A Method of Shaly Sand Correction for Estimating Gas Hydrate Saturations Using Downhole Electrical Resistivity Log Data

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U.S. Department of the Interior
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Abstract

Estimation of the amount of nonconductive and conductive constituents in the pore space of sediments, using electrical resistivity logs, generally loses accuracy when clays are present in the reservoir. Many different methods and clay models have been proposed to account for the conductivity of clay (for example, the shaly sand correction). In this study, the Simandoux model is employed to correct for the clay effect in order to more accurately estimate gas hydrate saturations.

This study utilizes the fact that the effect of clay on the resistivity of a sediment is manifested in the Archie constants *a* and *m*, values of which are generally $a = 1$ and $m = 2$ for clean-sand reservoirs. Results of the study indicate that as the clay content increases, *a* also increases whereas *m* decreases. On the basis of the relationship between the Archie constants *a* and *m* with respect to the clay amount, a method of correcting for the clay effect on the estimation of water saturation is proposed. This method works well if the relationship between porosity and resistivity on a log-log plot is approximately linear and if accurate Archie constants *a* and *m* for clean sand are known. However, because of the linearity condition, it is difficult to apply the method to low-porosity reservoirs. Gas-hydrate-bearing sediments generally have high porosities because of their shallow depth of occurrence, so the method can be effectively applied in estimating gas hydrate saturations.

Introduction

Most methods of electrical resistivity interpretation are based on Archie's empirical law (Archie, 1942), which works well for the estimation of water and nonconducting-constituent saturations in the pore space of clean sands, where formation matrices are poor conductors. However, Archie's law is not accurate in estimating water saturation for shaly sands, where clay minerals are present in the formation matrices. (Note: "Shaly sand" is a commonly used term for a clay-bearing sand; see Worthington, 1985.) Because clay minerals have high conductivities, in some cases higher than the conductivity of water in the formation, the effect of clay on electrical resistivity can be significant. Thus, the estimation of water saturation in the pore space using electrical resistivity log data is generally inaccurate because the resistivity from the conducting clay material was not accounted for.

In order to correct for clay conductivity's effects on formation resistivity, a number of clay models have been proposed; of these, Worthington (1985) summarized all available shaly sand models. One of the earlier models was based on the assumption that the conductivity of an aggregate of conductive particles saturated with conducting fluid can be represented by resistors in parallel (Wyllie and Southwick, 1954). Simandoux (1963) used this concept and proposed a shaly sand model that shows the conductivity of the formation to be the sum of the conductivity through the water and the conductivity through the clay minerals (hereafter referred to as the Simandoux model). Other models include (1) a shaly sand model by Waxman and Smits (1968), based on the fact that clay particles contribute exchange cations to the electrolyte, thereby increasing the conductivity of the formation; and (2) a dual-water model by Clavier and others (1977), based on the assumption that the exchange cations contribute to the conductivity of clay-bound water that is spatially separated from the bulk water.

All models have essentially two components—one for the conductivity of the water in the formation and the other for the conductivity of the clay. The difference among the models is the way the clay conductivity is computed.

In our study, the Simandoux model was used to account for the effects of the clay conductivity on the formation resistivity. On the basis of Archie's law and the Simandoux equation, a relationship between the amount of clay conductivity and the Archie constants is established, and a method of correcting for the clay effect on the estimation of water saturations is proposed.

Theory

The electrical resistivity of clean sands, saturated with 100 percent water (R_0), can be expressed through the use of the Archie equation (Archie, 1942) in the following way:

$$\frac{1}{R_0} = \frac{1}{a\phi^{-m} R_w}, \quad (1)$$

where R_0 is the formation resistivity, R_w is the resistivity of the connate water, a and m are Archie constants, and ϕ is the porosity. Archie constants a and m can be derived empirically; m is related to the cementation of the sediment and is commonly called the cementation factor. Equation 1 indicates that a plot of log ϕ versus log R_0 is linear and the slope is given by m. The linear relationship between log ϕ and log R_0 was considered to be the most important property for the purposes of our study, and the relationship is widely used in well-log analyses (Pickett, 1966).

