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Estimating shallow shear velocities with marine multicomponent seismic data

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ABSTRACT

Accurate models of shear velocities in the shallow subsurface (<300 m depth beneath the sea floor) would help to focus images of structural discontinuities constructed, for example, with P to S converted phases in marine environments. Although multicomponent marine seismic data hold a wealth of information about shear velocities from the sea floor to depths of hundreds of meters, this information remains largely unexploited in oil and gas exploration. We present a method, called the multiwave inversion (MWI) method, designed to use a wide variety of information in marine seismic data. As presented here, MWI jointly uses the observed traveltimes of P and S refracted waves, the group and phase velocities of fundamental mode and first overtone interface waves, and the group velocities of guided waves to infer shear velocities and V_p/V_s ratios. We show how to obtain measurements of the traveltimes of these diverse and, in some cases, dispersive waves and how they are used in the MWI method to estimate shallow shear velocities. We illuminate the method with synthetic and real multicomponent marine data and apply MWI to some real data to obtain a model of V_s with uncertainty estimates to a depth of 225 m and V_p/V_s to about 100-m depth. We conclude by discussing the design of offshore surveys necessary to provide information about shallow shear-velocity structures, with particular emphasis on the height of the acoustic source above the sea floor.

INTRODUCTION

The ability to construct reliable models of the shear velocities of marine sediments down to 100 m or more beneath the sea floor is important in a number of disparate disciplines. For exploration seismologists, for example, these models would help to improve the shear-wave static correction needed in oil and gas exploration (e.g., Mari, 1984; Marsden, 1993). This need has grown in importance as multicomponent marine surveys have become common (e.g., Caldwell, 1999). Images of deep shear-velocity horizons are sometimes better than those achievable with P-waves particularly in and around gas clouds (e.g., Zhu et al., 1999) and beneath high-velocity layers (e.g., Purnell, 1992), and together with P-waves provide estimates of Poisson's ratio which is used as a proxy for porosity (e.g., Hamilton, 1979; Gaiser, 1996). For geotechnical engineers, these models would help to constrain the shear modulus for investigations of foundation vibrations, slope instabilities, and expected earthquake effects (e.g., Akal and Berkson, 1986; Frivik and Hovem, 1995; Stokoe and Rosenblad, 1999). Also, knowledge of sedimentary acoustic properties is needed to understand acoustic wave loss, which is important for sonar propagation, particularly in shallow water (e.g., Stoll et al., 1988).

Over the past few decades, the shear or geoacoustic properties of marine sediments have been extensively studied in the laboratory and in situ in a variety of marine environments from near the shore to the deep oceans (e.g., Bibee and Dorman, 1991). Akal and Berkson (1986), Stoll (1989), and Hovem et al. (1991) present reviews or collections of articles on aspects of the subject. The greatest advances appear to have been in the use of interface waves to estimate shallow shear velocities, which is perhaps ironic, given the pains taken to filter out these waves in land surveys (e.g., Saatçilar and Canitez, 1988; Herrmann and Russell, 1990; Shieh and Herrmann, 1990; Ernst and Herman, 1998).

In a marine setting, the waves trapped near the solid-fluid interface are sometimes called Scholte waves (Scholte, 1958), in contrast with Stoneley waves near a solid-solid interface or Rayleigh waves near the air-solid interface. All of these waves, however, are dispersive with phase and group velocities that are sensitive primarily to shear velocities at depths that are

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inversely related to frequency. The methods of analysis fall into four general categories. First, there is the measurement of the velocities of the fundamental and first overtone with multiple-filtering methods, sometimes called frequency-time analyses (e.g., Dziewonski et al., 1969; Levshin et al., 1972, 1989; Cara, 1973). More recent studies include Dosso and Brooke (1995), Essen et al. (1998), and Kawashima and Kimura (1998). Second, there are differential multireceiver or multisource phase-velocity measurements, which have been applied primarily to the fundamental mode (e.g., recent studies include Park et al., 1999; Stokoe and Rosenblad, 1999; Xia et al., 1999). The third method is the measurement of the phase velocities of the fundamental mode and several overtones using ω-k analyses (e.g., Gabriels et al., 1987; Snieder, 1987). Finally, waveform fitting has also been applied in a few studies to estimate shear velocities and Q simultaneously (e.g., Ewing et al., 1992; Nolet and Dorman, 1996). We note that modes higher than the first or second overtones are typically not interface waves, but may sum to generate guided waves, each of which is trapped in a waveguide which may extend well below the interface (e.g., Kennett, 1984). Techniques for studying surface waves are also highly developed in regional and global seismology (e.g., Knopoff, 1972; Ritzwoller and Levshin, 1998; and many others).

Each of the methods described above has its strengths and weaknesses. Any technique that uses the fundamental and first overtone exclusively will provide little information about shear velocities below a few tens of meters unless waves can be observed at very low frequencies (i.e., below 2 Hz, which is uncommon in exploration or geotechnical seismic surveys). Waveform-fitting methods require detailed knowledge of the amplitude and phase response of the instruments, information about instrument-sediment coupling, and a priori knowledge of or joint inversion for a Q model. Finally, methods based on ω-k analyses are typically best suited for 1-D inversions, and typical shot spacings in marine exploration may be too coarse for analysis of interface waves.

We describe a method that is not intimately dependent on knowledge of instrument responses or Q, is designed for application in multiple dimensions, and provides information below the top few tens of meters beneath the sea floor. The method is based on the joint inversion of interface wave and guided wave dispersion and body wave traveltimes. We call this method multiwave inversion (MWI). As presented here, MWI simultaneously interprets interface wave group and phase velocities, the group velocities of guided waves, and refracted S-wave traveltimes, but MWI is generalizable to other wave types such as multiple S bounce phases and converted phases.

We follow the common practice of interpreting the dispersion of interface waves in terms of the normal modes of the medium of propagation (e.g., Aki and Richards, 1980; Levshin et al., 1989). Normal mode eigenfunctions give the particle motion of the waves, phase and group velocities may be computed from the eigenfrequencies and their frequency dependence, and it is also a simple matter to compute integral sensitivity kernels (e.g., Rodi et al., 1975). Guided waves are also dispersive but, as we describe below, are not as naturally interpreted from a modal perspective because each guided wave typically comprises more than a single mode. This characteristic of guided waves renders the inverse problem nonlinear, and we discuss how to deal with this nonlinearity. We model the refracted S-waves using ray theory.

Some discussion of our body-wave notation is needed at the outset. The notation we use for body waves may be unusual for exploration seismologists because it follows earthquake seismology conventions. We will discuss both refracted and reflected body waves including refracted P- and S-waves, multiply refracted S-wave bounces, and phases that convert from P-to-S in the sediments. In fact, all of the shear waves that we consider (interface waves, guided waves, and body waves) are converted from acoustic energy in the water layer. Our notation does not reflect this fact, however. Thus, by a refracted S-wave, we mean a wave that emanates from an acoustic source in the water, converts to shear energy near the sediment-water interface, dives into the sediments, and refracts back to the surface. By refracted SS, we mean a doubly refracted S-wave, that refracts twice in the sediments. These bounce phases form a sequence (SS, SSS, etc.) similar to reflection multiples, but refract at depth rather than reflect from a discrete interface. We also discuss briefly a phase denoted PdS, which is a down-going P-wave in the sediments that converts to an up-going S-wave at a discontinuity d meters below the sea floor. This is a phase well known to exploration seismologists, but here we particularly mean conversions that occur in the shallow sediments, say within 100–200 m of the sea floor.

The MWI method is applied to a small data set provided to the authors by Fairfield Industries. These four-component ocean-bottom cable (OBC) data were recorded in very shallow water ($\sim$5 m) off Louisiana. There were three receivers spaced at about 1 km, and several hundred shots spaced at about every 25 m. The depth of the model is determined by the maximum range to which refracted S is observed. Shear waves are unambiguously observed to about 1.2-km distance. This means that the S model extends to a little more than 200 m beneath the sea floor, which is about the maximum turning point of observed refacted S-waves. P-wave traveltimes are measured to the same distance and, because P-waves turn above S-waves, the P model extends only to a depth of about 100 m. Due to this source-receiver geometry, we present results from our Monte-Carlo inversion only for a 1-D model, but MWI is applicable in multiple dimensions. Indeed, we provide evidence for strong variability of interface wave dispersion over the region of study.

