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Detecting sub-wavelength layers and interfaces in synthetic sediments using seismic wave transmission

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Abstract. The interface between two different homogeneous sediment layers, each composed of uniform grain sizes, is a region of heterogeneity comprising a thin layer with a thickness typically much smaller than a seismic wavelength. Seismic waves propagating *parallel* to the interface experience a reduction in both their amplitude and frequency content but the effect on group velocity is unresolvable. In the case of a single homogeneous layer bounded on both sides by homogeneous halfspaces, the ability to spatially resolve the layer thickness from amplitude or frequency information is limited by diffraction when the layer thickness is smaller than a seismic wavelength. However, the presence of a sub-wavelength interface or layer is always marked by a decrease in amplitude and in some cases by a decrease in frequency.

Introduction

A quantitative understanding of the physical properties of seafloor sediments is important when considering the environmental quality or stability of strata. The physical properties of a deposit are ultimately determined by a balance of factors such as age, structure, lithology, grain size, and hydraulic environment within this complex system. Physical structures caused by layering, cross-bedding, ripples, laminae, biological burrows and biological debris affect acoustic wave propagation. Geo-acoustic techniques can therefore be used to characterize spatial and temporal changes in sediment formations.

In some sediments, a layer is defined by a change in physical grain size although the grains may have the same chemical composition. This results in sediment structure characterized by: (1) layers with different grain sizes but without significant changes in seismic impedances, and (2) interfaces between layers that are a mixture of grain sizes. A variation in grain size with similar packing can result in layers with acoustic impedances that vary by only a few percent and do not make strong reflectors. Similarly, interfaces are transition regions between two sediment layers, and their thicknesses are often much smaller than a wavelength and may also have similar impedances to the layers. All of these factors make detection difficult. Therefore, it is important to determine the acoustic signature that will enable the detection of layering in materials with small acoustic impedance variations.

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In this paper, we examine the effect of layering, caused solely by changes in grain size, on seismic group velocity and attenuation of waves propagated parallel to the interfaces in idealized saturated-sediments. An acoustic imaging system similar to those used to study single crystals (Hauser et al., 1992) and to study permeability variations in sandstone (Nagy et al., 1995) is used to perform a detailed mapping of the seismic response of layered structures. From this study, we find that low-impedance-contrast layers that have thicknesses much less than a seismic wavelength produce distinct seismic signatures even though the ability to spatially resolve the layer thickness from amplitude or frequency information is prevented by diffraction. By analogy with optical diffraction theory, when the layer thickness is smaller than a seismic wavelength the layer cannot be resolved. Inhomogeneity or roughness of the interfaces that demarcate the boundaries of a layer can produce distinct seismic signatures.

Samples

Synthetic unconsolidated, saturated sediments were created from soda-lime silica beads to investigate the ability to seismically detect interfaces that demarcate the boundary between layers with different grain sizes. The glass beads were spherical in shape with mean diameters of 143 microns (fine bead size) and 643 microns (coarse bead size). The synthetic sediments were wet- packed in an optical cuvette with inner dimensions of 60 mm $\times$ 60 mm $\times$ 60 mm. The optical cuvette was used to ensure that the sample sides were parallel and deviations in path length did not occur. To wet-pack a sample, the cuvette is partially filled with water and then the beads are slowly poured into the cuvette. The water level is always maintained above the beads during packing.

A series of eight synthetic sediment samples with multiple layers were investigated. Sample H was a control sample consisting of a homogeneous packing of fine beads, i.e., no layers. To investigate the ability to delineate thin layers, samples L/8, L/2, L, and 2L were composed of three layers, with the middle layer composed of coarse beads and the two surrounding layers composed of fine beads. The thicknesses of the middle layers for the layered samples were constructed to be multiples of the signal wavelength ($\lambda = 8$ mm). The wavelength of the signal was determined from the arrival time of a wave propagated through a homogeneous sample composed of coarse beads. Sample L/8 consisted of the fine grain size with a 1 mm layer of coarse-grain-size beads located 32 mm from the water-sediment interface. The layer thickness in sample L/8 was approximately an eighth of a wavelength ($\lambda/8 = 1$ mm). Sample L/2 was constructed with a half- wavelength layer ($\lambda/2 = 4$ mm), sample L was constructed with a one-wavelength layer ($\lambda = 8$ mm), and

