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Estimating the Amount of Gas Hydrate in Marine Sediments in the Blake Ridge Area, Southeastern Atlantic Margin

by
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ABSTRACT

A relative amount of gas hydrate in marine sediments can be estimated by use of either interval velocity or amplitude blanking in seismic profiles. Under the assumption of constant concentration of hydrate irrespective of porosity, the average bulk hydrate amounts for the lower portion of marine sediments above the bottom simulating reflector in the Blake Ridge area, south-eastern Atlantic Margin, is estimated to be about 8.7% of the sediments when using velocity analysis and about 10% when using amplitude blanking. Under the assumption of variable hydrate concentration proportional to the porosity, the estimate is about 8.1% when using velocity information and about 10% when using amplitude blanking.

The estimation method using amplitude is comparable to the estimation by interval velocity and provides a convenient way of quantitative classification of the degree of hydrate cementation. In the amplitude method, three classes of blanking are defined; class boundaries represent a change in reflection amplitude by a factor of 2, and the classes may be used to predict the amount of hydrate in bulk sediments.

INTRODUCTION

Gas hydrate in oceanic sediments contains immense amounts of methane. This is of potential importance as an energy resource and may be significant as a greenhouse gas (Dillon and others, in press). An ability to identify, quantify, and map gas hydrates in sea-floor sediments by a remote-sensing technique is critical to determine the significance of hydrates to energy and climate. This report presents a method of doing this by the use of seismic reflection data. The profiles used are located on the continental rise off North and South Carolina.

A gas hydrate is a crystalline solid; its building blocks consist of a gas molecule surrounded by a cage of water molecules that are stabilized by hydrogen bonding (Sloan, 1990). Thus it is similar to ice, except that the crystalline structure is supported by the guest gas molecule. Gas hydrates are stable at the temperature and pressure within ocean floor sediments at water depths greater than about 300 m, and they commonly exist there in the form of methane hydrates (Sloan, 1990). In deep-sea sediments, the temperature normally increases downward and the temperature eventually is reached at which hydrate is unstable. The base of the hydrate stability zone, commonly several hundred to a thousand meters beneath the sea floor, will generally parallel the sea floor at any particular water depth because the thermal gradient within a restricted region is normally fairly constant.

Because gas hydrates have relatively high acoustic velocity compared to the pore-filling fluid, they increase the velocity of the gas-hydrate bearing sediments. In seismic profiles, therefore, the base of the hydrate-stable zone is observed as a reflection that approximately parallels the sea floor; known as the bottom simulating reflection, or BSR (Markl and others, 1970; Ewing and Hollister, 1972; Shipley and others, 1979). In addition to causing an increase of sediment velocity and formation of a BSR, the hydrate causes cementation of sediments in the hydrate-stable zone above the BSR. The cementation appears to create a reduction in the amplitude of reflections from sedimentary strata (Shipley and others, 1979; Dillon and others, in press; Lee and others, 1992), an effect known as blanking when observed in seismic profiles.

We will make estimates of the amount of hydrate in the sediment by two approaches, one using the increased velocity and the other using the blanking effect. Even though elevated interval velocities of gas-hydrated sediments are real, the quantitative aspect of the velocity changes due to the hydrate cementation in sediments is largely unknown. Thus the estimated hydrate amount in this paper contains high uncertainty. The observed amplitude blanking cannot be fully explained in terms of reflection seismology (Lee and others, 1992). Because almost nothing is known about the details of natural occurrence of gas hydrates, we are not certain whether the observed amplitude blanking in the study area can be generalized to other areas or not. However, the approach using amplitude blanking in estimating the amount of hydrate in this area is sound because the amplitude information is firmly constrained by the observed interval velocities.

Hydrate amounts estimated using amplitude information of two-channel seismic profiles in the Blake Ridge area are shown in Dillon and others (1992) and Fehlhaber and others (1992). A brief discussion of the estimation method is given here; more details are available in Lee and others (1992).

ESTIMATION METHOD

Interval velocity and median reflectance were determined for a layer about 250 ms thick directly above the BSR using data from the marine multichannel seismic reflection profiles shown in Figure 1. Median reflectance is defined as a seismic amplitude determined from the reflection data which has been adjusted for changes caused by varying traveltime (due to the changes in water depths) using measured sea floor reflection coefficients from this area. Changes in median reflectance are assumed to result from cementation of sedimentary strata by gas hydrate, producing the blanking observed in seismic profiles. Therefore, we anticipate the increased blanking would be accompanied by higher compressional wave velocities in the sediments. The relation between these parameters is shown in Figure 2.

In order to relate amplitude blanking owing to the hydrate cementation, Lee and others (1992) introduced a model, in which two end members consisting of ordinary marine sediments and representative hydrated sediments (RHS) are mixed in various proportion. The choice of RHS for the Blake Ridge area based on 6 multichannel seismic lines (Figure 1) is a sediment having 57.5% porosity with 27.5% hydrate concentration in the pore volume. Asterisks in Figure 2 indicate the computed values for the two-end-member model and show that the model will predict values of velocity and blanking that are consistent with those observed.

The relation between amplitude blanking and interval velocity for mixtures of RHS ("hydrated sediments") and unhydrated sediments is shown in Figure 3. The various curves in the plot show changes resulting from different porosities in the RHS's. All RHS's have a hydrate concentration of 27.5% in their pore space. As the RHS "replaces" the ordinary marine sediments (moving from 0% to 100% RHS), the interval velocity (solid curves) and amplitude blanking (dashed curves) increase, so the information shown in Figure 3 can be used in estimating hydrate amount. Note that in our terminology, an increase in blanking is indicated by a decrease in reflection amplitude ratio. For example, let's assume that the average observed velocity is about 1.8 km/s and 60% porosity RHS curve is appropriate in this case. Figure 3 shows that the average velocity of 1.8 km/s indicates 50% substitution of RHS. Therefore the amount of hydrate is about 8.2 % (porosity * hydrate concentration in pore space of RHS * amount of RHS or 0.6 * 0.275 * 0.5) in bulk volume.

Likewise, we can use amplitude information. Let's assume that the amplitude is reduced by 50% and again choose 60% porosity RHS. Figure 3 indicates that 50% amplitude reduction results in about 52% substitution of RHS. In this case, the blanking is not sensitive to the porosity value chosen because the blanking is a relative quantity (for details, consult Lee and others, 1992). Thus the amount of hydrate is about 8.3% (0.6 * 0.275 * 0.52). This illustrates that for a single assumed RHS, we can calculate the amount of hydrate using either velocity or amplitude blanking.

DETERMINATION OF HYDRATE AMOUNT

GENERAL FORMULA

The previous section presented a method of estimating hydrate amount for a given porosity and hydrate concentration. Using the previous concept, we can develop a method of estimating the total amount of in-situ hydrate cemented in marine sediments whose porosities and hydrate concentrations vary from locality to locality.

The total amount of in-situ hydrate per unit volume can be estimated using the following equation:

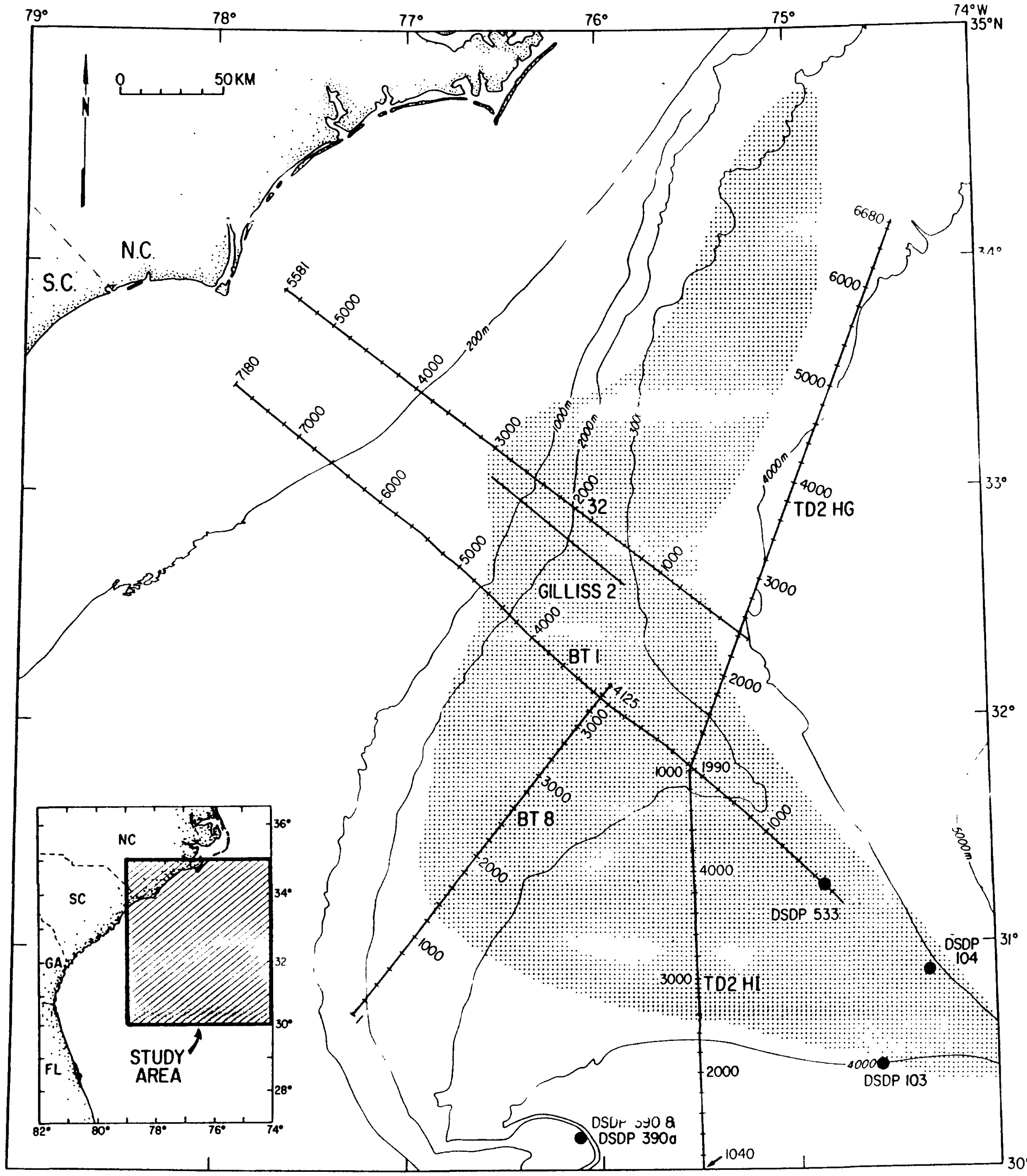

Figure 1. Bathymetry, in meters, of southeastern U.S. continental margin, location of multichannel seismic reflection profiles, DSDP sites 103, 104, 390, and 533. The dot pattern shows the extent of Bottom Simulating Reflector (BSR). Modified from Dillon and Popenoe (1988).

