Seismic Modeling of Reservoir Heterogeneity Scales: An Application on Gas Hydrate Reservoirs

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Summary

Heterogeneous petrophysics reservoir models were constructed based on the P-wave and S-wave velocity logs showing a von Karman style autocorrelation function and a bimodal probability density function. P- and S-wave side scattering, wave mode conversion, and their integration play a significant role in seismic wave propagation. Synthetic reflections imply that the strong attenuation observed in the field data might be caused by the scattering and the small scale heterogeneities do not generate continuous reflections on the surface data. The Monte Carlo approach will be applied to simulate reservoirs with well log constraints and acoustic impedance from surface seismic data. Three dimensional modeling will assist the interpretation of true reflection amplitudes obtained from a simulated heterogeneous reservoir.

Introduction

Natural gas hydrates, a type of inclusion compound or clathrate, are composed of gas molecules trapped within a cage of water molecules. The presence of gas hydrates in permafrost regions and in deep ocean along continental slopes have been confirmed by core samples recovered from boreholes. However, neither the geological nor the seismic model of the gas hydrate reservoirs is fully understood. Significant variations in P- and S-wave velocities from borehole logs indicate the cementation of sediment due to the formation of gas hydrates. Cross-well survey (Pratt et al., 2005) and zero-offset Vertical Seismic Profiling data (Milkereit et al., 2005) indicate strong attenuation in the gas hydrate bearing zone. In addition, the structures of gas hydrate bearing zones are almost transparent to the conventional surface seismic methods. The contradictive properties from gas hydrate reservoirs can be attributed to wave scattering and energy conversions (Huang et al., 2006). We believe that within the gas hydrate stability zone, the lithological heterogeneities (e.g., lithology, porosity, fluid saturation, pore pressure etc.) control the distribution of gas hydrates.

From observations of a von Karman style autocorrelation function and a bimodal probability density function in the P-wave velocity logs from MITI Nankai Trough Post Survey well #1, Kamei et al. (2005) constructed a random heterogeneous P-wave model and successfully explained the frequency dependence of the Bottom Simulating Reflector (BSR) as well as the scattering attenuation. The same stochastic features are observed in the borehole logs from Mallik 2L-38 and Mallik 5L-38. Considering that energy dissipation due to wave mode conversion was ignored in acoustic modeling, we modified their algorithm and constructed a 2D elastic heterogeneous random field. Elastic finite difference modeling of seismic wave propagation demonstrated that a petrophysics reservoir with small scale heterogeneities do not generate continuous reflections. In field data processing, care must be taken to compensate the waveform distortion before stacking.

A geostatistical approach characterized by integrating seismic data and well logs was used to estimate the porosity and lithology of a reservoir (Doyen and Guidish, 1992). A similar approach will be applied to simulate gas hydrate reservoirs by combining available information from surface seismic, VSP data, and well logs.

Algorithm of Heterogeneous Random Construction

A multi-dimentional stationary random medium is characterized by an autocorrelation function (ACF) and probability density function (PDF). A spectral-based approach was adopted to simulate the randomly heterogeneous model (Yamazaki and Shinozuka, 1988).

Firstly, a linear trend was identified and then subtracted from the processed well logs of Vp and Vs in the sediment strata (Figure 1). Velocity logs were scaled by estimated standard deviations. Secondly, a bimodal probability density function was obstained by fitting the histogram of well logs from the gas hydrate strata: 890 m – 1144 m (Figure 2). The bimodal probability function was considered as a linear combination of two weighted Gaussian distribution functions (Kamei et al., 2005):

$$p(V) = \frac{w_1}{\sqrt{2\pi}\sigma_1}\exp\left(-\frac{(V-\mu_1)^2}{2\sigma_1^2}\right) + \frac{(1-w_1)}{\sqrt{2\pi}\sigma_2}\exp\left(-\frac{(V-\mu_2)^2}{2\sigma_2^2}\right) \tag{1}$$

where V is the random parameter related to the velocity, μ and σ are mean velocity and standard deviation, respectively. Least square fitting provide σ_1 values. To have a zero mean weight factor can be decided from the mean value: $w_1=\mu_2/(\mu_2-\mu_1)$, and to have a unit variance the second variance is governed by: $\sigma_2^2 = \left[\mu_2\sigma_1^2 - (\mu_2-\mu_1)(\mu_2\mu_1+1)\right]/\mu_1$. The mean values and standard deviations are listed in Table 1.