Future enhancements and extensions of MWI include generalizing the inversion to multiple dimensions and investigating its application to land data. MWI, as we describe, is appropriate for any medium in which the heterogeneities are sufficiently smooth so as not to strongly scatter the interface, guided, and refracted waves. Marine environments characterized by active sedimentary deposition tend to display such characteristics, but so do some land settings with particularly strong "ground roll" (e.g., Al-Husseini et al., 1981). In addition, if the detailed information needed to perform waveform fitting exists, MWI would provide a very good starting model for waveform inversion. Although we regard waveform inversion to be a desirable direction for the future development of the MWI method, it remains to be seen if it will provide superior results to the method as it currently exists, which is based purely on traveltimes and wave dispersion.

The remainder of the paper is divided into four sections. In the section entitled "Theoretical Expectations," we present a discussion of the physics of seismic waves in a marine environment. In the next section, called "Data and Measurement," we describe the data and measurements used in this study. In the third section, entitled "Inversion," we present the use of MWI to estimate a 1-D S model and assess its uncertainty. Finally, we conclude with a discussion of the specifications of a marine survey designed to provide the information needed for the MWI method.

THEORETICAL EXPECTATIONS

Synthetic experiments provide insight into the nature of the various wave types and phases that appear in multicomponent marine data. The purpose of this section is to use synthetic wavefields constructed using the shallow marine model discussed in the inversion section of the paper (i.e., Figure 1) to identify the main phases and wave types expected in a marine survey and to guide the use of the MWI method to infer shallow shear-velocity structure. The wave types that we identify as potentially useful include phase and group velocity dispersion measurements of fundamental and first-overtone interface waves, group velocities of guided waves, refracted S-wave and P-wave traveltimes, differential traveltimes for refracted multiple bounce phases (e.g., S–SS, etc.), and traveltimes of P-to-S converted phases.

For the synthetic seismograms shown in this section, we have summed the first 11 Rayleigh modes (the fundamental and the first 10 overtones) from 1 to 15 Hz, tapering the resultant spectrum from 1 to 1.5 Hz and from 12 to 15 Hz. The shallow marine shear model has a 20-m thick water layer overlying a layered half-space. An explosive source with a characteristic time of 10^{-3} s is placed 2 m above the ocean floor. Without lateral heterogeneities or anisotropy, Love waves will not be generated by an acoustic source in a fluid region. Thus, Love waves are not included in the synthetic seismograms shown here, and all horizontal components are directed radially away from the source. The shear-Q model is frequency independent and approximately constant with depth with an average value of 23, and physical dispersion is included in the elastic moduli.

To illustrate modal summation, Figure 2 presents a horizontal displacement seismogram in which each of the modal contributions is plotted separately. Each higher mode contributes successively higher group velocities, but the amplitudes reduce systematically so that the entire seismogram is very well approximated by the first seven modes. The frequency content of the seismograms is determined by the Q model and the height of the acoustic source above the sea floor.

Figure 3a and 3b display the excitation spectra of the fundamental mode for source heights ranging from 1 m to 50 m above the sea floor for two different subsurface models. This characterizes the dependence of the observed spectral amplitudes of surface wave modes on the depth of the source. Figure 3a was constructed with the marine model displayed in Figure 1. A source height of 3 m with this model produces an excitation spectrum that is flat from 3 to 10 Hz. As the source is raised above the sea floor, the excitation of the fundamental mode reduces systematically. The spectrum also becomes narrow and peaks at successively lower frequencies. The details of these excitation curves depend strongly on the subsurface model. In particular, as the shear velocities in the near-surface sediments increase, the efficiency of conversion from acoustic energy in the water layer to shear energy in the sediments improves. Figure 3b shows that if the shear velocities are multiplied by a factor of two, then to achieve a specific excitation, the source can be farther off the sea floor than for the model with lower shear velocities. Finally, Figure 3c displays the excitation spectra for the fourth overtone using the marine model in Figure 1. The excitation for the overtones decays with increasing source height slower than for the fundamental modes. The consequences for the design of marine surveys are discussed later in the paper.

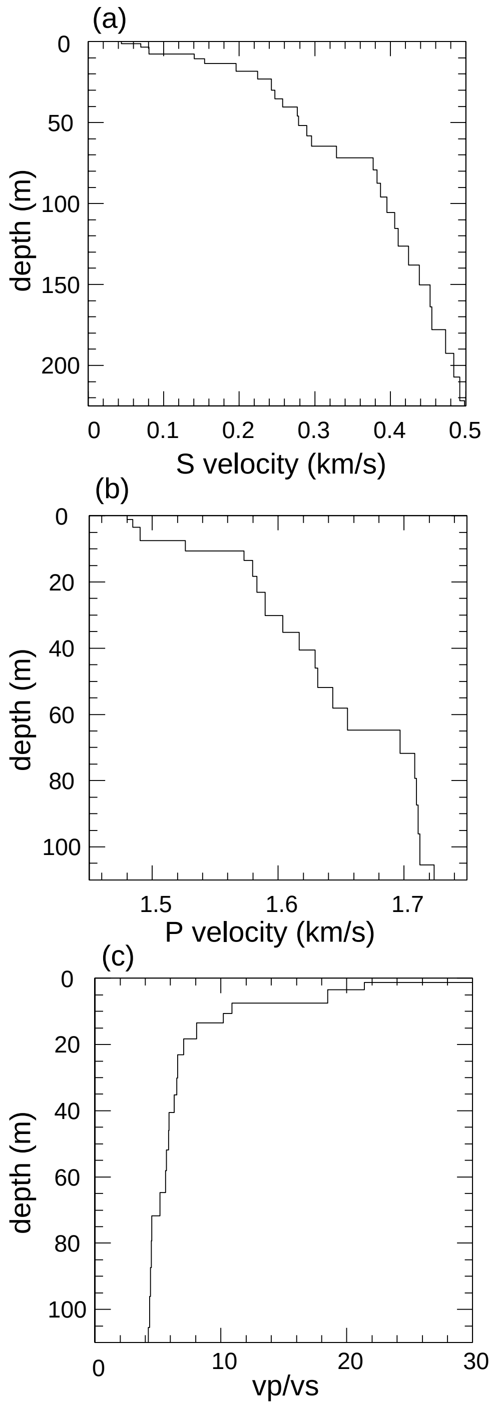

FIG. 1. One of the shallow marine models that fits the average composite data set shown in Figure 12: (a) shear-velocity V_s, (b) compressional velocity V_p, and (c) V_p/V_s. This is the model used throughout this paper.

All of the modes that contribute to Figure 2 are dispersive; that is, their phase and group velocities are frequency dependent and are not equal to one another. The group and phase velocity curves for the shallow marine model in Figure 1 are displayed in Figure 4. The amplitudes of the resultant waves will be expected to maximize near the Airy phases; that is, near the local maxima and minima of the group velocity curves. Strong arrivals, therefore, are expected at frequencies above ~2 Hz for the fundamental mode and above 5 Hz for the first overtone. As Figure 5 shows, the displacement eigenfunctions of the fundamental and first overtone at these frequencies maximize near the sea floor and are trapped in the top few tens of meters beneath the sea floor. These waves are, therefore, referred to as interface waves, and we identify them as I_0 and I_1, respectively. Different modes that have nearly the same group velocities and similar phase velocities will sum coherently and may generate a large amplitude arrival. For our shallow-marine model, the Airy phases from the first (~3 Hz), second (~4–6 Hz), third (~8–9 Hz), and higher overtones create a plateau or ridge in group velocity (e.g., Figure 4a) and sum to produce a wave guide arrival at about 140 m/s that we call a guided wave and denote as G_1. There may be several guided waves trapped in different waveguides, each creating a separate ridge on the group velocity diagram. We also identify a wave labeled G_2 that is composed of the fourth and fifth overtones with a speed of about 185 m/s. Figure 5c demonstrates that G_1 is trapped in about the top 70 m beneath the sea floor. Thus, the interface and guided waves provide information about different depth ranges of the subsurface. This fact is exploited by the MWI method.