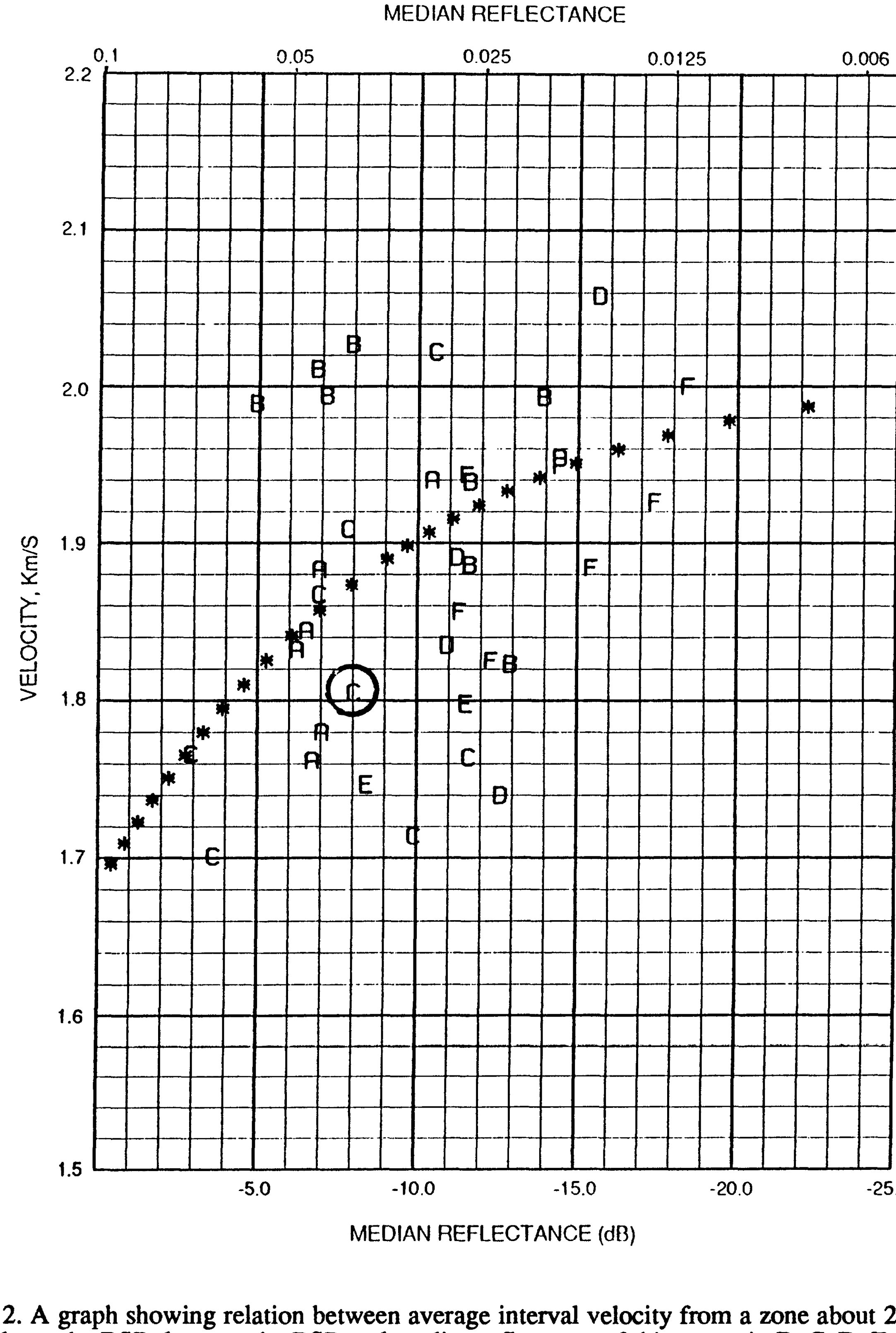

Figure 2. A graph showing relation between average interval velocity from a zone about 250 ms above the BSR down to the BSR and median reflectance of this zone. A, B, C, D, E, and F represent multichannel seismic reflection profiles TD2HI, TD2HG, BT1, BT8, Gillis 2, and USGS 32, respectively. Asterisks (*) represent the computed relationship between velocity and relative median reflectance derived from two-end-member model. From Lee and others (1992).

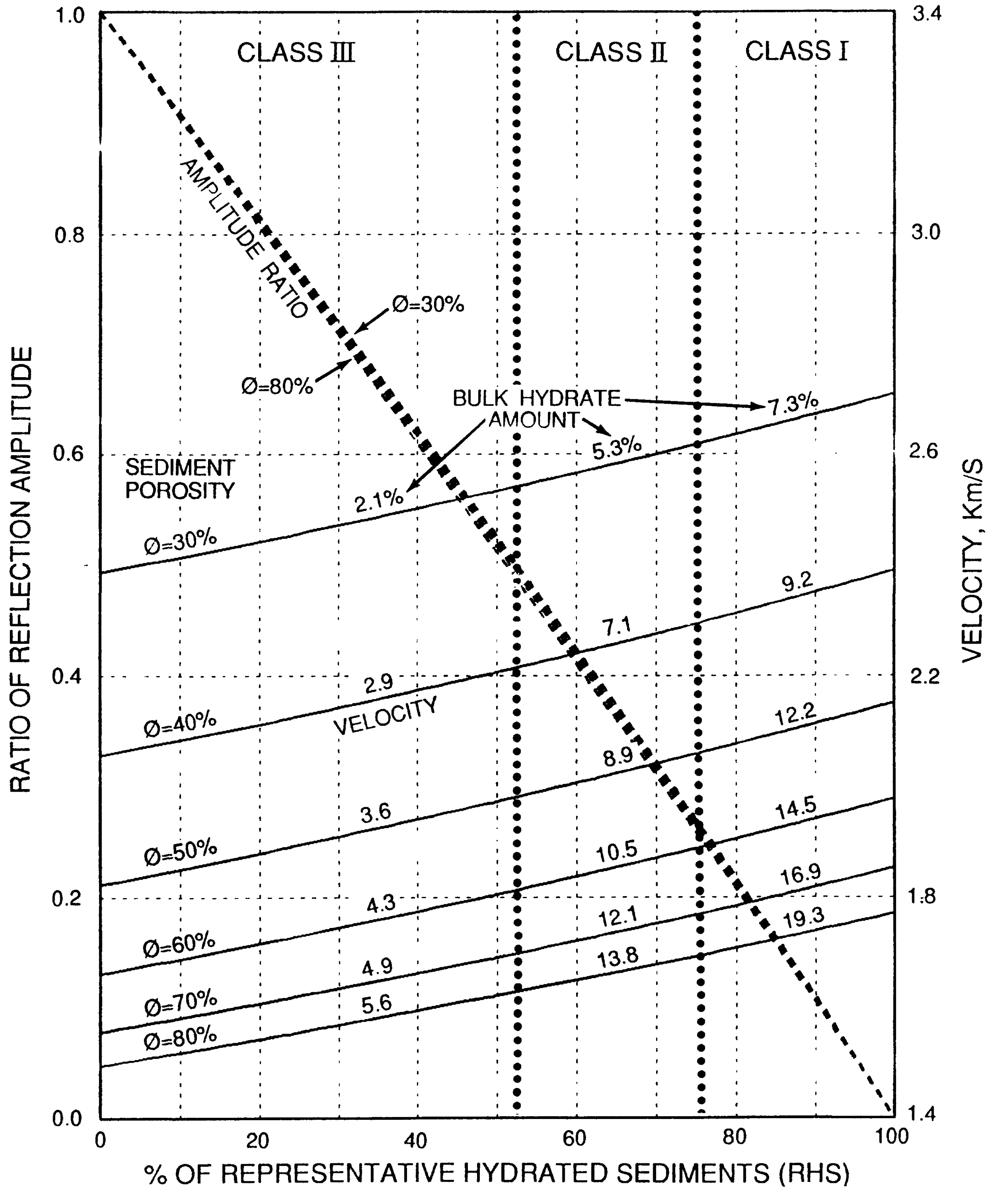

Figure 3. Computed velocity and amplitude decrease (blanking) for representative hydrated sediments of various porosities with a constant hydrate concentration of 27.5% in the pore volume. The numbers above each curve are average hydrate amounts in bulk % for three classes.

$$\mathbf{T}(v) = \int\int \mathbf{H}(v,\phi)\mathbf{f}(v,\phi)dv\,d\phi \qquad (1)$$

where

$\mathbf{T}(v)$: the total amount of hydrate in unit volume estimated by velocity information of marine sediments.