The electrical conductivity of an aggregate of conductive particles saturated with a conducting electrolyte can be represented by resistivity elements in parallel (Wyllie and Southwick, 1954). Therefore, the effect of clay in sediments (Simandoux, 1963) can be formulated as

$$\frac{1}{R_0} = \frac{1}{a\phi^{-m} R_w} + \frac{(1-\phi)V_c}{R_c} \equiv \frac{1}{FR_w} + Q_c = \frac{1}{FR_w}(1 + FR_w Q_c), \quad (2)$$

where F is a formation factor for clean sands ($F = a\phi^{-m}$), V_c is the volume fraction of clay in solid matrix, R_c is the resistivity of the clay, and Q_c is the effective clay conductivity:

$$Q_c = V_c(1-\phi)/R_c. \quad (3)$$

The effective clay conductivity (Q_c) is defined in this report as the clay effect on the resistivity measurement. From equation 2, the porosity of the sediments using clean-sand Archie parameters (a, m) is given by

$$\phi^{-m} = \frac{R_0}{aR_w(1 - Q_c R_0)}. \quad (4)$$

Because the porosity is a positive number, $(1 - Q_c R_0)$ should be greater than zero. Furthermore, because $(1 - Q_c R_0)$ is less than 1, porosities estimated by using equation 4 are greater than true porosities; thus, for shaly sands, the porosity calculation from a resistivity measurement is higher than the true porosity, if the clay correction is not applied.

As demonstrated in the next section, the cross plot of log ϕ versus log R_0 is approximately linear even for shaly sands under certain conditions. If a^* and m^* are defined for the Archie parameters derived from shaly sands by linearly fitting the logarithm of resistivities and logarithm of porosities, equation 2 can be written as

$$\frac{1}{R_0} = \frac{1}{a^*\phi^{-m^*} R_w} = \frac{1}{F^* R_w}, \quad (5)$$

where F^* is the formation factor for shaly sands and is given by $F^* = a^*\phi^{-m^*}$. Combining equations 2 and 5 yields the following:

$$\frac{1}{a^* R_w \phi^{-m^*}} = \frac{1}{aR_w\phi^{-m}} + Q_c. \quad (6)$$

From equation 6, a relationship between parameters for clean and shaly sands can be written as

$$a^*\phi^{-m^*} = \frac{a\phi^{-m}}{(1 + aQ_c R_w \phi^{-m})}. \quad (7)$$

Therefore, the conductive term can be written as

$$Q_c = \frac{\phi^{m^*}(a - a^*\phi^{m-m^*})}{aa^* R_w}. \quad (8a)$$

Generally, the Archie parameters for a clean sand are chosen to be $a = 1$ and $m = 2$. The deviations of Archie parameters a^* and m^* from $a = 1$ and $m = 2$ for shaly sands represent the effect of clay on the formation resistivity measurement. If the values $a = 1$ and $m = 2$ are assumed for the clean sand, the conductive term can be written as

$$Q_c = \phi^{m^*}(1 - a^*\phi^{2-m^*})/R_w a^*. \quad (8b)$$

Equations 8a and 8b indicate that the effect of clay on the resistivity can be computed if Archie parameters a^* and m^* can be estimated from the resistivity of shaly sands. Because Q_c should be positive, $(a - a^*\phi^{m-m^*})$ should be positive; thus, there is a constraint for Archie parameters a^* and m^* when equations 8a and 8b are used for the clay correction. To have a positive value of Q_c, the following relationship should be satisfied:

$$m > m^* + \ln(a/a^*)/\ln\phi. \quad (9)$$

The formation's water saturation (S_w) calculated from the resistivity log value (R_t) for shaly sand without explicit clay correction has been given by Archie (1942) as

$$S_w = \left(\frac{a^* R_w}{\phi^{m^*} R_t}\right)^{1/n}, \quad (10a)$$

where n is an empirically derived parameter close to 2 and R_t is the formation resistivity with gas hydrate. The parameter n varies between 1.715 (unconsolidated sediment) and 2.1661 (sandstone); although somewhat dependent on the lithology of the reservoir, n is typically 1.9386 (Pearson and others, 1983).