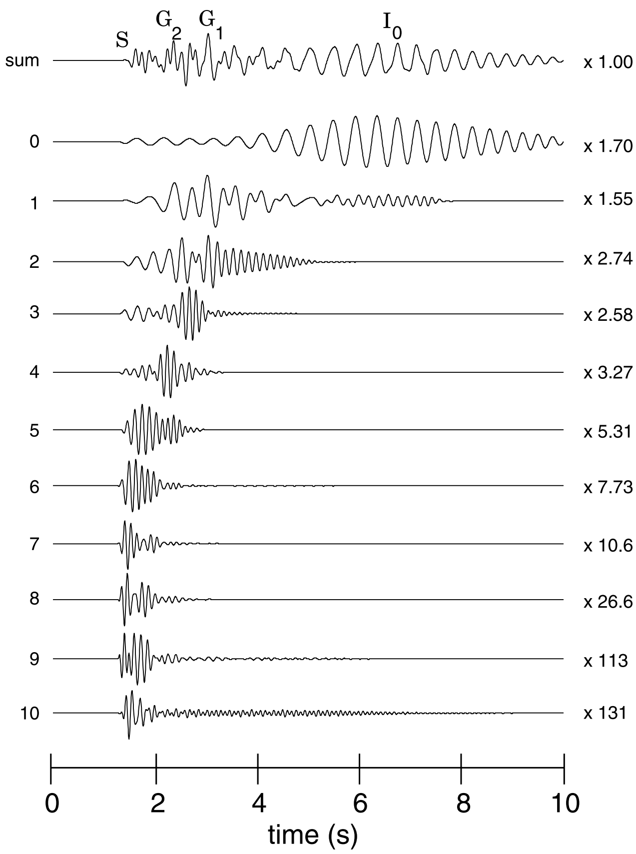

FIG. 2. Separate modal contributions to the horizontal component of a synthetic waveform for a receiver 400 m from the source. The complete synthetic seismogram is at the top, labeled as "sum" left of the trace. The fundamental mode and the first ten overtones that together sum to the complete synthetic waveform are labeled with the mode number and arrayed below it. Amplitude normalization factors are arrayed right of every trace. The approximate location of the S-wave, the first and second guided waves (G_1, G_2), and the fundamental interface wave (I_0) are indicated on the sum. The guided wave G_1 is mostly the sum of first and second overtones, G_2 is composed of the third and fourth overtones, and the S-wave is the sum of these and higher modes. The basis model is from Figure 1.

Figure 5 further demonstrates that the polarization of each mode is frequency dependent. Two good rules of thumb follow. First, the fundamental mode is approximately vertically polarized above 5 Hz, is nearly circularly polarized at 3 Hz, and is horizontally polarized at 2 Hz. Second, the overtones are all nearly horizontally polarized at the sea floor, except at very low frequencies. Thus, the fundamental is observable on both vertical and horizontal components, but the other modes are poorly observed on vertical records except at frequencies below about 3 Hz.

These expectations are confirmed by the synthetic record sections displayed in Figure 6. We wish to determine how information can be extracted from these waveforms to infer shallow subsurface S structure. The inverse problem using measurements of group and phase velocity has been well studied. Given the full set of theoretical dispersion curves presented in Figure 4, the input model could be very accurately reconstructed. These curves, however, cannot be fully estimated from the data.

Dispersion measurements are commonly obtained using frequency-time analysis (e.g., Dziewonski et al., 1969; Levshin et al., 1972, 1989; Cara, 1973). An example is shown in Figure 7. Low frequency (~2–8 Hz) dispersion measurements of the fundamental interface wave are obtainable on both the vertical and horizontal components. Dispersion measurements for the first overtone interface wave are also possible on the horizontal component from about 5 to 8 Hz. Note that for the higher modes the largest amplitudes are, indeed, near the Airy phases. Thus, broad-band dispersion curves for the higher modes would be difficult to obtain even on synthetic data. The best that can be done in practice is to measure the velocity of each guided wave on the horizontal component. These velocities then define the associated ridges or plateaus in the group velocity diagram (e.g., the first through third overtones for G_1 seen in Figure 7).

In summary, these synthetic experiments indicate that one should be able to measure and interpret the group and phase velocities of I_0 and I_1 and, potentially, the group velocity of any guided wave that exists in the data. Inspection of the vertical component frequency-time diagram in Figure 7 also suggests that a group velocity measurement can be made for the first overtone at very low frequencies (~2.5 Hz). This may, indeed, be the case in some marine surveys, but in the next section we show that this feature does not appear in the Fairfield Industries data, probably due to low-frequency instrument insensitivity.

The remaining information in the synthetic data is more fruitfully considered from a body-wave perspective. Observations of the traveltimes of refracted S-waves are relatively easy to make on horizontal-component marine data as we show later in the paper. In addition, these measurements complement interface and guided waves by providing sensitivity to structures deeper than the 50–75 m that guided waves sample. As discussed in the next section, S-wave traveltimes may be obtained from the Fairfield Industries data to a range of only about 1.2 km, which means that the shallow S model can extend no deeper than about 225 m. The double and triple refracted surface bounce phases SS and SSS are also apparent in the synthetic wavefield in Figure 6, with each bounce phase emerging successively farther from the source. Measurements of the absolute traveltimes of these phases are difficult to obtain, but global scale studies have shown that the differential times SS–S, SSS–S, and SSS–SS can be measured robustly and interpreted, with some caveats, in a straightforward way (e.g., Woodward and Masters, 1991). Finally, the converted phase that we call P*d*S is also useful to help constrain the depths of jump discontinuities.

DATA AND MEASUREMENTS

The discussion in this and the subsequent section will focus on measurements and interpretation of a small data set provided to us by Fairfield Industries. Figure 8 displays the experimental layout in which a line of shots is recorded at three receivers. The data divides naturally into three receiver gathers, and each gather separates into shots on either side [northing (N) or southing (S)] of the receiver: lines 1N, 1S, 2N, 2S, 3N, and 3S. Air-gun shots occur in about 5 m of water, so source heights average about 3 m above the sea floor. As discussed further in the section of the paper on designing marine surveys, it is the proximity of the shots to the sea floor that makes these data so useful to infer shallow shear-velocity structure.

Figure 9 presents examples of vertical and horizontal component record sections. The main wave types in evidence in the

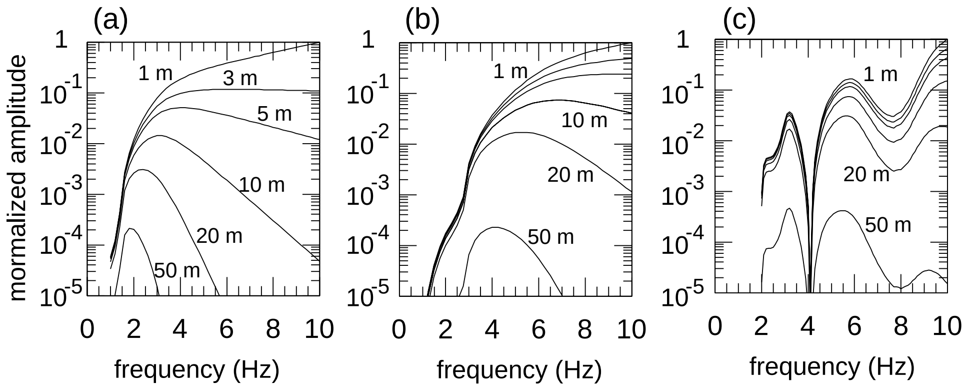

FIG. 3. Excitation curves for shots in the water at different elevations above the sea floor with receivers on the sea floor: (a) the fundamental mode using the shallow marine model in Figure 1, (b) the fundamental mode with a model in which the shear velocities in the shallow marine model are multiplied everywhere by two, (c) the fourth overtone with the shallow marine model. Elevations above the sea floor are indicated next to the associated excitation function. The product of these curves with the displacement eigenfunctions (e.g., Figure 5) gives the amplitude of the response of the medium to a point source in the fluid layer. No attenuation is included.