$\mathbf{H}(v,\phi)$: the amount of hydrate in pore space for a given porosity (ϕ) and velocity (v). This quantity can be calculated using the two-end-member model presented in the previous section.

$\mathbf{f}(v,\phi)$: a joint probability density function of porosity and the velocity of the sediment.

The joint probability density function $\mathbf{f}(v,\phi)$ can be represented as follows by the Bayes theorem (Tarantola, 1987)

$$\mathbf{f}(v,\phi) = \mathbf{F}(v \mid \phi)\mathbf{P}(\phi) \qquad (2)$$

where

$\mathbf{F}(v \mid \phi)$: a conditional probability density function of velocity for a given porosity

$\mathbf{P}(\phi)$: a marginal probability density function of porosity.

The conditional probability density function is assumed to be normally distributed and is given by:

$$\mathbf{F}(v \mid \phi) = \frac{1}{\sigma\sqrt{2\pi}} E^{-\frac{(v-\mu)^2}{2\sigma^2}} \qquad (3)$$

where

σ : a standard deviation

μ : a mean velocity, which depends on the porosity and hydrate concentration.

STATISTICAL ANALYSIS

In order to use Equation (1), we should have information about the statistical properties of hydrated sediments. In our analysis, we assumed that all variables such as velocity, porosity and amplitude blanking are normally distributed. Therefore, a mean (μ) and a standard deviation (σ) are sufficient to describe the statistics of each variable.

Figure 4 shows the histogram of porosity for unconsolidated sediments sampled by DSDP on the U.S. Atlantic continental rise in the Blake Ridge area. The solid smooth curve is the computed normal curve with a mean of 57% and a standard deviation of 13%. As indicated in Figure 4, the assumption of normal distribution for the porosity is reasonable. The marginal probability density function for porosity, defined in Equation (2), is assumed to be equal to the statistics shown in Figure 4.

The statistics of interval velocity and amplitude blanking for typical hydrated sediments in the Blake Ridge area can be calculated using the data shown in Figure 2 and the statistics are shown in Table 1.

COMPUTATION OF TOTAL AMOUNT OF HYDRATE

The key element in estimating hydrate amounts is the velocity. The interval velocities of hydrated sediments depend on the porosity of the sediment exclusive of hydrate and the amount of hydrate cemented in the pore space. In order to estimate the amounts of hydrate, we have to differentiate the velocity change caused by the porosity change from that due to the change of hydrate

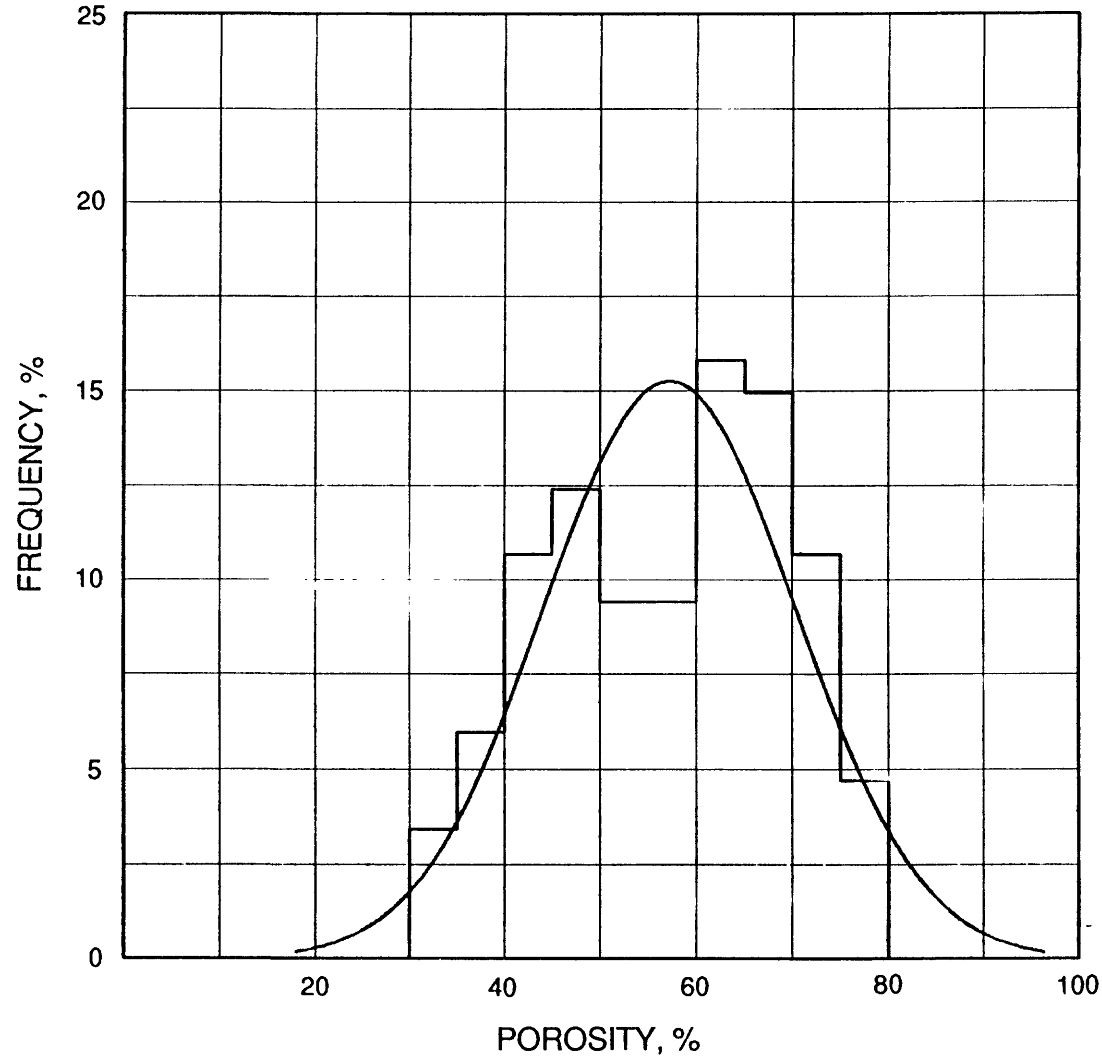

Figure 4. Histogram of porosity values for sediments on the U.S. Atlantic continental rise from DSDP sites. (The source of porosity values is the DSDP CD-ROM data set, NGDC-03, produced by NGDC with support from U.S. Science Support Program of the Joint Oceanographic Institutions, Inc.). The smooth curve is the computed normal distribution with a mean of 57% and a standard deviation of 13%.

concentration. Therefore, as indicated in Lee and others (1992), different RHS's are required for sediments of different porosities. Selecting a reasonable RHS is critical in estimating hydrate amounts using amplitude information.

The study in the Blake Ridge area (Lee and others, 1992) indicates that an appropriate RHS in this area is a sediment having 57.5% porosity with 27.5% of the pore space filled with hydrate. We estimate the total amount of hydrate under two different assumptions of hydrate concentration: constant concentration irrespective of the porosity and variable concentration proportional to the porosity.

The following estimation is valid only for the lower portion (approximately the lower half) of the sedimentary section between the sea floor and the BSR, because all parameters (velocity and blanking) were analyzed in this zone.

A) Constant Concentration

In this case, we assume that the hydrate concentration in the RHS is a constant factor of the pore space irrespective of the porosity and is equal to 27.5% of the pore space. We choose this number, because it is the hydrate concentration suitable to the observation shown in Figure 2, producing the velocity/reflectance curve shown by the line of asterisks.

In order to use Equation (3), we have to know the mean and standard deviation of velocities of hydrated sediments as a function of porosity. We assume that the standard deviations of velocities of hydrated sediments with various porosities are fixed at 0.1 km/s, which is the standard deviation for the velocity of hydrated sediments in which 57.5% porosity RHS is appropriate. In the study area, the velocity of RHS is determined to be 2.016 km/s, whereas the observed mean velocity of the hydrated sediment is 1.875 km/s (Table 1), which is 93% of RHS velocity. We also assume that this relationship between mean velocity of hydrated sediment and RHS holds for sediments with other porosity. For example, the mean velocity of hydrated sediment where 45% porosity RHS is appropriate can be calculated as follows: The velocity of RHS (45% porosity with 27.5% hydrate concentration in the pore space) is about 2.3 km/s from Figure 3. The mean velocity in which this RHS is applicable is 0.93 * 2.3, which is 2.139 km/s. The mean and standard deviation of a hydrated sediment computed in this way determines the conditional probability defined in Equation (3).

STATISTICS

Variable	Mean	Standard Deviation	Remarks
Porosity	57%	13%	
Velocity	1.875 km s	0.1 km/s	Lower sedimentary section
	1.713 km/s	0.05 km/s	Whole sedimentary section
Blanking	9.95 db	3.84 db	Lower sedimentary section

Table 1. Statistics of sediments in the Blake Ridge area. The velocity of the whole sedimentary section means that the interval velocities were estimated for a sedimentary section from the sea floor to the approximate BSR depth (about 500 ms - 600 ms in two-way traveltime) and the lower sedimentary section means the sedimentary section from BSR up to about half the distance to the sea floor.

In order to better understand Equation (1), we define the following quantity :

$$M = H(\nu,\phi)F(\nu \mid \phi) \quad (4)$$

in such a way that the integration of Equation (4) with respect to the interval velocity yields the total amount of hydrate in bulk percent for a given porosity. Figure 5 shows the result of Equation (4) for various porosities ranging from 30% to 80%. The amount of hydrate contained in a sediment of given porosity increases as the interval velocity increases. However, the occurence of higher or lower velocity than average velocity is less likely, which is determined by the normal curve. So the net amount of hydrate for a given porosity with respect to the velocity is peaked near the average velocity and decreases away from the average velocity. The ordinate shows the normalized relative amount of hydrate for a given porosity and velocity. For example, if the interval velocity is 1.75 km/s for 80% porosity sediments, the relative amount of bulk hydrate is 0.8 relative to the amount for interval velocity 1.7 km/s (maximum numerical value in Figure 5). The area under each curve gives the amount of hydrate in percent for the sediment of that porosity; the bulk amount of hydrate in percent cemented in the sediment for each porosity is shown in Table 2.

