Amount of gas hydrate estimated from compressional- and shear-wave velocities at the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well

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Abstract: The amount of in situ gas hydrate concentrated in the sediment pore space at the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well was estimated by using compressional-wave (P-wave) and shear-wave (S-wave) downhole log measurements. A weighted equation developed for relating the amount of gas hydrate concentrated in the pore space of unconsolidated sediments to the increase of seismic velocities was applied to the acoustic logs with porosities derived from the formation density log. A weight of 1.56 ($W = 1.56$) and the exponent of 1 ($n = 1$) provided consistent estimates of gas hydrate concentration from the S-wave and the P-wave logs. Gas hydrate concentration is as much as 80% in the pore spaces, and the average gas hydrate concentration within the gas-hydrate-bearing section from 897 m to 1110 m (excluding zones where there is no gas hydrate) was calculated at 39.0% when using P-wave data and 37.8% when using S-wave data.

Résumé : L’estimation de la quantité d’hydrates de gaz en place concentrés dans l’espace poral des sédiments dans le puits de recherche sur les hydrates de gaz JAPEX/JNOC/GSC Mallik 2L-38 a été réalisée en utilisant les mesures en sondage des ondes de compression (ondes P) et des ondes de cisaillement (ondes S). Une équation pondérée élaborée pour établir une relation entre la quantité d’hydrates de gaz concentrés dans l’espace poral des sédiments meubles et l’augmentation de la vitesse des ondes sismiques est appliquée aux diagraphies acoustiques avec les taux de porosité dérivés des diagraphies de la densité de la formation. Un coefficient de pondération de 1,56 ($W = 1{,}56$) et une exponentielle de 1 ($n = 1$) fournissent des estimations cohérentes des concentrations d’hydrates de gaz provenant des diagraphies des ondes S et des ondes P. La concentration des hydrates de gaz dans les espaces poraux atteint jusqu’à 80 %, et la concentration moyenne des hydrates de gaz dans la section renfermant des hydrates de gaz entre 897 et 1 110 m de profondeur, à l’exclusion des zones dans lesquelles les hydrates de gaz sont absents, est, selon les calculs, respectivement de 39,0 % et de 37,8 % selon que l’on utilise les données des ondes P ou des ondes S.

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INTRODUCTION

Gas hydrate, or clathrate, is an ice-like crystalline solid composed of water molecules surrounding gas molecules. In recent years, methane hydrate has been the focus of many investigations because of its widespread occurrence in most of the world's oceans and in permafrost regions (Kvenvolden, 1993). Also, large amounts of methane may have escaped from deep-sea, gas-hydrate-bearing sediments to the atmosphere as a result of dissociation of gas hydrate caused by sea-level and climatic changes, and acted as a negative-feedback control on global temperature fluctuations (Dillon et al., 1991; Paull et al., 1991). Gas hydrate is also important as a potential energy resource and significant in seafloor stability and safety issues (Dillon et al., 1993)

Gas hydrate exhibits relatively high elastic velocities, both compressional-wave (P-wave) and shear-wave (S-wave) velocities, compared to the pore-filling fluids; therefore, the velocities of acoustic waves in gas-hydrate-bearing sediments are usually elevated (Stoll, 1974; Tucholke et al., 1977). Based on the elevated velocity in the sediments due to the presence of gas hydrate, a number of studies have attempted to estimate in situ gas hydrate amounts using seismic velocities (Mackay et al., 1994; Lee et al., 1994; Wood et al., 1994; Spence et al., 1995; Kastner et al., 1995; Yuan et al., 1996; Lee, in press).

Based on velocities from acoustic logs and a vertical seismic profile (VSP) on the Cascadian Continental Margin at Ocean Drilling Program (ODP) Site 889, Kastner et al. (1995) estimated that at least 15% of the sediment pore space is occupied by gas hydrate in locations where the velocities of acoustic waves in gas-hydrate-bearing sediments are greater than expected by greater than 100 m/s from a normal velocity-porosity relation. Using velocities acquired by an ocean-bottom seismometer, Spence et al. (1995) also estimated that 11–20% of the pore space above the Bottom Simulating Reflector (BSR) is filled by gas hydrate at ODP Site 889 on the Cascadia Margin. Elsewhere, an average of 5.7% gas hydrate concentration in sediments having an average porosity of 57% was estimated using a weighted equation at the ODP Site 997 in Blake Outer Ridge (Lee, in press), which compared favorably to concentrations calculated by other methods (Shipboard Scientific Party, 1996).

In the Mallik 2L-38 gas hydrate research well, P-wave and S-wave velocities were measured with Schlumberger Dipole Shear Sonic Image tool (DSI). The borehole conditions and quality of the well logs were excellent in the gas-hydrate-bearing interval and provided a unique and first data set for accurately estimating the amount of in situ gas hydrate using both P-wave and S-wave velocity data.