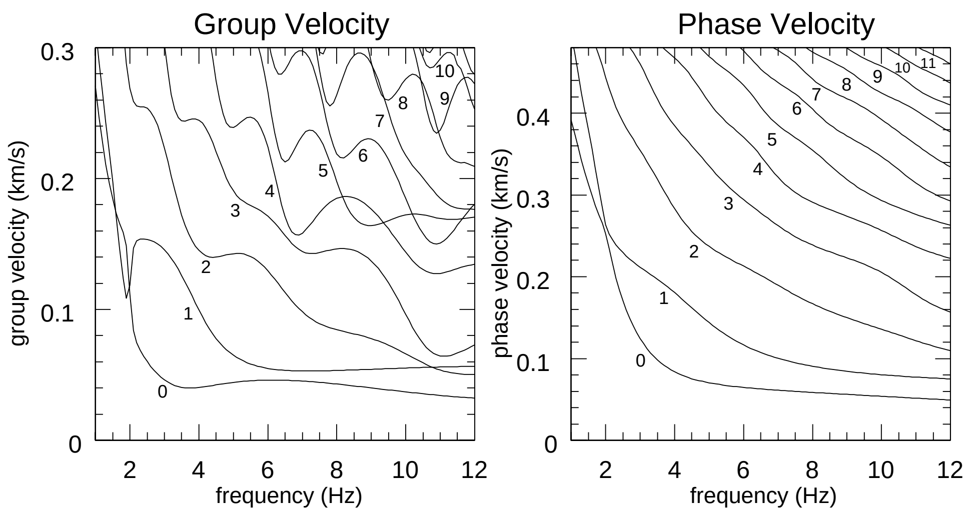

FIG. 4. Dispersion curves for the shallow marine model shown in Figure 1: (a) group velocity curves, (b) phase velocity curves. Mode numbers are labeled on the plot from the fundamental mode (0) up to the eleventh overtone (11).

observed wavefield are similar to those of the synthetic wavefield in Figure 6. The major difference between the observed and synthetic wavefields is in the amplitudes and frequency content. Improving agreement in these quantities will require a knowledge of the amplitude response of the instruments and a model of Q, which may be frequency dependent.

We measure the fundamental and first-overtone dispersion curves from vertical and horizontal component data, respectively. Figure 10 displays an example of the frequency-time diagrams used for these measurements. The guided wave G_1 is observed between 4 and 9 Hz and averages about 140 m/s, and G_2 is observed between about 6 and 9 Hz and averages about 170 m/s. Refracted S-wave traveltimes are also measurable, as Figure 11 shows.

Fundamental-mode group-velocity measurements are obtained from source-receiver distances ranging from about 75 m to 650 m. The maximum distance is limited by the length of the observed time series (16 s). Consequently, the first overtone, being faster than the fundamental, is measured to greater distances, out to about 1 km in some cases. The locations of the refracted S-wave traveltime measurements are typically obtained at source-receiver distances ranging from about 100 m up to 1.5 km. Observations past about 1.2 km become difficult with this data set.

The phase velocities of the dispersed waves are also potential observables. Although phase and group velocities are simply related through a frequency derivative, the group velocity measurements are obtained on the envelope of the waveform, whereas phase velocity estimates derive from observations of the phases themselves. Thus, although phase and group velocity measurements are not completely independent, it is useful to measure them both. Observations of phases are defined unambiguously only modulo 2π, so there is an inherent ambiguity in the phase velocity inferred from the observed phase at a given source-receiver distance. This problem worsens as the source-receiver distance increases. One way around it is to measure the difference in the observed phase for two paths that are nearly coincident, so that the expected phase difference between the two observations is much smaller than 2π. We measure differential phases for shots that are nearly the same distance from a particular receiver. These differential phase velocity measurements constrain the phase velocity of the wave only between the shots and, therefore, provide higher horizontal spatial resolution than the absolute velocity measurements.

We made about 150 fundamental and first-overtone group-velocity measurements across the study region (Figure 8) and about 250 differential fundamental mode phase velocity measurements. We obtained a similar number of S-wave traveltimes and guided wave velocity measurements. The average of the velocities or traveltimes of these wave types is shown in Figure 12. The standard deviations of the measurements about these means are shown in Figure 13. The standard deviations of the G_1 and G_2 measurements (not shown here) also vary with frequency. In the middle of both of the G_1 and G_2 curves,

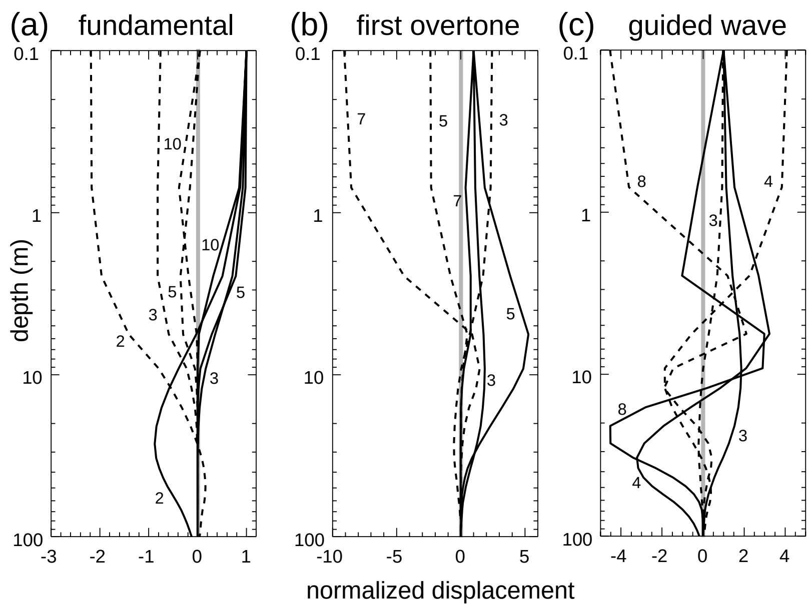

FIG. 5. Displacement eigenfunctions computed from the model in Figure 1 for (a) the fundamental mode (I_0), (b) the first overtone (I_1), and (c) the guided wave (G_1). Vertical and horizontal eigenfunctions are plotted as solid and dashed lines, respectively. The frequency is indicated next to each eigenfunction: 2, 3, 5, 10 Hz for the fundamental; 3, 5, 7 Hz for the first overtone; and 3, 4, 8 Hz for the guided wave. The guided wave is a mixture of modes and what is shown in (c) are the eigenfunctions for the first overtone at 3 Hz, the second overtone at 4 Hz, and the third overtone at 8 Hz. The eigenfunctions are unitless and are normalized such that the vertical eigenfunctions are unity at the solid-water interface (0 depth) and the associated horizontal eigenfunction has the same normalization. Thus, for each mode at each frequency, the ratio of horizontal to vertical eigenfunction is as presented in this figure, but amplitudes are not comparable across mode types and frequencies. The scales for the horizontal eigenfunctions for the fundamental mode at 2 Hz and the guided waves have been divided by 2 and 2.5, respectively, so that the vertical eigenfunction would be visible. The vertical grey lines indicate the zero levels.

the standard deviation is small (~5m/s, ~3%), but it more than doubles near the end points. The guided wave measurements are somewhat more difficult to interpret than other dispersion measurements because they are composed of several modes, and their appearance on frequency-time images is variable. We discuss the implications of this for inversion in the next section.

Although we mentioned in the section on theoretical expectations that differential refracted S-wave traveltime measurements can be obtained and the SS and SSS phases are quite apparent in the observed record section shown in Figure 9, we do not use these phases here, and this is left as a direction for future work.

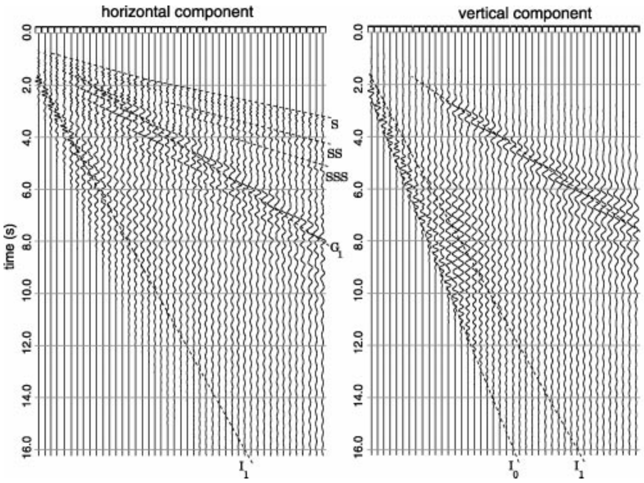

FIG. 6. Vertical and horizontal component synthetic seismograms computed by normal mode summation using the fundamental mode and the first 11 overtones for the model in Figure 1. Receivers are placed at 25-m intervals ranging from 100 m to 1200 m from the source. The main wave types are indicated with dashed lines: phases I_0, I_1, G_1, and S are described in the text, and SS and SSS are double and triple surface bounce phases, respectively. No instrument responses are applied, and ground motion is displacement. The horizontal component is the direction radially away from the source at the receiver. The seismograms have been band-pass filtered with corners at 1.5 and 8 Hz.

