SHEAR PROPERTIES OF OCEAN SEDIMENTS DETERMINED FROM NUMERICAL MODELLING OF SCHOLTE WAVE DATA

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ABSTRACT

Recently it has become apparent that shear properties of ocean sediments are most easily determined from measured propagation characteristics of seismic interface waves. We use a newly developed numerical model of wave propagation in horizontally stratified viscoelastic media to reconstruct from Scholte-wave records the shear-speed and shear-attenuation profiles in the upper sediment layers of a shallow-water test area. For an unconsolidated sand-silt bottom we find the shear speed to increase with depth from 85 m/s at the sea floor to 300 m/s at 60 m depth. On the other hand, the shear attenuation at 3 Hz decreases with depth from 0.45 dB/λ at the sea floor to 0.15 dB/λ at 60 m depth, with an approximately quadratic frequency dependence.

INTRODUCTION

It is well established that shear rigidity of the ocean bottom affects propagation of waterborne sound through the conversion of acoustic energy into shear waves. This energy conversion is of particular importance in low-frequency shallow-water acoustics, in which the excitation of shear waves in the bottom often becomes the dominant loss mechanism for waterborne sound [1]. Under these circumstances a realistic physical model of the ocean bottom is a viscoelastic solid described by compressional and shear-wave velocities, by the attenuation factors associated with these waves, and by the material density.

While density and the compressional-wave properties (speed and attenuation) in sediments can be determined by direct methods, the shear-wave properties are difficult to measure. This is because of the usually high attenuation of these waves and because it is difficult to generate a wave that consists of predominantly transverse particle motion. The shear speed and attenuation can be indirectly determined, however, through the measured propagation characteristics of the ocean-bottom interface wave. The existence of this wave is intrinsically related to the shear properties of the sediments.

We shall review the characteristics of seismic interface waves and give some simple formulas that relate their speed and attenuation to those of shear bulk waves. We shall also provide examples from the literature of indirectly determined shear speeds in sediments. Finally, we will demonstrate how the use of a sophisticated numerical model of seismic-wave propagation allows us to reconstruct from seismic records the shear speed and shear attenuation profiles in the upper sediment layers.

SEISMIC INTERFACE WAVES

This particular wave type - sometimes named a boundary, surface, or interface wave - is a guided wave propagating along the interface between two media with different shear speeds [2,3]. The wave is generally given different names according to the media of propagation involved [4]. Hence, if propagating on a free surface of a solid, it is called a Rayleigh wave, if propagating along a liquid/solid interface, it is called a Scholte wave and if associated with a solid/solid boundary, it is called a Stoneley wave. Note that at least one of the media must be a solid for the interface wave to exist. In the case of a water/sediment interface, the pertinent wave type is a Scholte wave with the following characteristics:

- The wave propagates along the sea floor with exponentially decaying amplitude away from the guiding interface (the wave is evanescent in both media).
- Its particle motion is elliptical in the depth/range plane.
- There is no low-frequency cutoff.
- Its propagation speed and attenuation are closely related to the shear properties of the sediment.

For a simplified environment consisting of two homogeneous media in contact, the Scholte wave is non-dispersive. Its propagation speed (V_{sch}) and attenuation (Δ_{sch}) then relate in an extremely simple manner to the sediment shear properties as:

$$V_{sch} \simeq 0.9\, V_s \tag{1}$$

and

$$\Delta_{sch} \simeq 1.1\, \Delta_s, \tag{2}$$

where the attenuation is in decibels per unit length. Using numerical simulation these formulas were determined to be accurate to within a few percent for unconsolidated sediments (clay, silt, sand) with low shear speeds. The formulas indicate that the Scholte wave properties are virtually independent of densities and compressional wave properties in the two media [5]. Consequently the Scholte interface wave is ideal for determining the shear properties of ocean sediments.