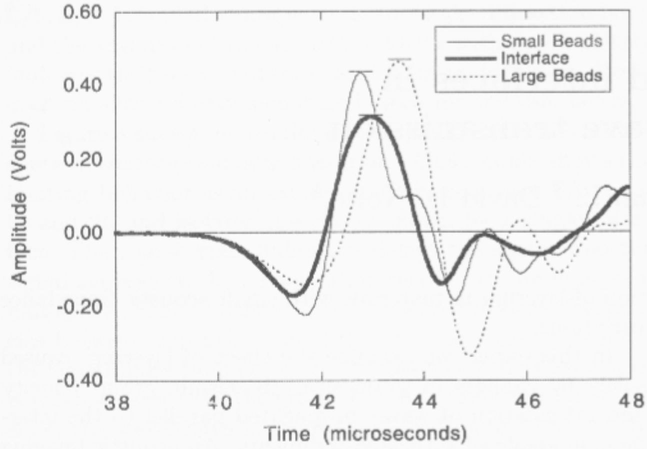

Figure 1. A 20 microsecond window of received acoustic waveforms from depths in the sampled region of 13 mm (coarse grain half-space), 23 mm (interface between the half-spaces), and 33 mm (fine grain half space) for sample HS which has a single interface between two half-spaces.

sample 2L was constructed with a two-wavelength layer (2λ 16 mm).

To investigate the ability to delineate interfaces alone, samples HPb, HCello, and HS were constructed. Samples HPb and HCello were composed of fine beads with lead foil (thickness 25 μm) and a cellophane sheet (50 μm), respectively, located at a depth of 33 mm from the sediment-water interface. Finally, sample HS consisted of two half-spaces with coarse beads overlying fine beads. The densities of the glass beads were calculated from X-ray computer tomographic (CT) data. The saturated coarse grain beads had an average density of 1952 kg/m^3 and the saturated fine grain beads had an average density of 1939 kg/m^3 (see Figure 3).

Experimental Set-up

An acoustic imaging system was designed and constructed to acquire seismic data over a two dimensional area of synthetic sediments (Mullenbach, 1996). The system is equipped with spherically-focused water-coupled source and receiver transducers with a central frequency of 500 kHz, a diameter of 25.4 mm, and a focal length of 35.5 mm. To perform a measurement, the sample is placed between the source and receiver in a water-filled tank. The source is focused on the interface between the glass beads and the inner surface of the glass cuvette to approximate a finite-size point source (8 mm diameter) at this location. At the antipodal location to the source, the receiver is also focused on the interface between the glass beads and the inner surface of the glass cuvette to approximate a finite-size point detector. The source and receiver are focused on the inner surface of the glass cuvette to minimize the effects of the container. Using focused transducers guarantees that the detected signal is in the far-field regime.

The source and receiving transducers are moved in unison by computer-controlled actuators (Newport 850B4 and