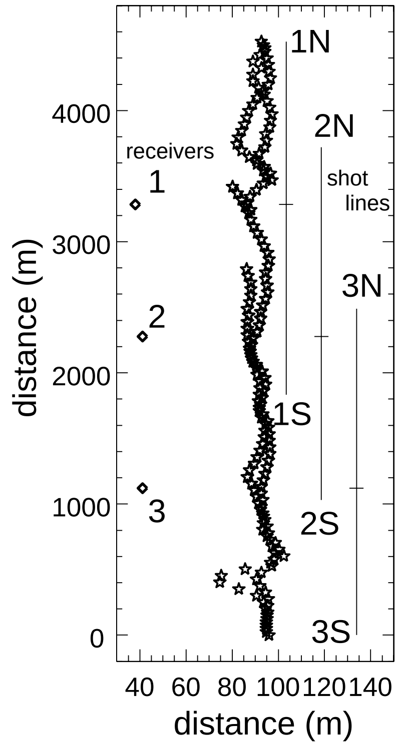

FIG. 8. Layout of the shots and receivers for the multicomponent marine OBC data provided by Fairfield Industries. Each shot is denoted by a star and each receiver by a diamond. There are three receiver gathers divided into "northern" and "southern" parts so that, for example, 1N denotes the northern half of shots for the first receiver. (The actual geographical directions are unknown to the authors.)

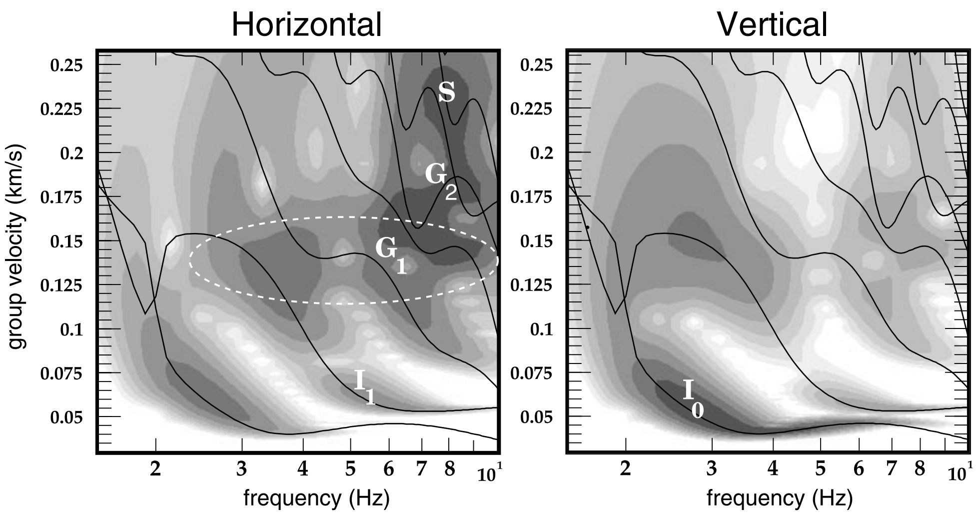

FIG. 7. Frequency-time diagrams constructed from the synthetic seismogram shown in Figure 6: (left) horizontal component, (right) vertical component. Darker shades denote larger amplitudes. The records are 400 m from the source. Theoretical group velocity curves from Figure 4a are overplotted, and wave types are indicated. The region of the diagram that contributes to the guided wave G_1 is circled and G_2 is also indicated.

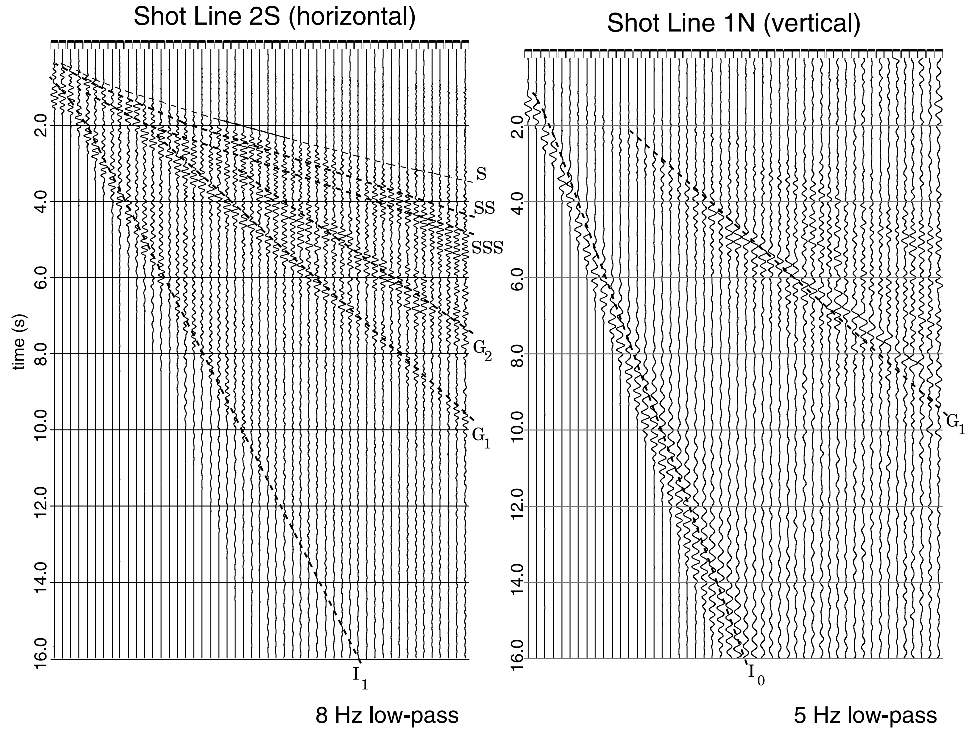

FIG. 9. Marine OBC data from Fairfield Industries. Water depth is about 5 m, and air-gun acoustic sources are about 3 m above the sea floor. Vertical and horizontal component receiver gathers are from shot line 1N for the vertical component and shot line 2S for the horizontal component (Figure 8). Dashed lines on the vertical records are approximate arrival times of the fundamental Rayleigh wave (I_0) and the first guided wave (G_1), and on the horizontal records they are the refracted shear phase S, the refacted surface bounce phases SS and SSS, and the group arrival times of the first Rayleigh overtones (I_1) and two guided waves (G_1, G_2). Shots range from about 50 m to about 1.2 km from the associated receiver. The vertical and horizontal records are low-pass filtered with a high-frequency corner at 5 Hz and 8 Hz, respectively, to accentuate the prominent low-frequency shear phases and modes.

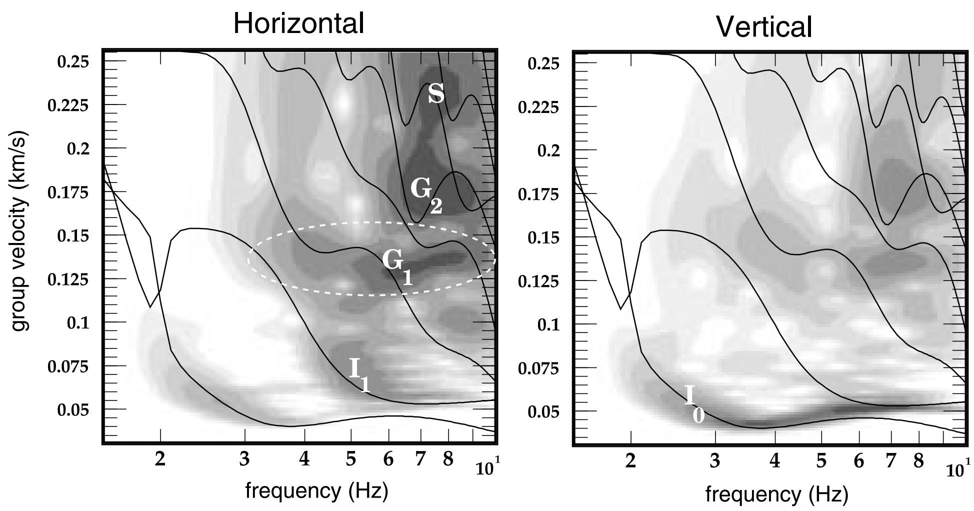

FIG. 10. Example of frequency-time diagrams for the Fairfield Industries data from receiver gather 2S (Figure 8). The vertical component is at left and a horizontal component at right. Theoretical group velocity curves (Figure 4a) computed from the shallow-marine model (Figure 1) are overplotted. Wave types are indicated. The shot-receiver distance is about 500 m.

