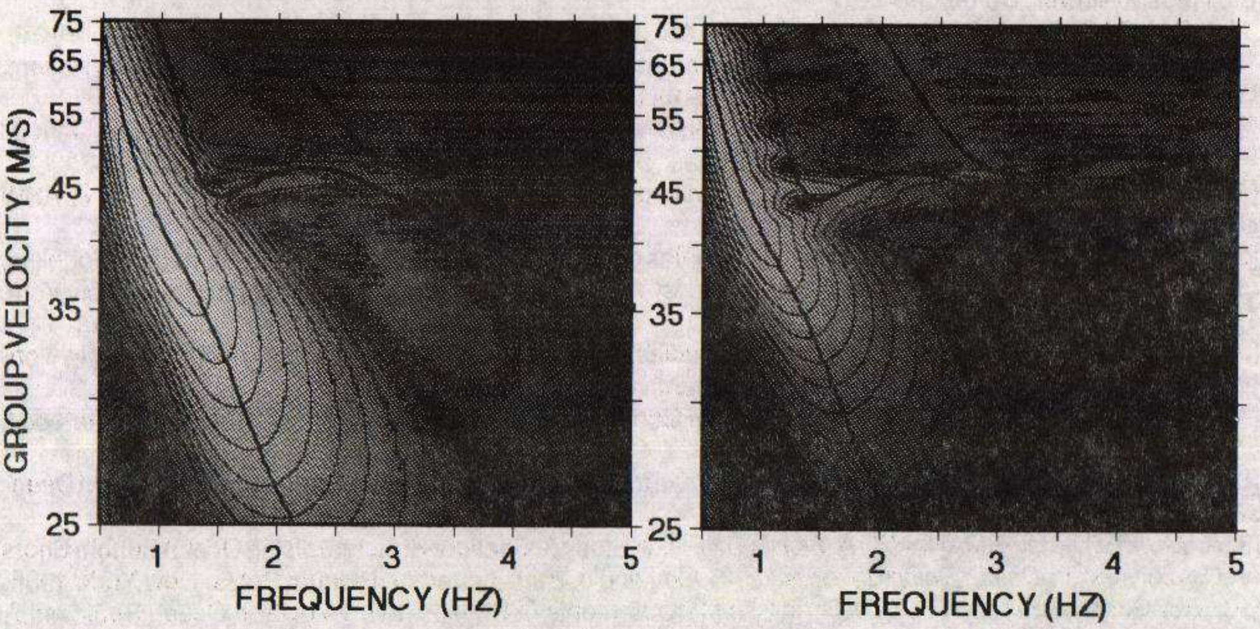

Figure 8. Gabor matrices for the synthetic seismograms at the seafloor (left) and 20 m burial depth (right). The dispersion curves for the fundamental (lower left) and first and second overtones are superimposed. Note the increased resolution of the overtones on the buried sensor, particularly for the second overtone at velocities between 50 and 75 m/s.

6. CONCLUSIONS

A set of measurements of Scholte waves in the deep ocean suggest that the shear wave velocity in marine sediments is highly variable between sites and sometimes within small areas that otherwise appear rather uniform. Experimental techniques to measure the shear wave parameters using ocean bottom seismometer systems and seafloor explosive shots are capable of defining these differences. Advanced inversion techniques and experimental procedures using seismometers placed below the seafloor offer potential advances in resolution and increases in depth to which shear wave parameters can be defined using surface wave techniques.

7. ACKNOWLEDGEMENTS

This work was funded by the Naval Research Laboratory 6.1 basic research program, Program Element 0601153N, Subelement 32. The author is grateful to Dr. Leroy Dorman and Dr. Henrik Schmidt for use of their numerical prediction computer codes. Hassan Ali provided many useful discussions and suggestions.

9. REFERENCES

[1] J. GETTRUST and M. ROWE, 'Constraints on Shear Velocities in Deep Ocean Sediments as Determined from Deep-tow Multichannel Seismic Data', in *Shear Waves in Marine Sediments*, Hovem, Richardson and Stoll (eds.), Kluwer, Dordrecht, 1991.

