Gas Hydrate Estimation Error Associated with Uncertainties of Measurements and Parameters

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Abstract

Downhole log measurements such as acoustic or electrical resistivity logs are often used to estimate in situ gas hydrate concentrations in sediment pore space. Estimation errors owing to uncertainties associated with downhole measurements and the parameters for estimation equations (weight in the acoustic method and Archie's parameters in the resistivity method) are analyzed in order to assess the accuracy of estimation of gas hydrate concentration. Accurate downhole measurements are essential for accurate estimation of the gas hydrate concentrations in sediments, particularly at low gas hydrate concentrations and when using acoustic data. Estimation errors owing to measurement errors, except the slowness error, decrease as the gas hydrate concentration increases and as porosity increases. Estimation errors owing to uncertainty in the input parameters are small in the acoustic method and may be significant in the resistivity method at low gas hydrate concentrations.

Introduction

Gas hydrate has become an important research topic because of its significance as (1) a potential resource, (2) a controlling factor in global warming, and (3) a factor relevant to sea-floor stability (Sloan and others, 1999). In this context, accurate estimation of the amount of in situ gas hydrate present in sediments is important. Because gas hydrate increases elastic velocities and electrical resistivities of sediments, downhole acoustic and electrical resistivity logs are often used in order to identify and quantify natural gas hydrates in sediments.

Collett (1983, 1995) used extensive downhole measurements not only to identify the presence of gas hydrate in sediments but also to quantify the amount of gas hydrate. Mathews (1986) used electrical resistivity logs to estimate gas hydrate saturation at the NW-Eileen #2 well, Alaska, and the deep-sea drilling project site 570, Blake Ridge, U.S. Atlantic continental margin. Using resistivity logs, Collett and Ladd (2000) estimated the amount of gas hydrate at Blake Ridge for the Ocean Drill Program leg 164, sites 994, 995, and 997, and Miyairi and others (1999) quantified the gas hydrate at the Mallik 2L-38 gas hydrate research well, northwestern Canada. Acoustic data were also used to estimate gas hydrate concentrations at the North Slope of Alaska (Collett, 1983, 1995), at Blake Ridge (Guerin and others, 1999; Lee, 2000), and at the Mallik 2L-38 well (Lee and Collett, 1999).

There exist many estimations of gas hydrate concentrations, but the accuracy of these estimates is unknown. This paper presents a method to estimate errors introduced in gas hydrate estimation owing to errors in downhole measurement and errors in the selection of parameters for acoustic and electrical resistivity relations. In the acoustic method, a weighted equation (Lee and others, 1996) is used to estimate the error, and, for the resistivity method, Archie's equation (Archie, 1942) is used. Theoretical errors based on the weighted and Archie's equations are compared with the actual error computed using downhole well logs acquired at the Mallik 2L-38 gas hydrate research well, Mackenzie River delta, Northwest Territories, Canada.

Acknowledgments

Well logs were acquired by Schlumberger Ltd. at the Mallik 2L-38 gas hydrate research well, which was drilled to investigate gas hydrate in a collaborative research project among Japan National Oil Company, Japan Petroleum Exploration Company, the Geological Survey of Canada, and the U.S. Geological Survey (USGS). We thank J.J. Miller and W.F. Agena for many helpful comments.

Theory

Equations for Estimation

A weighted equation by Lee and others (1996) is used to estimate gas hydrate concentration from acoustic downhole

measurements, and Archie's law (Archie, 1942) is used for electrical resistivity measurements in this study. This section briefly describes the basic equations for gas hydrate estimation.

Acoustic Method

A weighted equation (WE) can be written as follows using slowness of the constituents (from Lee and others, 1996):

$$S_p = W\phi(1-c)S_{p1} + [1 - W\phi(1-c)]S_{p2} \tag{1}$$

where

S_p is the slowness by the weighted equation,
S_{p1} is the slowness by the Wood equation,
S_{p2} is the slowness by the time average equation,
W is a weighting factor or a weight,
ϕ is the porosity, and
c is the gas hydrate concentration.

The slowness by the Wood equation (S_{p1}) and slowness by the time average equation (S_{p2}) are given by:

$$S_{p1} = \sqrt{\frac{\rho\phi(1-c)S_w^2}{\rho_w} + \frac{\rho\phi c S_h^2}{\rho_h} + \frac{\rho(1-\phi)S_m^2}{\rho_m}}$$

$$S_{p2} = \phi(1-c)S_w + \phi c S_h + (1-\phi)S_m \tag{2}$$

where

ρ, ρ_w, ρ_h, and ρ_m are the density of gas-hydrate-bearing sediment, density of water, density of gas hydrate, and density of modified matrix, respectively, and
S_w, S_h, and S_m are the slowness of water, gas hydrate, and modified matrix, respectively.