On the basis of equation 10a, the water saturation for clean sand with $a = 1$, $m = 2$, and $n = 2$ can be calculated as

$$S_w = \frac{\sqrt{R_w/R_t}}{\phi}. \quad (10b)$$

For shaly sands with explicit clay correction using the term Q_c, the water saturation can be written from equations 2 and 10b as

$$S_w = \frac{\sqrt{R_w(1 - R_t Q_c)/R_t}}{\phi} \quad . \tag{11a}$$

In summary, equations 2, 8, and 11a indicate that the water saturation for shaly sands can be computed by estimating the effective clay conductivity (Q_c) using equation 8, subtracting the Q_c term from the observed conductivity of the formation (inverse of formation resistivity) using equation 2, and determining water saturation using equation 11a.

In the general case, when $a \neq 1$, $m \neq 2$, and $n \neq 2$, water saturation can be written as

$$S_w = \left(\frac{aR_w(1 - R_t Q_c)/R_t}{\phi^m} \right)^{1/n} \quad . \tag{11b}$$

Modeling

Figure 1 shows graphs of formation resistivity versus porosity, as computed with equation 2; the parameters for the model are also shown. In this model, Archie constants for clean sands are $a = 1$ and $m = 2$. When the resistivity of the clay in the formation is much less than the resistivity of the connate water (fig. 1*A*), the log-log plot of resistivity versus porosity is approximately linear if the porosity is greater than about 30 percent. However, when the resistivity of the clay is greater than the resistivity of the connate water (fig. 1*B*), there is no apparent linear relationship between log R_0 and log ϕ.

When porosity is more than 30 percent, the accuracy of the linearity between log R_0 and log ϕ is demonstrated in figure 2 where plots of linear equations computed with least-squares methods are shown for resistivity data modeled as in figure 1*A*. Table 1 shows the a^* and m^* values estimated from the linear approximations. As the clay content increases, the data indicate that (1) a^* increases but m^* decreases in this model and (2) the linearity between log R_0 and log ϕ degrades but is still good at a clay content as high as 75 percent (fig. 2*D*).

Under what conditions does log R_0 versus log ϕ show the linear relationship? As indicated in equation 2, the Archie equation for clean sand ($Q_c = 0$) is perfectly linear in the log R_0 versus log ϕ plot. Therefore, it can be inferred from equation 2 that when FR_wQ_c is smaller than 1, the linear approximation of log R_0 versus log ϕ is better for shaly sand. Choosing the maximum value of FR_wQ_c, one that provides an approximate linear relationship between log R_0 and log ϕ, is subjective. In our study, the value for the maximum allowable FR_wQ_c was set at 0.4, corresponding to a value calculated from parameters used for the data shown in figure 2*D*. So the degree of linearity with $FR_wQ_c < 0.4$ is similar or better than that shown in figure 2*D*.

