ATTENUATION OF SEISMIC P-WAVES IN MULTILAYERED GAS HYDRATE-BEARING SEDIMENTS

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ABSTRACT

An increasing interest in gas hydrates as a potential energy source gave reason for numerous field studies, laboratory and numerical experiments, that have revealed some interesting aspects of sedimentary layers containing gas hydrates. Still the mechanism of formation of gas hydrates and the reasons for an observed strong attenuation are not fully understood. Two rock physical models are controversly debated: one attributes the content of gas hydrate to the properties of the rock's matrix, the other relates presence of hydrates to the properties of the pore fluid.
In our approach we assume, that an occurrence of gas hydrates affects the properties of the fluid, the frame and the grain of the host sediment. A poroelastic generalization of the O'Doherty-Anstey theory indicates that this would result in increased values for attenuation.
In order to create realistic models of multilayered, poroelastic media and to account for the observed strong fluctuations in gas hydrate-bearing sedimentary layers we investigate exponentially correlated, random media. Numerical as well as analytical results confirm, that correlated fluctuations in properties of the frame, grain and fluid can cause significant attenuation values. Especially in the seismic frequency range they are comparable to those observed in field measurements.

INTRODUCTION

Gas hydrates are ice-like solids or clathrates composed of water and natural gas, mainly methane, which form under conditions of low temperature, high pressure, and proper gas concentration. The ice-like structure causes strong changes in the physical 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. 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 strong attenuation are observed. The increase of velocity and attenuation in gas hydrate-bearing sediments can be caused by different parameters: microstructure, gas hydrate concentration, porosity, pore and confining pressures, dominant frequency of signal, and gas and water saturation. Numerous laboratory experiments and core measurements have shown, that an accumulation of crystals of gas hydrate in the pore space can cause partial replacement of the pore fluid and stiffening of the rock's usually weak frame, which results in increased seismic velocities (Guerin and Goldberg, 2002; Bauer et al., 2005; McConnell and Kendall, 2002; Tinivella et al., 2002). Several authors consider increased acoustic velocities in the proper geological environment a reliable proxy for the presence of gas hydrates (Kumar et al., 2005; Ecker et al., 2000; Tinivella and Lodolo, 2000).
The reasons for the observed strong attenuation, however, still are not fully understood. In our numerical experiments we therefore primarily investigate seismic attenuation of vertically incident plane waves by using a poroelastic model. The theory of poroelasticity enables us to model attenuation mechanisms in multilayered media that could be related to the known geology and physics of hydrate-bearing sediments.

BASIC CONCEPTS OF MODELING LAYERS CONTAINING GAS HYDRATES

Analysis of drilled cores and log data of sediments containing gas hydrates reveal strong fluctuations of the various involved parameters (Winters et al., 2005). In terms of rock physics, for each layer these parameters can in general be described using a model consisting of the rock's skeleton (frame) and the fluid in the pore space. Considering seismic wave propagation certain physical parameters of the three phases (frame, fluid, grain) can be used to calculate the properties of an effective medium (Mavko et al., 1998).
Most of the modeling work published so far relates hydrate content to frame properties and porosity (Gei and Carcione, 2003; Kumar et al., 2005; Guerin and Goldberg, 2002). In those models the properties of the fluid are solely altered by the presence of gas, which results in a pore fluid, that is effectively less dense, less viscous and more compressible.
Recent laboratory experiments indicate, that crystals of hydrate are chemically subject to a permanent, dynamic balance of formation and decay. This implies that the pore fluid permanently contains crystals of hydrate smaller than the pore size, what would cause the pore fluid to be less compressible and more viscous [e.g. Tohidi et al. (2001)].
Further the deposition of gas hydrates in the pore space would not only alter the properties of the frame. Since hydrate becomes a constituent of the frame, it affects the bulk properties of the grain as well. In a similar way this was implemented by Tinivella et. al (2000, 2002), who calculate frame properties (e.g. bulk and shear moduli) from one effective solid material.
To implement the observed fluctuations in fluid, grain and frame into our model, and to account for possible correlations of these fluctuations we used a random media approach. The random fluctuations were exponentially correlated to statistically characterize the random medium. In our model we assume that an increasing content of hydrate in the pore space would at the same time:

- decrease the porosity (ϕ), hydraulic permeability (k), the grain's bulk modulus (K_{gr}) and bulk density (ϱ_{gr})
- increase the frame's bulk- (K_{fr}) and shear modulus (μ_{fr}), the fluid's viscosity (η) and bulk modulus (K_{fl}).

