Temperature contrasts in the water column inferred from amplitude-versus-offset analysis of acoustic reflections

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[1] We show that seismic amplitude-versus-offset (AVO) analysis can be used to remotely quantify the temperature contrasts responsible for acoustic reflections in the ocean. We inferred the sound speed and density contrasts associated with two reflections in the Norwegian Sea by comparing their AVO response to that predicted by the Zoeppritz equations. Estimates of temperature contrasts were calculated from sound speed contrasts using Wilson’s equation and compared with in situ temperature measurements from coincident expendable bathythermographs (XBTs). A strong reflection from Line 9 is best explained by a −6 m/s step in sound speed, corresponding to a temperature decrease of ~1.5°C. A weaker reflection from Line 11 yielded a sound speed contrast of −1.2 m/s, corresponding to a temperature decrease of ~0.3°C. The inferred temperature contrasts match those found in XBT data remarkably well. L1-norm misfits between predicted and calculated values indicate that the acoustic impedance contrasts are principally controlled by sound speed contrasts, rather than density contrasts. AVO analysis offers an accurate and robust technique for estimating sound speed (and therefore temperature) contrasts in the water column. Citation: Páramo, P., and W. S. Holbrook (2005), Temperature contrasts in the water column inferred from amplitude-versus-offset analysis of acoustic reflections, Geophys. Res. Lett., 32, L24611, doi:10.1029/2005GL024533.

1. Introduction

[2] The analysis of variations of seismic amplitudes with offset has been used for decades to infer physical property contrasts at reflective boundaries in the solid Earth [e.g., Rutherford and Williams, 1989]. The amplitude of a wave reflected from a density and/or sound speed contrast depends on the incident angle of the wave, θ, and the physical properties of the medium above and below the interface: p-wave sound speed, Vp, s-wave sound speed, Vs, and density, ρ [Ostrander, 1984]. The mathematical description for estimating the Vp, Vs, and density contrasts at an interface at different incidence angles is given by Zoeppritz’s equations [Aki and Richards, 1980]. Because s-waves do not propagate in a fluid, these equations are further simplified for the reflectivity structure of the oceans. Here we investigate the application of AVO analysis to the inference of physical properties in the water column.

[3] Layers of varying gradients of temperature and salinity, known as thermohaline finestructure, are characteristic of the world’s ocean [Gregg and Briscoe, 1979]. Characterizing the temperature and density finestructure of the ocean is important for understanding numerous ocean processes, including internal waves, mixing, and thermohaline circulation. Because these changes in temperature and salinity form contrasts in density and/or Vp (and hence acoustic impedance, ρVp), seismic reflection profiling can detect them [Holbrook et al., 2003]. Seismic imaging has recently been applied to imaging thermohaline fronts [Holbrook et al., 2003; Tsuji et al., 2005], mapping water-mass boundaries [Nandi et al., 2004], and quantifying ocean internal wave energy [Holbrook and Fer, 2005]. The reflection method is remarkably sensitive to temperature finestructure, with low-amplitude seismic reflections recorded from temperature contrasts as small as 0.03°C [Nandi et al., 2004].

[4] Here we show that AVO analysis can be used to infer the temperature contrasts that create acoustic reflections in the ocean. The analysis was performed on two seismic lines in the Norwegian Sea, and the results were corroborated by coincident, simultaneous XBT profiles (Figure 1). Our results provide proof-of-concept that quantitative temperature information can be gleaned from acoustic reflection strengths.

2. Methods

[5] We measured the AVO response of acoustic reflections from the water column and compared it to that predicted from the Zoeppritz equations for a range of Vp and density variations. Water column temperature structure was acquired through XBT profiles at the same time and location as the seismic data. An expendable conductivity-temperature-depth (XCTD) profile from our survey (Figure 2) constrained salinity and density variations. The seismic data were acquired in September 2003 with a 480-channel, 6-km-long streamer aboard R/V Maurice Ewing. Shots generated by a 6-element airgun array (1340 cubic inches) were fired at constant distance intervals of 37.5 m. The hydrophone group spacing was 12.5 m and each group was formed by 16 hydrophones located 0.694 m apart.