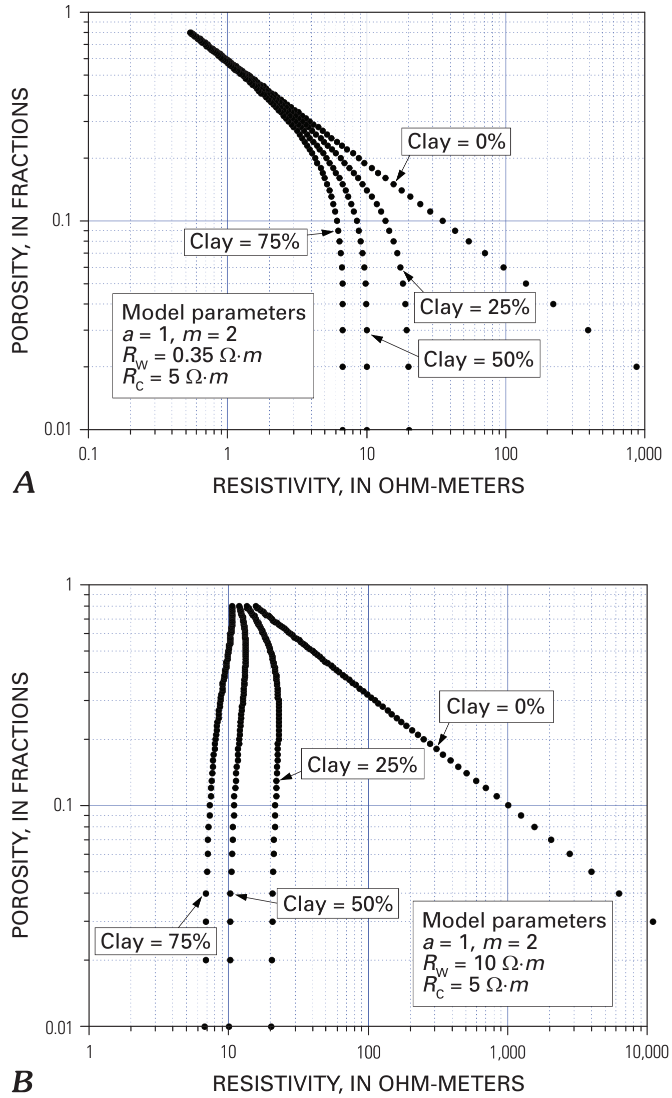

Figure 1. Graphs showing electrical resistivity versus porosity for various clay contents that were calculated from the Simandoux (1963) equation. Archie parameters for clean sand are $a = 1$ and $m = 2$. *A*, Results when resistivity of the connate water (R_w) is lower than resistivity of the clay (R_c) ($R_w = 0.35\ \Omega\cdot$m, $R_c = 5\ \Omega\cdot$m). *B*, Results when resistivity of the connate water is higher than resistivity of the clay ($R_w = 10\ \Omega\cdot$m, $R_c = 5\ \Omega\cdot$m).

Table 1. Archie constants a* and m* for shaly sands.

[These constants were derived by least-squares fitting of log-porosity and log-resistivity shown in figure 2]

Lithology	a*	m*
Clean sand	1.00	2.00
25 percent clay content	1.03	1.89
50 percent clay content	1.06	1.79
75 percent clay content	1.09	1.70