In a realistic environment with sediment layering, the Scholte wave becomes dispersive. In addition, a finite number of ducted shear modes will be present. Figure 1 shows dispersion curves for a solid layer of low shear speed on a high-speed solid substratum. The fundamental mode (M_0) is an interface wave that in the low-frequency limit, $kH \to 0$, propagates as a Rayleigh wave on the substratum, and in the high frequency limit, $kH \to \infty$, propagates as a Rayleigh wave on the surface of the upper layer. The higher-order modes are ducted shear modes in the upper layer. They all have a cutoff frequency at which they propagate with the shear speed of the substratum. In the high-frequency limit these modes propagate with the shear speed of the upper layer. In this case there is no

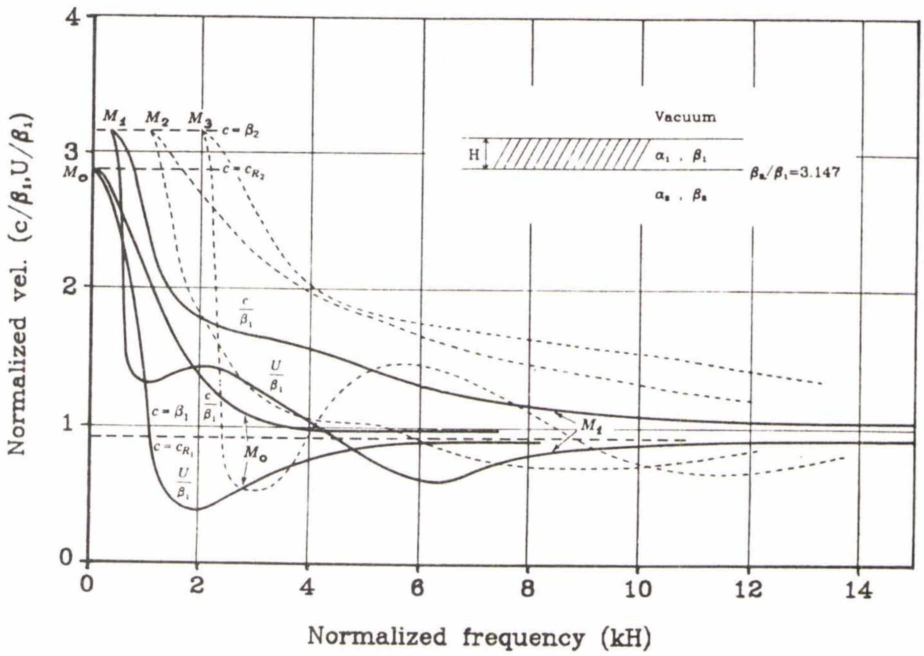

Fig. 1 Dispersion curves for elastic layer on a semi-infinite elastic substratum (Tolstoy and Usdin [2]).

Stoneley wave due to the stringent conditions necessary for the existence of this type of wave. A Stonely wave exists only when the change in shear speed across a solid/solid boundary is less than 10%.

In the following section we show how the complex information contained in experimentally determined dispersion curves similar to those of Fig. 1 can be used to extract shear information about the ocean bottom. Such an analysis generally requires the use of a numerical model. However, if experimental results show negligible dispersion, we can use simple formulas (Eqs. 1 and 2) to determine shear properties for the upper sediment layer. No dispersion means that the sediment is homogeneous to a depth of 1 to 2 wavelengths, the approximate penetration depth of the Scholte wave.

SEDIMENT SHEAR PROPERTIES

Over the past 20 years various investigators [6-17] have used Scholte waves to determine the shear properties of unconsolidated sediments. Their experimental results are summarized in Table 1. Note that experiments were done in water depths ranging from 1 to 5260 m, over sandy or silty bottoms, and for frequencies between 3 and 35 Hz. The measured Scholte wave attenuations (with geometrical spreading removed) vary more than three orders of magnitude, with the highest attenuation being associated with the highest centre frequency. The inferred shear speeds are between 25 and 260 m/s and in excellent agreement with the values quoted by Hamilton [18].