The total bulk amount of hydrate in sediments having different porosities can be computed by integrating curves like those in Figure 5 with respect to velocity and porosity. Using a porosity range of 30% to 80% in the integration, the amount of bulk hydrate contained in sediments is estimated as 8.7%.

Instead of velocity, we can use amplitude blanking in our estimation. Substituting the statistics of amplitude blanking shown in Table 1 into Equation (4), the amounts of hydrate for given porosities can be estimated and are shown in Figure 6 and in Table 2. Like Figure 5, the area under each porosity curve yields the percent of hydrate cemented for the sediment of that particular porosity. Table 2 indicates that the estimation using amplitude is slightly higher than the estimation using velocity for each porosity value. From Equation (1), the total amount of hydrate per unit volume of marine sediments using amplitude is estimated as 10%, which is about 15% higher that the estimated hydrate amounts using velocity.

B) Variable Concentration

In this case, we assume that the hydrate concentration is proportional to the porosity. The proportioning constant is assumed to be 275/575, which is correct for RHS with 57.5% porosity. In other words, we assume that the ratios of porosity to hydrate concentration for various RHS's are identical to that of 57.5% porosity RHS. Also we assume that the mean velocity is the arithmetic average of the velocity of sediment with no hydrate concentration and the velocity of RHS.

Figure 7 and Table 3 show the results of Equation (4) and these are similar to the results of constant concentration. The total amount of hydrate per unit volume of marine sediments is 8.05% when using velocity and 9.98% when using amplitude blanking. These values are slightly less than the amount estimated under constant hydrate concentration, but, for all practical purposes, these values are the same. Therefore, it is reasonable to say that the average amount of bulk hydrate per unit volume of the lower portion of hydrated marine sediments in the study area is between 8% and 10 %.

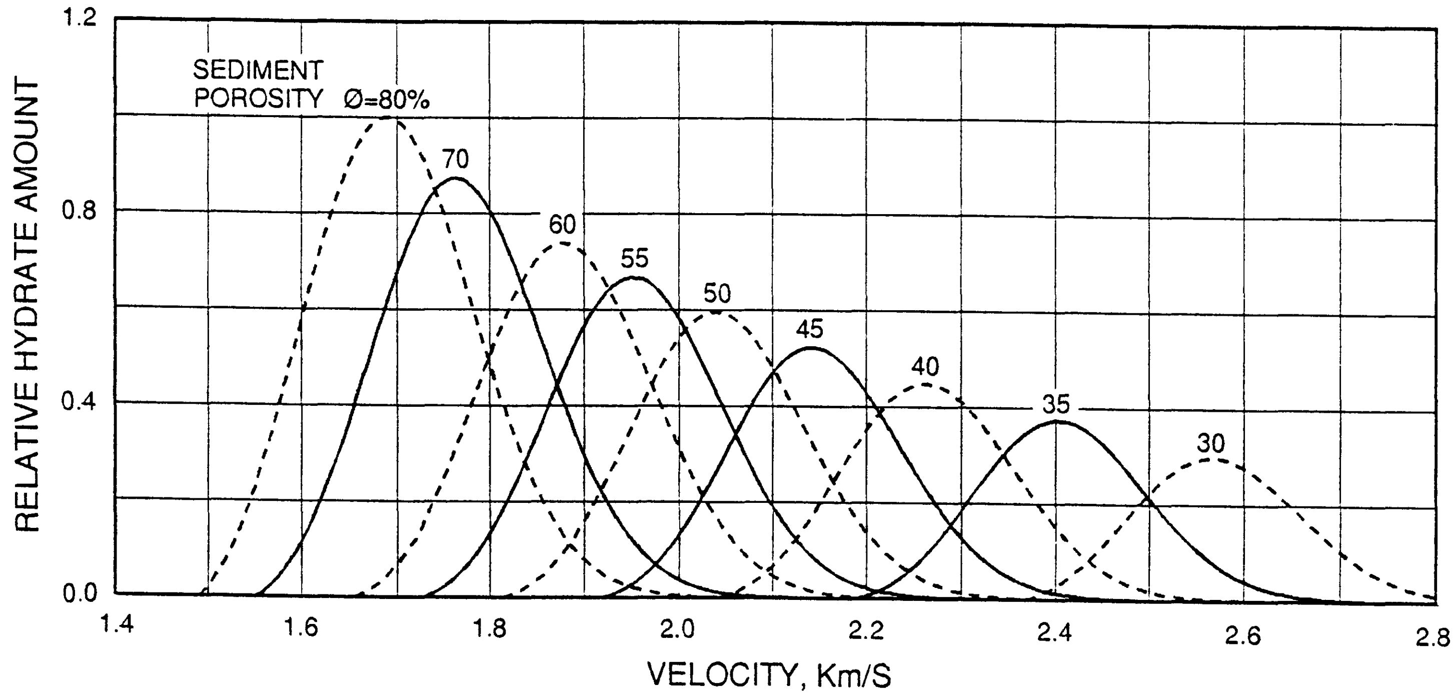

Figure 5. The estimated relative amount of hydrate for sediments of different porosities with respect to the interval velocity when velocity information is used under the assumption of constant hydrate concentration irrespective of porosity. Dotted and solid lines were used for visual purposes only. The area under each curve yields the amount of hydrate for the sediment of that porosity; amounts of hydrate in percent are listed in Table 2.

HYDRATE AMOUNT

Porosity (%)	Bulk Amount (%) by Velocity	Bulk Amount(%) by Blanking	Remarks
30	3.855	5.597	Lower Sedimentary Section
35	4.919	6.536	
40	5.693	7.472	
45	6.981	8.403	
50	7.970	9.326	
55	8.927	10.247	
60	9.846	11.158	
70	11.547	12.952	
80	12.995	14.707	
30	1.982	3.016	Whole Sedimentary Section From water bottom to the BSR depth
35	2.541	3.521	
40	3.087	4.023	
45	3.619	4.525	
50	4.133	5.025	
55	4.627	5.523	
60	5.099	6.018	
70	5.959	7.001	
80	6.663	7.973	

Table 2. The bulk amounts (in bulk percent) of hydrate per unit volume of marine sediments at the Blake Ridge area estimated using velocity and amplitude blanking with respect to the porosities of representative hydrated sediments under the assumption of constant hydrate concentration. The lower sedimentary section means the sedimentary section from BSR up to about half the distance to the sea floor.

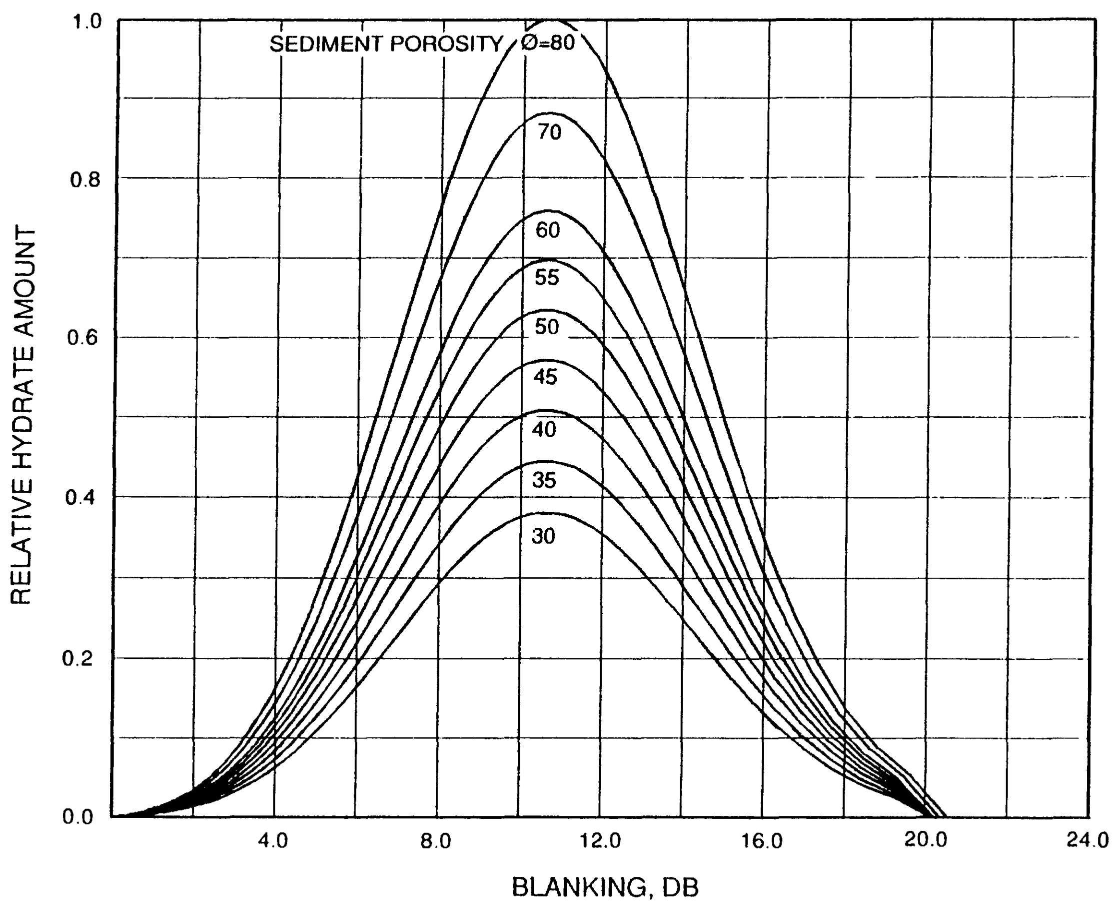

Figure 6. The estimated relative amount of hydrate for sediments of different porosities with respect to the amplitude blanking under the assumption of constant hydrate concentration irrespective of porosity. The area under each curve yields the amount of hydrate for sediment of that porosity; amounts of hydrate in percent are listed in Table 2.