The third step was to fit the autocorrelation of the Vp logs and Vs logs by a von Karman style autocorrelation function (Goff and Jordan, 1988):

$$C\left(r(\mathbf{x})\right) = \frac{G_\nu\left(r(\mathbf{x})\right)}{G_\nu(0)} = \frac{r^\nu K_\nu\left(r\right)}{2^{1-\nu}\Gamma\left(\nu\right)}, \quad r(\mathbf{x}) = \sqrt{\left(\frac{x}{a_x}\right)^2 + \left(\frac{y}{a_y}\right)^2 + \left(\frac{z}{a_z}\right)^2} \tag{2}$$

where **x** is a vector in the multi-dimentional random field, **x**=[*x,y*] in 2D and **x**=[*x,y,z*] in 3D, and K_v is the modified Bessel function of the second kind, Γ(v) is the Gamma function, and parameter v is the Hurst number describing the roughness of the medium. The vertical characteristic scale a_z and the Hurst number v for both P-wave and S-wave velocity logs were obtained by a least square curve fitting (Figure 3). The values are in table 1.

The desired power spectrum density function (PSDF) of the medium, $S_d(\mathbf{K})$ was obtained from ACF equation (2) by a Fourier transfrom. The intermediate Gaussian random field g(**x**) was then generated from the PSDF which is followed by a mapping to construct the non-Gaussian bimodal random field: Vp and Vs (Yamazaki and Shinozuka, 1988). A strong positive correlation of Vp and Vs was assumed. In our case, the PSDF is

$$2D: S_d(\mathbf{k}) = \frac{4\pi\nu a_x a_y}{\left(1+k^2\right)^{\nu+1}}, |\mathbf{k}| = \sqrt{k_x^2 a_x^2 + k_y^2 a_y^2} \text{ and } 3D: S_d(\mathbf{k}) = \frac{(4\pi)^{\frac{3}{2}} a_x a_y a_z}{\left(1+k^2\right)^{\nu+\frac{3}{2}}} \cdot \frac{\Gamma\left(\nu+\frac{3}{2}\right)}{\Gamma(\nu)}, |\mathbf{k}| = \sqrt{k_x^2 a_x^2 + k_y^2 a_y^2 + k_z^2 a_z^2} \quad (3)$$

where k_x, k_y, k_z are the wave number component, a_x, a_y, a_z are the characteristic scales in 3-D. More general expressions can be found in Lord (1954).

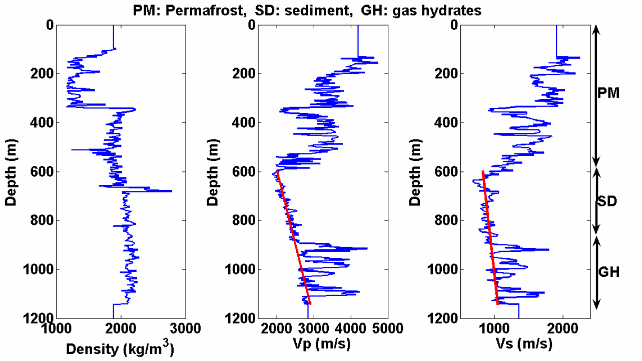

Figure 1: Linear trend identified from the sediment and gas hydrate bearing strata.

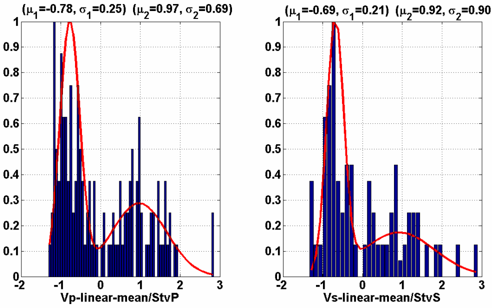

Figure 2: Least square curve fitting of velocity logs histograms. “Vp-linear-mean/stvP” means P-wave velocity logs subtracted by the linear trend and the mean value and was scaled by estimated standard deviations.