[2] A. BARBAGELATA, M. RICHARDSON, B. MIASCHI, E. MUZI, P. GUERRINI, L. TROIANO, AND T. AKAL, 'ISSAMS: An In Situ Sediment Acoustic Measurement System', in *Shear Waves in Marine Sediments*, Hovem, Richardson and Stoll (eds.), Kluwer, Dordrecht, 1991.

[3] J. EWING, J. CARTER, G. SUTTON, AND N. BARSTOW, 'Shallow Water Sediment Properties Derived From High-Frequency Shear and Interface Waves', *J. Geophys. Res.*, 97, p. 4739-4762, 1992.

[4] H. ALI AND B. SCHMALFELDT, 'Seismic sensing of low-frequency radiated ship noise', SACLANT ASW Research Centre Report SR-77, 1984.

[5] F. JENSEN AND H. SCHMIDT, 'Shear Properties of Ocean Sediments Derived from Numerical Modelling of Scholte Wave Data', in *Ocean Seismo-Acoustics*, T. Akal and J. Berkson (eds.), Plenum Press, New York, 1986.

[6] M. SNOEK, 'Interface-Wave Propagation Studies: An Example of Seismo-acoustic Propagation in Non-homogeneous Materials', SACLANT ASW Research Centre Report SM-229, 1990.

[7] D. DAVIES, 'Dispersed Stonely Waves on the Ocean Bottom', *Bull. of the Seismological Soc. of America*, 55, p. 903-918, 1965.

[8] R. WHITMARSH AND R. LILWAL, 'A New Method for Determination of In Situ Shear-wave Velocity in Deep-sea Sediments', *Geophysics*, 47, p. 1745, 1982.

[9] A. SAUTER, L. DORMAN, AND A. SCHREINER, 'A Study of Seafloor Structure Using Ocean Bottom Shots and Receivers', in *Ocean Seismo-Acoustics*, T. Akal and J. Berkson (eds.), Plenum Press, New York, 1986.

[10] R. WHITMARSH AND P. MILES, 'In Situ Measurements of Shear-Wave Velocity in Ocean Sediments', in *Shear Waves in Marine Sediments*, Hovem, Richardson and Stoll (eds.), Kluwer, Dordrecht, 1991.

[11] M. LANDISMAN, A. DZIEWONSKI, AND Y. SATO, 'Recent Improvements in the Analysis of Surface Wave Observations', *Geophys. J. Royal Astr. Soc.*, 17, p. 369-403, 1969.

[12] W. KUPERMAN, M. COLLINS, AND H. SCHMIDT, 'A Fast Simulated Annealing Algorithm for the Inversion of Marine Sediment Seismo-acoustic Parameters', in *Shear Waves in Marine Sediments*, Hovem, Richardson and Stoll (eds.), Kluwer, Dordrecht, 1991.

[13] D. BIBEE, AND L. DORMAN, 'Implications of Deep-Water Seismometer Array Measurements for Scholte Wave Propagation', in *Shear Waves in Marine Sediments*, Hovem, Richardson and Stoll (eds.), Kluwer, Dordrecht, 1991.

[14] A. SCHREINER, L. DORMAN, AND D. BIBEE, 'Shear Wave Velocity Structure from Interface Waves at Two Deep Water Sites in the Pacific Ocean', in *Shear Waves in Marine Sediments*, Hovem, Richardson and Stoll (eds.), Kluwer, Dordrecht, 1991.

[15] G. SUTTON AND F. DUENNEBIER, 'Optimum Design of Ocean Bottom Seismometers', *Mar. Geophys. Res.*, 9, p. 47-65, 1987.

[16] H. SCHMIDT, 'SAFARI, Seismo-acoustic Fast Field Algorithm for Range Independent Environments: Users Guide', SACLANT ASW Research Centre Report SR-113, 1988.