INTRODUCTION

Gas hydrates, or clathrates, are ice-like crystalline solids composed of water molecules surrounding a gas molecule. In recent years, methane hydrates have been the focus of many studies because of their widespread occurrence in permafrost regions and in most of the world oceans (Kvenvolden, 1993). Also, immense amounts of methane may have escaped from deep-sea gas hydrates to the atmosphere as a result of dissociation of gas hydrates caused by sea-level and climatic changes, and acted as a negative feedback control on global temperature fluctuations (Dillon et al., 1991; Paul et al., 1991). Gas hydrate is also of potential importance as an energy resource and significant for seafloor stability and safety issues (Dillon et al., 1993).

Gas hydrates exhibit relatively high acoustic velocities compared to the pore-filling fluids; therefore, the velocity of gas hydrate-bearing sediments is usually elevated (Stoll, 1974; Tucholke et al., 1977). Based on the elevated velocity because of the presence of gas hydrate, a number of studies have attempted to estimate in situ hydrate amounts using seismic velocities (Mackay et al., 1995; Lee et al., 1993; Wood et al., 1994; Spence et al., 1995; Kastner et al., 1995; Yuan et al., 1996).

Kastner et al. (1995) estimated a minimum of 15% pore-space occupancy based on velocities from acoustic logs and vertical seismic profiles (VSP) on the Cascadia Margin at Ocean Drilling Program (ODP) Site 889, where the velocities of gas hydrate-bearing sediments are greater than expected by 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 Site 889.

In this paper, the amount of gas hydrates in the pore space was estimated by applying a weighted equation proposed by Lee et al. (1996) to acoustic logs along with three distributions of porosity. This study shows that estimations using acoustic logs and core porosities are comparable to those estimated from other methods such as those using chloride anomalies or resistivity measurements.

THEORY

This section reviews the essentials of the theory necessary for the computation of the amount of hydrate concentrated in the sediment’s pore space. The relation between the velocity and hydrate concentration in the pore can be described by the following three-phase weighted equation. This equation predicts the velocity for the unconsolidated sediment with high porosity such as the sediment in the study area. The weighted equation is defined as a weighted combination of the rigid, consolidated rock with little fluid, and the Wood equation (Wood, 1941), which pertains to particles in suspension.

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

$$\frac{1}{V_p} = \frac{W\phi(1-S)^n}{V_p^1} + \frac{1 - W\phi(1-S)^n}{V_p^2},$$  

(1)

where $V_p$ = compressional (P) velocity of hydrated sediments; $V_p^1$ = compressional velocity of hydrated sediments computed from the three-phase Wood equation; $V_p^2$ = compressional velocity of hydrate sediments computed from the three-phase time-average equation; $W$ = a weighting factor; $\phi$ = sediment porosity (as a fraction); $S$ = concentration of hydrate in the pore space (as a fraction); and $n$ = a constant simulating the rate of lithification with hydrate concentration.

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

$$\frac{1}{V_p^2} = \frac{\phi (1 - S)}{\rho_f V_f^2} + \frac{\phi S}{\rho_V V_V^2} + \frac{(1 - \phi)}{\rho_m V_m^2},$$  

(2)

where $\rho_f$ is the density of the fluid, $\rho_p$ is the density of pure hydrate, $\rho_m$ is the density of matrix, and $\rho$ is the bulk density of sediments. The bulk density is given by

$$\rho = (1 - \phi)\rho_p + (1 - S)\rho_m + S\rho_h.$$

(3)

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

$$\frac{1}{V_p^2} = \frac{\phi (1 - S)}{V_f^2} + \frac{\phi S}{V_h^2} + \frac{(1 - \phi)}{V_m^2},$$

(4)

where $V_f$ is the compressional velocity of the fluid, $V_h$ is the compressional velocity of pure hydrate, and $V_m$ is the compressional ve-
Estimation of Hydrate Amount

The amounts of hydrate concentrated in the sediment pore spaces were estimated using Equation 1 with parameters shown in Table 2 and the results are summarized in Figures 1–3 and Table 1. The hydrate concentration in pore space generally increases as depth increases at all three sites and is about 10%–15% near the BSR depths at the base of the hydrate zone. The average of gas hydrate concentration in the pore space varies between 12.1% and 3.8% at Site 997 depending upon the porosity data used. Table 1 indicates that the estimation based on the linear approximation of porosity trend is slightly higher than the estimation calculated from the core porosity, but they are very similar. The estimation based on the core porosities agrees with the estimation based on the chloride anomalies and resistivity logs (Shipboard Scientific Party, 1996a, 1996b, and 1996c). The average hydrate concentration in the pore space at all three sites, based on the core porosity, is 4.4%, and the average porosity is 57.5%. Therefore, about 2.5% of the sedimentary section (2.5 vol%) is occupied by hydrates.

The choice of weight \( W = 1.1 \) is based on the velocity and porosity samples acquired in this region (Lee et al., 1996) and the samples of Leg 164 above the hydrate-bearing interval. If a smaller weight such as \( W = 1 \) is used in the computation, then the amounts of hydrate are less than those shown in Table 1. For example, \( W = 1 \) yields a mean hydrate concentration of 7.19%–5.44% at Site 955 when using porosities computed from the bulk density, which is a 26% decrease in the hydrate concentration.

As indicated in Equation 1, if a higher exponent \( n \) is used, the hydrate concentrations become less than those shown in Table 1. As far as this exponent factor is concerned, there is no information to confirm the validity of \( n = 1 \) used in this estimation. If shear velocities are available, the exponent may be better constrained (Lee et al., 1996).

