Seismic Wave Attenuation in Gas Hydrate-Bearing Sediments from Vertical Seismic Profiling Data, Mallik, Northwest Territories, Canada

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Summary

We present results from an attenuation study based on seismic data from Mallik, Northwest Territories, Canada, showing that effects from attenuation should be taken into account prior to gas hydrate resource characterization. Compressional quality factors were estimated from zero-offset Vertical Seismic Profiling (VSP) data acquired in borehole 2L-38 at Mallik. The estimated Q-factors show significant attenuation for permafrost and hydrate-bearing sediments and are in agreement with previous estimates obtained from sonic logs and cross-hole surveys at other frequency intervals. Our results show that attenuation of thin gas hydrate layers can be observed and measured using conventional seismic exploration methods. This suggests that compensation of attenuation effects, especially those related to thick permafrost, could improve seismic imaging of hydrate-bearing sediments and reservoir characterization in the Mackenzie River Delta.

Introduction

The Mallik gas hydrate field is located on Richards Island in the Mackenzie River Delta on the coast of the Beaufort Sea. During the last 10 years, two internationally-partnered research drilling programs have intersected three major intervals of sub-permafrost gas hydrates at Mallik, and have successfully extracted core samples containing significant amount of gas hydrates (Dallimore and Collett, 2005). Individual gas hydrate intervals are up to 40m in thickness and are characterized by high in situ gas hydrate saturation, sometimes exceeding 80% of pore volume of unconsolidated clastic sediments having average porosities ranging from 25% to 40%.

Sonic logs acquired in two boreholes at Mallik show that compressional and shear velocities of sediments increase with gas hydrates concentration (Guerin and Goldberg, 2005). P-wave velocities range from 2400m/s in sediments having no gas hydrates to 3200m/s in strata with 80% pore occupancy by gas hydrate, while shear-wave velocities for similar sediments range from 900m/s to 1600m/s. The sonic logs and crosshole data also showed strong attenuation within the gas hydrate intervals (Guerin and Goldberg, 2005; Pratt et al., 2005), with estimated Q-factors ranging from 5 to 20. We present results from an attenuation study based on VSP data showing that attenuation of thin gas hydrate layers can be determined from conventional seismic exploration methods.

Attenuation from 2L-38 VSP Data

Here, we use a zero-offset P-wave VSP data acquired in 2L-38 (Sakai, 1999) to estimate seismic attenuation in sediments with and without gas hydrates. The VSP data was chosen over surface 3D data because they provide attenuation estimates that are not substantially influenced by complex data processing operations. In general, downhole seismic data provides higher accuracy for Q-factor estimates than those obtained from surface seismic data (White, 1992). The zero-offset VSP was acquired with Schlumberger CSI^{TM} (Combinable Seismic Imager) three-component receiver deployed every 5m between 500m and 1145m. This depth range covers the lower part of the permafrost (500-640m) and the three major gas hydrate zones at Mallik (890-1105m). An IVI mini-vibrator producing a 10 to 200 Hz sweep was used as a source. Further details about the survey specifications and initial data analysis can be found in Sakai (1999).

VSP data often exhibit first-arrival amplitude variations deriving from changing geophone-to-formation coupling characteristics along the well-bore. These variations were taken into account prior to the estimation of attenuation with the application of a weighted average amplitude filter. The filter is computed over a moving window comprising five adjacent traces and applied to the trace at the center of the window. Five layers can be defined from the normalized first arrival RMS amplitudes (Figure 1). Seismic attenuations are estimated for these five layers. The shallowest layer (layer1) corresponds to the lower part of permafrost. Gas hydrates intervals correspond to layer 3 and 5.