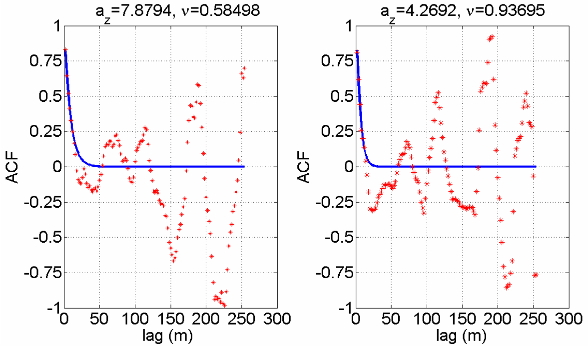

Figure 3: Least square curve fitting of the autocorrelations of scaled velocity logs.

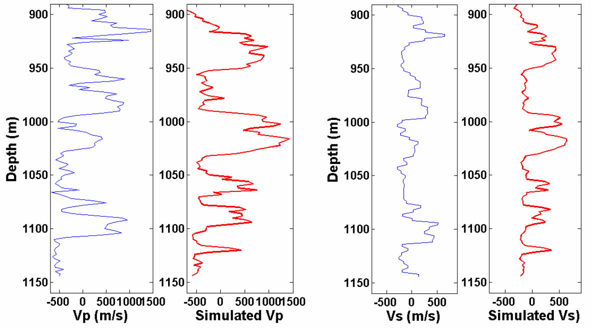

Figure 4. Field well logs before scaling are compared with the simulated well logs. The linear trend and the mean values are subtracted.

Best Fitting of P-wave velocity logs						Best Fitting of P-wave velocity logs					
μ_1 (m/s)	μ_2 (m/s)	σ_1 (m/s)	σ_2 (m/s)	a_z (m)	ν	μ_1 (m/s)	μ_2 (m/s)	σ_1 (m/s)	σ_2 (m/s)	a_z (m)	ν
-400	500	128.4	355.3	7.9	0.59	-150	200	46.0	196.2	4.3	0.94

Table 1: List of the best fitting parameters: the standard deviations, vertical characteristic scales and Hurst numbers are scaled up by estimated standard deviations.

Results from Heterogeneous Gas Hydrate Reservoirs

Selecting the horizontal characteristic scale a_x as 10m and 500m, we generated two 2D elastic random media and imbeded it into a stratified background model with reference reflectors below gas hydrate bearing zones (Figure 5, 6). A downgoing plane wave with vertical force was initiated at the free surface to simulate zero-offset response from the model. Due to strong scattering and wave conversion, small scale heterogeneities was represented as laterally discontinous seismic amplitude which has a severe impact on conventional seismic data processing, such as stacking. The presence of small scale heterogeneities has weak influence on the deep reference reflections (Figure 5) while the large scale heterogeneities do not influence the arrival time but the amplitude.

Conclusions & Outlook

A random elastic 2D medium with a bimodal PDF was constructed based on the spectral approach. The influence of different heterogeneity scales on surface seismic data was analyzed. Sythetic reflections imply that the strong attenuation observed in the field data might be caused by the strong scattering in the gas hydrate bearing zone and small scale heterogeneities do not generate continuous reflections. Large scale heterogeneities generate laterally continuous reflections with amplitude variation. In order to accurately quantify the heterogeneity of reserviors, 3D models will be constructed using the similar algorithm (Bohlen and Milkereit, 2001). Geostatistical approach based on Monte Carlo simulation will integrate available information from well logs and field data to produce an optimized petrophysics reservior model.

