Gas-hydrate concentration estimated from P- and S-wave velocities at the Mallik 2L-38 research well, Mackenzie Delta, Canada

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Abstract

We estimate the concentration of gas hydrate at the Mallik 2L-38 research site using P- and S-wave velocities obtained from well logging and vertical seismic profiles (VSP). The theoretical velocities are obtained from a generalization of Gassmann's modulus to three phases (rock frame, gas hydrate and fluid). The dry-rock moduli are estimated from the log profiles, in sections where the rock is assumed to be fully saturated with water. We obtain hydrate concentrations up to 75%, average values of 37% and 21% from the VSP P- and S-wave velocities, respectively, and 60% and 57% from the sonic-log P- and S-wave velocities, respectively. The above averages are similar to estimations obtained from hydrate dissociation modeling and Archie methods. The estimations based on the P-wave velocities are more reliable than those based on the S-wave velocities.
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1. Introduction

Gas hydrate is composed of water and natural gas, mainly methane, which forms under conditions of low temperature, high pressure, and proper gas concentration (1 m^3 hydrate = 164 m^3 free gas + 0.8 m^3 water). The processes to produce hydrates in the laboratory are known from the beginning of the 19th century.[1] In nature, methane hydrate occurs in two types of geo-logic settings: on land in permafrost regions, and beneath the ocean floor at water depths greater than about 500 m where high pressures dominate. Gas hydrate is a potential energy resource, and can be the cause of slope failure offshore (a submarine geo-hazard) and an important issue in global warming (greenhouse effect).

Bottom Simulating Reflectors (BSRs) on seismic profiles are interpreted to represent the seismic signature of the base of gas-hydrate formation; a free gas zone may be present just below the BSR (e.g., Andreassen et al., 1995). Where no direct measurements are available, detailed knowledge of the seismic properties is essential for quantitative estimations of gas hydrate and free gas in sediments (Helgerud et al., 1999; Sakai, 2000; Tinivella and Carcione, 2001). The

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[1] Joseph Priestley is believed to have produced oxygen hydrate in 1778, and Humphrey Davy in 1810 and Michael Faraday in 1823 synthesised chlorine hydrate.

discrepancies between the velocity profile and the velocity for water-filled, normally compacted, marine sediments are interpreted as due to the presence of gas hydrate (positive anomalies) and free gas (negative anomalies). These anomalies can be translated in terms of concentration of clathrate and free gas, knowing the velocity trend versus gas hydrate and free gas content.

We use the model developed by Leclaire et al. (1994), and generalized by Carcione and Tinivella (2000) and Gei and Carcione (2003) to evaluate the concentration of gas hydrate at the Mallik 2L-38 test site (Fig. 1). (Carcione and Tinivella, 2000 have included the interaction between the two solid phases, neglected in the original model.) The model is based on a three-phase Biot theory (grains, gas hydrate and fluid), and uses the P- and S-wave velocities obtained from well logging and VSP seismic data (Miyairi et al., 1999; Walia et al., 1999; Guerin and Goldberg, 2002). The Mallik 2L-38 well penetrates 1150 m of sands and sandstones interbedded with silt/clay layers. The upper part has 640 m of permafrost. Gas hydrate occurs from 897 to 1110 m. Water zones are interpreted below each gas hydrate zone, beginning at 897, 952, 1010 and 1075 m (Miyairi et al., 1999). Walia et al. (1999) obtained profiles of the P- and S-wave velocities from vertical seismic profile (VSP) meas-

urements (their Fig. 5). Sakai (1999) estimates the gas-hydrate saturation and concludes that there is no cementation at grain boundaries. However, laboratory measurements indicate that the deviator stress is 4.4 to 8.1 times stronger for samples containing hydrates, thus supporting the fact that hydrate cements the grains (Winter et al., 1999b). We calibrate our model with the sonic-log data and only need the dry-rock moduli in the absence of gas hydrate, which are obtained from the wet-rock moduli at 100% water saturation, by using the inverse Gassmann's equation (e.g., Carcione, 2001). Clay affects the bulk modulus of the grains. Values of clay content can be found in Katsube et al. (1999) and Winter et al. (1999a), but we have estimated them from the gamma-ray profile (Chand et al., 2003).

2. The wave-velocity model

Wave velocity is an important property which can give information about lithology, saturation, and the in situ conditions of rocks. Carcione and Tinivella (2000) model the acoustic properties of gas-hydrate bearing sediments saturated with water in the framework of Biot's theory of poroelasticity. The original theory, for frozen porous media, was proposed by Leclaire et al. (1994), and Leclaire et al. (1995) have confirmed it with laboratory experiments. Unlike previous theories, simply based on slowness and/or moduli averaging or two-phase models, the Biot-type three-phase theory considers the existence of two solids (grains and gas hydrate) and a fluid. The resulting P-wave dispersion relation constitutes a generalization of Gassmann equation for two frames and one fluid. The model is based on the assumption that hydrate fills the pore space and shows interconnection. (This structure has been observed in the Mallik 2L-38 cores (Katsube et al., 1999; Uchida et al., 1999)).