The fluctuations in the density of the fluid (brine with density ϱ_{fl}) are mainly interpreted as variations in gas concentration, since both, hydrate and brine are much denser than gas.

NUMERICAL MODELING

Our model approach can seismically be addressed with the theory of wave propagation in fluid saturated, poroelastic media (Biot, 1956). A seismic wave propagating through a fluid-saturated, porous medium is being attenuated not only due to effects of elastic scattering, but due to the motion of the fluid relative to the solid matrix as well. This fluid flow generally takes place at different scales, and can therefore be divided into three different types: Biot global flow (Biot, 1956), squirt or local flow (Dvorkin et al., 1995) and interlayer flow (Gurevich and Loplatnikov, 1995). Attenuation due to Biot global flow reaches it's maximum at the Biot critical frequency $\omega_c = \phi\,\eta/k\,\varrho_{fl}$, which is usually much higher than seismic frequencies (Müller, 1997). Consequently, we focus on attenuation due to scattering and interlayer flow, which is caused by differences in pressure and fluid compressibility within the scale of a wavelength.
For our numerical experiments we used the Reflection Coefficient Module (OASR) of the OASES software, consisting of several modules for calculating seismic wave propagation in layered media using the matrix propagator method (Schmidt and Tango, 1986). From input files containing information on thirteen physical parameters, related to the three phases involved (fluid, frame and grain) OASR is able to calculate complex, frequency-dependent reflection- and transmission coefficients ($|T|$, Phase φ) in poroelastic, fluid saturated, layered media for a given range of frequencies and angles of incidence.
From the complex transmission coefficient $T = |T| \cdot e^{i\,\varphi}$ and the thickness L of the stack of layers we calculate the inverse P-wave quality factor Q^{-1} using (Mavko et al., 1998):

$$Q^{-1} = -\frac{\ln|T|}{L} \cdot \frac{v}{\pi\,f} \tag{1}$$

where v is the phase velocity $v = \omega\,L/\varphi$ of the P-wave, that can be calculated from frequency $\omega = 2\pi\,f$ and vertical phase increment φ/L.

In order to create realistic models of multilayered media we used the following approach: A gaussian random process provides us with a random field of n normally distributed numbers R, where n is the desired number of layers in our model. For a given average $\langle X \rangle$ and average-normalized standard deviation σ_{XX}, we yield the fluctuation part ε_{X_i} of the physical quantity X in the $i-th$ layer by: $\varepsilon_{X_i} = \sigma_{XX} \cdot \langle X \rangle \cdot R_i$. In general a random medium is mathematically characterized by it's auto-correlation-function (ACF) and it's probability-density-function (PDF) (Kamei et al., 2005). To statistically correlate our depth-dependent fluctuations we used a spectral-based method (Frankel and Clayton, 1986): The Fourier-Transform of the ACF, the so-called Pseudo-Spectral-Density-Function (PSDF), was multiplied with the Fourier-Transform of the average-normalized fluctuations. The result was then inversely transformed and now contains the properly correlated average-normalized fluctuations.
For derivation of average background values we chose properties of a highly permeable water-saturated unconsolidated sediment: $K_{gr} \approx 35\,GPa$, $\varrho_{gr} \approx 2.65\,g/cm^3$, $K_{fr} \approx 3\,GPa$, $\mu_{fr} \approx 2\,GPa$, $\phi \approx 0.35$, $k \approx 1000\,mD$. To model the impact of gas hydrates we slightly modified these values according to the properties of hydrate ($\varrho \approx 0.9\,g/cm^3$, $K \approx 8\,GPa$, $\mu \approx 5\,GPa$, see Guerin and Goldberg (2002); Gei and Carcione (2003)) and according to estimations we have made using effective media theories (Mavko et al., 1998). This enables us to interpret the fluctuations of the properties as variations in content of gas hydrate.