Assuming the shear attenuation to be linear with frequency [18], we can conveniently express it in decibels per wavelength. This has been done in the last column of Table 1, using the simple formulas of Eqs. (1) and (2) to relate measured attenuation of the Scholte wave with the bulk shear-wave attenuation. We obtain values that still vary more than two orders of magnitude (0.02 - 2.3 dB/λ_s), whereas Hamilton [18], based on

Table 1 Interface wave experiments

Investigators	Year	Water depth (m)	Bottom type	Centre freq. (Hz)	Measured att. (dB/km)	Inferred shear speed (m/s)	Inferred shear att. (dB/λ_s)
Bucker, Whitney, Keir[6]	1964	1 20	sand sand	20 25	300 200	100 195	1.4 1.4
Davies[7]	1965	4410	-	6	-	50-190	-
Herron, Dorman, Drake[8]	1968	5	silt	5	-	40-115	
Hamilton et al.[9]	1970	390 985	silt silt	- -	- -	100 90	- -
Schirmer[10]	1980	130	sand	4.5	7	120	0.2
McDaniel, Beebe[11]	1980	32	sand	10	-	200	-
Essen et al.[12]	1981	1	silt	4	-	75-250	-
Tuthill et al.[13]	1981	7	mud	4.5	-	25-50	-
Whitmarsh, Lilwall[14]	1982	5260	-	4.5	-	25-170	-
Holt, Hovem, Syrstad[15]	1983	-	sand	35	600	135-195	2.3
Brocher et al.[16]	1983	67	sand	5	0.43	260	0.02
Schmalfeldt, Rauch[17]	1983	20 30	- -	3 3	10 2	100 150	0.3 0.1

sparse in situ measurements for silt and sand sediments, quotes attenuation values around 0.5 - 2 dB/λ_s. Note, however, that the very low attenuation values are all associated with low-frequency experiments (3 to 5 Hz).

There are two possible explanations for the observed large variation in shear attenuation with frequency. First, that the shear attenuation in sediments decreases with depth as reported by Hamilton [18]. This leads to lower attenuation values for the low-frequency experiments, since the Scholte wave here penetrates deeper into the bottom. The second explanation is that the attenuation does not depend on the first power of frequency as assumed above, but rather follows a power law (f^n) where the exponent is between 1 and 2. Some experimental evidence for this latter assumption does exist [18]. In particular, Stoll in a recent paper [19] has strongly advocated the hypothesis of a marked frequency dependence of attenuation in fluid-saturated sediments, based both on recent field and laboratory data, and on theoretical results from the Biot model. However, more experimental work is needed in order to definitely resolve the depth and frequency dependence of shear-wave attenuation in marine sediments.

NUMERICAL MODELLING OF SCHOLTE WAVES

Figure 2 displays the Scholte wave data from which shear speed and shear attenuation profiles can be determined using a sophisticated propagation model. Stacked time signals for both the vertical and horizontal (radial) particle velocities are shown as recorded by a geophone on the ocean bottom [17]. The source was an explosive charge detonated near the sea floor in 20 m of water. The charge size was increased with range as indicated by the black dots in Fig. 2. We clearly see the dispersed low-frequency Scholte-wave arrivals with group velocities between 78 and 235 m/s.