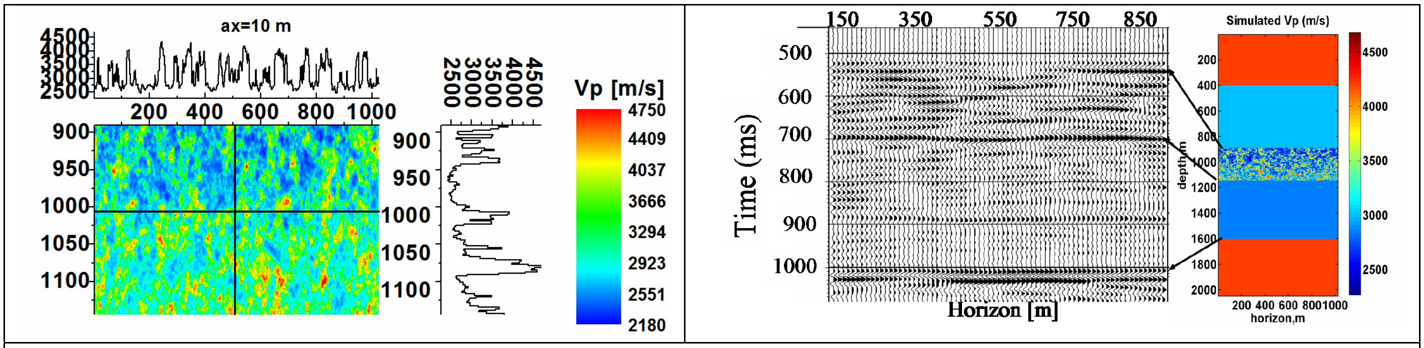

Figure 5: (Left) The randomly heterogeneous gas hydrate reservoirs with a bimodal PDF and the horizontal characteristic scale is 10m. The vertical and horizontal variation of P-wave velocity are shown in the logs. (Right) Zero-offset response from a stratified model with imbedded heterogeneous gas hydrates. Energy from gas hydrate zones arrived between 0.5 s and 0.7 s. The reflection amplitude was severely distorted due to multiple scattering.

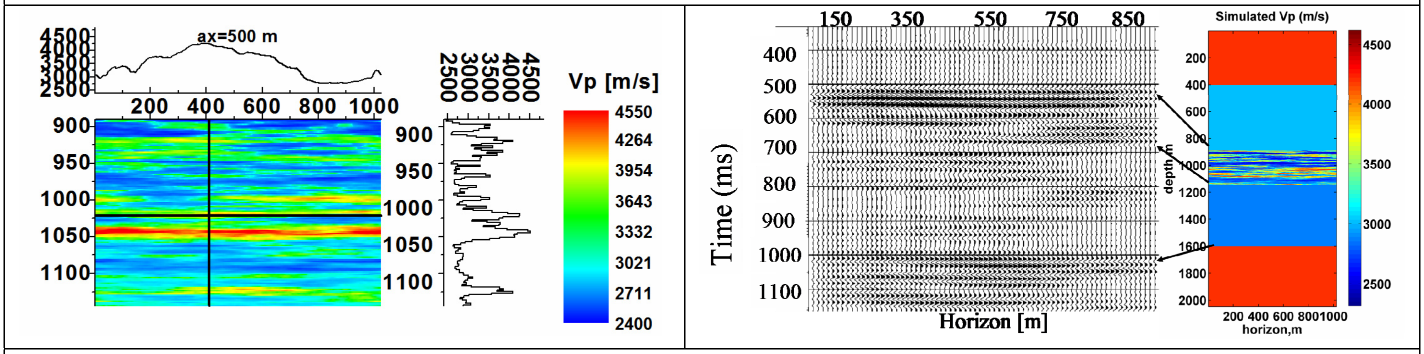

Figure 6: (Left) The randomly heterogeneous gas hydrate reservoirs with a bimodal PDF and the horizontal characteristic scale is 10m. The vertical and horizontal variation of P-wave velocity are shown in the logs. (Right) Zero-offset response from a stratified model with imbedded heterogeneous gas hydrates. Energy from gas hydrate zones arrived between 0.5 s and 0.7 s. Continuous reflections can be observed with amplitude variation.

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