INVERSION

Based on the source height above the sea floor (discussed further in the next section), the Fairfield Industries data are particularly amenable to inversion for shallow shear-velocity structure. These data are distributed approximately linearly in two-dimensions, as seen in Figure 8. Thus, a 3-D inversion is out of the question and, with receivers spaced about 1 km apart, it is not even possible to do a meaningful 2-D inversion because subsurface shear velocities vary on much smaller scales than the receiver spacing. Thus, the best we can do here is an inversion of the average measurements for a 1-D model. With a suitable distribution of sources and receivers, however, the MWI method is entirely suitable for 2-D or 3-D inversions.

To investigate the spatial variability of the measurements prior to inversion, we use all 115 fundamental-mode group-velocity dispersion curves to produce an estimate of the smooth spatial variation in group velocities. This is an example of surface wave tomography (e.g., Barmin et al., 2001) and a similar approach was taken by Stoll et al. (1994). We obtain Figure 14, which shows that group velocities are considerably slower toward the "north" by up to 25% relative to the far "south." The relative error of most of the measurements is presented in Figure 13. This smooth spatial variation of fundamental mode group velocities reduces the relative error in the measurements from about 6–9% to under 2% on average. Therefore, most of the variability in the measurements is systematic, and we conclude that measurement variance dominantly has a structural cause. A 2-D model would be able to fit the measurements considerably better than the 1-D model whose construction we describe here.

We invert six curves that represent the average of all measurements for a 1-D model: the five dispersion curves and one traveltime curve shown in Figure 12. These include the group velocities of the fundamental and first-overtone interface waves and two guided waves (G_1, G_2), the phase velocity of I_0, and the traveltime curve of the refracted S-wave.

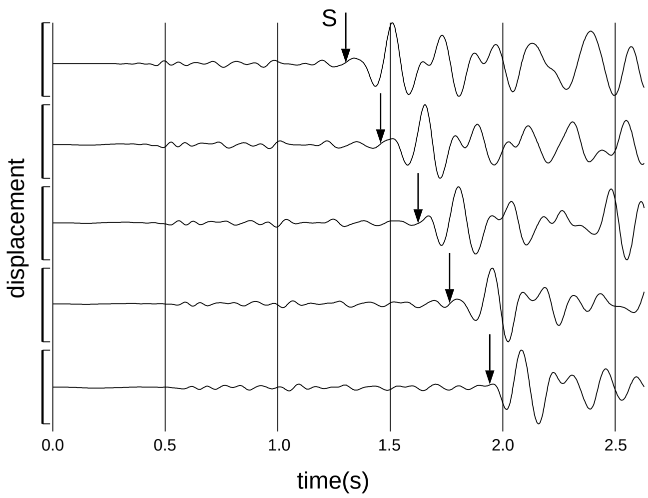

FIG. 11. Examples of the measurement of S velocities for a set of horizontal component records on the 1N shot line (Figure 8) from the marine Fairfield Industries data. A low-pass filter with high-frequency corner at 8 Hz was applied to reduce the high-frequency noise (multiple P arrivals and P to S conversions) preceding the S arrivals. Shot-receiver distances range from 341 m to 541 m.

As discussed briefly in the preceding section, each guided wave is composed of a different combination of modes. This renders these waves more difficult to interpret in practice than the dispersion measurements for a single mode. For this reason, we do not attempt to fit the dispersion curves of G_1 and G_2 directly but only to fit certain discrete velocities along each average group velocity curve. For G_1, we use the velocities at 5.5 and 7.0 Hz (~130 m/s and ~140 m/s), which we interpret as the second and third overtones, respectively. For G_2, we only use the velocity at 7.0 Hz (~170 m/s), which we interpret as the fourth overtone. The assignment of the modal constitution of the guided waves requires insight into the general dispersion characteristics of the medium. This insight must be based on a fairly good subsurface S model prior to the introduction of the guided waves into the inversion. In practice, the guided waves must be introduced after models that fit the other data are found. This renders the inversion formally nonlinear because the interpretation of the guided waves depends on the models that fit the other data. Thus, guided waves are only useful in the context of an inversion with other more simply interpreted data, such as the refracted S and interface dispersion measurements here, or a priori information about subsurface structure (e.g., from bore-hole measurements).

Inversions can be performed with any of a variety of different methods. We choose a Monte Carlo method because it is simple and provides several advantages. First, it permits the application of a wide variety of side constraints on the model. Second, it presents a range of acceptable models which allows uncertainties to be assigned to the estimated model. These estimates, however, depend on the weights assigned to the different data types in the penalty function and the side constraints to which the model must adhere. Finally, it is easy to add new data as they become available, which allows the model to develop iteratively.

We parameterize each model as a stack of horizontal constant-velocity layers that extend from the sea floor to a depth of about 300 m underlying the water layer. Layer thicknesses grow gradually with depth from 1.2 m directly below the sea floor to ~16 m in the lowermost layer. Each model is a perturbation to a starting model that we constructed by explicitly inverting the group velocity curves of the fundamental mode and the first overtone for a shallow model down to a depth of about 30 m below the sea floor, fixing the top 30 m at this model, and then inverting the S-wave traveltimes for a model from 30-m to 300-m depth. This model appears sufficient to identify the modal constitution of the guided waves. The allowable perturbations in each layer are uniformly distributed in a wide band about this starting model such that the resultant model exhibits monotonically increasing velocities with depth. To avert unnecessarily oscillatory models, some kind of "smoothing constraint" on the allowable models is necessary in the absence of explicit a priori information about the location of low-velocity layers. We choose the monotonicity constraint because there is little indication of shadow zones in the S arrivals. If shadow zones were to exist, then it would be reasonable to allow low-velocity zones in the appropriate depth ranges.

The penalty function that defines the set of acceptable models is based solely on total χ^2 misfit. This statistic divides into

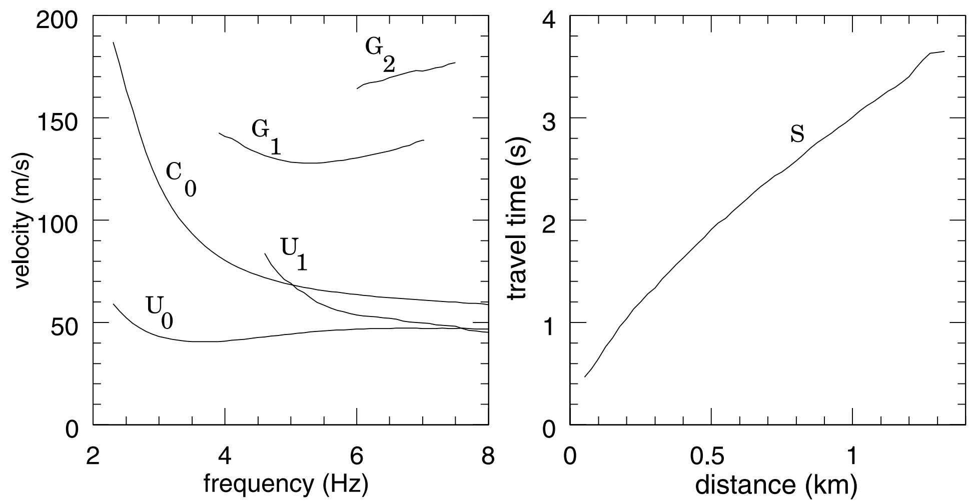

FIG. 12. Average of interface and guided wave dispersion and S-wave traveltime measurements obtained from the Fairfield Industries data: (left) fundamental mode (U_0), first overtone (U_1), and guided wave (G_1, G_2) group velocities and the phase velocity of the fundamental (C_0) are shown; (right) average S-wave traveltime.