Once W, which is the only parameter necessary for the saturation calculation, is estimated from the slowness-porosity data for non-gas-hydrate-bearing sediments, equation 1 can be used to estimate gas hydrate concentrations using the acoustic log.

Resistivity Method

The estimation of gas hydrate concentration using electrical resistivity logs can be accomplished using Archie's law (Archie, 1942). Water saturation (C_w) from Archie's equation is given by:

$$C_w = \left(\frac{aR_w}{\phi^m R_t}\right)^{1/n} \tag{3}$$

The gas hydrate concentration, c, is given by $c = (1 - C_w)$. The exponent n varies between 1.715 for unconsolidated sediments to 2.1661 for sandstone, according to Pearson and others (1983).

In the resistivity method, parameters a, m, and R_w should be estimated from the resistivity of non-gas-hydrate-bearing sediments and the exponent n is usually set to be 1.9386 (Pearson and others, 1983).

Equations for Estimation Error

Uncertainties in the calculated gas hydrate concentrations from downhole measurements come from two different sources: (1) errors associated with uncertainties in downhole measurement, and (2) errors associated with uncertainties in parameters selected for the equations. Measurement errors are associated with uncertainties in (1) porosity and slowness for the acoustic method and (2) porosity and electrical resistivity for the resistivity method. For the acoustic method, error is associated with the selection of the weighting factor (W). For the resistivity method, error is associated with the selection of Archie's constants, a and m, and with the value chosen as the resistivity of connate water (R_w).

Acoustic Method

The error in gas hydrate concentration (Δc) owing to uncertainty of the slowness is given by (from eq. 1):

$$\Delta c = \left(\frac{\Delta S_p}{\Delta c}\right)^{-1} \Delta S_p \tag{4}$$

where

$$\frac{\Delta S_p}{\Delta c} = -W\phi S_{p1} + W\phi S_{p2} + W\phi(1-c)\frac{\Delta S_{p1}}{\Delta c} + [1 - W\phi(1-c)]\frac{\Delta S_{p2}}{\Delta c}$$

$$\frac{\Delta S_{p1}}{\Delta c} = 0.5\left[-\rho\phi S_w^2/\rho_w + \rho\phi S_h^2/\rho_h\right]/S_{p1} \text{ , and}$$

$$\frac{\Delta S_{p2}}{\Delta c} = -\phi S_w + \phi S_h \tag{5}$$

Likewise, the error owing to the error in porosity is given by:

$$\Delta c = -\left(\frac{\Delta S_p}{\Delta c}\right)^{-1} \phi\left(\frac{\Delta S_p}{\Delta \phi}\right)\left(\frac{\Delta \phi}{\phi}\right) \tag{6}$$

where

$$\frac{\Delta S_p}{\Delta \phi} = W(1-c)(S_{p1} - S_{p2}) + W\phi(1-c)\frac{\Delta S_{p1}}{\Delta \phi} + \left[1 - W\phi(1-c)\right]\frac{\Delta S_{p2}}{\Delta \phi}$$

$$\frac{\Delta S_{p1}}{\Delta \phi} = 0.5\left[\rho(1-c)S_w^2/\rho_w + \rho c S_h^2/\rho_h - \rho S_m^2/\rho_m\right]/S_{p1}$$

$$\frac{\Delta S_{p2}}{\Delta \phi} = (1-c)S_w + cS_h - S_m \text{ , and}$$

$(\Delta S_p / \Delta c)^{-1}$ is given in equation 5.

The error associated with uncertainty of the weighting factor (W) is given by the following equations (from equations 1 and 2):

$$\Delta c = -\frac{\Delta c}{\Delta S_p}\frac{\Delta S_p}{\Delta W}\Delta W = -\left(\frac{\Delta S_p}{\Delta c}\right)^{-1} W\left(\frac{\Delta S_p}{\Delta W}\right)\frac{\Delta W}{W} \tag{7}$$

where

$$\frac{\Delta S_p}{\Delta W} = \phi(1-c)(S_{p1} - S_{p2}) \text{ , and}$$

$(\Delta S_p / \Delta c)^{-1}$ is given in equation 5.

Because $\Delta c / \Delta S_p$ is negative, the overestimation of W or porosity results in the underestimation of gas hydrate amounts; overestimation of slowness results in the underestimation of gas hydrate concentration.