ESTIMATING P-WAVE ATTENUATION USING THE GENERALIZED ODA-FORMALISM

In order to estimate the influence of each of the nine varying parameters we made use of the poroelastic generalization of the O'Doherty-Anstey formulas developed by Gelinsky and Shapiro (1997). For a statistically stationary, exponentially correlated, multilayered medium, they derived simple descriptions of attenuation and phase velocity from a restricted number of statistical parameters characterizing the medium (Shapiro and Hubral, 1999). Given a constant background average and small average-normalized fluctuations $\varepsilon_i = (X_i - \langle X \rangle)/\langle X \rangle \ll 1$ the inverse quality factor $Q^{-1} = 2\,\gamma/\kappa_1$ can be expressed using the attenuation coefficient γ:

$$\gamma = \kappa_1^I + \frac{2\,B\,a}{1 + 2a\kappa_2 + 2\,(a\kappa_2)^2} + \frac{C\,a}{1 + 4\,(a\kappa_1)^2}, \tag{2}$$

where $\kappa_1 = \omega \cdot \sqrt{\varrho_{sat}/H}$ and $\kappa_2 = \sqrt{\omega\,\eta/2\,k\,N}$ are the wavenumbers of the fast and slow P-wave respectively. Equation (2) reveals the additive character of the three attenuation mechanism involved: κ_1^I is the imaginary part of the complex wavenumber κ_1 and accounts for Biot global flow (Müller, 1997), which has been neglected in our experiments since it occurs at frequencies much higher than the seismic frequency range. The second term in eq. (2) describes the interlayer flow, where:

$$\begin{aligned} \frac{2\,B}{\kappa_2} &= \frac{\omega}{2} \cdot \sqrt{\frac{\varrho_{sat}}{H_0}} \cdot \frac{P_0\,\alpha_0^2\,M_0}{H_0^2} \cdot \Bigg(\frac{(P_0 - \alpha_0^2\,M_0)^2}{P_0^2}\,\sigma_{\alpha\alpha}^2 + \\ &+ \sigma_{PP}^2 - 2\,\sigma_{PM}^2 + \sigma_{MM}^2 - 2\,(\sigma_{P\alpha}^2 - \sigma_{M\alpha}^2) \cdot \frac{P_0 - \alpha_0^2\,M_0}{P_0} \Bigg) \end{aligned} \tag{3}$$

is a combination of the variances and covariances of the poroelastic parameters α (factor for relative loss of stiffness), P (P-wave modulus of the dry material), M (a modulus accounting for fluid saturation) and H (saturated P-wave modulus). The quantities marked with an index 0 are assumed to be averaged values:

$$\alpha = 1 - \frac{K_{fr}}{K_{gr}} \qquad M = \left(\frac{\phi}{K_{fl}} + \frac{\alpha - \phi}{K_{gr}} \right)^{-1}$$

$$P = K_{fr} + \frac{4}{3}\,\mu_{fr} \qquad H = P + \alpha^2 M$$

Further Gelinsky and Shapiro (1997) derived expressions for calculating the frequencies, at which attenuation caused by scattering or interlayer flow would have their peaks. With $N = P\,M/H$ and the correlation length a those frequencies are $f_{flow} = N\,k/\pi\,\eta\,a^2$ and $f_{scat} = \sqrt{H/\varrho_{sat}}/4\,\pi\,a$, which indicate that attenuation due to interlayer flow occurs at lower frequencies than attenuation caused by scattering.
For each of the attenuation mechanisms it is assumed that the fluctuations and correlations of the quantities (e.g. the variances and covariances) are the dominant influence controlling the amplitude of attenuation

(Shapiro and Müller, 1999). This makes our approach less dependent on the absolute values of the parameters, which are sometimes difficult to estimate, since exact in-situ measurements of all of the required properties related to gas hydrates are not available.
The third term in eq. (2) accounts for scattering effects:

$$\begin{aligned}\frac{C}{2\,\kappa_1} &= \frac{\omega}{8}\cdot\sqrt{\frac{\varrho_{sat}}{H_0}}\cdot\frac{P_0^2}{H_0^2}\cdot\Big(\sigma_{PP}^2 + 2\,\frac{\alpha_0^2\,M_0}{P_0}\,(\sigma_{PM}^2 + 2\,\sigma_{P\alpha}^2) + \\ &+ \frac{\alpha_0^4\,M_0^2}{P_0^2}\,(\sigma_{MM}^2 + 4\,\sigma_{\alpha\alpha}^2 + 4\,\sigma_{M\alpha}^2)\Big) \end{aligned} \tag{4}$$