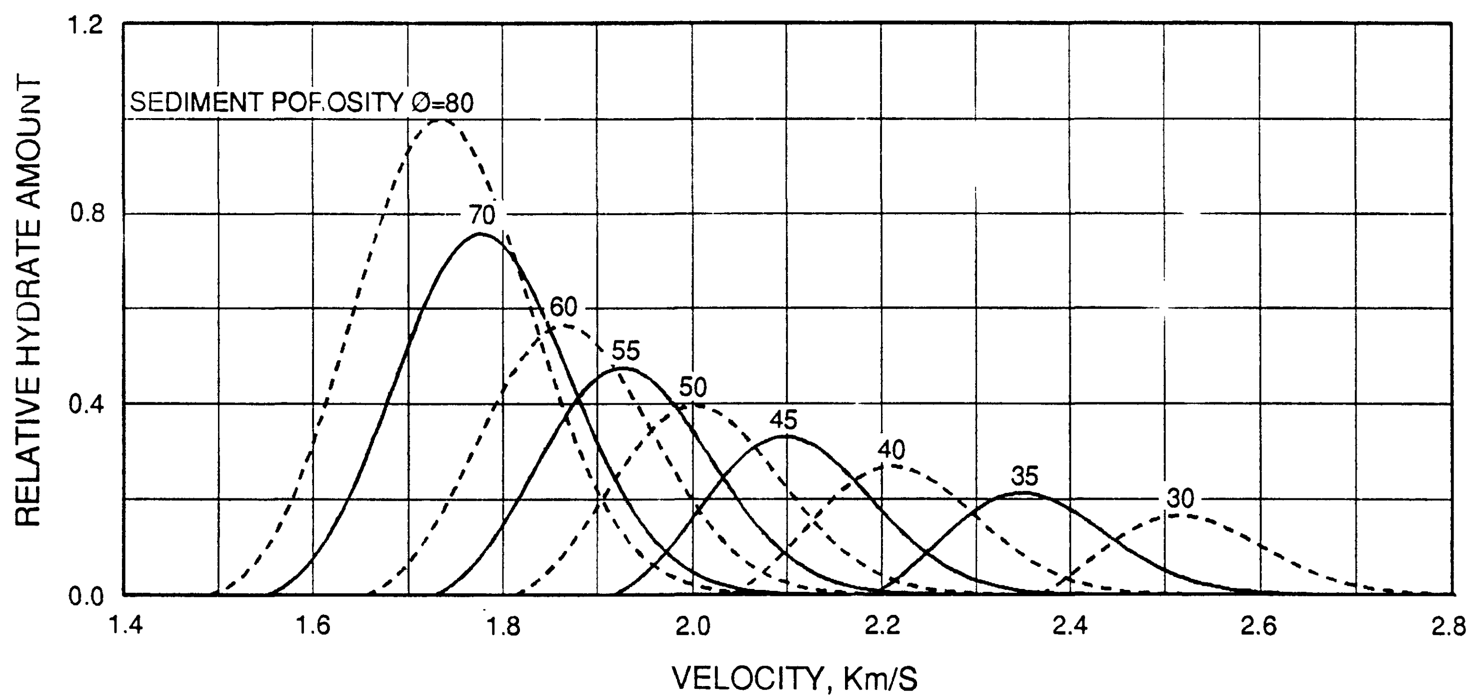

Figure 7. The estimated relative amount of hydrate for sediments of different porosities with respect to the interval velocity when velocity information is used under the assumption of variable hydrate concentration proportional to the porosity. Dotted and solid lines were used for visual purposes only. The area under each curve yields the amount of hydrate for sediment of that porosity; amounts of hydrate in percent are listed in Table 3.

HYDRATE AMOUNT

Porosity (%)	Bulk Amount (%) by Velocity	Bulk Amount(%) by Blanking	Remarks
30	2.388	2.883	Lower Sedimentary Section
35	3.153	3.936	
40	4.067	5.153	
45	5.133	6.536	
50	6.229	8.083	
55	7.599	9.790	
60	9.136	11.655	
70	12.531	15.838	
80	16.381	20.575	

Table 3. The bulk percent of hydrate per unit volume of marine sediments at the Blake Ridge area estimated using velocity and amplitude blanking with respect to the porosities of representative hydrated sediments under the assumption of variable hydrate concentration proportional to the porosity of the sediment. Lower sedimentary section means the sedimentary section from BSR up to about half the distance to the sea floor.

CLASSIFICATION

The variation in seismic amplitude reduction (blanking in seismic profiles) seems to be related in some way to the presence and probably the amounts of hydrate in the sediments. The previous section used this property to estimate total amounts of hydrate. We also wish to classify the amplitude blanking in order to use this observation to map hydrates by the direct effect of hydrate cementation on seismic reflections. Previous seismic mapping of hydrates has concentrated on recognition of the BSR, which defines just one side (the bottom) of hydrate-cemented sediments, and can only indicate the presence of hydrates. This does not mean that all BSR's define the base of hydrated sediments. BSR's are also caused by the diagenesis of silica-rich sediments (Hammond and Gaither, 1983), but the BSR's from diagenesis or chemical alteration are irrelevant to this paper. The BSR alone gives no information about volume of sediments involved or variations in concentration of hydrate within the sediments, parameters that we hope to estimate from seismic blanking. The classification of hydrate cementation based on the amplitude information rather than velocity information is important for single channel seismic data, because the amplitude is the only information we can get from such data.

Class boundaries are selected at amplitude reduction of 6 db, as shown in Figure 3. Another way of displaying the classification is to generate a synthetic seismogram. In order to simulate such a seismogram for unhydrated sediments, 200 random porosities in the porosity range of 50% to 70% were generated. Based on porosities, corresponding velocities and densities were computed. We then "replaced" non-hydrated sediment with increasingly larger amount of RHS (porosity 57.5%, hydrate concentration 27.5%) and velocities and densities were modified accordingly. A reflection coefficient series was computed based on the modified velocity and density, and a band-pass filter having a frequency content of 6/12 - 48/60 Hz was applied to reflection coefficients with 4-ms sampling interval. The RHS was replaced in the ordinary sediments at proportions of 0%, 25%, 50%, 60%, 70%, 80%, and 90% (Figure 8). Figure 8 illustrates how amplitude blanking is proportional to the amount of RHS substituted above and below the reflecting boundaries. The RHS replacement model is not a physical model to be able to explain the mechanism of seismic amplitude blanking; we present this model just to relate the amount of gas hydrates to the seismic amplitude blanking constrained by interval velocities. In other words, this model serves as a convenient tool to use in estimating hydrate amount from seismic amplitude. The quantitative aspect of this analysis are valid only for sediments characteristic of the Blake Ridge.

For the convenience of quantitative classification, we divided the degree of hydrate cementation in sediments into the following 3 classes in the Blake Ridge area:

Class I (High cementation). This class is characterized by a median reflectance less than 0.024. The bulk volume of hydrate in sediments is between 12% and 16% with an average 14%. The average interval velocity varies from 1.94 km/s to 2.02km/s.

Class II (Medium cementation). This class is characterized by a median reflectance of 0.05 to 0.025. The bulk volume of hydrate in the sediments ranges from 8% to 12% with an average of 10%. The average interval velocity varies from 1.85 km/s to 1.94 km/s.

Class III (Low cementation). This class is characterized by a median reflectance greater than 0.05. The amount of hydrate in the sediments is between 0% and 8% with an average of 4%; the corresponding average velocity ranges from 1.7 km/s to 1.85 km/s.

This classification can be used directly on seismic profiles by visually comparing the observed blanking with the synthetic seismograms generated in Figure 8 (Dillon and others, 1991). Alternatively, a quantitative approach is possible by plotting the median reflectance within a subbottom along a seismic profile (Figure 9). This presents a direct comparision of seismic blanking in the profile to the class boundaries and therefore allows a precise selection of blanking class. In Figure 9, produced from seismic data from profile BT1 (Figure 1), most of the Class III hydrated sediments occurs near CMP 1000-1500 and Class I hydrated sediments occur near CMP 3000-4000. On the average, the BT1 profile belongs to Class II hydrated sediments and the amount of gas hydrate in the selected subbottom window, which represents approximately the lower half of the hydrate-cemented zone, is about 10%. This amount is similar to the average bulk hydrate per unit volume of marine sediment calculated in the previous section using Equation (1).

DISCUSSION

The estimation of hydrate amounts cemented in the pore space depends on the effect of hydrate on the interval velocity computation. Our estimation is based on the assumption that the interval velocity of marine hydrated sediments can be calculated by equally weighting the Wood (1941) and the Wyllie and others (1956) equations (Appendix A). The Wood equation is approximately valid for particles in suspension and good for high porosity sediments. On the other hand, the Wyllie equation or time-average equation is good for the consolidated and low porosity sediments. Because neither the Wood equation nor the Wyllie equation alone describes the behavior of interval velocities of marine sediments, Nobes and others (1986) proposed a weighted average equation. This weighted average method has been used sucessfully for the computaion of interval velocities of marine sediments (Nobes and others, 1986; Lee and others, in press). However the lack of in-situ interval velocity measurements for hydrated marine sediments hampers any quantitative study relating the amount of hydrate to the interval velocity of a hydrated sediment. An in-situ velocity of almost pure hydrate is estimated in the range of 3.3 to 3.8 km/s (Mathews and von Huene, 1985). But there is no in-situ velocity estimates for "hydrated marine sediments". Therefore there is great uncertainty in computing interval velocities of hydrated sediments and thus in the amount of hydrates estimated in this paper.