Resistivity Method

From equation 3, errors owing to errors in resistivity and porosity measurements are given by:

$$\Delta c = \frac{(1-c)}{n}\frac{\Delta R_t}{R_t} \tag{8}$$

$$\Delta c = \frac{(1-c)}{n}\frac{m\Delta \phi}{\phi} \tag{9}$$

Likewise, errors associated with parameters in Archie's equation are as follows:

$$\Delta c = \frac{(1-c)mLn(\phi)}{n}\frac{\Delta m}{m} \tag{10}$$

$$\Delta c = \frac{-(1-c)}{n}\frac{\Delta a}{a} \tag{11}$$

$$\Delta c = \frac{-(1-c)}{n}\frac{\Delta R_w}{R_w} \tag{12}$$

$$\Delta c = (1-c)\ln(1-c)\frac{\Delta n}{n} \tag{13}$$

As indicated in equations 8–12, gas hydrate estimation errors owing to errors in a, n, R_w , and R_t are independent of porosity, whereas error owing to the error in m is a function of porosity. Overestimation of a, m, and R_w results in the underestimation of gas hydrate saturation, and overestimation of the true resistivity results in the overestimation of gas hydrate saturation. Note that the magnitude of gas hydrate concentration errors owing to errors in a, R_w, and R_t are the same (eqs. 8, 11, and 12).

Error Analysis

Figure 1 shows errors in gas hydrate concentration caused by measurement errors (slowness and porosity) for 30- and 50-percent-porosity sediments. Details of parameters used for the analysis are shown in table 1. With a relative porosity error of 10 percent, the gas hydrate estimation error is about 12 percent at low gas hydrate concentrations and decreases as the gas hydrate concentration increases; error reaches about 3 percent at 100 percent gas hydrate concentration. As indicated in figure 1, the estimation error is insensitive to porosity of the sediment. With a relative slowness error of 10 percent, the gas hydrate estimation error is about 20 percent for 30-percent-porosity sediment at low gas hydrate concentrations and decreases somewhat as gas hydrate concentration increases. The error owing to slowness error decreases as sediment porosity increases.

Gas hydrate estimation error owing to the error in W is shown in figure 2. With a relative weight error of 10 percent, estimation error is about 3 percent at low gas hydrate concentrations and decreases as the gas hydrate concentration increases—it approaches zero as gas hydrate concentration approaches 100 percent. The estimation error decreases as porosity decreases, but there is not much difference between 30- and 50-percent-porosity sediments.

Figure 3 shows estimation error (Δc) with respect to the errors in a, m, and R_w. The error decreases as the gas hydrate concentration increases or porosity increases. When the relative error in a or R_w is 10 percent, the error in gas hydrate

Table 1. Values used in error analysis.

Meaning	Symbol	Value	Remarks
Slowness of hydrate (s/m)	S_h	0.303	Type-1 gas hydrate
Slowness of water (s/m)	S_w	0.667	
Slowness of modified matrix (s/m)	S_m	0.2028	30 % volume clay content
Density of gas hydrate (g/cm^3)	ρ_h	0.91	Type-1 gas hydrate
Density of water (g/cm^3)	ρ_w	1.0	
Density of modified matrix (g/cm^3)	ρ_m	2.65	
Weighting factor	W	1, 1.44	W =1.44 for real data
Cementation factor	m	2, 1.95	m =1.95 for real data
Archie's parameter	a	1.02	For real data
Resistivity of water (ohm-m)	R_w	0.4	For real data
Exponent	n	1.9386	
Fractional error	$\Delta p/p$	10%	p stands for measurements or parameters.