We consider the low-frequency limit of the theory, thus neglecting dissipation. At this limit, grains, hydrate and water are in the isostrain state, implying the conditions of a "closed system". In this case, the equations have a simplified form. Let us denote the grains, hydrate and water by the subscripts "s", "h" and "w", and let ϕ, K, μ and ρ indicate material proportion (or fraction), bulk modulus, shear modulus
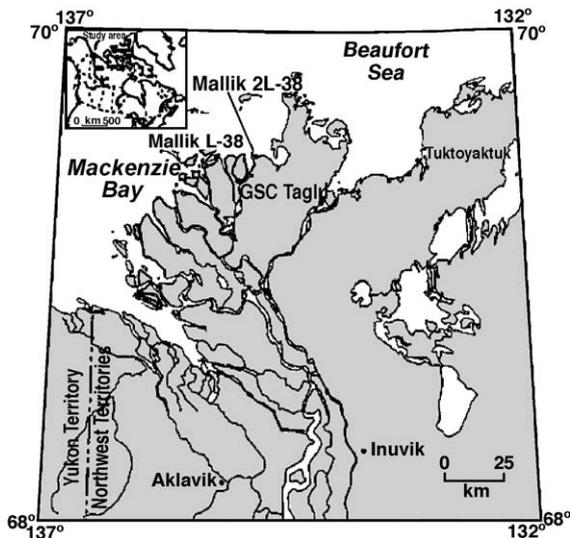

Fig. 1. Location of the Mallik 2L-38 gas hydrate research well (from Miyairi et al., 1999).

and density, respectively. The gas-hydrate concentration is defined as

$$S_h = \frac{\phi_h}{\phi}, \tag{1}$$

where $\phi = \phi_h + \phi_w$ is the actual rock porosity. Hence, the fraction of each component can be expressed as

$$\phi_h = \phi S_h,$$

$$\phi_w = \phi(1 - S_h),$$

$$\phi_s = 1 - \phi. \tag{2}$$

If K_{sm} and K_{hm} denote the bulk moduli of the rock and hydrate frames, the bulk modulus of the closed system can be expressed as

$$K_G = K_{sm} + K_{hm} + \left(1 - \frac{K_{sm}}{K_s} - \frac{K_{hm}}{K_h}\right)^2 M, \tag{3}$$

where

$$M = \left[\left(\phi_s - \frac{K_{sm}}{K_s}\right)\frac{1}{K_s} + \frac{\phi_w}{K_w} + \left(\phi_h - \frac{K_{hm}}{K_h}\right)\frac{1}{K_h}\right]^{-1}. \tag{4}$$

The modulus K_G is a generalization of the Gassmann (low-frequency) modulus of the classical Biot theory (e.g., Carcione, 2001). The shear modulus of the system is simply the sum of the moduli of the rock and hydrate frames (these are given below, in Eqs. (12) and (15), respectively),

$$\mu_m = \mu_{sm} + \mu_{hm}. \tag{5}$$

The P and S velocities are then

$$v_P = \sqrt{\frac{K_G + 4\mu_m/3}{\rho}}, \quad \text{and} \quad v_S = \sqrt{\frac{\mu_m}{\rho}}, \tag{6}$$

where

$$\rho = \phi_s \rho_s + \phi_w \rho_w + \phi_h \rho_h \tag{7}$$

is the bulk density.

The presence of clay modifies the effective bulk modulus of the grains. That is, the grains are formed by a mixture of quartz and clay. If K_q and K_c are the sand-grain and clay-particle bulk moduli, we assume that K_s is equal to the average of the upper and lower Hashin−Shtrikman bounds (Hashin and Shtrikman, 1963). Defining the sand fraction as ϕ_q, the clay fraction as ϕ_c, and the clay content as C, the following relations hold

$$\phi + \phi_q + \phi_c = 1, \quad \text{and} \quad C = \frac{\phi_c}{\phi_c + \phi_q}. \tag{8}$$

The Hashin−Shtrikman upper and lower bounds for the bulk modulus are

$$K^{HS+} = K_q + \frac{C}{(K_c + K_q)^{-1} + (1 - C)\left(K_q + \frac{4}{3}\mu_q\right)^{-1}}, \tag{9}$$

and

$$K^{HS-} = K_c + \frac{1 - C}{(K_q - K_c)^{-1} + C\left(K_c + \frac{4}{3}\mu_c\right)^{-1}}, \tag{10}$$

respectively. The average grain density is simply $\rho_s = (1 - C)\rho_q + C\rho_c$.