In this paper, the amount of gas hydrate in the pore space of the sediments was estimated by applying a weighted equation proposed by Lee et al. (1996) to P-wave and S-wave velocities along with density-log-derived porosities. This study shows that a weighted equation with $W = 1.56$, exponent $n = 1$, and the measured ratio of P-wave velocity/S-wave velocity accurately estimated the amount of gas hydrate concentrated in the pore space of the sedimentary section drilled in the Mallik 2L-38 well.

THEORY

The relation between the compressional velocity and gas hydrate concentration in the pore space can be described by three-phase weighted equation (Lee et al., 1996). This equation predicts accurately the P-wave velocity in the unconsolidated sediment, particularly for sediments with high porosities. The weighted equation is defined as a weighted combination of the time-average equation (Timur, 1968), which predicts velocity in a rigid, consolidated rock with little fluid, and Wood equation (Wood, 1941), which pertains to particles in suspension.

A three-phase weighted equation is defined as (Lee et al., 1996):

$$\frac{1}{V_p} = \frac{W\phi(1-S)^n}{V_{p1}} + \frac{1-W\phi(1-S)^n}{V_{p2}} \tag{1}$$

where

V_p compressional-wave (P-wave) velocity in gas-hydrate-bearing sediments,

V_{p1} compressional-wave velocity in gas-hydrate-bearing sediments computed from the three-phase Wood equation,

V_{p2} compressional-wave velocity in gas-hydrate-bearing sediments computed from the three-phase time-average equation,

W a weighting factor,

ϕ sediment porosity (as a fraction),

S concentration of gas hydrate in the pore space (as a fraction), and

n constant simulating the rate of lithification with gas hydrate concentration.

The three-phase Wood equation (Wood, 1941) is given by

$$\frac{1}{\rho_b V_{p1}^2} = \frac{\phi(1-S)}{\rho_w V_w^2} + \frac{\phi S}{\rho_h V_h^2} + \frac{(1-\phi)}{\rho_m V_m^2} \tag{2}$$

where

ρ_w is the density of the fluid,

ρ_h is the density of pure gas hydrate,

ρ_m is the density of matrix, and

ρ_b is the bulk density of sediments.

The bulk density is given by

$$\rho_b = (1-\phi)\rho_m + (1-S)\phi\rho_w + S\phi\rho_h \tag{3}$$

The three-phase time average equation (Pearson et al., 1983; Timur, 1968) can be written as

$$\frac{1}{V_{p2}} = \frac{\phi(1-S)}{V_w} + \frac{\phi S}{V_h} + \frac{(1-\phi)}{V_m} \tag{4}$$

where

V_w is the compressional-wave velocity in the fluid,

V_h is the compressional-wave velocity in pure gas hydrate, and

V_m is the compressional-wave velocity in the matrix, respectively.

In this formulation, V_m is a 'modified matrix velocity' (P-wave velocity in the matrix) as defined in Lee et al. (1996), which is the 'grain' or 'matrix' velocity computed at zero porosity considering the effect of clay content (Castagna et al., 1985; Han et al., 1986). In this paper, Han's equation was used for the computation of the modified compressional-wave velocity in the matrix (V_m), which is given by

$$V_{ph} = 5.59 - 6.93\phi - 2.18C, \tag{5}$$

where V_{ph} is the compressional velocity derived by Han et al. (1986) and C is the volume clay content.

A value W>1 favors the Wood equation and a W<1 favors the time-average equation. The weighting factor (W) can be estimated using the velocity versus porosity data for sediments with no gas hydrate concentration (Lee et al., 1996). It should also be noted that as n increases, the weighted equation approaches the time-average equation more rapidly, because (1-S) is less than or equal to 1.

Lee et al. (1996) also proposed a shear-wave velocity equation for gas-hydrate-bearing sediments by the following equation.

$$V_s = V_p\left[\alpha(1-\phi) + \beta\phi S + \gamma\phi(1-S)\right], \tag{6}$$

with

$\alpha = V_s / V_{p|matrix}$,

$\beta = V_s / V_{p|hydrate}$, and

$\gamma = V_s / V_{p|fluid}$.

As can be seen from equation (6), the parameter α can be estimated from the modified velocities of P- and S-waves in the matrix, or can be estimated from measured P- and S-wave velocities in the sediments when S = 0, i.e., non-hydrate-bearing sediment. The fluid cannot sustain shear velocity, so the last term (γ) can be dropped.

POROSITY AND VELOCITY DATA

The density-log-derived porosities and acoustic transit time from the Mallik 2L-38 well for three different depth ranges are shown in Figure 1 (all depths were measured from kelly bushing [8.31 m above sea level]). The acoustic and porosity data for the gas-hydrate-bearing interval between 897 m and 1110 m are shown with solid dots, those for the non-hydrate-bearing intervals above the gas-hydrate-bearing interval (between 740 and 897 m), and below the gas-hydrate-bearing interval (between 1110 and 1143 m) are shown with open squares. The majority of the sediment's porosity ranges from 20 to 40%. The anomalous data points in Figure 1 with low porosity values and high velocities are from hard stringers (well cemented sedimentary layers), and the data points with high porosity and low velocities are from coal units.