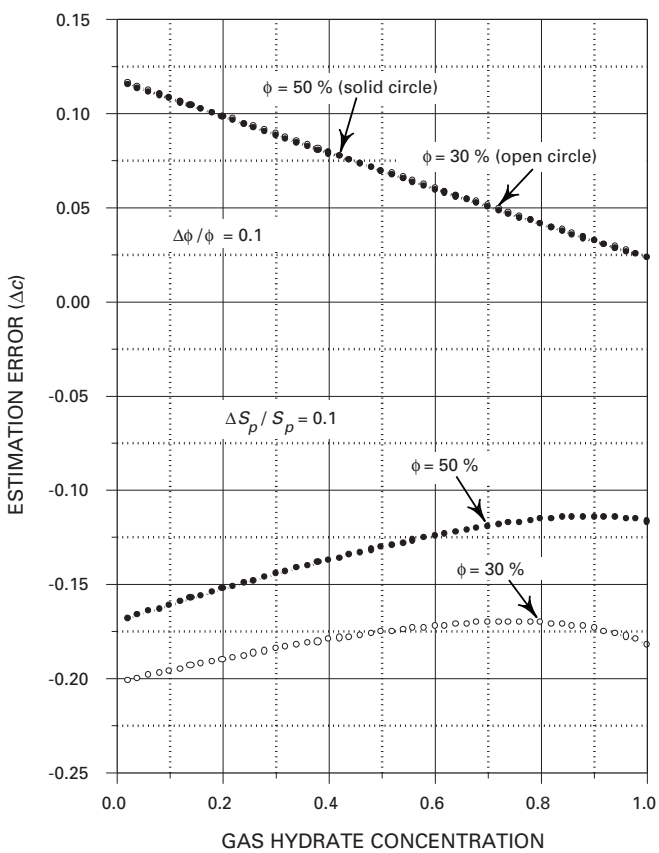

Figure 1. Graph showing error in estimation of gas hydrate concentration owing to the error in porosity and slowness measurement for 30- (open circle) and 50-percent-porosity (solid dot) sediments; fractional errors in porosity and slowness are both 10 percent.

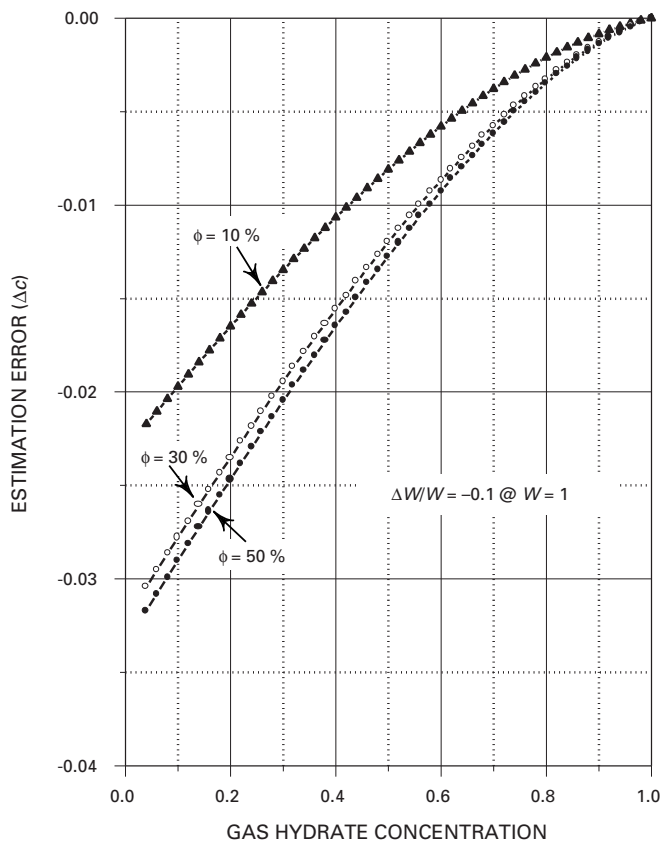

Figure 2. Graph showing error in the estimation of gas hydrate concentration owing to the error in weight of the weighted equation for 10- (solid triangle), 30- (open circle), and 50-percent-porosity (solid dot) sediments; fractional error in weight is 10 percent.

estimation is about 5 percent at c = 5 percent and approaches zero as the gas hydrate concentration increases. Errors associated with the parameter m are much greater than errors owing to a or R_w. When relative error in m is 10 percent, the total error in gas hydrate estimation is about 7 percent at c= 5 percent and about 2.5 percent at c = 80 percent for a 50-percent-porosity sediment. These errors are 23 percent and 5 percent, respectively, for a 10-percent-porosity sediment.