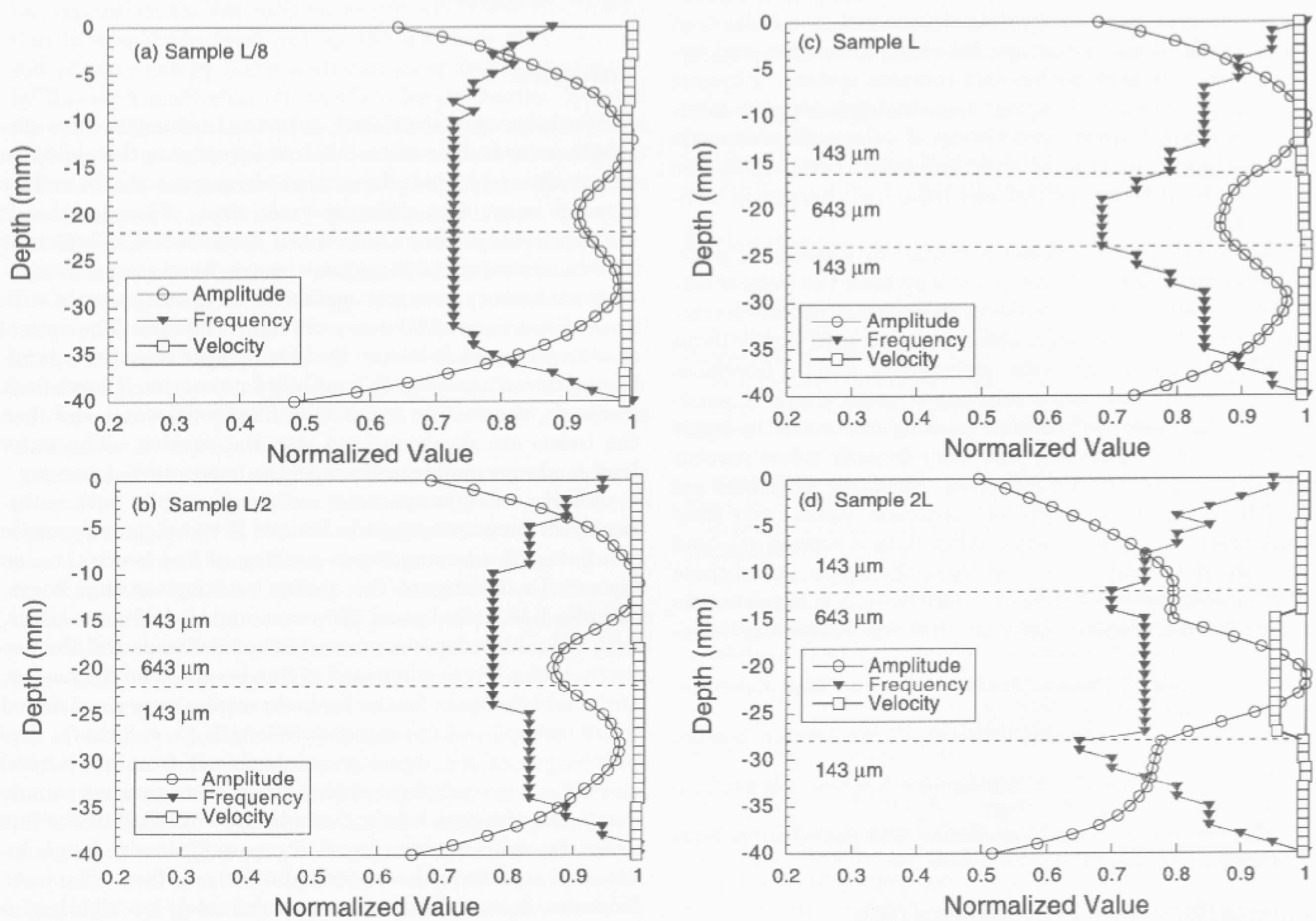

Figure 2. Comparison of normalized frequency, group velocity, and spectral amplitude for synthetic sediment samples (a) L/8, (b) L/2, (c) L, and (d) 2L. The seismic attributes are normalized with respect to the maximum value of each data set to compare relative changes in these parameters.

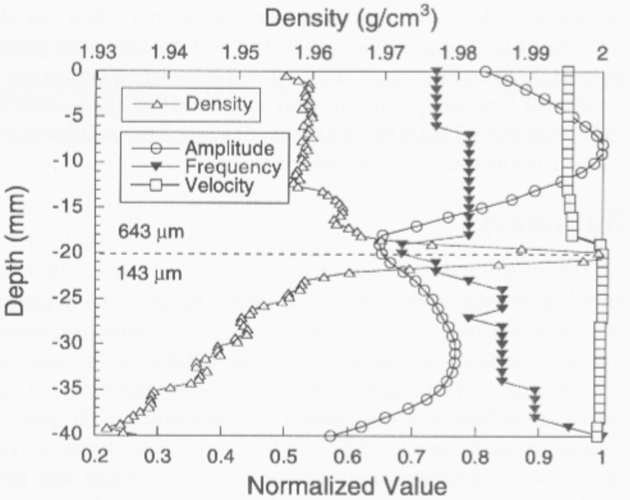

Figure 3. For sample HS, i.e., a half-space of coarse grains overlying a half-space of fine grains, the variation with depth in the sample of group velocity, amplitude, and frequency, and density.

Motion Master 2000) in 1 mm increments over a 40 mm × 40 mm region. The top edge of the sampled region is 10 mm below the water-sediment interface and the bottom edge of the sampled region is 10 mm above the inner surface of the bottom of the cuvette. At each receiving location, 1000 points of the waveform are recorded, which represented a 20 microsecond window containing the compressional-wave. The waveforms are collected by a digital oscilloscope and stored on a computer. This method produces a three-dimensional data set composed of two spatial dimensions and one temporal dimension.

Discussion

Figure 1 shows representative signals of the received waveforms from sample HS which had a single interface between two halfspaces of the different grain sizes. The waveforms were acquired at depths of 13 mm (coarse-grain half-space), 23 mm (interface between half-spaces), and 33 mm (fine-grain half-space) assuming that a depth of 0 mm corresponds to the top edge of the sampled region. The wave propagated along the interface has the same arrival time as the wave propagated through the fine-grain half-space, but has an amplitude smaller than the amplitude of the waves propagated in either half-space. This signature of a reduced amplitude near an interface is common to all the samples.

