LEAKY MODE: A SEISMIC WAVE ATTENUATION MECHANISM IN A GAS-HYDRATE-BEARING SEDIMENT

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ABSTRACT

This paper is concerned with the leaky mode, a possible attenuation phenomenon of seismic waves in a gas-hydrate-bearing sediment layer. This attenuation mechanism in horizontal direction occurs when a high-velocity layer is embedded in a low velocity zone. This is a typical situation for gas hydrate occurrences. To quantify this mechanism a numerical model orientated on the crosswell-data of the Mallik 2002 Gas Hydrate Research Project is created. In our purely elastic simulations we can exclude the usual attenuation mechanism like scattering loss and intrinsic absorption. We will demonstrate that the leaky mode is a significant attenuation mechanism which cannot be neglected.

INTRODUCTION

Gas hydrates are ice-like solids or clathrate composed of water and natural gas, mainly methane, which forms under conditions of low temperature, high pressure, and proper gas concentration. The ice-like structure causes strong changes in the physical (i.e., elastic) properties of the host sediment (Guerin and Goldberg, 2002). Naturally these gas hydrates are located in sediments of permafrost regions and in marine sediments under high pore fluid pressure and low temperature conditions. The common formula for gas hydrate is $M * nH_2 0$ (M is a molecule of hydrate-forming gas, n is ratio of the quantity of water molecules to one molecule of gas that varies from 5,75 to 17). At present time three different crystal structures of gas hydrates are known: SI, SII and S-H (Sloan, 1998). However, it is not reported that they behave elastically different. Wave velocities and attenuation are two important properties of seismic investigations which can give information about lithology, saturation, and the in situ conditions of rocks (Gei and Carcione, 2003). In gas-hydrate-bearing sediments high velocity and high attenuation are observed. The increase of velocity and attenuation in gas-hydrate-bearing sediments can caused by different parameters: microstructure, gas hydrate concentration, porosity, pore and confining pressures, dominant frequency of signal, and gas and water saturation. During the crosswell ray-based tomography from the Mallik 2002 Project, in the Northern West Territorium of Canada, the phenomenon of high velocities and attenuation were observed. This is a very typical observation for gas hydrate occurrences in general. The tomograms are dominated by the effects of the gas hydrate deposits, which cause higher seismic velocities. The location of laminated silts is correlated with increased velocity anisotropy. A combination of high velocities and strong attenuation ($Q_p < 15$) is observed in sediments with the highest gas hydrate saturation (up to 80 %), which provides constraints on models for the microscopic structure of the deposits (Bauer et al., 2005a). Many theoretical estimations are proposed in which strong attenuation of seismic waves caused by three mechanisms: intrinsic absorption, scattering loss and interlayer-fluid flow between layers induce by the passing wave. Dai et al. (2004) investigated that the microstructure of gas hydrates also has an influence of the attenuation. We want to show that the observation of high attenuation and high P-wave velocity can be explained partly by the so called leaky mode. This kind of acoustic energy propagates in one direction and is limited in the other two directions, and can be considered as multiply reflected and constructively interfering waves. For example these waves are propagating in a gas-hydrate bearing sediment layer as a type of a guided wave. Each time a compressional wave hits the layer boundary, one part of the energy is reflected back into the layer, while the rest is converted to compressional or shear energy that radiates into the non gas-hydrate-bearing sediment layer or propagates along the interface of the two solids.

NUMERICAL EXPERIMENT

This study is mainly inspired on the crosswell seismic data from the Mallik 2002 drilling program. Mallik is a subpermafrost location in the Mackenzie Delta, N.W.T., Canada. This drillings where carried out by the Geological Survey of Canada (GSC), the Japan National Oil Corporation (JNOC/JAPEX), the United States Geological Survey (USGS) and the Geoforschungszentrum Potsdam (GFZ). The wells named Mallik 3L-38, 4L-38, 5L-38, were drilled through gas hydrate layer of depths approximately 900m-1100m beneath 600m of permafrost on a line of 40m spacing (Takahashi et al., 2005). The boreholes 3L-38 and 4L-38 were used as source and receiver wells and the borehole 5L-38 as a production research well. The following physical parameters [see Figure 1] for the Mallik crosshole data are determined by Bauer et al. (2005b): velocity range of the elastic P-wave of 2000-4000 m/s. The petrophysical parameter of gas-hydrate-bearing sediment are determined by Kulenkampff and Spangenberg (2005): a bulk and matrix density range of 1900-2000 kg/m^3 and 2300-2600 kg/m^3.