Equation (3), (4) and especially the parameters α and M indicate that fluctuations in the properties of the fluid and grain have an influence on attenuation. Although the generalized ODA formulas have been verified by several authors (Shapiro and Müller, 1999; Müller and Gurevich, 2004), we consider this formalism rather an estimation than an exact calculation, since in bore hole data we observe strong fluctuations (up to 60 % in porosity, Guerin and Goldberg (2002) and several orders of magnitude in permeability). Modeling results still show that the ODA formulas are suitable for identifying and estimating the parameters related to attenuation.

EXAMPLES OF MODELING AND INTERPRETATION

In our models we investigate the influence of the fluctuations in fluid, frame and grain. All models consist of 500 isotropic layers with a layer thickness of $0.3\,m$. The stack of layers therefore had a thickness of $L = 150\,m$ and was embedded in a homogenous, elastic halfspace. The fluctuations were exponentially correlated with a correlation length of $a = 1.3\,m$. To account for the range of seismically relevant frequencies we modeled attenuation for frequencies from $0.5\,Hz$ to $700\,Hz$.
In this study we consider three different scenarios:

- In order to compare and demonstrate the influence of fluctuations we started modeling stacks of layers with **small and intermediate fluctuations** (Fig. 1). Attenuation is mainly caused by scattering at higher frequencies and has it's maximum peak of $Q \approx 40$ around $100\,Hz$. The influence of interlayer flow ($Q_{max} \approx 200$) on attenuation is visible at lower frequencies ($\approx 1\,Hz$) and rather small, which is consistent with the results of Müller (1997). The results of our experiments with small and intermediate fluctuations are not comparable to the strong attenuation of $Q \approx 20$ observed in field experiments (Bauer et al., 2005). Analytically [i.e. by solving eq. (2)] calculated attenuation is in good agreement with the numerical results obtained by the OASES software.