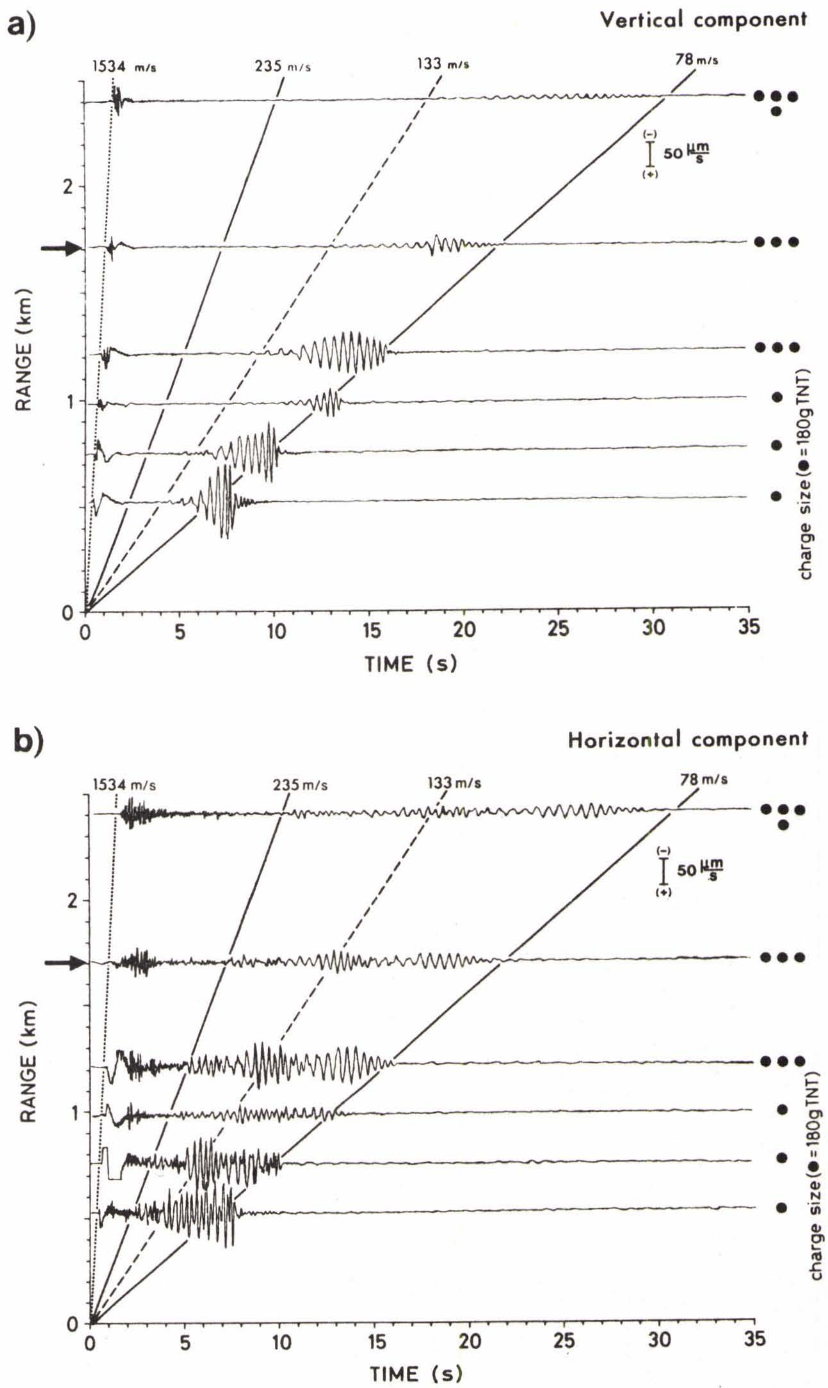

Fig. 2 Stacked time signals for vertical (a) and horizontal (b) particle velocities as recorded by a geophone on the sea floor.

Before performing detailed modelling of this propagation situation, it is convenient to carry out a dispersion analysis of the experimental data. By applying the multiple filter technique [17] to the recorded time series at range 1.7 km, we obtain the dispersion diagrams shown in Fig. 3. The contours indicate energy levels in arbitrary decibels (max level = 99 dB). It is evident that the radial component of the particle velocity gives more information about the propagation situation than does the vertical component. Thus Fig. 3b shows that energy is arriving in three discrete modes, of which the slowest arrival is the Scholte mode (M_0) with its energy centred around 2 Hz. The first shear mode (M_1) is strongly excited, with maximum energy around 2.8 Hz, while the second shear mode (M_2) is only weakly excited.