The cross plots of porosity with respect to velocity for the non-hydrate-bearing interval (open circles and squares) are indicative of normal trends of velocity with porosity, which means that as the porosity becomes higher, the velocity becomes lower. However, for the majority of data in the gas-hydrate-bearing section, the velocity and porosity trends are opposite to those for the non-gas-hydrate-bearing sediment interval. The high-velocity with high-porosity trend suggests that high-porosity sediments have higher gas hydrate concentration in their pore space.

The density porosities shown in Figure 1 are derived from the bulk-density measurements assuming a two-component system: fluid (water) and matrix. Since the density of methane hydrate is less than that of water (Table 1), the porosity derived from the bulk-density log using a two-component system for highly concentrated hydrated sediments is in error (Collett, 1998). For the gas-hydrate-bearing sediments, a three-component system using fluid, hydrate, and matrix is more accurate for porosity computation. The porosity equation from the bulk density can be written as follows:

$$\phi = \frac{\rho_m - \rho_b}{\rho_m - \rho_w + S(\rho_w - \rho_h)} \tag{7}$$

where ρ_b is the bulk density measurement. Equation (7) can be expanded using a Taylor series into the following equation,

$$\phi = \phi_2(1 - Q + Q^2 - \ldots\ldots\ldots\ldots), \tag{8}$$

where $Q = S(\rho_w - \rho_h)/(\rho_m - \rho_w)$ and ϕ_2 is the porosity computed from the two-component system. Using the density data shown in Table 1, Q becomes 0.06S.

The average porosity without hydrate correction is around 33% in the gas-hydrate-bearing interval in the Mallik 2L-38. Assuming a high concentration of S = 0.8, the corrected porosity becomes 0.33 * (1-0.8*0.06) = 0.31. Therefore there exists an error of about 2% in the porosity estimates when using the standard two-component density-porosity equation for this data. Without a gas hydrate porosity correction in the

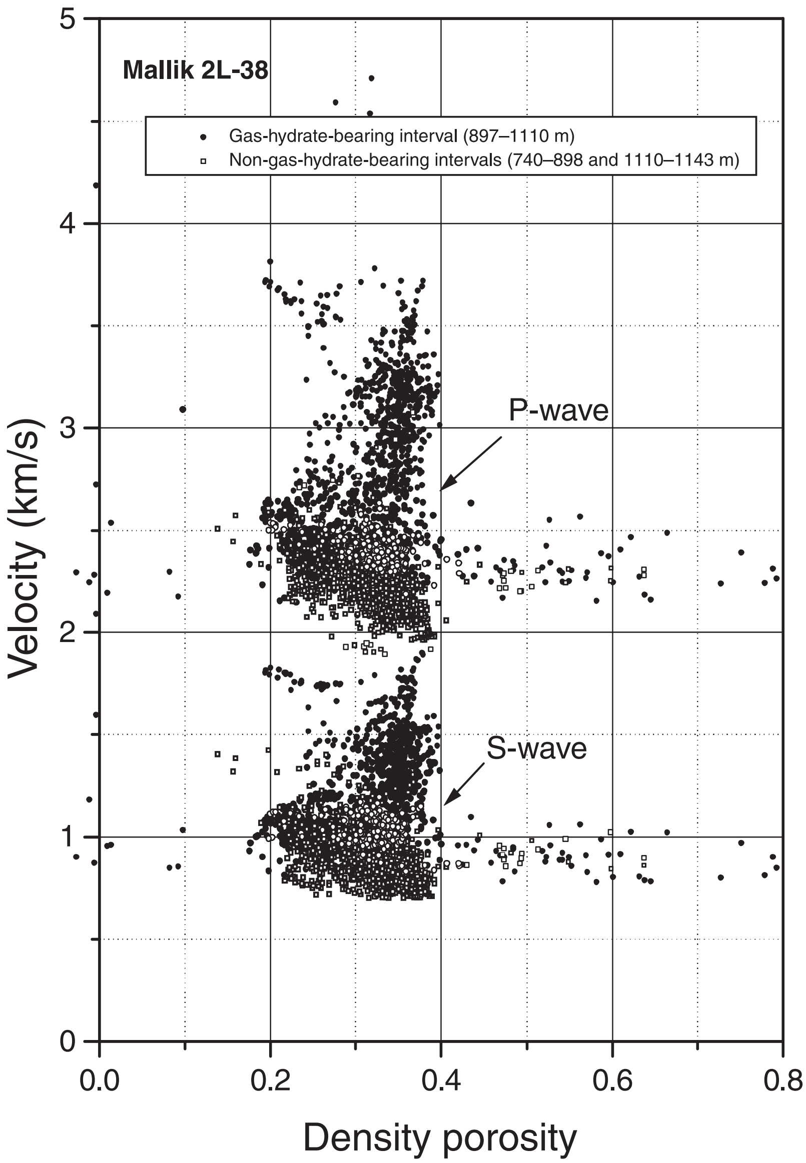

Figure 1.