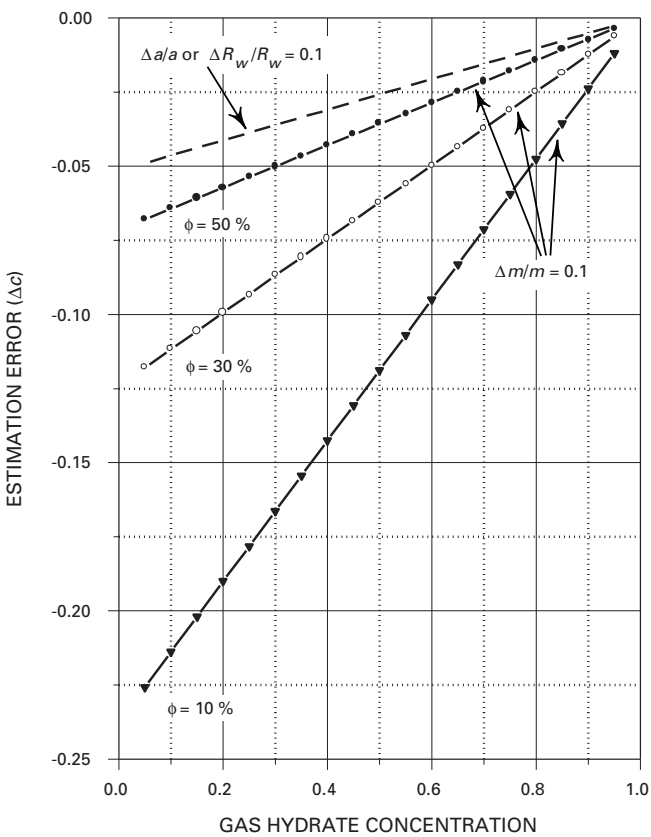

Figure 3. Graph showing errors in the estimation of gas hydrate concentration owing to errors in Archie's parameters (a and m) and resistivity of water (R_w) for 10- (solid triangle), 30- (open circle), and 50-percent-porosity (solid dot) sediments; fractional errors in a, m, and R_w are 10 percent.

The estimation error associated with measurement error in resistivity is the same as the error owing to the error in a, except for the sign of the error. Equation 9 indicates that the estimation error owing to porosity error is about twice the error owing to the error in resistivity because the parameter m is equal to about 2.

Figure 3 demonstrates that the estimation of gas hydrate saturation in sediment using electrical resistivity becomes less accurate as the gas hydrate content and (or) porosity decreases in the sediment.

Error from using an erroneous exponent n is independent of any other Archie's parameters and depends only on the gas hydrate concentration as shown in equation 13. When fractional error in n is 10 percent, the maximum error of about 4 percent occurs near a gas hydrate concentration of 60 percent and approaches zero away from this maximum. The commonly used value for n is 1.9386, but Pearson and others (1983) indicated that it varies between 1.715 for unconsolidated material and 2.1661 for sandstone. These values, n = 1.715 and n = 2.1661, are slightly higher than ±10 percent of the commonly used value of 1.9386. Therefore, the maximum error of gas hydrate concentration associated with the uncertainty in n is about 4 percent.

Real Data Example

In 1998, a gas hydrate research well (Mallik 2L-38 well) was drilled in the Mackenzie River delta, northwestern Canada. During this period, a suite of high-quality downhole well logs was obtained (Collett and others, 1999), including sonic and resistivity logs. These logs were used in this study to calculate errors introduced in the estimation of gas hydrate concentration caused by uncertainties either in downhole measurements or in equation parameters. The numeric values used for the weighted equation and Archie's equation are given in table 1. For figures 4–6, calculated errors indicate errors computed from theoretical equations (shown previously) with a 33-percent-porosity sediment (average porosity of the porosity log). As indicated in the equations, estimation errors are symmetrical functions with respect to fractional errors of measurements or parameters (linear approximation of error function). But actual errors calculated from real well logs show that the error due to the positive fractional error is slightly different from the error due to the negative fractional error—this is caused by local nonlinearity of the weighted and Archie's equations. However, the difference in this estimation error is negligible.

Figure 4 shows the gas hydrate estimation error owing to uncertainties in the slowness and porosity values, calculated using the weighted equation, and figure 5 shows the error owing to the resistivity and porosity calculated using Archie's equation. Figure 6 shows errors caused by errors in the weighting factor and in the cementation factor m.

These examples demonstrate that errors calculated from the theoretical relationship shown in this paper agree well with the actual errors computed from well logs when fractional errors in the measurements or parameters are less than 10 percent. With 10 a percent fractional error limit, the maximum difference between the theoretical and actual error is about 2–3 percent; this happens when a weighted equation is used with 10 percent error in porosity (fig. 4).