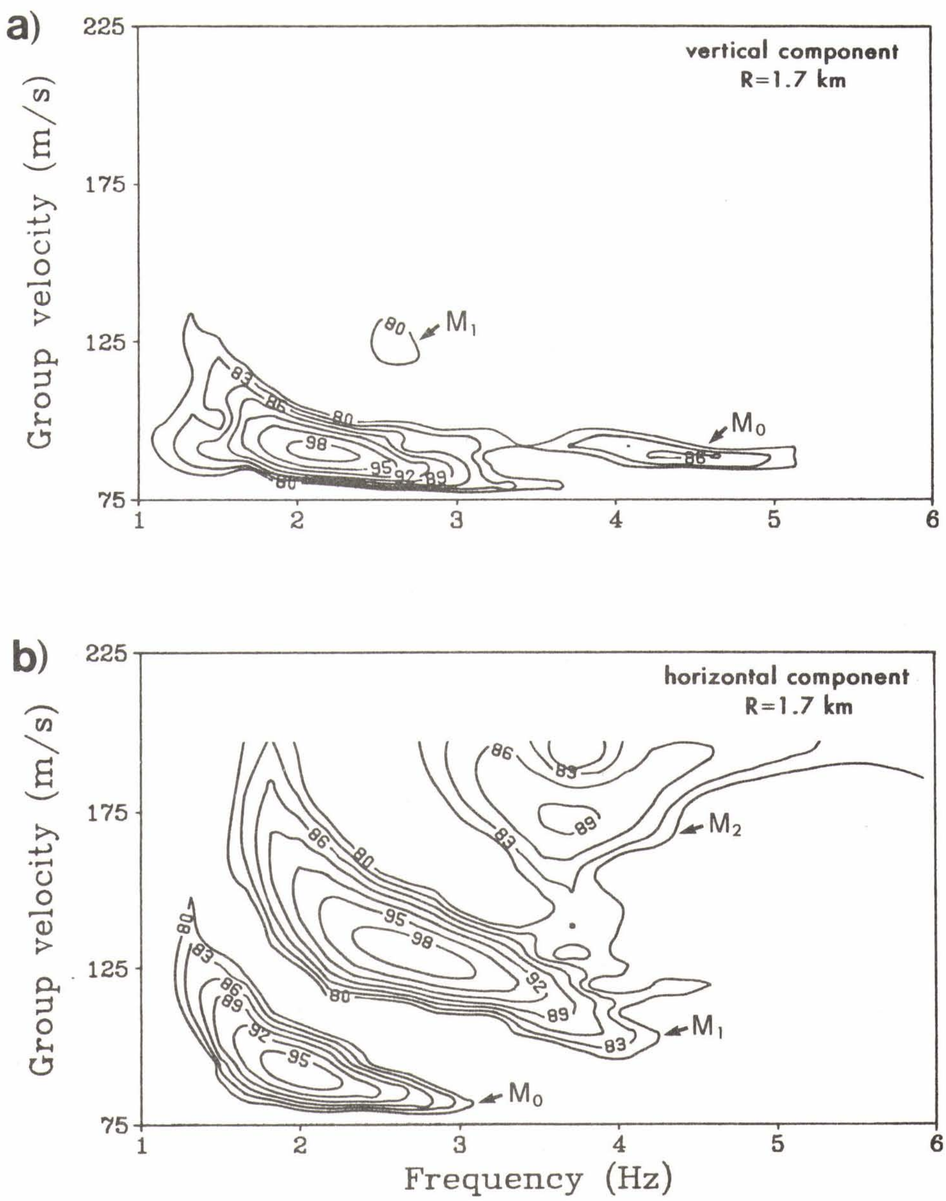

Fig. 3 Dispersion curves obtained by applying a multiple filter technique to the experimental records at range 1.7 km. Energy is seen to be propagating in three discrete modes: M_0, M_1, and M_2.

The modelling is done with a newly developed numerical model of seismic wave propagation in horizontally stratified media [20,21]. The aim is to construct a model environment leading to computed dispersion characteristics that agree with the experimental results of Fig. 3. The modelling is done in a trial-and-error fashion, in which environmental parameters are changed in a systematic way until acceptable agreement is obtained between theory and experiment. Since we are interested in determining the shear properties for an unconsolidated sediment, we can fix, a priori, the compressional-wave properties and densities, which are known to have negligible effect on the propagation characteristics of bottom interface waves [5]. The compressional-wave properties (C_c,β_c) and densities (ρ) used as input to the seismic model are shown in Fig. 4. Also shown are the final choices of shear-speed (C_s) and shear-attenuation (β_s) profiles for the bottom.