Measured compressional- and shear-wave velocities versus density porosities at the Mallik 2L-38 well. The gas-hydrate-bearing interval is between 897 and 1110 m and two non-gas-hydrate-bearing intervals are between 740 and 897 m and between 1110 and 1143 m.

Table 1. Parameters used to estimate the amount of gas hydrate at the Mallik 2L-38.

	Value	Equations used	Source
W	1.56	equation (1)	This study
n	1	equation (1)	Lee et al. (1996), Lee (in press)
V_w	1.5 km/s	equations (2) and (4)	Lee et al. (1996)
V_h	3.3 km/s	equations (2) and (4)	Sloan (1998)
V_m	5.37 km/s	equations (2) and (4)	Estimated from Han's Equation Han et al. (1986)
ρ_w	1.0 g/cm^3	equations (2) and (3)	
ρ_h	0.91 g/cm^3	equations (2) and (3)	Sloan (1998)
ρ_m	2.65 g/cm^3	equations (2) and (3)	Winters et al. (1998)
α	0.558	equation (6)	Estimated from log values
β	0.51	equation (6)	Sloan (1998)

density-porosity computation, the amount of gas hydrate will be overestimated. To apply the three-component density-porosity equation, the amount of gas hydrate concentration must be known. The porosity of the gas-hydrate-bearing sediments was corrected after the gas hydrate concentration was estimated, assuming the porosity determined from the two-component system was correct. As shown later, this porosity correction is not significant for the estimation of gas hydrate concentration in the Mallik 2L-38 well.

DERIVATION OF CONSTANTS

In order to derive a baseline relationship that relates the porosity and velocity for non-gas-hydrate-bearing sediments, several parameters must be estimated from the log responses in the non-gas-hydrate-bearing sediments. The compressional velocity in modified matrix used in equation (4) was estimated from Han et al.'s (1986) relation, equation (6), assuming 10% volume clay content. Inserting 10% clay content and 0% porosity into Equation (6), the P-wave velocity in the modified matrix is 5.37 km/s.

A weight (W) of 1.56 is estimated by a least-squares method from the velocity and porosity samples between 748 and 897 m in depth, with the modified velocity in the matrix of 5.37 km/s and other parameters shown in Table 1. Figure 2 shows the observed velocities and the weighted equation with W= 1.56. The weight equation bisects the data points of non-gas-hydrate-bearing samples, but the majority of data inside the gas-hydrate-bearing interval lie above the line representing the weighted equation, indicating a significant gas hydrate concentration.

In order to derive an S-wave velocity relationship for the gas-hydrate-bearing sediments, parameters α and β must be derived. The parameter β is taken from the V_s/V_p ratio for a Type I methane hydrate given in Sloan (1997). As mentioned previously, the parameter α is estimated from the observed P-and S-wave velocities of non-gas-hydrate-bearing