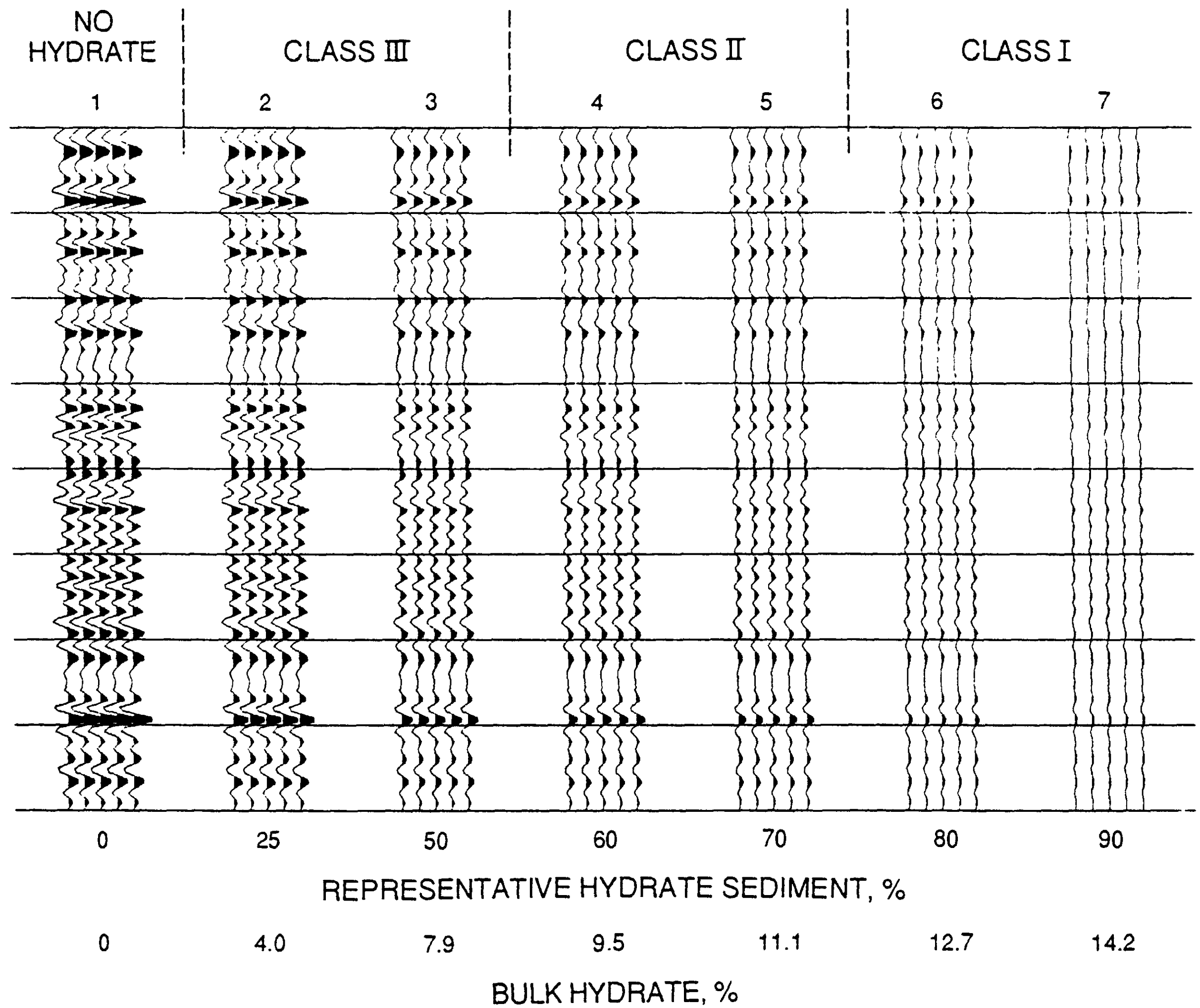

Figure 8. Synthetic seismogram, filtered with a frequency content of 6/12 - 48/60 Hz, which shows an amplitude blanking similar to seismic profiles in the study area. The degree of blanking is proportional to the amount of representative hydrated sediment replacing unhydrated sediment.

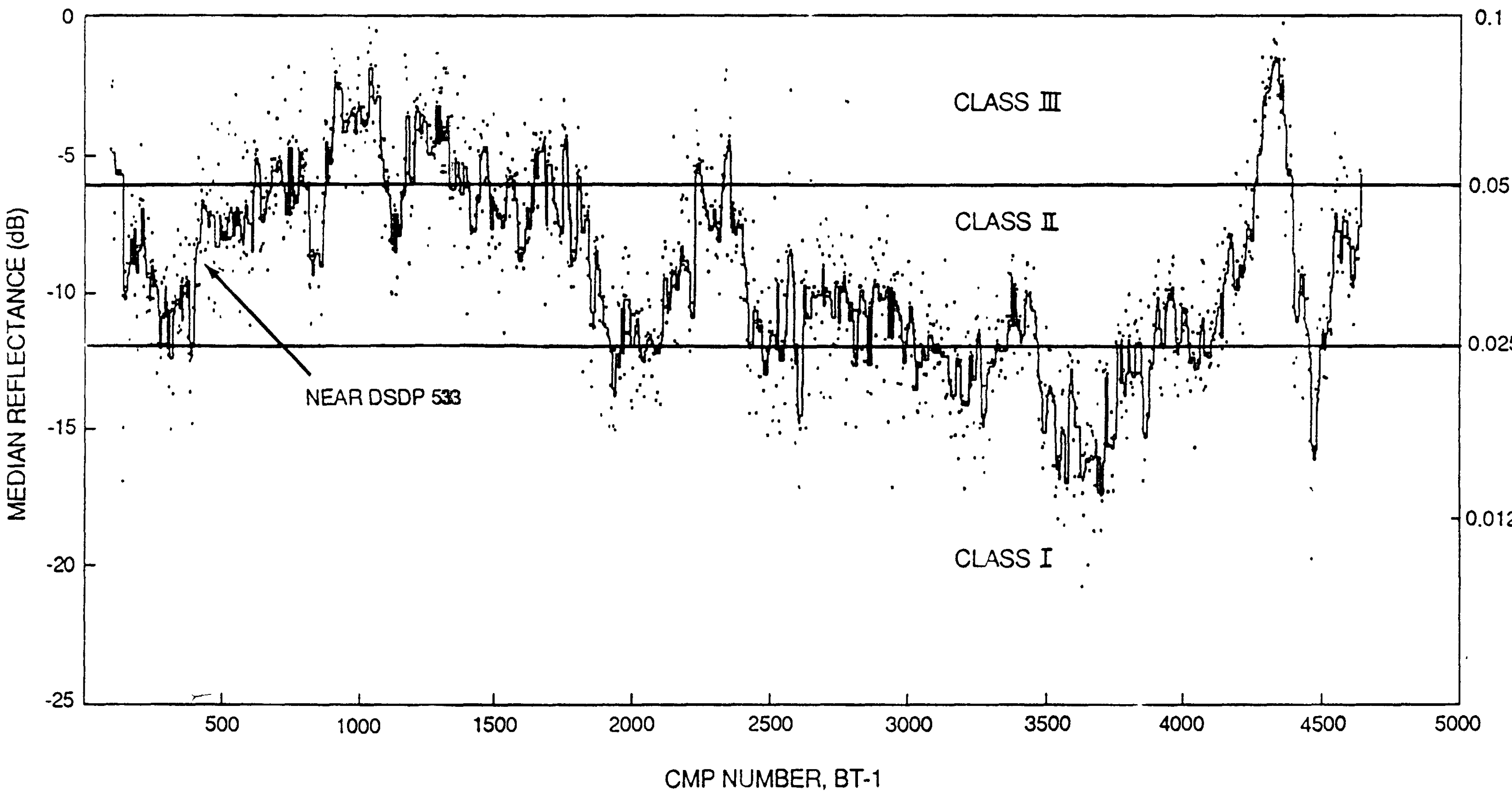

Figure 9. Classification of the hydrate cementation for seismic profile BT1 based on the median reflectance estimated between 250 ms and 500 ms sub-bottom reflection time. The average hydrate occurence on line BT1 is class II and corresponds to a bulk volume of about 10% gas hydrate in sediments. The dots indicates the individual reflectance measured at each common-mid-point (CMP) and the solid line indicates the 7 CMP running median reflectance.

Figure 10 shows the computed relation between the velocity and the amount of hydrate for a sediment of 57.5% porosity. In Figure 10, the Wood equation provides the lower limit of the velocity, while the Wyllie equation indicates the upper limit of velocity. Three dotted lines are velocities computed with various weights for the Wood equation (Appendix A), which are 0.65, 1.0, 1.35. A weight of 1.0 was used for the velocities of marine sediments in the Blake Ridge area (Lee and others, 1992) and Nobes and others (1986) used the weight of 1.2 for the velocities of undercompacted sediments in Middle Valley near Juan de Fuca Ridge.