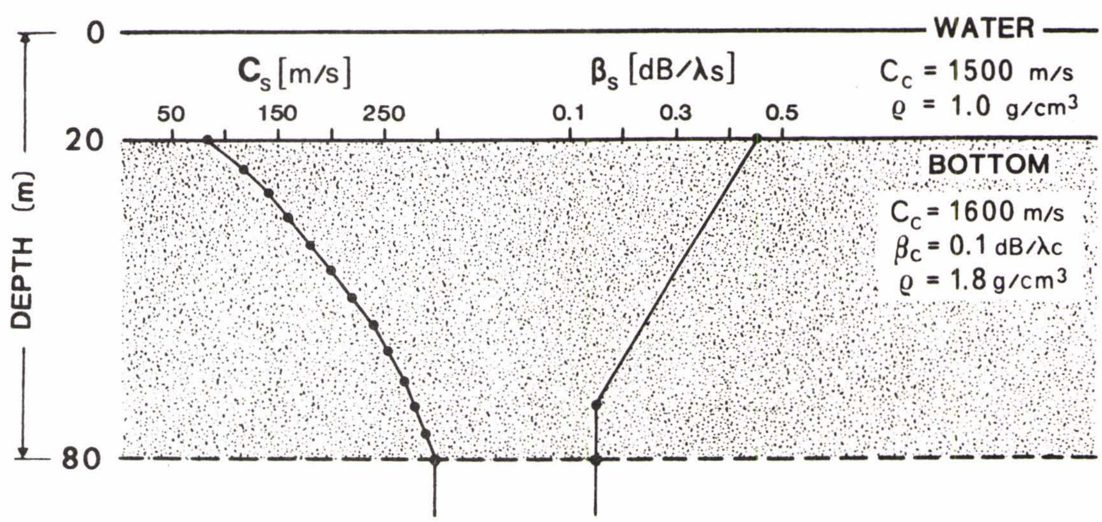

Fig. 4 Model environment used for generating synthetic seismograms.

The computed low-frequency dispersion curves for the model environment are shown in Fig. 5. In Fig. 5a we have superimposed the theoretical dispersion curves (dashed lines) on the experimental data. Clearly there is good agreement between theory and experiment for the modal arrival structure, particularly for the two lower-order modes. This, in turn, means that we have chosen an appropriate shear-speed profile. Figure 5b shows the relative energy distribution in the first three modes as determined from the numerical model. Again there is good agreement with the experimental results in Fig. 5a, indicating that the choice of shear-attenuation profile is also appropriate. It should be pointed out, however, that it was necessary to assume a quadratic frequency dependence of shear attenuation in order to get agreement on energy levels over the entire frequency band.

The inferred shear speeds (85 to 300 m/s) and shear-speed gradients ($<$ 6 m/s/m) agree well with values given by Hamilton [18] for sand-silt bottoms. Reported data concerning the shear-attenuation profiles are so sparse that no comparison with those in the literature can be made.

As a final confirmation of the validity of this modelling exercise, we have created synthetic seismograms for both the vertical and horizontal (radial) particle velocities (Fig. 6). We notice a good overall agreement with the experimental results in Fig. 2, the main difference being fast, low-frequency arrivals present in the synthetic seismograms but filtered out in the experimental data.

CONCLUSIONS

Direct measurements of shear properties of ocean sediments are difficult to perform. However, both shear-speed and shear-attenuation profiles can be inferred from measured dispersion characteristics of bottom interface waves through the use of a sophisticated propagation model. The modelling is considerably simplified because the propagation characteristics of Scholte waves depend entirely on the sediment shear properties and have only negligible dependence on the compressional-wave properties and the density. For a shallow water test area we find sediment shear speeds (85 to 300 m/s) and shear attenuations (0.15 to 0.45 dB/λ at 3 Hz) that are in good agreement with values reported in the literature. Moreover, in accordance with recent sediment studies, we find the shear attenuation to have an approximately quadratic frequency dependence.