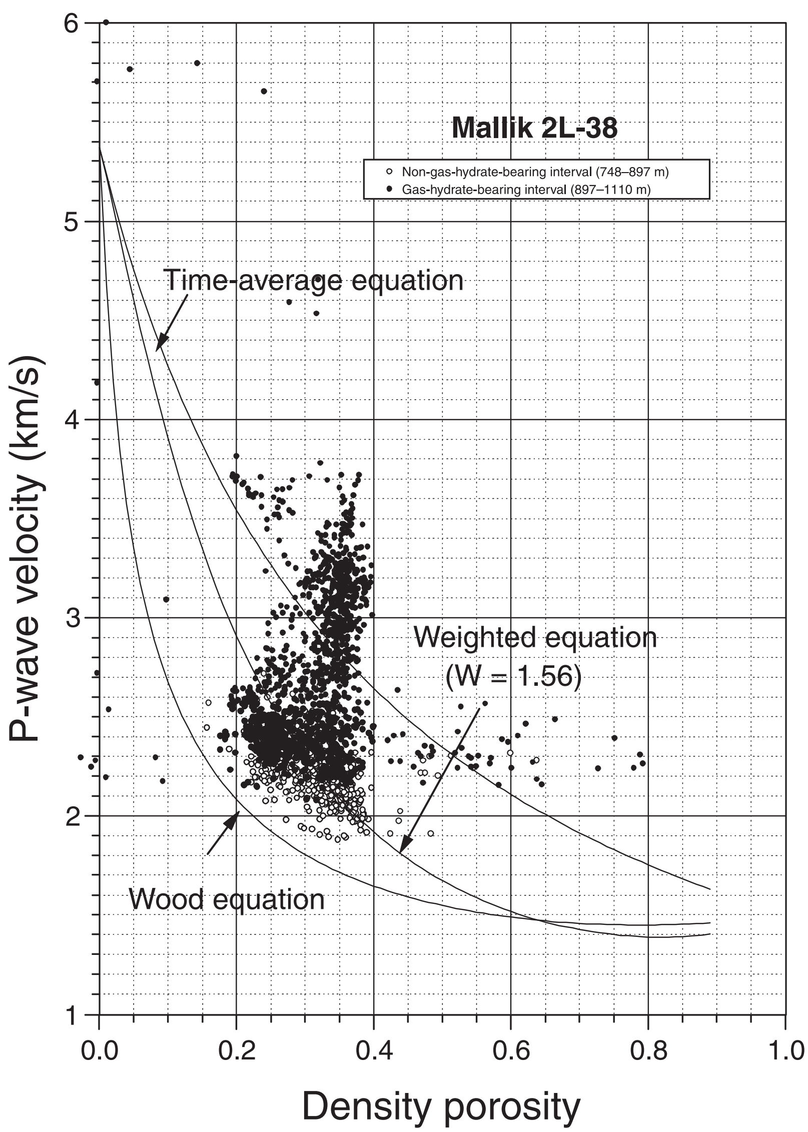

Figure 2.

Graph showing porosity versus compressional-wave velocity for time average, Wood, and weighted equations using parameters shown in Table 1. The velocities for non-gas-hydrate-bearing sediments are represented by open circles and solid circles represent velocities of gas-hydrate-bearing sediments.

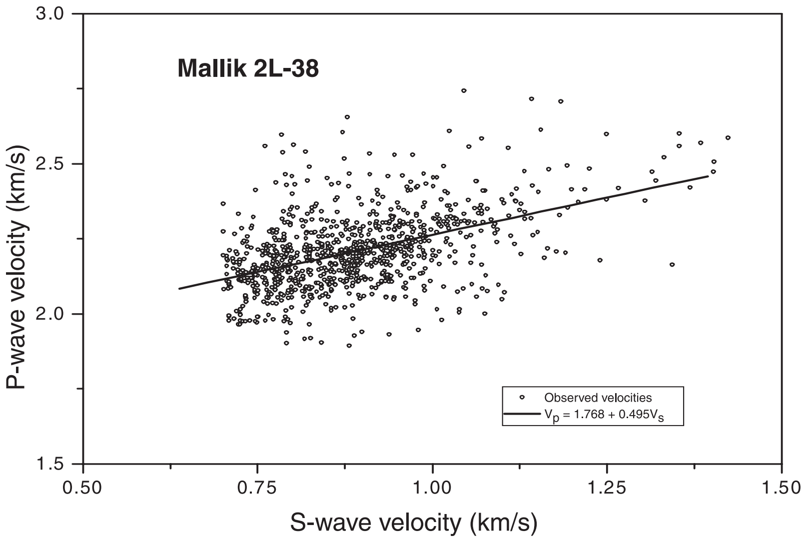

Figure 3.

Relationship between compressional- and shear-wave velocities of the sediments for the non-gas-hydrate-bearing interval between 740 m and 1107 m in depth.

Table 2. Gas hydrate concentration estimated from P-wave and S-wave data at the Mallik 2L-38 well.

Weight (W)	Exponent (n)	P-wave Ave S.D. (%)	S-wave Ave S.D. (%)	Remarks
1.56	1	29.1 ± 24.9	27.9 ± 24.2	NPC, WH, C = 10%
1.56	1	28.0 ± 24.2	26.8 ± 23.5	PC, WH, C = 10%
1.56	1	39.0 ± 9.8	37.8 ± 9.3	PC, H, C = 10%
1.60	1	27.4 ± 23.7	26.4 ± 23.2	PC, WH, C = 0 %
1.51	1	28.7 ± 24.7	27.3 ± 23.9	PC, WH, C = 20%
1.44	1	29.4 ± 25.3	27.7 ± 24.3	PC, WH, C = 30%

PC: porosity correction for gas hydrate concentration is applied. NPC: no correction for the porosity. WH: estimated from the whole section from 897 m to 1110 m in depth. H: estimated from 897 m to 1110 m excluding the zones where the gas hydrate concentration is zero either from P-wave or S-wave. C: volume clay content. Ave: average. S.D.: standard deviation.

sediments. Figure 3 shows the measured P-wave and S-wave velocities for the non-gas-hydrate-bearing sediments from 740 to 897 m and the least-squares fitting curve of the relationship, which is given by:

$$V_p = 1.768 + 0.495 V_s \tag{9}$$

The average density-log-derived porosity for the depth interval from 740 to 897 m is 33%. Inserting this value to the weighted equation with W = 1.56, the P-wave velocity is 2.17 km/s. Inserting V_p = 2.17 km/s into equation (9), the velocity of S-waves for the non-gas-hydrate-bearing sediment is estimated to be V_s = 0.81 km/s; this result yields $\alpha = 0.557$.