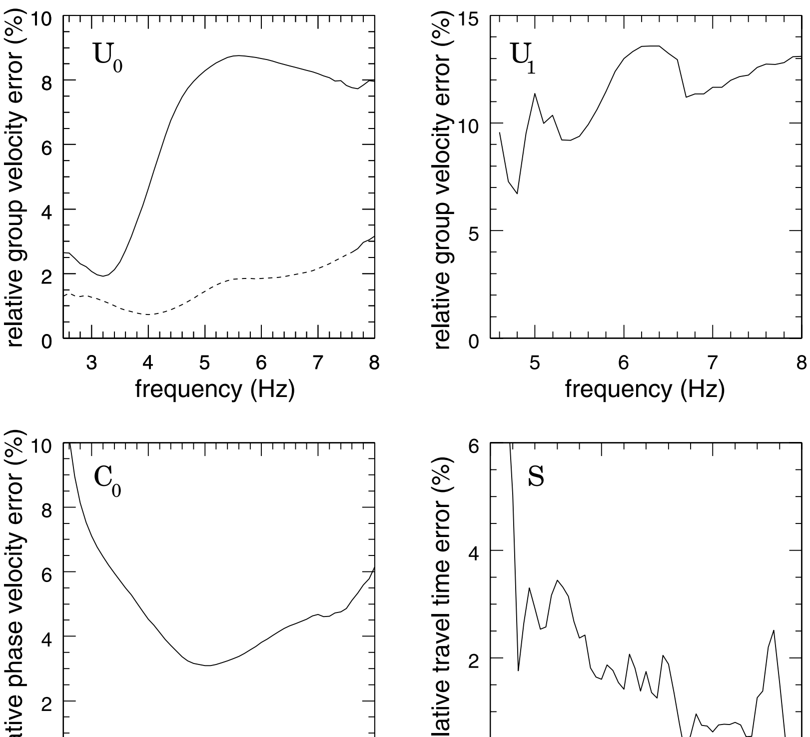

FIG. 13. Relative rms misfit between the measurements and the mean values shown in Figure 12 for the fundamental-mode Rayleigh wave-group velocity (U_0), the first-overtone Rayleigh wave-group velocity (U_1), the fundamental-mode Rayleigh wave-phase velocity (C_0), and the S-wave traveltime. When the group velocities from Figure 14 are taken as the reference, the misfit to the fundamental Rayleigh wave-group velocity measurements reduces to the dashed line in the top-left panel. Interface wave results are plotted versus frequency, and the S-wave results versus horizontal distance. All units are percent.

the misfit to the measurements of single mode dispersion ($\chi^2_{\rm disp}$), S-wave traveltimes ($\chi^2_{\rm S}$), and the discrete guided wave velocities ($\chi^2_{\rm gw}$) as follows:

$$\chi^2 = \chi^2_{\rm disp} + \chi^2_{\rm S} + \chi^2_{\rm gw}, \tag{1}$$

$$\chi^2_{\rm disp} = \sum_n^N \frac{1}{\Delta\omega_n} \int \sigma_n^{-2}(\omega)[U_n(\omega) - \hat{U}_n(\omega)]^2 \, d\omega, \tag{2}$$

$$\chi^2_{\rm S} = \frac{1}{\Delta\ell} \int \sigma_T^{-2}(\ell)[T(\ell) - \hat{T}(\ell)]^2 \, d\ell, \tag{3}$$

$$\chi^2_{\rm gw} = M^{-1} \sum_m^M \sigma_m^{-2}[U_m(\omega) - \hat{U}_m(\omega)]^2, \tag{4}$$

where ω is frequency, ℓ is distance, U represents a measured velocity, T is a measured traveltime, $\hat{U}$ and $\hat{T}$ are quantities predicted by a model, n is the dispersion measurement index, m is the index for the discrete guided-wave velocities, σ_n represents the frequency-dependent standard deviation of dispersion measurement n, σ_T is the distance-dependent standard deviation of the S-wave traveltime, and the integrals are performed over the limits of the measurements of width $\Delta\omega_n$ for dispersion measurement n and $\Delta\ell$ for the traveltime.

The ensemble of acceptable models is defined by a total $\chi^2 < 4$, which means that the data on average are fit to twice the standard deviation of the measurements (see Figure 13). We considered several hundred thousand trial models from which about 300 "winners" emerged. One of the better fitting models, shown in Figure 1, is the model we use as a reference throughout the paper. S velocities range from about 45 m/s at the sea floor to nearly 500 m/s at a depth of 225 m. The depth gradient is very high in the top 20 m, as expected for compacting marine sediments (e.g., Hamilton, 1980; Meissner et al., 1985), and between depths of 40 and 80 m, but generally decreases with depth. The high gradient regions are modeled with prominent discontinuities between about 10 and 20 m and at a depth of about 70 m. The P model in Figure 1b is estimated independently from the S model using the measured refracted P-wave traveltimes with the constraints that the velocity at the sea floor is the acoustic velocity in sea water and that P velocity also increases monotonically with depth. Like the S model, the P model exhibits prominent jump discontinuities between 15 and 20 m depth and at a depth of about 70 m. At a given source-receiver distance, P turns at about half the depth of S. Because we obtained P-wave traveltimes on the same records as S-wave traveltimes and, therefore, only to a distance of about 1.4 km, the P model extends only to about 100 m beneath the sea floor. P-wave travel times can be measured to much greater ranges than S, and the P model is extendible to greater depths easily. The V_p/V_s ratio, shown in Figure 1, is more than 20 in the shallow layers, decreases rapidly to a depth of about 20 m, and then decreases more gradually to about 4 at a depth of 100 m.

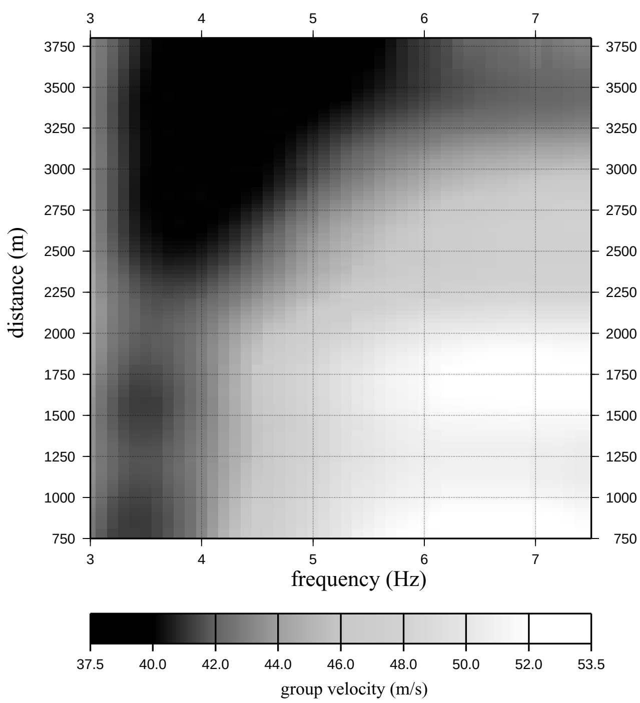

FIG. 14. Spatial variation of group velocity dispersion for the fundamental Rayleigh wave (I_0) from the marine Fairfield Industries data. Distances refer to the spatial scale in Figure 8.

Figure 15a quantifies the range of acceptable models. The uncertainties are fairly conservative. We used a 2σ misfit criterion ($\chi^2 < 4$) and then plotted error bars that are twice the standard deviation across the acceptable models in each layer. Figure 15b displays the range of vertical shear-wave traveltimes exhibited by the ensemble of models for each depth. There are no acceptable models that run systematically along the outskirts of the errors bars in Figure 15a. Rather an acceptable model may approach one end of an error bar at some depth, but then returns to more normal values at other depths. For this reason, the error bars on the vertical traveltimes are much smaller than the uncertainties in the model (<2% in half-width compared with ~7% at the bottom of the model). If a model is faster than average deep in the model, it will compensate by being slower than average higher up in the model. The use of a variety of wave types with differing depth sensitivities is designed to limit these trade-offs, but only the S-wave traveltimes constrain features below a depth of ~70 m beneath the sea floor. Thus, these trade-offs occur mainly between 70 m and the bottom of the model. The error bars in the model and in the vertical traveltime both are dominantly caused by variance in the data due to lateral structural inhomogeneity. Therefore, the uncertainties in these quantities would be substantially reduced with a 2-D inversion.

The importance of modeling S-wave traveltimes accurately for the shear static correction is seen by the fact that S-waves spend an inordinate amount of time in shallow layers in a marine environment: in this model, about 750 ms in the top 250 m and nearly 200 ms in the top 25 m alone. Physically reasonable a priori uncertainties in the shear velocities in the top 25 m could translate to ~100 ms receiver static prior to inversion.