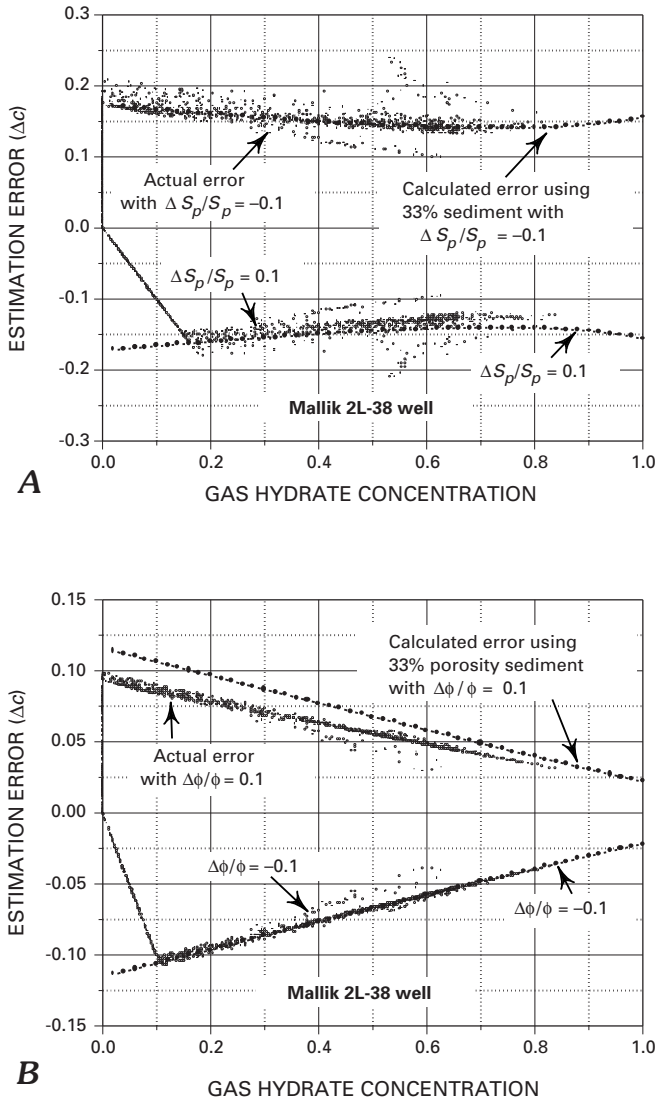

Figure 4. Graph showing theoretical (calculated) errors for 33-percent-porosity sediments and actual errors using real well logs at the Mallik 2L-38 gas hydrate research well. The weighted equation was used in estimating gas hydrate concentration. *A*, Fractional error in slowness is 10 percent. *B*, Fractional error in pososity is 10 percent.

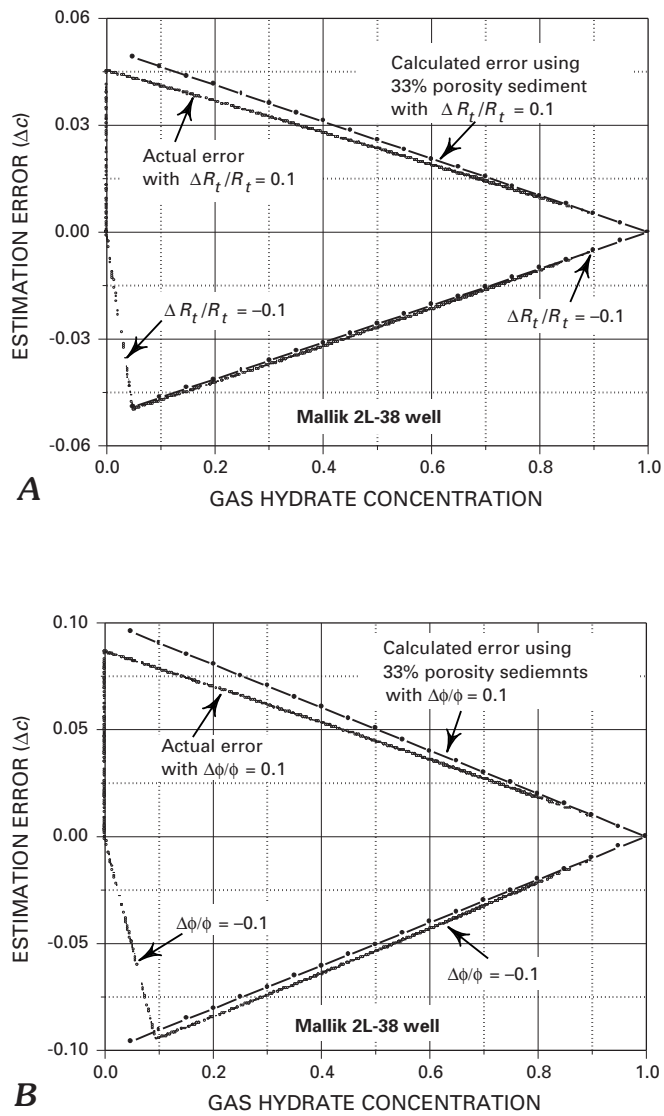

Figure 5. Graph showing theoretical (calculated) errors for 33-percent-porosity sediments and actual errors using real well logs at the Mallik 2L-38 gas hydrate research well. Archie's equation was used in estimating gas hydrate concentration. *A*, Fractional error in resistivity is 10 percent. *B*, Fractional error in porosity is 10 percent.