The exponent factor ‘n’ is assumed to be n = 1 in this study, because observed velocities in gas-hydrate-bearing sediments do not indicate any significant cementation owing to the gas hydrate in the pore spaces (Lee, in press) and an analysis of amplitude versus offset data implies that the gas hydrate is deposited away from grain contacts (Ecker and Lumley, 1994). Another piece of evidence supporting a low exponent value is the fact that n = 1 is appropriate for describing the elastic behavior of permafrost samples (Lee et al., 1996).

ESTIMATION OF GAS HYDRATE AMOUNT

The amounts of gas hydrate concentrated in the sediment pore spaces were estimated using equation (1) for the compressional-wave data and equation (6) for the shear-wave data, along with parameters shown in Table 1, and the results are summarized in Figure 4 and Table 2. As mentioned previously, the density porosity overestimates the porosity of sediment in the presence of the gas hydrate without density correction; resulting in the overestimation of gas hydrate concentration. The result shown in Figure 4 is the estimation of gas hydrate concentration after the density correction for the gas hydrate was applied. For example, the initial gas hydrate concentration using P-wave data without density correction at depth 898.5 m is 66.3% with 39.6% porosity. After the gas hydrate correction was applied to the density computation, the corrected density-porosity is 38.1% and the gas hydrate concentration is 64.4%. Therefore, the density-porosity correction reduced the gas hydrate concentration by about 2%. Unless both the porosity and gas hydrate concentration are very high, the density-log-derived porosity using the two-component system does not affect the estimation of gas hydrate concentration significantly.

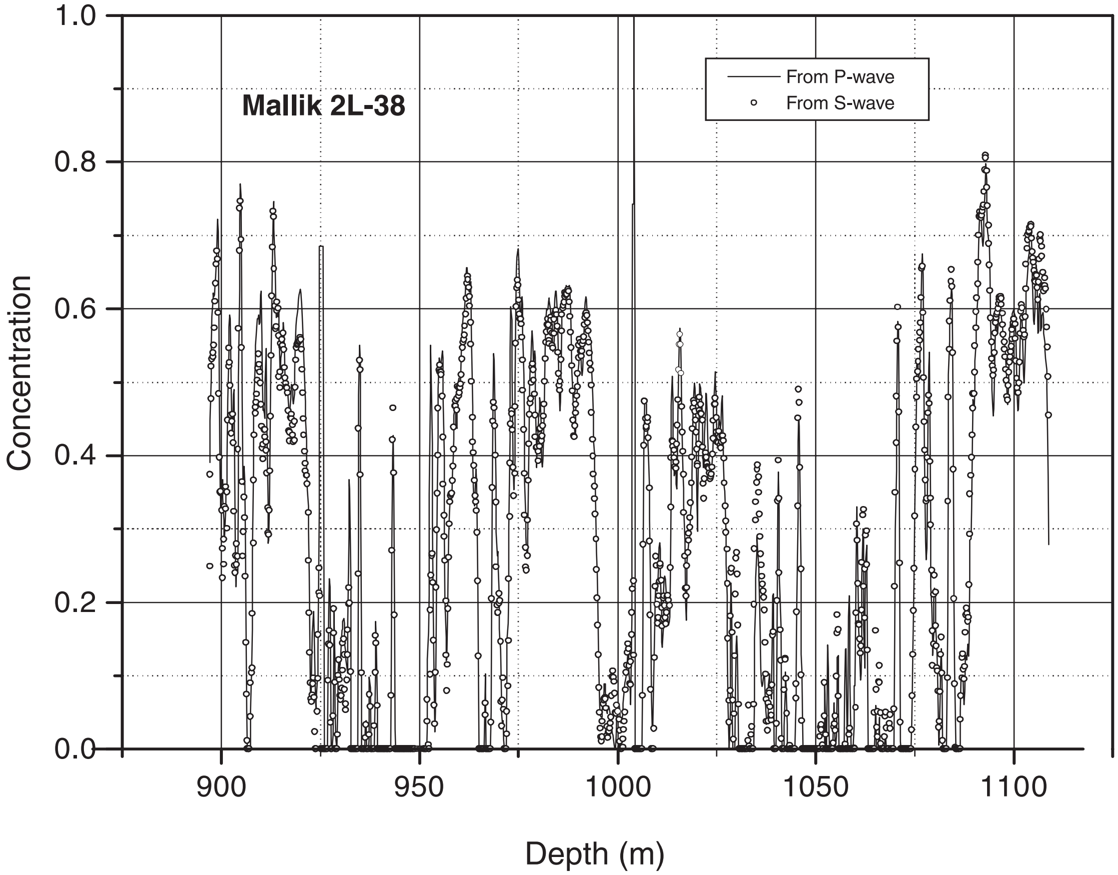

Figure 4. *Graph showing concentration of gas hydrate in the sediment's pore space using the compression-wave velocity (line) and the shear-wave velocity (dot) versus depth.*

Two outliers having very high gas hydrate concentration (greater than 40% estimated from P-wave velocity) with low gas hydrate concentration (less than 10% estimated from S-wave velocity) are located near 925 m and 1027 m. These zones represent tight sandstone intervals with a P-wave velocity of about 5 km/s and a S-wave velocity of 1.2 km/s. At present we do not know why the tight sandstone has such a low S-wave velocity. These zones are excluded from the discussion.