The largest uncertainty in the model occurs around 70 m depth because the depth of the discontinuity near this point in the model is not unambiguously determined by the data we invert. All of the models in the ensemble do possess a significant discontinuity somewhere between 60 and 80 m. The discontinuity that appears in the P model is consistent with this depth range, but is similarly poorly constrained. In principle, we can obtain more information from the phase PdS, which would help in localizing shallow discontinuities. The instrument response of the data should be deconvolved and, if possible, the phase should have an anti-attenuation filter applied prior to processing. Unfortunately, the instrument responses of the Fairfield Industries data are unknown to the authors and, to date, we have constructed only a very crude Q model. Therefore, we have not included observations of P*d*S in the inversion. Comparison of theoretical arrival times with the raw waveforms indicates that P*d*S is a promising phase for imaging shallow discontinuities given an accurate model of P and S velocities above the reflectors.

DESIGNING MARINE SURVEYS

To generate seismic wavefields that exhibit the full complement of phases that provides information about shallow S structures, a marine survey must satisfy certain requirements. We discuss these requirements here.

First and foremost, as Figure 3 shows, the efficiency with which the acoustic wavefield in the sea converts to a shear wavefield in the marine sediments depends strongly on the height of the acoustic source above the sea floor. Moving the source off the bottom can rapidly attenuate the amplitude of the shear phases and reduce their bandwidth to very low frequencies. For example, for the marine model shown in Figure 1, moving a source from 1 m to 10 m above the sea floor reduces the amplitude of the fundamental mode at 3 Hz by an order of magnitude and at 5 Hz by nearly three orders of magnitude. The interface waves produced by sources more than a few meters above the sea floor, therefore, would be limited to very low frequencies, and much of the potential information about shallow shear structures would be missing.

Figures 3b and 3c present two caveats to these observations. First, the excitation of the overtones decays less quickly than the fundamental mode as source height is increased. This means that guided waves may be observed and interface waves may be missing. As discussed in the previous section, however, without the interface waves the guided waves are hard to interpret. Second, the amplitude decrease and the narrowing of the band width of observation are mitigated if the near surface shear velocities are increased. Thus, regions of active sedimentation, which are characterized by very low near-surface shear velocities, will require acoustic sources nearer to the sea floor than regions with more consolidated sediments.

Second, there is a variety of information that is very important in modeling slow low-frequency horizontally propagating waves that may be much less important in studying seismic reflections. For example, complementary to the height-of-source requirement is the requirement that the instrument accurately record low-frequency arrivals. Thus, it is desired that the instrument record down to 1 Hz, and the phase response of the instruments should be known well. An instrumental phase advance or lag of, for example, $\pi/2$ at 3 Hz would change the measured group velocities by about 1%. This is lower than the variance in the data by about a factor of 2–3 and, therefore, is unlikely to affect appreciably the 1-D model that we present here. In a 2-D inversion, however, 1% errors would become meaningful. The inversion of traveltimes alone makes information about the instrumental amplitude response unnecessary, but if wavefield modeling or Q estimation are desirable, then the amplitude response of the instrument must also be known. Improving the agreement between the observed and simulated wavefields beyond that exhibited by Figures 6 and 9 will require using this information. Another important piece of information is accurate source and receiver locations. If we desire traveltimes with an accuracy better than 1%, then we would like source and receiver positions determined to about 1 m, which appears to be beyond current accuracy standards for marine surveys. Finally, if we wish to measure waves propagating at 40 m/s to distances of 500 m, say, measured time series must be at least 12 s in duration. This limits the shot spacing with time.

Third, as discussed above, the MWI method is ideally suited for a 2-D or 3-D inversion. For a multidimensional inversion,

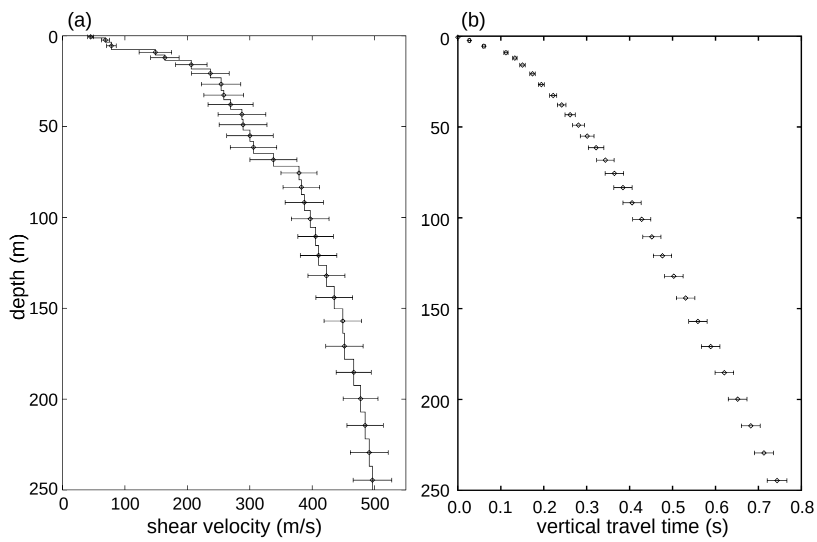

FIG. 15. Results of the Monte-Carlo inversion for V_s. (a) The best fitting model and 2σ error bars, where σ is the standard deviation in each layer of the ensemble of acceptable models. The best fitting model is shown as the solid line. (b) Vertical shear-wave traveltime to the surface computed from each depth and 2σ error bars, where σ is the standard deviation of the traveltime for the ensemble of acceptable models.

the sources and receivers should be spaced to match the lateral heterogeneity in the medium. The data set provided to us by Fairfield Industries has about a 1-km receiver spacing and a 25-m shot spacing. The receiver spacing defines the lateral resolution deep in the model and, therefore, should be no coarser than the minimum lateral resolution that is desired at depth, perhaps 25–100 m. A shot spacing of 25 m may be adequate for most purposes. It may be worth noting, however, that the wavelength of the fundamental mode at frequencies above 5 Hz is less than 10 m, so the unambiguous application of any stacking method based on ω-k analysis would require a shot spacing less than 5 m. This may mean that ω-k analyses are economically prohibitive.

Finally, as with any inversion, the quality of the estimated shear-velocity model is conditioned by the quality of a priori information used in the inversion. The inversion for shallow shear structure would be improved if information from shallow boreholes or other sources could be used. Particularly useful would be "ground truth" information on lithological boundaries at which the shear-velocity would be expected to jump discontinuously.

CONCLUSIONS

The seismic wavefield produced by an acoustic source in a water layer overlying marine sediments is rich in information about shallow subsurface shear velocities if the conditions discussed in the previous section are met. It is particularly important for the acoustic source to be very near the sea floor, particularly in regions of active sedimentation (i.e., very low near-surface shear velocities). We have argued that multicomponent OBC data currently being accumulated as part of offshore exploration can be used to construct reliable models of shear velocities to a depth of about 200 m. Such an S model, together with a P model constructed by inverting refracted P-wave traveltimes, appears to constrain V_p/V_s well in the examples presented here.

The characteristics of the marine seismic wavefield are very site dependent. The observable waves, their traveltimes, frequency contents, and dispersion properties will vary from site to site, and the application of MWI must adapt to these variations. In almost any case, however, the waves that will be the most straightforward to interpret are the dispersion characteristics of the fundamental and first-overtone interface waves and the traveltimes of the refracted S-waves. For the Fairfield Industries data collected off Louisiana, the group and phase velocities of the interface waves provide useful, although not entirely independent, constraints on shear velocities to a depth of 20–30 m. Although guided waves may be difficult to interpret, they provide valuable information to somewhat greater depths ($\sim$70 m) than the interface waves. The traveltimes of refracted S-waves provide information to the deepest point of penetration of the farthest S-waves observed. S is unambiguously observed in the Fairfield Industries data to a source-receiver range of about 1.2 km, which corresponds to an S-wave turning depth of about 225 m.

To date, we have proceeded only part of the way toward exploiting the full richness of the marine seismic wavefield. We have designed the MWI method specifically to allow the incorporation of observations on other types of waves. For example, multiple bounce S phases (e.g., SS, SSS) are well observed in the Fairfield Industries data, and differential traveltimes between arrivals are relatively easy to measure and interpret to improve constraints at depths between about 30 and 100 m. In addition, the converted phase PdS would be useful to constrain the location of jump discontinuities. Finally, the full capabilities of the MWI method await its application to appropriate data sets for 2-D and 3-D inversions.

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