Discussion

Both estimation methods, acoustic and resistivity, use porosity as the measured quantity. By comparing results in figures 4 and 5, it can be seen that estimation error owing to the error in porosity is almost the same for both methods. The estimation error decreases as the gas hydrate concentration increases and is about 10 percent at $c = 0$ percent and approaches 0 percent at $c = 100$ percent.

However, estimation error from error in the slowness measurement is much greater than that due to resistivity measurement. The gas hydrate estimation error caused by a relative error of 10 percent in the slowness measurement varies between 11 percent and 17 percent for a 50-percent-porosity sediment and decreases as porosity increases (as shown in fig. 1). On the other hand, the estimation error caused by error in the resistivity measurement decreases linearly with the gas hydrate concentration, approaches zero at $c = 100$ percent, and is independent of the porosity of the sediment.

The amount of error in the measurement has a complex relationship with borehole conditions and depends on each individual logging tool, so it may not be possible to adequately compare fractional error present in sonic and resistivity measurements. However, the error analysis suggests that the resis-

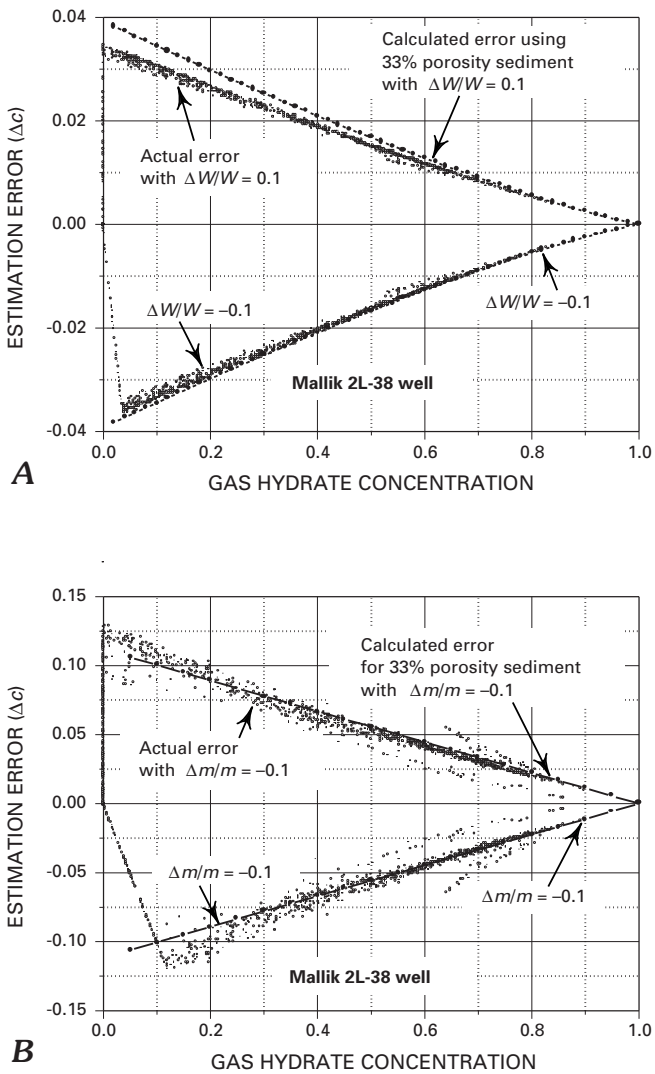

Figure 6. Graph showing theoretical (calculated) errors for 33-percent-porosity sediments and actual errors using real well logs at the Mallik 2L-38 gas hydrate research well. *A*, Fractional error in weight is 10 percent. *B*, Fractional error in Archie's parameter *m* is 10 percent.

tivity method may have an advantage over the acoustic method for estimating gas hydrate concentration in sediments when using low-quality well logs.

The analysis for errors owing to error in the parameters indicates that the estimation error is smaller in the acoustic method (only one parameter) than in the resistivity method. With a 10 percent fractional error for a 33-percent-porosity sediment, the maximum error by the acoustic method—from error in the weight—is about 4 percent, whereas, for the resistivity method, errors are 13 percent, 5 percent, and 5 percent for errors in m, a, and R_w, respectively.