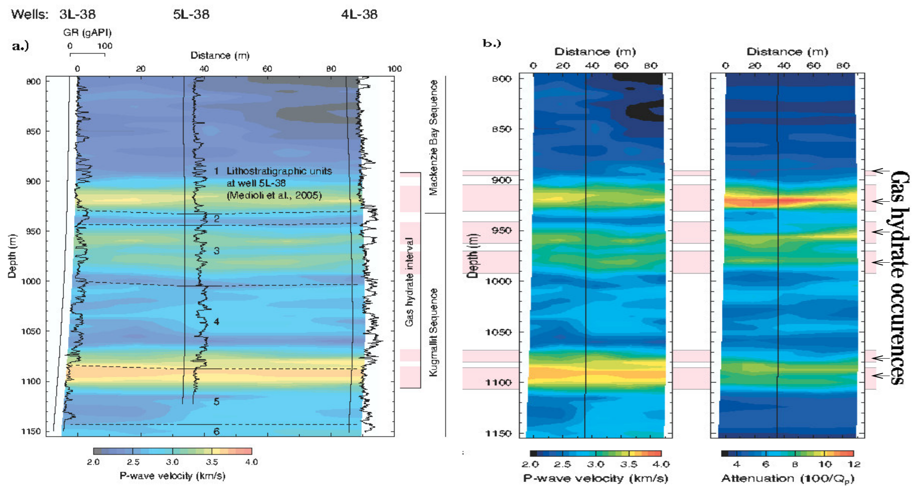

Figure 1: a).This illustration shows the Mallik setup of the boreholes and the major regional stratigraphic sequences and the depth range of the gas hydrate interval indicated on the right hand side., b). These two tomograms modified from Bauer et al. (2005a) show high P-wave velocity correlated with high attenuation in the gas-hydrate-bearing sediment.

The numerical simulations performed in this study are based on the RSG-FD-scheme (Saenger et al., 2000). Two simplified 2-D numerical models of Mallik are created to simulate the wave propagation in a gas hydrate-bearing sediment [i.e, a high-velocity layer, see Figure 2]. The models are made up of maximal 2600x1200 grid points with an interval of 0.25m and the parameters given in Table 1. A explosion source is used in the different models. The source wavelet in the experiments is always the first derivative of a gaussian curve with a dominant frequency of $f_{dom} = 95Hz$. The P-wave generated in the models propagates as a type of a guided wave through the gas-hydrate-bearing sediment layer. Within a vertical line of 5 receivers, with a distance of 25-50-75-125-175m from the explosion source, we measure the seismic wavefield.

model	thickness of LVL [m]	thickness of HVL [m]	vp and vs of LVL [m/s]	vp and vs of HVL [m/s]	ρ $[kg/m^3]$
A	300	25-37-50	2400 950	3700 1500	2200
B	300	25	2400 950	3700-3300-2900-2600-2500-2450 1500-1300-1100-950-950-950	2200

Table 1: The parameter of the different 2-D digital rock models.

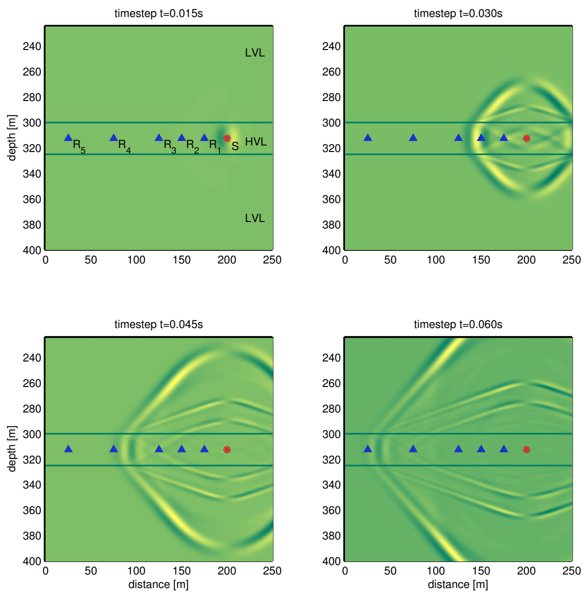

Figure 2: Z-Snapshots of the numerical simulations at a timestep of t=0.015s, t=0.030s, t=0.045s and t=0.060s. HVL is the high-velocity-layer (i.e., gas-hydrate-bearing sediment) and LVL the low-velocty-layers (i.e., non gas-hydrate-bearing sediment). The dot is the location of the explosion source and the triangles of the five receivers.