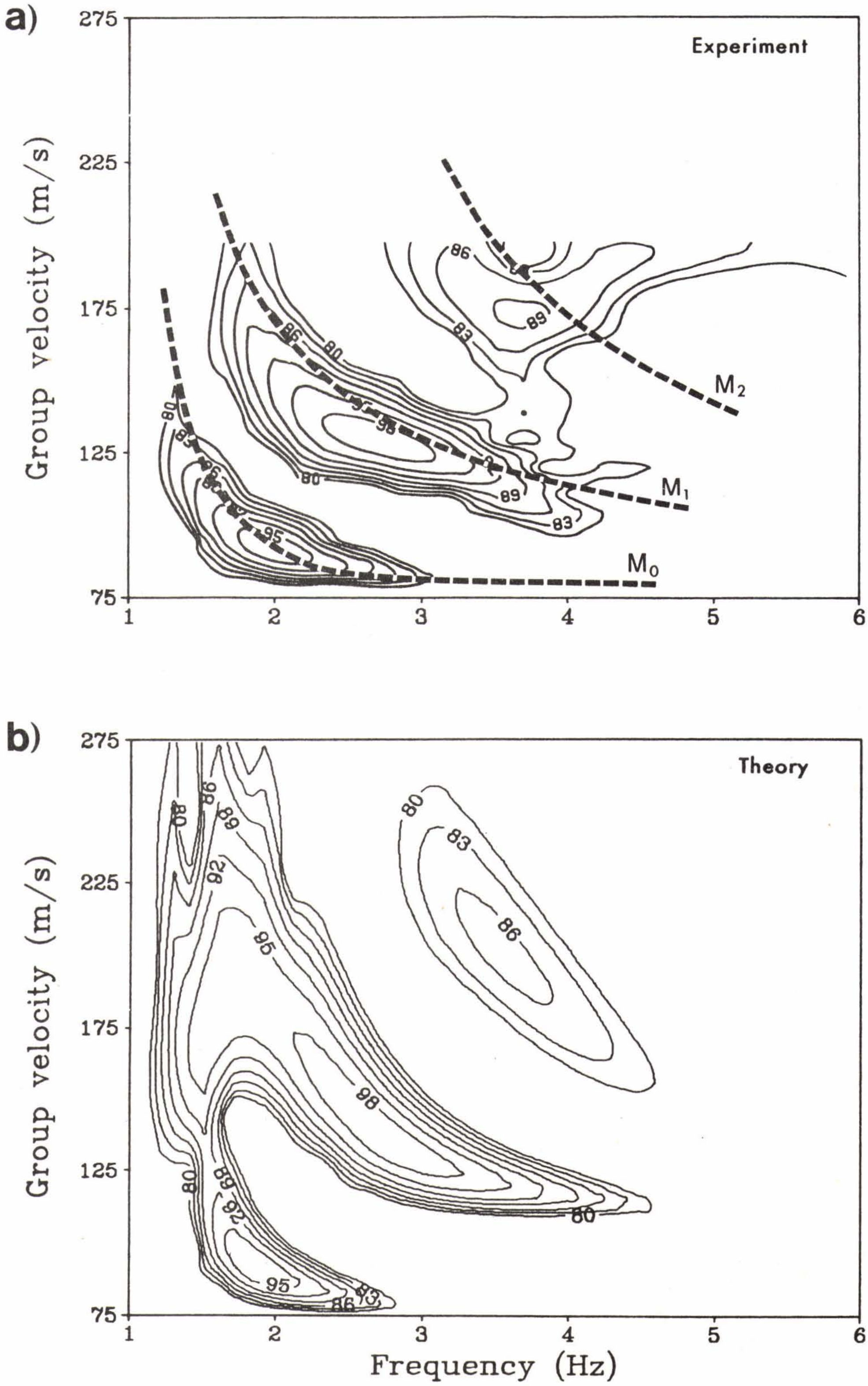

Fig. 5 Experimental (a) and theoretical (b) dispersion curves associated with the horizontal particle velocity of the sea floor at range 1.7 km.