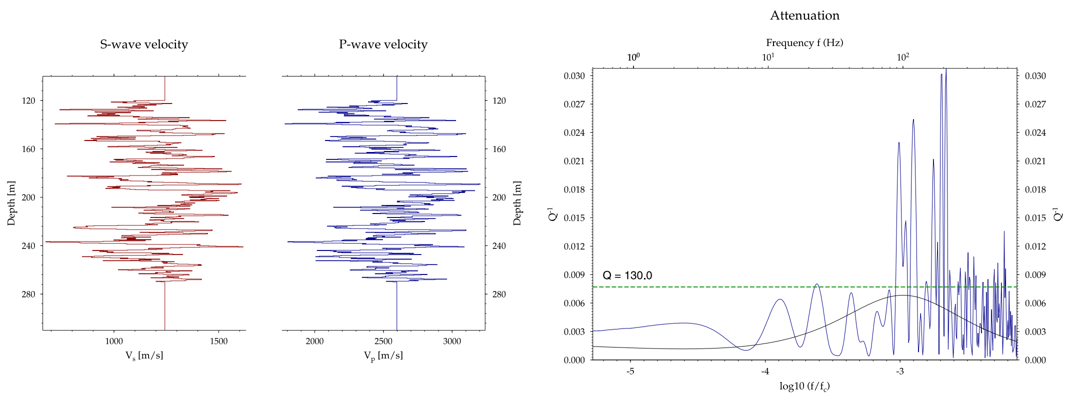

Fig. 1: Velocity and attenuation for a model with intermediate fluctuations in fluid, frame and grain. Averages (fluctuations) and variances are: $\varrho_{fl} = 0.95\,g/cm^3$ (9.6 %), $K_{fl} = 2.7\,GPa$ (16.4 %), $\eta = 1.6\,cP$ (0 %), $\varrho_{gr} = 2.45\,g/cm^3$ (10.3 %), $K_{gr} = 32.5\,GPa$ (21.1 %), $\phi = 0.39$ (31.4 %), $k = 1100.8\,mD$ (28.6 %), $\mu_{fr} = 2.73\,GPa$ (29.1 %), $K_{fr} = 3.4\,GPa$ (25.5 %), $\sigma_P^2 = 7.48\cdot10^{-2}$, $\sigma_M^2 = 0.11$, $\sigma_\alpha^2 = 4.27\cdot10^{-3}$, $\sigma_{P\alpha}^2 = -1.68\cdot10^{-2}$, $\sigma_{PM}^2 = 7.37\cdot10^{-2}$, $\sigma_{M\alpha}^2 = -1.88\cdot10^{-2}$

- Our modeling experiments with **large fluctuations** in general yield attenuation values, that are significantly higher. To distinguish between the influence of frame, grain, and fluid we calculated models with fluctuations **in frame properties only**. The modeling results shown in Fig. 2 indicate stronger attenuation due to interlayer flow ($Q \approx 40$ at $f \approx 2\,Hz$) and scattering ($Q \approx 20$ at $f \approx 200\,Hz$), than in our intermediate fluctuations model. Larger fluctuations obviously cause stronger attenuation by scattering and interlayer flow. The results are comparable to the numerical experiments conducted by Gei and Carcione (2003) and Guerin and Goldberg (2002), who calculated attenuations in the order of $Q \approx 20 - 70$.

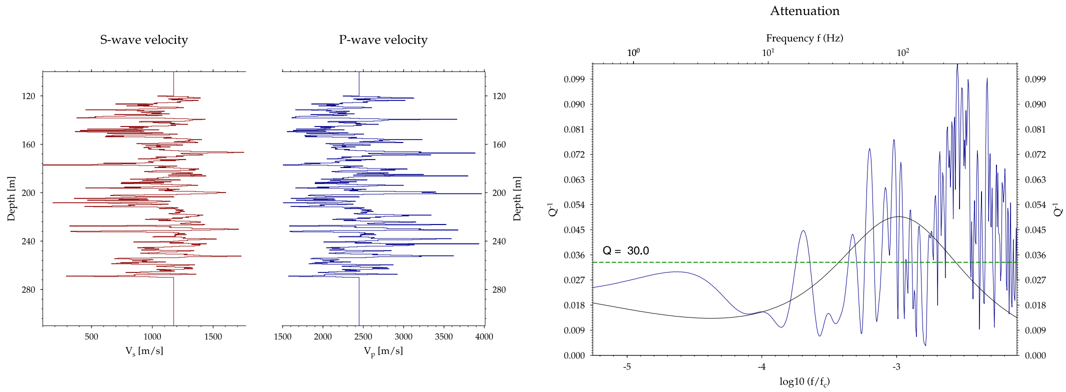

Fig. 2: Velocity and attenuation for a model with strong fluctuations in frame properties only. Averages (fluctuations) and variances are: $\varrho_{fl} = 1.03\,g/cm^3$ (0 %), $K_{fl} = 2.4\,GPa$ (0 %), $\eta = 1.6\,cP$ (0 %), $\varrho_{gr} = 2.65\,g/cm^3$ (0 %), $K_{gr} = 35.0\,GPa$ (0 %), $\phi = 0.38$ (45.6 %), $k = 1124.9\,mD$ (40.9 %), $\mu_{fr} = 2.67\,GPa$ (52.3 %), $K_{fr} = 3.3\,GPa$ (50.6 %), $\sigma_P^2 = 0.27$, $\sigma_M^2 = 0.94$, $\sigma_\alpha^2 = 2.81 \cdot 10^{-3}$, $\sigma_{P\alpha}^2 = -2.73 \cdot 10^{-2}$, $\sigma_{PM}^2 = 0.37$, $\sigma_{M\alpha}^2 = -3.85 \cdot 10^{-3}$

- Experiments with **large fluctuations in all of the involved phases** result in even stronger attenuation (Fig. 3). The amplitude of attenuation is similar to the one observed by Bauer et al. (2005) during a crosswell tomography. Attenuation values due to interlayer flow and scattering are comparable ($Q > 20$). Interlayer flow is less fluctuant than scattering and in the range of $1 - 5\,Hz$ the dominant effect, which has been observed by Müller (1997) as well. In models with strong fluctuations ($> 40\%$) the analytical solution of the generalized ODA theory significantly differs from numerical results, which is due to it's basic assumption, that the fluctuations are sufficiently small ($\varepsilon \ll 1$). Moreover, another important assumption of ODA theory is $\langle \varepsilon \rangle = 0$. In models with large fluctuations we observe that $\langle \varepsilon \rangle \neq 0$, which can be observed in bore hole data as well (Bauer et al., 2005).