NUMERICAL RESULTS

The numerical model shown in Figure 2 is the bases for several computations which simulate the P-wave propagation in a high velocity layer (HVL) caused by an explosion source. The seismic waves provided attenuation in this HVL [see Figure3]. The receivers measure the attenuation on the peak-to-peak ampli-

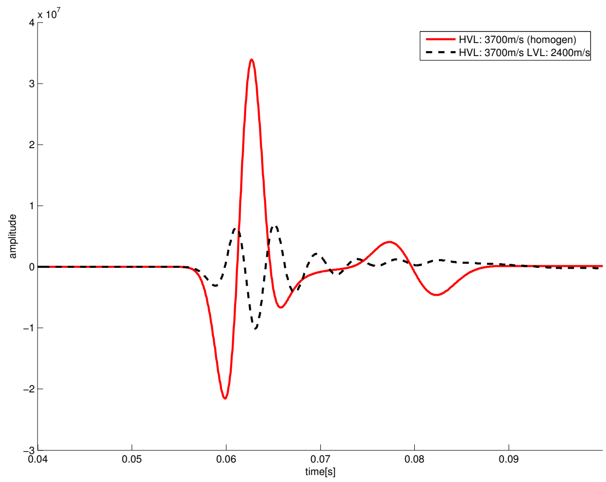

Figure 3: Two seismograms recorded at R5 (see Figure2) for exactly the same explosion source. Solid line: For a HVL with an infinite thickness. Dashed line: For a HVL of 25m thickness. The observed attenuation is due to the leaky mode.

tude of a single compressional pulse, observed as they arrive. These observation are made under different conditions as described in Table 1: In model A three different high velocity layer thicknesses with a constant P-wave velocity contrast and in model B a constant layer thickness with various P-wave velocities contrasts. To determine the attenuation by the quality factor Q we perform a correction for geometrical spreading. After this correction the seismic wave amplitude decay exponentially and the decay rates are proportional to Q^{-1} which characterizes the attenuation (Knopoff, 1964):

$$A(x) = A_0 e^{(-x\pi)/(\lambda Q)}, \quad (1)$$

where $A(x)$ is the displacement amplitude, A_0 is the amplitude at the receiver points, x is the distance from the explosion source, λ is the wavelength. The measured attenuation in the numerical calculations depends in model A on the layer thickness of the experiment, but in B on a contrast of the P-wave velocities of the high- to the low-velocity layers. As a result Q increases in model A with a decrease of the gas hydrate layer thickness (low Q) and in model B Q decreases with a loss of the P-wave velocity (high Q) [see Figure 4]. The observed losses can only be explained by the so called Leaky mode, because other attenuation mechanisms are not included in our elastic FD-modeling calculations.

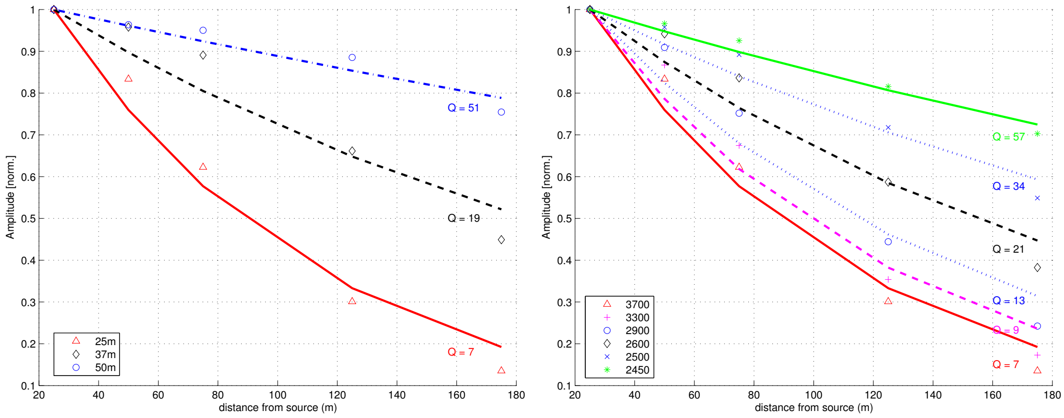

Figure 4: Observed quality factors Q for our different simulations due to the leaky mode for our different models. Left hand side: Different layer thickness and constant velocity contrast. Right hand side: Different velocity contrast and constant layer thickness. Representing in a least square fit (amplitude versus distance of travel).

CONCLUSIONS

In gas-hydrate-bearing sediments high velocity and high attenuation are observed. The increase of velocity and attenuation in gas-hydrate-bearing sediments can caused by different parameters: microstructure, gas hydrate concentration, porosity, pore and confining pressures, dominant frequency of signal, and gas and water saturation. However, with our numerical considerations we quantify another significant attenuation mechanism in horizontal direction: The phenomenon of leaky mode. By determing the attenuation of P-waves in gas-hydrate-bearing sediment layer (i.e., a high-velocity layer), we show that this absorption process can not be neglected. We can (partly) explain with our study the observed high attenuation which correlates with a high P-wave velocity [see Figure 2] in the crosswell-tomography of Mallik 2002 (Bauer et al., 2005a) .

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