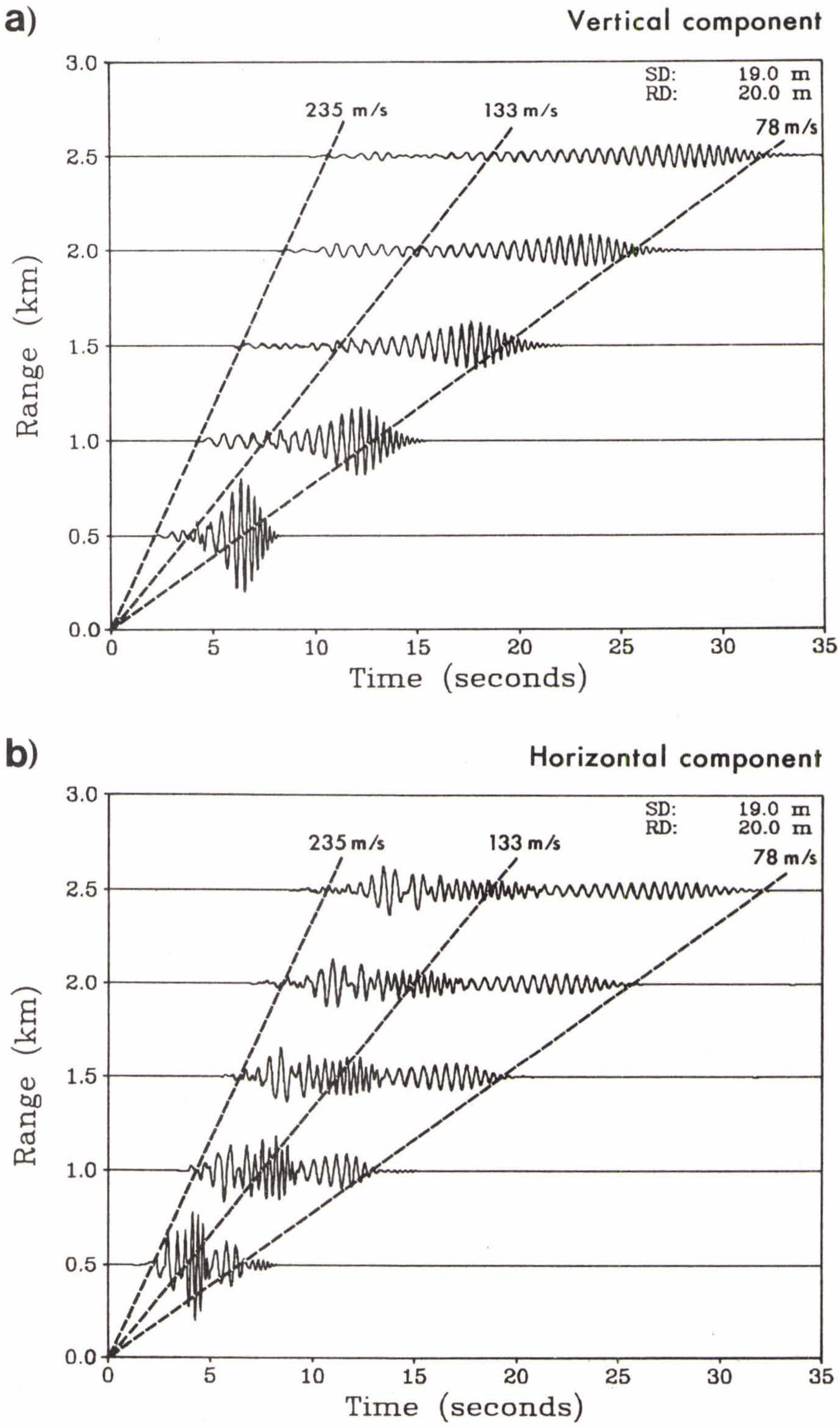

Fig. 6 Synthetic seismograms for vertical (a) and horizontal (b) particle velocities at the sea floor.

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