As unhydrated sediments are cemented by the gas hydrate in their pore spaces, the porosities of those sediments decrease and the sediments probably become more lithified by the hydrate cementation. The contribution of the Wyllie equation to the interval velocity computation may increase as gas hydrates progressively cement the pore spaces of sediments. Therefore the chance is high that interval velocity of a hydrated sediment is better approximated by using a low weight for the Wood equation (less than 1.0). The consequence of applying higher weight for the Wood equation is computation of velocities that are too low and overestimation of hydrate amount. For example, the velocity of a 57.5% porosity sediment at 27.5 % hydrate concentration in the pore space is 2.0 km/s when a weight of 1.0 is used for the average equation, whereas the velocity of 2.0 km/s would be calculated for 18% hydrate concentration when a weight of 0.65 is used (Figure 10). In this case, there is about 50% overestimation of hydrate amount (0.575 * 0.275 versus 0.575 * 0.18) as a result of using a higher weighting value.

The classification of hydrated sediments is based on amplitude blanking. In consequence, the quantitative aspects of classes depend on the properties of the RHS. Because the choice of RHS depends on the interval velocity of a sediment, a quantitative comparision of hydrate classes should be performed for the same interval where RHS is determined. The average interval velocity is a function of depth, so we can, for example, subdivide sediments from the sea floor to the BSR depth into two zones and choose two different RHS's based on the velocities of the two depth intervals. The amount of hydrate for a given class for the upper division of subbottom sediment may be different from that of the lower division of the same class. In the Blake Ridge area, the hydrate amount for the lower 250 ms of Class I is 14%, while for the upper 250 ms of the sediments of the same class the amount is about 2.5%.

The bulk amounts of hydrates in the lower portion of subbottom sediments are estimated as 8.7% using velocity and as 10% using amplitude blanking under the assumption of constant hydrate concentration in the pore volume. The bulk amounts of hydrate for the whole sedimentary section (from the sea floor to the BSR depth) under the assumption of the constant hydrate concentration are estimated as 4.5% using velocity and 5.4% using amplitude blanking for the porosity range of 30% to 80%. The appropriate RHS for the whole sedimentary section is a 62.5% porosity sediment with 15% hydrate concentration in the pore space, and the statistics shown in Table 1 are used in the estimation.

Figure 11 shows the bulk amount of hydrate in % with respect to the porosity for the whole sedimentary section above the BSR (dotted line) and for the lower sedimentary section (solid line) using velocity information. The characteristics of the Figure 11 are similar to those of a probability density curve. Let the ordinate of Figure 11 be $A(\phi)$. Then $A(\phi)d\phi$ is the amount of hydrate contained in the porosity range $d\phi$. The peak amount occurs at about 60% porosity irrespective of analysis interval, because we used the same porosity statistics for both computations. If we assume that the upper limit of porosity for the lower portion of the sediments is 70% instead of 80% which was used in the previous section, the total amount of hydrate in the lower portion of sediments is about 7.1%. So the amount of hydrate in the upper portion of the sediments is about 2% in total volume. This implies that most of hydrate cementation occurs in the lower portion of the interval between the sea floor and the BSR, which agrees with the observed spatial variation of amplitude blanking of seismic profiles.

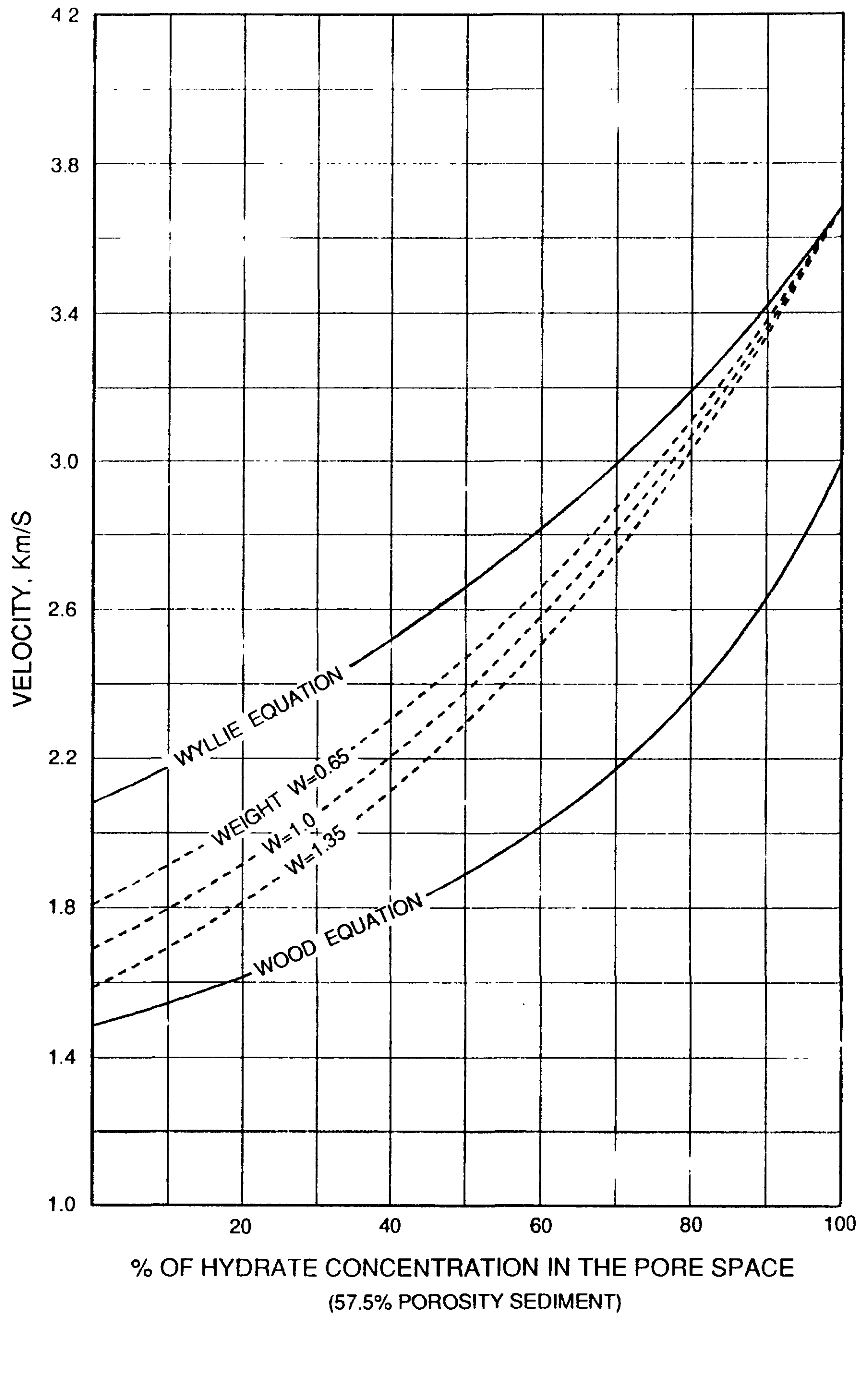

Figure 10. Graph showing velocities with respect to the amount of hydrate concentration for a sediment having 57.5% porosity with different weights for the Wood velocity as compared to the Wyllie velocity. (see Appendix A). The weights for the Wood velocity are 0.65 (more weight to Wyllie et al. velocity), 1.0 (equal weight), and 1.35 (more weight to the Wood velocity).

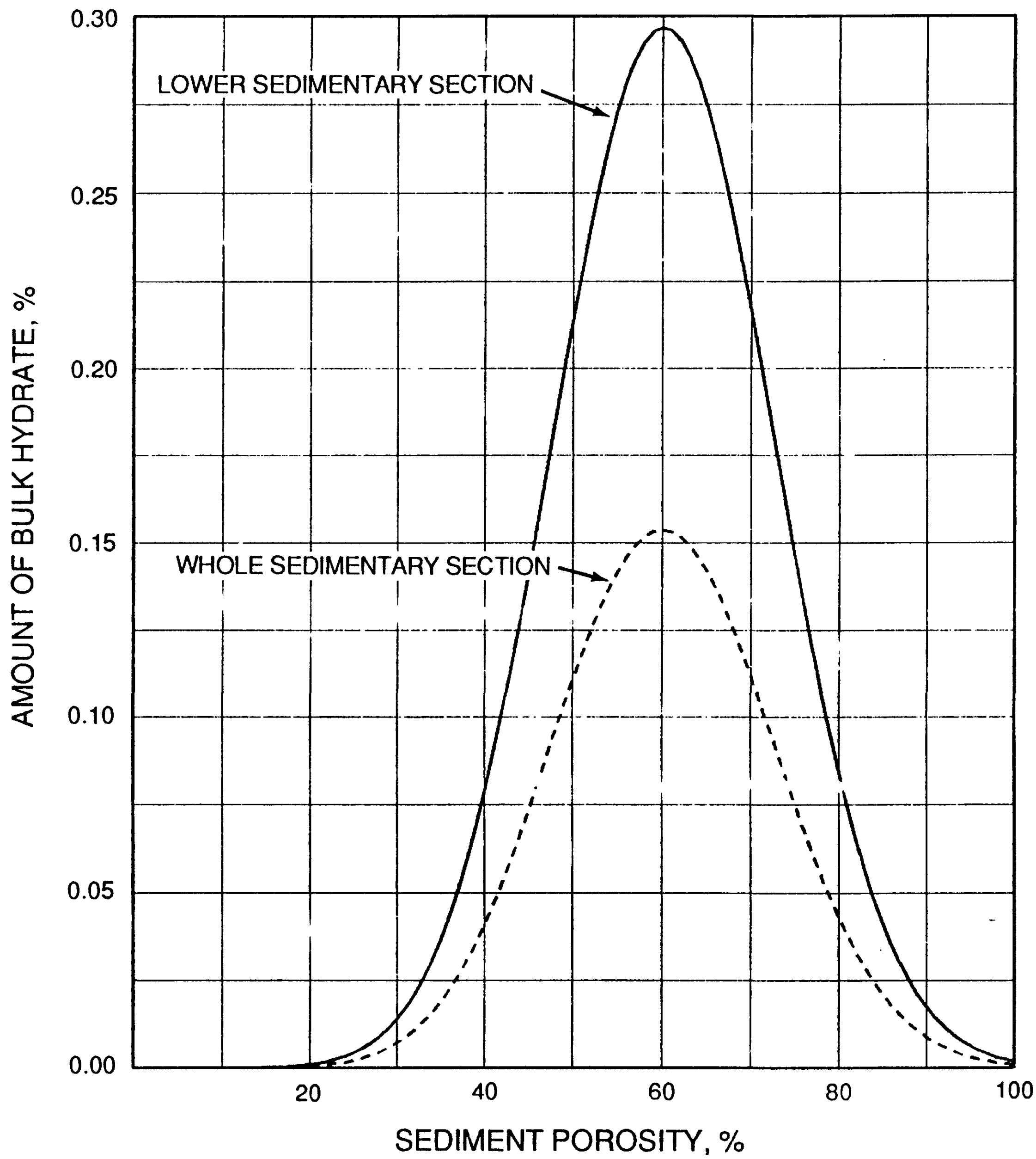

Figure 11. The amount of hydrate in bulk % in the Blake Ridge area with respect to the porosity of the sediments. The area under the curve yields the total in-situ hydrate amounts in bulk %. The solid line indicates amounts for the lower half of the sedimentary section between the seafloor and the BSR and the dotted line for the whole sedimentary section.