The moduli K_{sm} and μ_{sm} are estimated from the sonic-log profile at full water saturation. Denoting the shear modulus at $S_h = 0$ by μ_{sm0}, this is simply equal to ρV_P^2, where ρ is the bulk density and V_P is the S-wave velocity. We use the inverse Gassmann's equation to obtain the dry-rock bulk modulus:

$$K_{sm} = \frac{(\phi K_s/K_w + 1 - \phi)K - K_s}{\phi K_s/K_w + K/K_s - 1 - \phi} \tag{11}$$

(Carcione, 2001), where $K = \rho V_P^2 - (4/3)\mu_{sm0}$ is the wet-rock modulus, and V_P the P-wave velocity.

We assume that the rigidity modulus of the rock frame is affected by cementation of the grains by gas hydrate. It is based on a percolation model, where in the absence of hydrate the shear modulus is that at full water saturation (μ_{sm0}), and at 100% hydrate saturation the modulus is Kuster and Toksöz's shear modulus (μ_{mKT}), where the inclusion is air. That is,

$$\mu_{sm} = \mu_{sm0} + (\mu_{mKT} - \mu_{sm0})(\phi_h/\phi)^p, \qquad (12)$$

where $p = 3.8$ is the percolation coefficient,

$$\frac{\mu_{mKT}}{\mu_s} = \frac{(1-\phi)(9K_s + 8\mu_s)}{9K_s + 8\mu_s + \phi(6K_s + 12\mu_s)} \qquad (13)$$

(Kuster and Toksöz, 1974), and the shear modulus of air has assumed to be zero.

Similarly, the moduli of the hydrate frame are given by

$$K_{hm} = K_{hKT}(\phi_h/\phi)^p \qquad (14)$$

and

$$\mu_{hm} = \mu_{hKT}(\phi_h/\phi)^p, \qquad (15)$$

where K_{hKT} and μ_{hKT} are the Kuster and Toksöz moduli when water is totally frozen, and the solid is replaced by air, i.e.,

$$\frac{K_{hKT}}{K_h} = \frac{1 + [4\mu_h(K_a - K_h)/(3K_a + 4\mu_h)K_h](1-\phi)}{1 - [3(K_a - K_h)/(3K_a + 4\mu_h)](1-\phi)} \qquad (16)$$

and

$$\frac{\mu_{hKT}}{\mu_h} = \frac{\phi\mu_h(9K_h + 8\mu_h)}{9K_h + 8\mu_h + (1-\phi)(6K_h + 12\mu_h)} \qquad (17)$$

(Kuster and Toksöz, 1974), with K_a as the bulk modulus of air. (The bulk modulus of air used in this work is $K_a = 0.15$ MPa).

The theory given in Carcione and Tinivella (2000) has been generalized by Gei and Carcione (2003) to include the effects of pore pressure, partial saturation (gas and water) and the presence of attenuation.

3. Estimation of gas-hydrate content

The moduli and density of the single constituents are given in Table 1 (we are using the same notation of Carcione and Tinivella, 2000 and Gei and Carcione, 2003). The porosity is derived from the density log by using a two-phase medium (grains and water), since gas hydrate concentration is unknown a priori (this approximation is good enough and corrections due to the presence of hydrates are not significant). All the logs are averaged with a window of 15 m length for comparison to the results obtained from the VSP velocities. Fig. 2 shows the porosity, bulk density, clay content, permeability, and sonic-log and VSP (P- and S-wave) velocities and estimated hydrate concentrations. The S-wave velocities of the VSP are not reliable, mainly in the interval between 900 and 950 m, where the differences with the sonic-log velocities are too large. This difference cannot be attributed to velocity dispersion. On the other hand, the estimations based on the P-wave velocities are acceptable.

We obtain hydrate concentrations up to 75%, average values of 37% and 21% from the VSP P- and S-wave velocities, respectively, and 60% and 57% from the sonic-log P- and S-wave velocities, respectively. These averages are computed between