Without porosity correction, the average gas hydrate concentration within the depth range of 897 to 1110 m is 29.1% estimated from the P-wave velocity data and 27.9% estimated from the S-wave data. With porosity correction for the gas hydrate concentration, the estimates are 28.0% from P-wave data and 26.8% from S-wave data; less than 2% difference in the estimation. The above-average gas hydrate concentrations were computed regardless of whether or not there was gas hydrate within the 897 to 1110 m interval. If the non-gas-hydrate-bearing zones between 897 and 1110 m where the estimated gas hydrate concentrations from either P-wave or S-wave data are zero are excluded, the average gas hydrate concentration is 39.0% estimated from P-wave data, and 37.8% estimated from S-wave data (Table 2). The total thickness of the excluded zone is about 60 m.

Figure 4 indicates that the gas hydrate concentration is greater than 70% of the pore space in several depth ranges, regardless of the data type used (P-wave or S-wave velocities). Also, Figure 4 indicates that the gas hydrate concentration estimated from P-wave data is similar to that from the S-wave data.

DISCUSSION

The choice of modified matrix velocities for P-waves and S-waves should be rationally selected for an accurate estimation of the gas hydrate concentration. The choice of P-wave velocity in the matrix is directly determined from Han et al.'s (1986) relationship between P-wave velocity with respect to porosity and volume clay content (equation 5). Also, the S-wave velocity of a modified matrix may be estimated from the following shear-wave velocity (V_{sh}) relation from Han et al. (1986):

$$V_{sh} = 3.52 - 4.91\phi - 1.89C \tag{10}$$

Inserting C = 10% and = 0 into equation (10), the S-wave velocity in the modified matrix is 3.33 km/s. These P- and S-wave velocities yield $\alpha = 0.62$. Using this value of α with $W = 1.56$ and n = 1, the average gas hydrate concentration without porosity correction, estimated from P-wave data within the depth range from 897 to 1110 m, is 29.1% and 22.1% from S-wave data. When $\alpha = 0.558$, which is estimated from the measurements of P- and S-wave velocities at Mallik 2L-38, the average gas hydrate concentration is 29.1% from P-wave data and is 27.9% from S-wave data. The parameter α controls only the gas hydrate concentration from S-wave data, so the P-wave estimates are the same in both cases. This demonstrates that the P- and S-wave velocity relationship derived directly from the non-gas-hydrate-bearing samples provides more accurate estimates. However, this also demonstrates that when no data are available for non-gas-hydrate-bearing samples, the general relation between P- and S-wave velocities, such as the Han et al. relationship (1986), provides a reasonable S-wave velocity for the modified matrix.

The estimation of a weight (W) in equation (1) depends on the clay content of the sediments, which changes the P-wave velocity in the modified matrix. The clay content we assumed for the estimation of W was 10%, although clay content of some samples measured from laboratory is less than a few per cent (Winters et al., 1999). However, the log analysis based on the neutron porosity and density porosity measurements indicates that an average value of about 10% clay content is reasonable for the reservoir sediments. The weights of the weighted equation using the clay content of 0%, 10%, 20%, and 30% are 1.6, 1.56, 1.51, and 1.44 respectively. Using these weights, the estimated gas hydrate concentrations from P-wave data with n = 1 and with porosity correction are 27.4%, 28.0 %, 28.7%, and 29.4% for the clay content of 0%, 10%, 20%, and 30% respectively. The difference of average gas hydrate concentration is about 2% as the clay content changes by 30%. However, the maximum concentration varies as much as 5% as the clay contents increases by 30%.

Figure 5 shows a cross plot of the estimated gas hydrate concentrations using P-wave data (S_p) against that using S-wave data (S_s). If the equations used to estimated the gas hydrate concentrations, namely equation (1) for P-wave and equation (6) for S-wave, are correct, the cross plot would show scattering about 45° line. Figure 5 indicates that the majority of the data points follow 45° line. For low concentration (less than 20%) or high concentration (more than 60%) Figure 5 indicates that gas hydrate concentration estimated using S-wave is a little higher than that from P-wave. The linear fit of the data shown in Figure 5 is given by $S_s = 0.956S_p + 0.007$. The slope of 0.956 is close to the theoretical value of 1.0. The mean value of the difference in the concentration ($S_p - S_s$) is 0.8%, and its standard deviation is 4.8%. This result indicates that the equation employed in this paper is at least internally consistent.