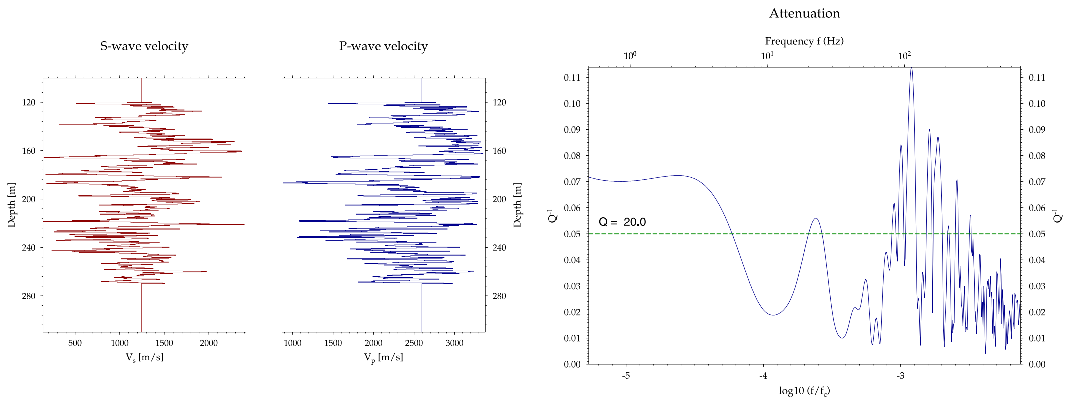

Fig. 3: Velocity and attenuation for a model with strong fluctuations in fluid, frame and grain. Averages (fluctuations) and variances are: $\varrho_{fl} = 0.98\,g/cm^3$ (10.5 %), $K_{fl} = 2.5\,GPa$ (36.2 %), $\eta = 1.6\,cP$ (0 %), $\varrho_{gr} = 2.44\,g/cm^3$ (21.2 %), $K_{gr} = 31.9\,GPa$ (42.7 %), $\phi = 0.38$ (57.1 %), $k = 1078.5\,mD$ (51.3 %), $\mu_{fr} = 2.88\,GPa$ (53.5 %), $K_{fr} = 3.6\,GPa$ (52.5 %), $\sigma_P^2 = 0.28$, $\sigma_M^2 = 11.41$, $\sigma_\alpha^2 = 5.07$, $\sigma_{P\alpha}^2 = -0.34$, $\sigma_{PM}^2 = 0.24$, $\sigma_{M\alpha}^2 = 0.12$

CONCLUSIONS

In our experiments we investigated P-wave attenuation in vertical direction caused by interlayer flow and scattering in poroelastic media. Since the experiments conducted so far mostly relate hydrate content to frame properties of the sediment we generated random models with fluctuations in frame only as well as models with fluctuations in frame, grain and fluid.
The generalized ODA formulas enabled us to identify involved parameters and estimate attenuation in our models. Deviations of analytical solutions from numerical calculations are due to assumptions made in the derivation of the ODA formulas, that are not entirely fulfilled in our models.
Results indicate, that with increasing fluctuations we observe increasing attenuation in both types of models. Still the attenuation appears to be stronger in models with fluctuating fluid, grain and frame properties, which is consistent with the results of Müller (1997). This indicates that especially fluid properties should be considered investigating seismic attenuation in porous rocks containing gas hydrates. Results of Tohidi et al. (2001) justify the assumption of fluctuating fluid properties.
Interlayer flow in highly permeable sedimentary layers may be a significant attenuation mechanism for vertically incident plane waves especially in the lower seismic frequency range (1 - 5 Hz). Poroelastic modeling yields attenuation values that are similar to field observations.

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