Table 1
Material properties

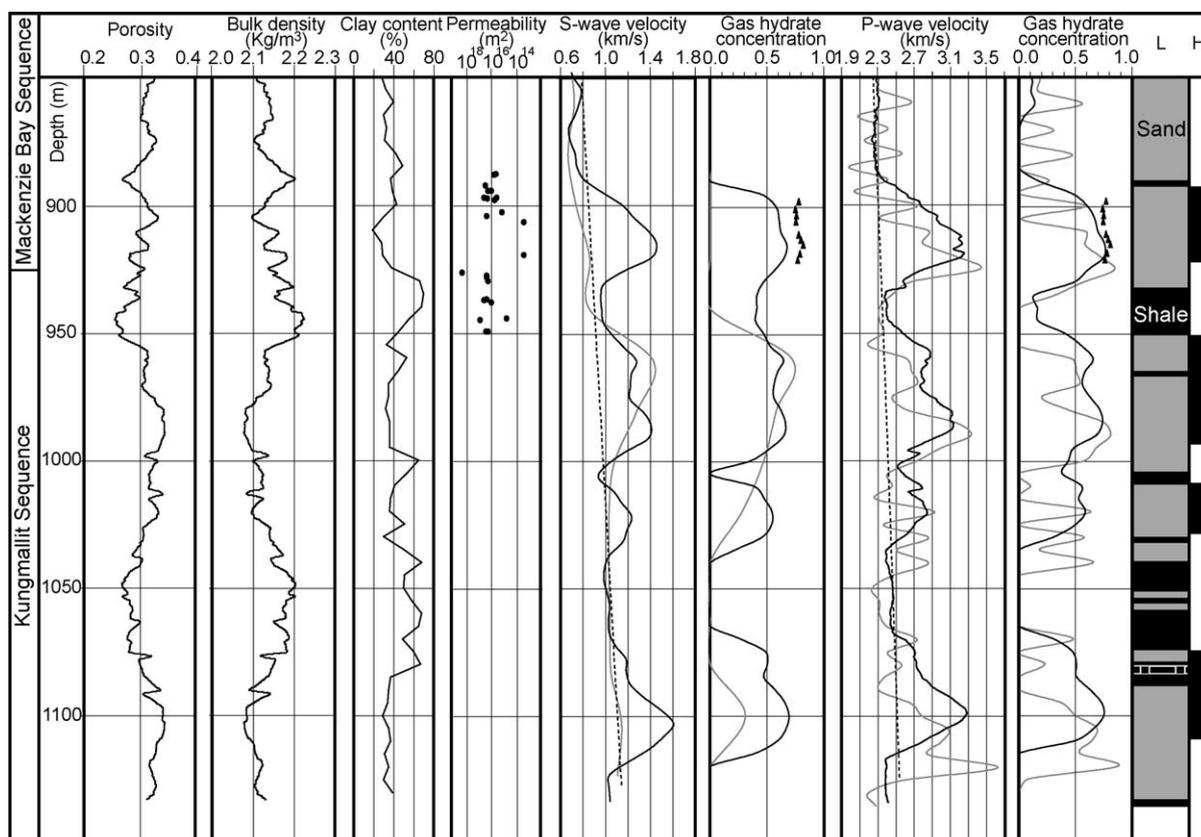|		
Quartz[a]	bulk modulus, K_q,	36 GPa
	shear modulus, μ_q,	45 GPa
	density, ρ_q	2650 kg/m³
Clay[a]	bulk modulus, K_c,	20.9 GPa
	shear modulus, μ_c,	6.8 GPa
	density, ρ_c	2580 kg/m³
Gas hydrate[a]	bulk modulus, K_h,	7.7 GPa
	shear modulus, μ_h,	3.2 Gpa
	density, ρ_h	900 kg/m³
Water	bulk modulus, K_w,	2.3 GPa
	density, ρ_w	1030 kg/m³

[a] Helgerud et al. (1999).

Fig. 2. Porosity, bulk density, clay content, permeability, and sonic-log and VSP (P- and S-wave) velocities and hydrate concentrations at the Mallik 2L-38 research site. The black curves correspond to the sonic-log estimations, and the grey curves the VSP estimations. The dashed lines are the wet-rock velocities estimated from the log profiles, where the rock is assumed to be fully saturated with water. The black bars in column H indicate zones where the hydrate is present. Grey zones in the lithologic column (L) indicate sandstones and black zones indicate shaley sandstones. For comparison, we show discrete saturation values estimated from hydrate dissociation modeling (triangles).

897 and 1110 m, excluding the zones where there is no gas hydrate. For comparison, we show discrete saturation values estimated by Wright et al. (1999) from hydrate dissociation modeling (triangles). Our results are lower than these saturation values, but are in good agreement with estimates obtained from Archie methods (Collet et al., 1999; Guerin and Goldberg, 2002).

75%, average values of 37% and 21% from the VSP P- and S-wave velocities, respectively, and 60% and 57% from the sonic-log P- and S-wave velocities, respectively. These averages are computed from 897 to 1110 m, excluding the zones where there is no gas hydrate. The above averages are similar to estimations obtained from hydrate dissociation modeling and Archie methods.

4. Conclusions

We estimate the concentration of gas hydrate at the Mallik 2L-38 research site using P- and S-wave velocities. We obtain hydrate concentrations up to

Acknowledgements

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