To extract the group velocity, dominant frequency, and the spectral peak amplitude of the received waveforms, a wavelet analysis was performed (Morlet et al., 1982; Combes et al., 1989; Pyrak-Nolte & Nolte, 1995). A derivative of Gaussian (1DOG) in quadrature with a second derivative of Gaussian (2DOG) wavelet was used to extract time, frequency, and amplitude information. The group information extracted from the wavelet analysis characterizes the acoustic characteristics of the dominant energy of the signal.

Figure 2 compares the variation with depth of the spectral amplitude, group velocity, and frequency of the maximum spectral amplitude among all four multi-layer samples with a coarse- grain layer between fine-grained half-spaces. The group velocity is based on the arrival time of the spectral peak in the wavelet transform, i.e., the time at which most of the energy arrives. Figure 2(a-d) compares the seismic attributes for waves propagated through

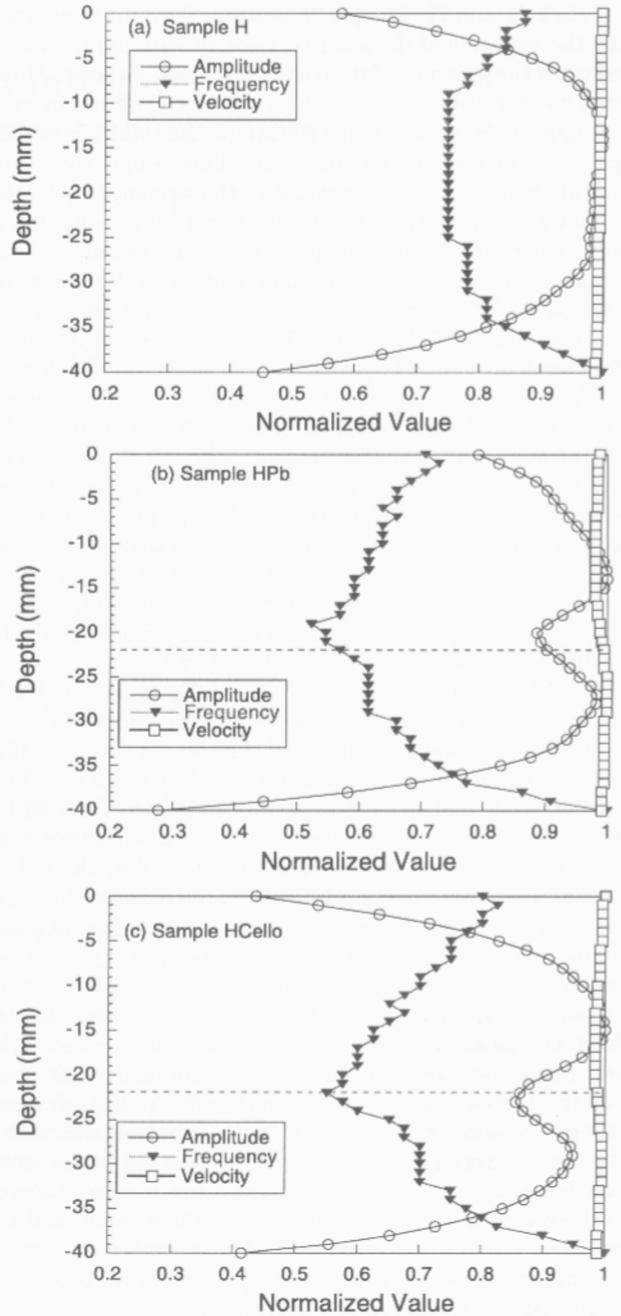

Figure 4. Comparison of normalized frequency, group velocity and spectral amplitude for synthetic sediments (a) H, (b) HPb, and (c) HCello.

samples L/8, L/2, L, and 2L to determine the ability to spatially resolve layer thickness or the location of interfaces. When the thickness of the middle layer is smaller than or equal to a wavelength (samples L/8, L/2 & L), the ability to seismically resolve the boundaries of the coarse-grain layer is limited by diffraction. However, a reduction in amplitude is still detected in the vicinity of the layer. In sample 2L (where the layer thickness is twice the wavelength) the amplitude, velocity, and the frequency response are clearly resolved and show the existence of a middle layer with distinct frequency, amplitude and velocity relative to the fine-grain half-spaces bounding the layer. The reduction in signal frequency caused by the interfaces is observable at the boundaries of the layer. Figure 2 also gives a comparison of the velocity response for waves propagated through samples

L/8, L/2, L. and 2L. Sample 2L is above the diffraction limit and the variation of the acoustic velocity with depth clearly indicates the presence of the coarse grain-middle layer. However, no such velocity signature is seen for the thin layers.