The weighted equation proposed by Lee et al. (1996) was never rigorously tested against gas-hydrate-bearing sediments. In order to test this theory, controlled experiments with P-wave and S-wave data from sediments with known gas hydrate concentration are required as demonstrated for permafrost samples (Lee et al., 1996). However, the data at Mallik 2L-38 provided an excellent data set to test the internal consistency of the theory. Most of the parameters for the

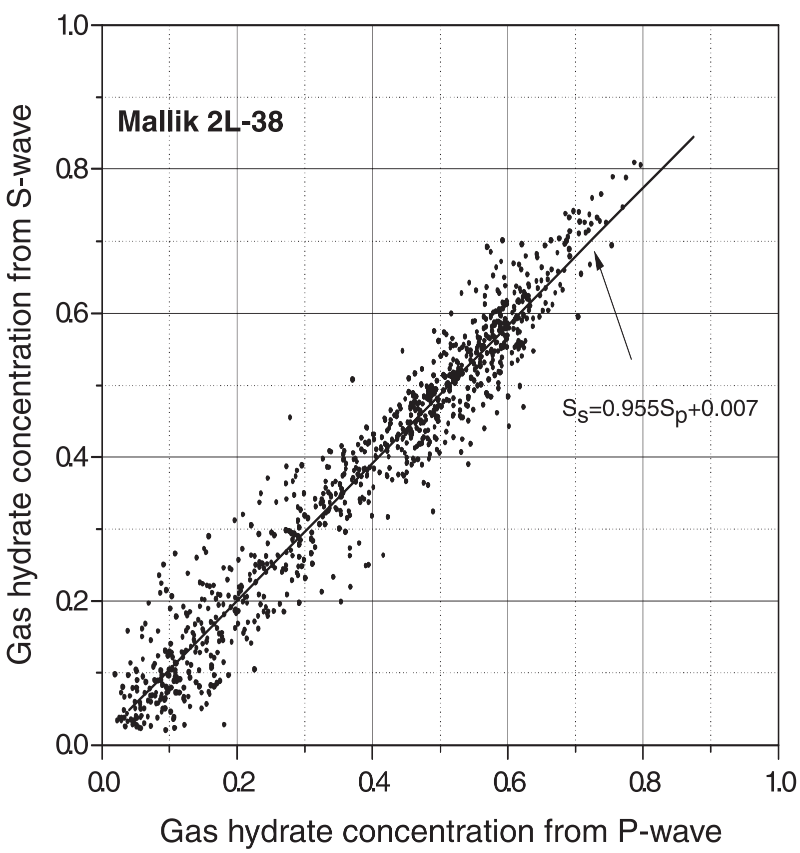

Figure 5.

A cross plot for the gas hydrate concentration estimated from the shear-wave and compressional-wave log velocity data.

weighted equation can be estimated from the non-gas-hydrate-bearing sediments, but the exponent 'n', which mimics the cementation effect of gas hydrate in sediments, can not be estimated from the observed data unless the gas hydrate concentrations were measured independently.

The similar estimation of gas hydrate concentrations from P- and S-wave data indicates that a low value of exponent is appropriate for describing the elastic behavior of gas-hydrate-bearing sediments in this study area. The low value of exponent has a significant implication for the effect of gas hydrate on the acoustic property of gas-hydrate-bearing sediments. This implies that there may be some lithification owing to the gas hydrate cementation in the pore space; however, the effect is not significant as suggested by Dvorkin and Nur (1993). This study suggests that the dominant effect of the gas hydrate is filling the pore spaces in the sediments.

CONCLUSIONS

This study shows that the weighted equation with $W = 1.56$, exponent n = 1 and V_s/V_p of 0.557 for non-gas-hydrate-bearing sediment with 33% porosity is appropriate for estimating the concentration of gas hydrate at the Mallik 2L-38. Log-derived P-wave velocity, S-wave velocity, and bulk density provided an excellent data set to test the weighted equation in relating the amount of gas hydrate to the in situ acoustic velocities. The following conclusions can be drawn from this study.

1. The average gas hydrate concentration (excluding the non-gas-hydrate-bearing section) in the interval between 897 and 1110 m is 39.0% when using P-wave data and 37.8% when using S-wave data. The highest concentration is about 80% near 1090 m. The total thickness of non-gas-hydrate-bearing section is about 60 m and 150 m of the section is gas hydrate bearing.
2. The choice of V_s/V_p for a modified matrix is important in estimating gas hydrate concentrations from P- and S-wave data. The optimum choice of V_s/V_p can be derived from the measured P-and S-wave velocities for the non-gas-hydrate-bearing sediments.
3. The low value of exponent (n = 1) is appropriate in describing the elastic properties of gas-hydrate-bearing sediments in this area. This signifies that the dominant effect of the gas hydrate is filling the pore spaces in the sediments.
4. The density-log porosity correction using three-component system (fluid, gas hydrate, and matrix) is not important unless both the porosity and gas hydrate concentration are very high. The error in the estimation of gas hydrate concentration in the pore space without density correction is less than 2% in this study area.
5. The effect of clay content in estimating the amount of gas hydrate concentration is not significant, as long as the volume clay content is reasonably assumed.

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