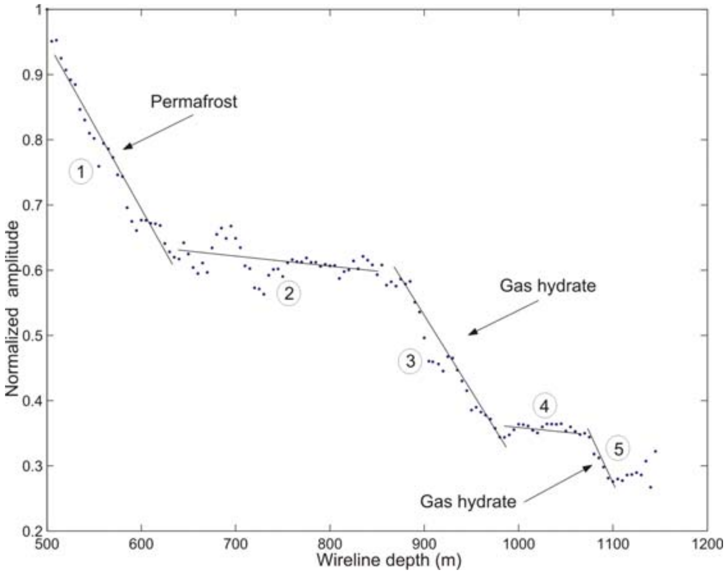

Figure 1. First arrival RMS amplitudes for the VSP data after pre-processing and normalization relative to first break amplitude at 500m. Five layers are defined and are used to estimate seismic attenuation. Gas hydrate intervals correspond to layer 3 and 5.

Zero-offset VSP are often used to establish the attenuation and dispersion characteristics of a medium. A number of techniques have been developed to take advantage of the receiver positions at depth (see Toverud and Ursin, 2005 and references therein). We adopted the approach of Toverud and Ursin (2005) to obtain estimates of Q-factors. This approach involves forward modeling (e.g. propagation at depth) of the direct wavefield recorded at a specific receiver using

$$\hat{P}(z,\omega) = \frac{P(z_o,\omega)\Gamma(z_o)}{\Gamma(z_o)+\Delta\Gamma(z)}\exp^{i\omega\Delta\tau(z,\omega)}$$

Where $\hat{P}(z,\omega)$ is the Fourier transform of the VSP data at depth z, $P(z,\omega)$ the Fourier transform at Z_o and Γ is geometrical spreading. The traveltime increment is given by

$$\Delta\tau(z,\omega) = \int_{z_0}^{z}\frac{d\zeta}{c(\omega)} = \frac{z-z_0}{c(\omega)}$$

where τ is the traveltime, ζ is the depth, and $c(\omega)$ is the complex velocity. Several models relate the complex velocity to the phase velocity and quality factor. We used the Kolsky-Futterman model (Kolsky, 1956; Futterman, 1962) given by:

$$\frac{1}{c(\omega)} = \frac{1}{c_r} + \frac{1}{\pi c_r Q_r}\ln\left|\frac{\omega_r}{\omega}\right| + i\frac{\mathrm{sgn}(\omega)}{2c_r Q_r}$$

with $\omega_r = 2\pi f_r$ and $f_r = 80Hz$. This frequency corresponds to the central frequency of the VSP data at Mallik. The quality factor and phase velocity (Q_r and c_r respectively) are the parameters tested and estimated by minimizing the difference between the forward modelled wavefield at z and the real data recorded at the same depth. A normalized misfit function is then calculated to determine optimal Q_r and c_r. The misfit function is calculated in a short time window containing only the direct arrivals, and over a group of traces within the layers shown in Figure 1.This layer-based misfit calculation assumes a constant Q_r and c_r within a specific layer, and has the advantage of providing estimates that are less sensitive to residual geophone-to-formation coupling effects and noise level at any specific receiver position. It also helps to avoid physically unrealizable negative Q values that are sometimes obtained when using a trace-by-trace approach (Matsushima, 2006). The trace at the top of each layer is used as an input to the process. The geometrical spreading was not estimated simultaneously with Q but rather corrected prior to the minimization process. We used a standard spherical spreading correction defined from the velocity function determined from the zero-offset VSP.

Figure 2 shows the misfit function for the five layers defined on Figure 1. The lower part of the permafrost (layer 1) and the two gas hydrate layers (layer 3 and 5) are characterized by strong seismic attenuation (low Q). The Q-factors for these three layers are 8, 13, and 7, respectively. Q-factors for the two gas hydrate layers are similar to those obtained from sonic logs and cross-hole survey. Sedimentary layers 2 and 4 between permafrost and gas hydrates show less attenuation (i.e. higher Q-factors of 54 and 81 respectively), also in good agreement with results from sonic logs and crosshole survey. The misfit functions show that the phase velocities and Q-factors for the permafrost and gas hydrate layers are relatively well estimated, wheras the Q-factor estimates for sedimentary layers 2 and 4 are not as well resolved. Higher Q-factors produce smaller variations on waveform, especially for waves propagating over short intervals. This likely explains the elongated shape of the misfit functions for layers 2 and 4.