[6] Each channel in a common midpoint (CMP) sorted gather samples a given reflection point with a different incidence angle, allowing us to study the AVO response at an interface. Amplitude analysis was performed on two CMP gathers using the following processing steps: CMP sorting, band-pass filtering (20 and 90 Hz corner frequencies), velocity analysis and normal moveout (NMO) correction. To maintain the true amplitude of the signal, geometric spreading compensation and hydrophone array corrections were also applied to the data in the processing stage, as described below.
between 0–65 degrees.

In the array response occurs at the arriving wave at the array. The array response, F, can be described as $F = \frac{1}{n} \sin((1/2)\gamma n)\sin((1/2)\gamma n)$, where $n$ is the number of hydrophones in the array and $\gamma$ is the phase difference between successive hydrophones. The phase difference depends on the distance between the hydrophones in a group, $\Delta x$, the wavelength of the incident wave, $\lambda$, and the incidence angle, $\theta$, according to $\gamma = (2\pi n \Delta x / \lambda) \sin \theta$. To correct for the array effect, we multiplied the reflection amplitudes by $1/F$. The array response approaches zero when the effective array length, $n\Delta x$, is an integral number of wavelengths. The array response was calculated for the range of frequencies present in the data (10–240 Hz) weighted by the energy spectral density of the source signal. For frequencies higher than $\sim 70$ Hz, a notch in the array response occurs at $\sim 70$ degrees incidence angle; therefore we limited the AVO analysis to incidence angles between 0–65 degrees.

The first step for the AVO analysis involved the correlation of two isolated reflections with the XBT temperature profiles. Reflection patterns in the two CMP gather match the finest structures of the XBT profiles remarkably well (Figure 3). We selected two reflections for AVO analysis: one on Line 9 that corresponds to a large step in temperature of $\sim 1.5^\circ$C observed in the XBT profile at $\sim 0.62$ s, and one on Line 11 that corresponds to a prominent, though weaker, step in temperature ($\sim 0.3^\circ$C) at $\sim 0.55$ s. To avoid waveform interference (“tuning”) of reflected energy from thin layers [Kallweit and Wood, 1982], we chose reflections from relatively isolated temperature steps. For Line 9, wavelet interaction from a smaller temperature step of $\sim 0.5^\circ$C observed at $\sim 0.595$ s creates amplitude modifications of $\sim 50\%$ in our target reflections, which fall within the error limits of the analysis and do not alter the final results.

To calculate the variation of reflection coefficient with angle for a given reflection, we used the following procedure. First, we used data corrected for spherical divergence to calculate the amplitude of the source energy, $A_0$, as $-A_d/A_{mul}$, where $A_d$ and $A_{mul}$ are the amplitudes of the seafloor reflection and the first seafloor multiple at the near offset, respectively [Warner, 1990]. The amplitudes of a reflection at different incidence angles, $A_a(\theta)$, were then used to calculate offset-dependent reflection coefficient by $A_a(\theta)/A_0$. The polarity of the two reflections we analyzed is opposite to that of the seafloor wavelet, indicating negative reflection coefficients. After reflection coefficients were calculated, the array correction was applied to the data. The reflection coefficients obtained from the seismic data oscillate with increasing angles (Figures 4a and 4c), but a general trend of increasing absolute value of reflection coefficient with angle is observed. The short-wavelength oscillation was removed using a low-pass Butterworth filter (normalized cutoff frequency of 0.006$\pi$ rad/sample). Reflection coefficients were calculated from the Zoeppritz equations by varying $V_p$ and density, respectively, at increments of 1 m/s and 0.0002 kg/m$^3$ for Line 9 and increments of 0.3 m/s and 0.00005 kg/m$^3$ for Line 11. The best-fitting sound speed and density contrasts were determined by calculating the L1-norm misfit between predicted and observed reflection coefficients (Figures 4b and 4d).