The error owing to m is usually the opposite direction to the error owing to a. Archie's parameters a and m are estimated from the linear relationship between resistivity and porosity on a log-log plot. Because of the linear relationship, the estimation of higher slope (m) results in the estimation of a lower intercept (parameter a is related to the intercept). So the error owing to errors in a and m may not be additive, but the total estimation error from the errors in Archie's parameters may be greater than the error owing to the error in W.

The Humble equation ($a = 0.62$ and $m = 2.15$) is used commonly in sandstone reservoirs or in soft formations for the estimation of water saturation (Winsauer and others, 1952). In the Mallik 2L-38 example, $a = 1.05$ and $m = 1.95$ are used for the computation of gas hydrate concentration. If Humble constants are used rather than the derived a and m for Mallik 2L-38, then the fractional error is about –40 percent for a and 9 percent for m. The gas hydrate concentration error can be estimated from figure 3 assuming 30-percent-porosity sediments. The error is about 10 percent owing to the error in a and –5 percent from the error in m at $c = 0.6$; it is +20 percent from the error in a and –10 percent from the error in m at $c = 0.1$. Therefore, the overall error using Humble constants instead of using estimated parameters at Mallik 2L-38 is 5 percent at $c = 0.6$ and 10 percent at $c = 0.1$. Figure 7 shows actual error computed using the Humble equation instead of estimated Archie's parameters at Mallik 2L-38. The actual error computed agrees well with the prediction based on figure 3.

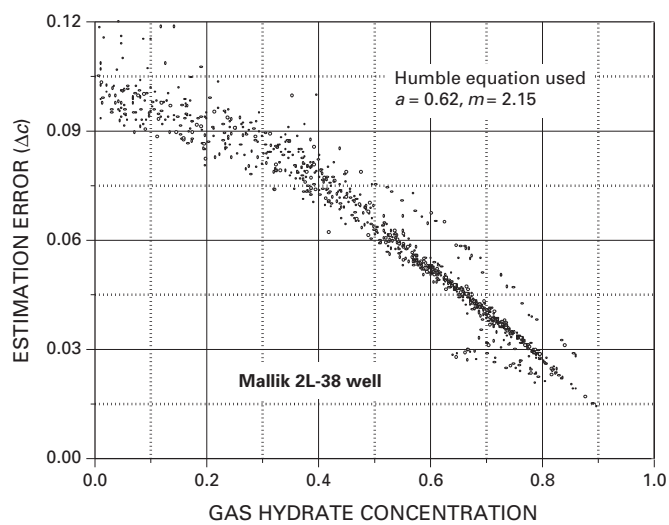

Figure 7. Graph showing actual errors calculated from real well logs at the Mallik 2L-38 gas hydrate research well when Humble parameters ($a = 0.62$ and $m = 2.15$) are used instead of estimated Archie's parameters ($a = 1.02$ and $m = 1.95$).

One of the problems in using the electrical method for estimating gas hydrate amounts is the uncertainty associated with R_w. The resistivity of connate water in non-gas-hydrate-bearing sediments can be estimated from resistivity values of the base line. As gas hydrate forms in sediment pore space, salt

will be excluded from the formation water. Owing to gravity, salt would migrate downward. But the question of the resistivity of connate water in gas-hydrate-bearing sediments arises. Is it in equilibrium with the surrounding non-hydrate-bearing sediments? Is it higher or lower than that base-line value? The estimation error owing to error in salinity is the same as the error owing to parameter a. Therefore, at high gas hydrate concentrations, the error owing to error in salinity would be very small, but the error at lower gas hydrate concentrations would be high.

Summary and Conclusion

Accurate downhole measurements are essential for accurate estimation of gas hydrate concentrations in sediments, particularly for low gas hydrate concentrations. The acoustic method requires more accurate measurements to yield reliable gas hydrate concentrations: for 30-percent-porosity sediments, the fractional error in slowness should be less than 5 percent in order to obtain less-than-10-percent error in gas hydrate concentrations. Except for the slowness error, estimation errors owing to measurement errors generally decrease as the gas hydrate concentration increases and as porosity increases.

The error analysis owing to the inaccuracy in equation parameters is simple in the acoustic method but complex in the resistivity method. These parameters can be estimated using measurements for non-gas-hydrate-bearing sediments. One of the problems in using the resistivity method is the estimation of R_w in the interval of gas-hydrate-bearing sediment. When Archie's parameters for the base line are difficult to obtain, the Humble equation may be used to calculate gas hydrate concentrations without rendering significant error, particularly for high gas hydrate concentrations.

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