Summary and Conclusion

The validity of the estimated hydrate amounts depends on the accuracy of the acoustic logs and reliability of in situ porosities. The log quality was degraded because of poor borehole conditions from washouts and borehole rugosity. Therefore, the data sets at ODP Leg 164 did not provide optimum data sets to test acoustic theories or to estimate accurate in situ hydrate amounts. However, the acoustic data with core porosity provided useful information in characterizing in situ hydrated sediments.

The average concentration of hydrate in the pore space at Sites 994, 995, and 997 using core porosities and acoustic logs are 3.9%, 5.7%, and 3.8% (Table 1), and these are about 2.2%, 3.3%, and 2.2% of the total sediment volume (vol%). These values are higher than those estimated from chloride anomalies, which are 1.3, 1.8, and 2.4 vol% for Sites 994, 995, and 997, respectively, and are similar to those estimates from resistivity logs, which are 1.9, 3.0, and 3.4 vol% (Collett and Ladd, Chap. 19, this volume). On the other hand, the hydrate concentrations based on porosities calculated from the density logs are much higher, which implies that the log porosity measurements are degraded greatly from the poor borehole conditions.

A weighted equation proposed by Lee et al. (1996) was never rigorously tested against hydrated sediments. To test this theory, a more accurate data set (acoustic and porosity) as well as shear-wave data are required as demonstrated for permafrost samples (Lee et al., 1996). However, similar estimations of hydrates in pore spaces compared to other methods strongly suggest that the weighted equation with \( W = 1.1 \) and an exponent \( n = 1 \) is adequate in describing the acoustic properties of hydrated sediments in the Blake Ridge area.

In conclusion, the estimated gas hydrate amount in all three sites using acoustic logs and core porosities averages about 2.6 vol% of the sediments, and this value is comparable to those estimates from chloride anomalies and resistivity log data.
Figure 1. (A) Porosity, (B) velocity, and (C) hydrate concentration using core porosities for Site 994. The sub-bottom depth of hydrated zone is 212–428.8 m (Shipboard Scientific Party, 1996a).
Figure 2. (A) Porosity, (B) velocity, and (C) hydrate concentration using core porosities for Site 995. The sub-bottom depth of hydrated zone is 193–450 m (Shipboard Scientific Party, 1996b).
Figure 3. (A) Porosity, (B) velocity, and (C) hydrate concentration using core porosities for Site 997. The sub-bottom depth of hydrated zone is 186.4–450.9 m (Shipboard Scientific Party, 1996c).
Table 1. Means and standard deviations of acoustic velocity, porosity, and estimated hydrate concentration for Sites 994, 995, and 997.

<table>
<thead>
<tr>
<th>Site</th>
<th>Log velocity (km/s)</th>
<th>Hydrate concentration (%)</th>
<th>Porosity (%)</th>
<th>Remarks</th>
</tr>
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<tr>
<td>994</td>
<td>1.70 ± 0.07</td>
<td>7.4 ± 6.6</td>
<td>61.0 ± 5.1</td>
<td>Porosity from bulk density</td>
</tr>
<tr>
<td></td>
<td>3.9 ± 3.6</td>
<td>7.0 ± 5.1</td>
<td>57.1 ± 2.8</td>
<td>Core porosity</td>
</tr>
<tr>
<td></td>
<td>4.9 ± 3.5</td>
<td>57.2 ± 3.5</td>
<td>57.9</td>
<td>Linear approximation of core porosity</td>
</tr>
<tr>
<td>995</td>
<td>1.72 ± 0.07</td>
<td>9.8 ± 5.4</td>
<td>62.2 ± 6.2</td>
<td>Porosity from bulk density</td>
</tr>
<tr>
<td></td>
<td>5.7 ± 4.1</td>
<td>57.9 ± 3.5</td>
<td>57.9</td>
<td>Core porosity</td>
</tr>
<tr>
<td></td>
<td>6.3 ± 3.5</td>
<td>58.2 ± 3.5</td>
<td>58.1</td>
<td>Linear approximation of core porosity</td>
</tr>
<tr>
<td>997</td>
<td>1.68 ± 0.09</td>
<td>12.1 ± 8.7</td>
<td>68.7 ± 9.1</td>
<td>Porosity from bulk density</td>
</tr>
<tr>
<td></td>
<td>3.8 ± 5.3</td>
<td>58.3 ± 3.5</td>
<td>58.3</td>
<td>Core porosity</td>
</tr>
<tr>
<td></td>
<td>4.0 ± 5.0</td>
<td>58.2</td>
<td>58.2</td>
<td>Linear approximation of pore porosity</td>
</tr>
</tbody>
</table>

Table 2. Acoustic parameters used to estimate the amount of hydrate.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Value</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>W</td>
<td>1.1</td>
<td>Lee et al. (1996)</td>
</tr>
<tr>
<td>n</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>V_w</td>
<td>1.5 km/s</td>
<td>2.4</td>
</tr>
<tr>
<td>V_s</td>
<td>3.3 km/s</td>
<td>2.4</td>
</tr>
<tr>
<td>V_m</td>
<td>4.37 km/s</td>
<td>2.4</td>
</tr>
<tr>
<td>( \rho_w )</td>
<td>1.0 g/cm^3</td>
<td>2.3</td>
</tr>
<tr>
<td>( \rho_s )</td>
<td>0.9 g/cm^3</td>
<td>2.3</td>
</tr>
<tr>
<td>( \rho_m )</td>
<td>2.7 g/cm^3</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Note: See “Theory” section for definitions of W, n, V_w, V_s, V_m, \( \rho_w \), \( \rho_s \), and \( \rho_m \).

REFERENCES


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