Figure 3 shows the results for sample HS, which is a half-space of coarse-grain over fine-grain. This sample shows the limiting behavior as an extension of the sequence L/8, L/2, L, and 2L and isolates the effects shown by a single interface. The coarse-grain half-space delays the signal, and the signal experiences less attenuation relative to the fine-grain half-space. Salin & Schon (1981) observed that for frequencies between 200 kHz – 500 kHz fine grain sizes attenuate the signal more than larger grain sizes when the wavelength is much greater than the grain. For the coarse and fine grain sizes, the wavelength is approximately 12 and 56 times the size of one grain diameter, respectively. A different seismic signature is observed at the interface between layers, where both the signal amplitude and frequency content are reduced. The reduction in amplitude and frequency correlate with an observed increase in density at the interface between the two half-spaces obtained through x-ray tomography (Figure 3). This high mass interface results from the mixing of the two grain sizes at the interface.

In the sequence of samples L/8, L/2, L, 2L, and HS, the amplitude is always reduced by the proximity of the interface, even though the interface thickness is much smaller than a wavelength. In addition, the interface tends to reduce the frequency content, although this can best be resolved for the thicker layers. In all these cases two mechanisms may be responsible for the reduced amplitude. First, the reduction in amplitude produced by the interface may be a result of wave energy being scattered away from the interface by Rayleigh scattering off interface heterogeneity. Second, the receiving transducer at the interface may capture waves propagated in both media. When two waves with slightly different velocities interfere at the point of reception, the low- frequency components survive a small phase difference, but the high-frequency components suffer partial destructive interference (P. Nagy, 1996, personal communication). For instance, the amplitude signature observed at the interface between coarse and fine grain layers is also observed at the water-sediment interface (top of the sample) and the sediment-glass interface (bottom of the sample). Therefore, an impedance discontinuity interface will always produce a strong seismic feature in layered samples.

To determine the effect of an interface on the seismic attributes of the signal, acoustic waves were propagated through samples HPb, HCello and L/8. For these three samples, the interface is much smaller than a wavelength (below the diffraction limit for layers) and the media on either side of the interface is the same (fine grain size). Samples HPb and HCello make it possible to investigate very thin high-mass and low-mass interfaces, respectively. Sample L/8 was used to determine the effect of a very thin interface composed of intermixed fine beads and coarse beads. Figure 4(a-c) compares the maximum spectral amplitude and dominant frequency for waves propagated through samples H, HPb and HCello. For the artificially high-mass and low-mass interfaces (Figures 4b & 4c), a decrease in dominant frequency and spectral amplitude is observed. However, for sample L/8 (Figure 2a) only a decrease in amplitude is observed.

The situations for samples HPb, HCello, and L/8, all exclude the interference mechanism for decreased amplitude and frequency because the media above and below the interface are identical. Furthermore, the nearly identical signatures of HPb and HCello discount a dominant role played by a high-mass interface. Therefore, the seismic signature of decreased frequency content and amplitude in these samples can most likely be attributed to scattering from inhomogeneity or roughness of the interface itself.

Summary

We examined the acoustic behavior of layers in saturated synthetic sediments that were formed by a change in the physical grain size but without significantly changing the porosity or density (< 1% difference in density). These sediment structures were characterized by: (1) layers with different grain sizes but low-contrast changes in seismic impedances (< 5%); and (2) interfaces between layers where a mixture of grain sizes occurs. When the middle layer thickness was greater than a wavelength, the wave amplitude, frequency, and velocity of the middle layer can be spatially resolved, as well as the interfaces that define the boundaries of the middle layer. When the thickness of the middle layer was less than or equal to a wavelength, a reduced compressional wave amplitude was observed, although the interfaces that define the boundaries of the middle layer could not be resolved. Possible mechanisms for the observed reduction in wave amplitude and frequency that occurred at the interfaces may be interference between the two compressional waves traveling on either side of the interface with slightly different velocities, and/or wave scattering from inhomogeneity of the interface. These experimental results on controlled synthetic sediments may be useful for the interpretation of seismic data on natural sediments.

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