3. Results and Discussion

The reflection coefficients calculated from the data show an increase in absolute value with angle that can be well matched by the Zoeppritz equations (Figure 4). The best fit between predicted and observed reflection coefficients on Line 9 was obtained for a $-6 \pm 1$ m/s step in sound speed and a $0.0008 \pm 0.001$ kg/m$^3$ step in density (Figure 4b). On Line 11, the best fit was obtained for a $-1.20 \pm 0.24$ m/s step in sound speed and a $0.0004 \pm 0.0004$ kg/m$^3$ step in density (Figure 4d). The L1-norm misfits show that the AVO response requires steps in sound speed but not in density, indicating that the acoustic

Figure 1. Location of XBT (red circles) and XCTD profile (star) and seismic lines in the Norwegian Sea. Solid black lines indicate the location of the seismic transects.

Figure 2. XCTD profile used in the analysis, showing salinity (solid black line) and temperature (gray line). The inset shows sound speed (red line) and density (blue line) in the thermocline.
impedance contrasts are mainly controlled by sound speed variations. This is not surprising: while sharp sound speed contrasts are a common feature of the ocean’s thermohaline finestructure, the density structure is comparatively smooth, as temperature and salinity often co-vary to compensate density [Rudnick and Ferrari, 1999]. This phenomenon is common in temperature and density profiles from XCTD data in our area (Figure 2).

The sound speed contrasts inferred from the AVO analysis predict temperature contrasts in excellent agreement with those observed on coincident XBT data, as described below. We calculated temperature from sound speed with Wilson’s equations [Wilson, 1960], using the best-fitting Vp from Figures 3a and 3c and estimates of the salinity and pressures at the depth of the reflections. We assumed a constant salinity of 35 ppt above and below each interface (Figure 2); salinity is the least important factor in Wilson’s equation, and errors caused by uncertainties in salinity are small. Based on the depth of the reflectors, hydrostatic pressures of 4.65 MPa and 4.15 MPa were used for Lines 9 and 11, respectively.

For Line 9, a change of −6 m/s in sound speed corresponds to a temperature contrast of −1.46°C, which compares well with the temperature step seen in the XBT data (Figure 3a). The change in sound speed of −1.20 m/s obtained through AVO analysis on Line 11 corresponds to a temperature contrast of −0.30°C, which also matches the temperature step observed on the XBT data from that line (Figure 3b). The remarkable match between estimates from the seismic data and the XBT data demonstrates that temperature steps in the water column can be remotely calculated through AVO analysis of acoustic reflections.

Our results suggest that AVO analysis adds significant value over simple near-offset reflection coefficients for inferring sound speed contrasts in the ocean. On Line 11, for example, there is a mismatch of ~0.6 m/s between the smoothed calculated values and the Zoeppritz prediction at the near offset. This mismatch is ~50% of the total sound speed contrast found through AVO comparisons at all angles. Therefore estimating sound speed contrasts by analyzing amplitudes at the near offset could result in substantial errors. Moreover, a larger range of sound speed and density contrasts will match the data when only a fixed angle of incidence is used for the calculations. AVO analysis offers a more accurate and robust technique for estimating density and sound speed contrasts in the water column.

4. Conclusions

This study presents the first application of AVO analysis of seismic data for calculating temperature contrasts in the water column. The method was corroborated with in situ measurements of temperature obtained from XBT data. The analysis was performed on two reflections from temperature contrasts with differing magnitudes and depths. There is a reasonably good match between temperature contrast calculated from the AVO analysis of seismic data and that found in XBT data, demonstrating that...
temperature contrasts in the ocean can be remotely quantified with seismic data. Given the remarkable sensitivity of reflection seismic imaging to temperature contrasts as small as 0.03°C [Nandi et al., 2004] and the dense lateral sampling (~6.25 m) of seismic data, an automated technique combining AVO analysis and waveform inversions may be able to invert seismic data for temperature contrasts through the entire water column with high sensitivity and lateral resolution.

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