A similar estimation of bulk amounts of hydrate using velocity and amplitude blanking suggests that the two-end-member model provides a means of relating the amplitude and velocity effect of hydrate in the pore space. Although the mechanism of amplitude blanking caused by the hydration is beyond our study, this work supports the concept that the use of amplitude information is a viable approach to estimating the degree of hydrate cementation in marine sediments.

CONCLUSIONS

Based on the increase of interval velocity and amplitude blanking caused by the cementation of pore space by hydrate, the bulk amount of in-situ hydrate is estimated by a statistical approach. Because of the general lack of in-situ acoustic measurements and geologic/geophysical knowledge controlling natural occurences of hydrated sediments, we are not able to test either the proposed methods or the validity of our approach. However, this paper describes an important first step to quantitative analysis of hydrated marine sediments. This study shows that:

1) The average amount of hydrate cemented in the lower portion of sedimentary interval between the sea floor and the BSR in the Blake Ridge area is about 8.7% when using velocity information and 10% when using amplitude information.

2) Amplitude information (blanking) can be used in estimating hydrate amounts in marine sediments and provides a result comparable to that estimated by velocity.

3) Blanking provides a convenient way of classifying the degree of hydrate cementation. Because amplitude blanking is a relative quantity, the quantitative analysis or comparision is valid only for the interval where the same representative hydrated sediment is applicable.

4) Because of the uncertainty in the computation of interval velocities of hydrated sediments, the current estimates of in-situ hydrate may have a large degree of uncertainty. For example, by changing the weighting factor for the Wood equation from 1 to 0.65, it can be shown that the bulk hydrate amount is overestimated by 50%. Even though the estimate contains a great uncertainty, this paper presents the first estimate of the amount of in-situ hydrate based on a quantitative approach to seismic data.

REFERENCES

Dillon, W.P., Booth, J.S., Paull, C.K, Fehlhaber, K., Hutchinson, D.R. And, Swift, B.A, Mapping sub-seafloor reservoirs of green house gas: Methane Hydrate: International Symposium on marine Positioning of the Marine Technology Society, in press.

Dillon, W.P., Fehlhaber, K., Lee, M.W., Booth, J., Paull, C.K., 1991, Methane hydrate in sea floor sediments off the southeastern U.S.: Amount and implications for climate change: Presented at the Northesat GSA meeting, Baltimore,, March 14-16, 1991, 1991 Abstracts with program p. 22.

Dillon, W.P., Mast, R.F., Fehlhaber, K., And Lee, M.W., 1992, Gas hydrate in deep ocean sediments offshore southeastern United States: A future resource, in Carter, L.M.H., ed., USGS research on energy and mineral resources, 1992, Programs and Abstract: U.S. Geological Survey Circular 1074, p. 18-21

Dillon, W.P. And Popenoe, P., 1988, The Blake Plateau basin and Carolina trough, The Geology of North America, v.I-2, The Atlantic continental margin: The Geological Society of America, p. 291-328.

Ewing, J.I. And Hollister, C.H., 1972, Regional aspects of deep sea drilling in the western North Atlantic, in Hollister et al., eds., Initial report of deep sea drilling project, v.11, p. 951-973.

Fehlhaber, K., Dillon, W.P., And Lee, M.W., 1992, Estimation of gas hydrate concentrations using seismic method, in Carter, L.M.H., ed., USGS research on energy and mineral resources, 1992, Program and abstract: U.S. Geological Survey Circular 1074, p. 26-27.

Hammond, R.D. And Gaither, J.R, 1983, Anomalous seismic character-Bering Sea Shelf, Geophysics, V. 48, p. 590-605.

Lee, M.W., Hutchinson, D.R., Dillon, W.P., Miller, J.J., Agena, W.F., And Swift, B.A., 1992, A method of estimating the amount of in-situ gas hydrates in deep marine sediments: U.S. Geological Survey Open-File Report 92-276 29 p.

Markl, R.G., Bryan, G.M., And Ewing, J.I., 1970, Structure of the Blake Bahama Outer Ridge: Journal of Geophysical Research, v. 75, p.4539-4555.

Mathews, M.A. And von Huene, R., 1985, Site 570 methane hydrate zone, In R. von Huene and J. Aubouin et al., Eds., Initial Report of Deep Sea Drilling Projects, v. 84, p. 773-790.

Nobes, D.C., Villinger, H., Davis, F.F., And Law, L.K,., 1986, Estimation of marine sediment bulk physical properties at depth from seafloor geophysical measurements: Journal of Geophysical Research, v. 91, p. 14033-14043.

Pearson, C.F., Halleck, P.M., McGulre, P.L., Hermes, R., And Mathews, M., 1983, Natural gas hydrate; a review of in situ properties: Journal of Physical Chemistry, v. 87, p.4180-4185.

Shipley, T.H., Houston, M.H., Buffler, R.T., Shaub, F.J., Mcmillen, K.J., Ladd, J.W., And Worzel, J.L., 1979, Seismic evidence for widespread possible gas hydrate horizons on continental slopes and rises: The American Association of Petroleum Geologists Bulletin, v.63., p.2204-2213.

Sloan, E.D., Jr., 1990, Clathrate hydrates of natural gas: Marcel Dekker, Inc., New York, 641 p.

Tarantola, A., 1987, Inverse problem theory: Elsevier, New York, 613 p.

Wood, A.B., 1941, A text book of sound: Macmillan, New York, 578 p.

Wyllie, M.R.J., Gregory, A.R., And Gardner, L.W., 1956, Elastic wave velocities in hetrogeneous and porous media: Geophysics, v. 21, p.41-70.

APPENDIX A

Nobes and others (1986) proposed a weighted mean of the Wood (1941) and Wyllie and others (1956) equations for the calculation of interval velocities for marine sediments. The Wood equation is approximately valid for particles in suspension and is defined by

$$\frac{1}{\rho V_1^2}=\frac{\phi}{\rho_w V_w^2}+\frac{(1-\phi)}{\rho_m V_m^2} \tag{A1}$$

where

ϕ: porosity of sediment

V_w: velocity of fluid in the sediment pore space

V_m: grain velocity of matrix

V_1: the Wood velocity

ρ_w: density of pore fluid

ρ_m: density of matrix

ρ: bulk density of the mixture.

The Wyllie and others (1956) equation, which is approximately valid for the velocity of mixtures of two rigid media or for a medium containing little fluid, i.e., of low porosity, is given by

$$\frac{1}{V_2}=\frac{\phi}{V_w}+\frac{(1-\phi)}{V_m} \tag{A2}$$

where V_2 is the Wyllie velocity. Neither the Wyllie nor the Wood equation adequately describes the behavior of interval velocities of marine sediments, In order to calculate the interval velocities of marine sediments, Nobes and others (1986) proposed the following equation

$$\frac{1}{V}=\frac{W\phi}{V_1}+\frac{(1-W\phi)}{V_2} \tag{A3}$$

where W is a weighting factor introduced to account for the underconsolidation of marine sediments and V is the velocity of marine sediments.

Based on the above weighted equation and three-phase time-average equation by Pearson and others (1986) for hydrated sediments, Lee and others (in press) proposed the following equation for the computation of interval velocities of hydrated marine sediments.

$$\frac{1}{V}=\frac{W\phi(1-S)}{V_1}+\frac{1-W\phi(1-S)}{V_2} \tag{A4}$$

where S is the hydrate concentration in the pore space. In Equation (A4), V_1 is the three-phase Wood equation defined as:

$$\frac{1}{\rho V_1^2} = \frac{\phi(1-S)}{\rho_w V_w^2} + \frac{\phi S}{\rho_h V_h^2} + \frac{(1-\phi)}{\rho_m V_m^2}$$

and V_2 is the three-phase Wyllie equation defined as:

$$\frac{1}{V_2} = \frac{\phi(1-S)}{V_w} + \frac{\phi S}{V_h} + \frac{(1-S)}{V_m}$$

where

V_h: velocity of pure hydrate

ρ_h: denisty of pure hydrate.

As S or the hydrate concentration increases in the pore space, the contribution of the Wood equation in the velocity computation from Equation (A4) decreases. At the 100 % concentration of hydrate in the pore space (S=1), the contribution of the Wood velocity in Equation (A4) is zero. Therefore, irrespective of weighting factor, the velocity of a hydrated sediment approaches the velocity predicted by the Wyllie et al. equation as the hydrate concentration increases (see Figure 10).