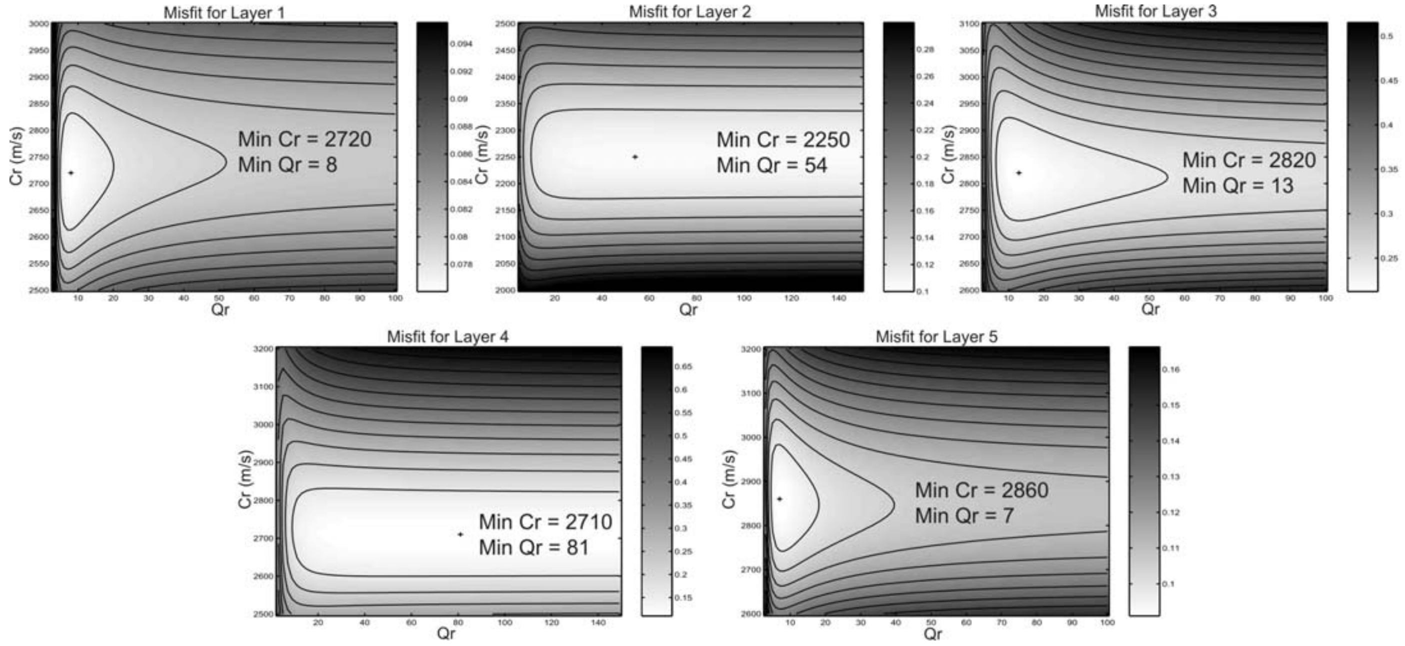

Figure 2. Misfit function for the 5 layers defined on Figure 1. The cross shows the minimum of the function. Limits of axis and gray scales for normalized misfit vary for each layer.

Conclusions

Compressional quality factors estimated from zero-offset VSP data acquired in borehole 2L-38 at Mallik demonstrate significant wave attenuation for hydrate-bearing sediments. These results are in agreement with previous estimates obtained from sonic logs and cross-hole data at different frequency intervals and confirm that seismic attenuation is an important characteristic of gas hydrates. Our results show that attenuation of thin gas hydrate layers can be observed and measured using conventional seismic exploration methods. This suggests that compensation of attenuation effects, especially those related to permafrost, could improve seismic imaging of hydrate-bearing sediments and gas hydrate reservoir characterization in the Mackenzie River Delta.

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