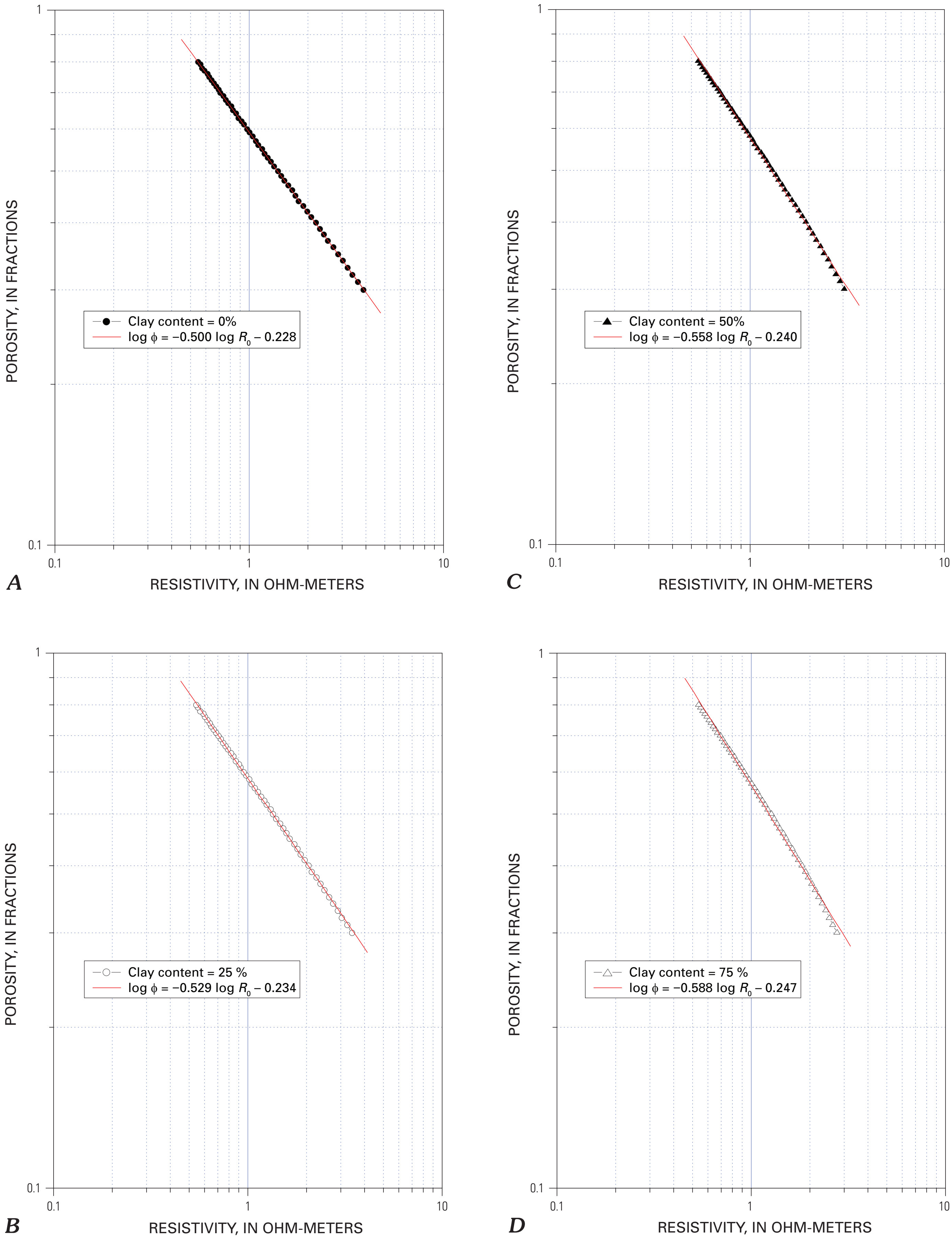
A
Clay content = 0%
log ϕ = −0.500 log R_0 − 0.228
POROSITY, IN FRACTIONS
RESISTIVITY, IN OHM-METERS
C
Clay content = 50%
log ϕ = −0.558 log R_0 − 0.240
POROSITY, IN FRACTIONS
RESISTIVITY, IN OHM-METERS
B
Clay content = 25 %
log ϕ = −0.529 log R_0 − 0.234
POROSITY, IN FRACTIONS
RESISTIVITY, IN OHM-METERS
D
Clay content = 75 %
log ϕ = −0.588 log R_0 − 0.247
POROSITY, IN FRACTIONS
RESISTIVITY, IN OHM-METERS

Figure 2 (previous page). Plots of logarithm of the porosity versus logarithm of the resistivity to show the linear relationship. The model parameters are identical to those for figure 1*A*, which are $a = 1$, $m = 2$, water resistivity (R_w) = 0. 35 Ω·m, and clay resistivity (R_c) = 5 Ω·m. Plots are for *A*, clean sand; *B*, 25 percent clay; *C*, 50 percent clay; and *D*, 75 percent clay.

Figure 3 shows the ranges of connate-water resistivities, clay resistivities, and clay contents (termed clay volumes, C_v), with respect to the minimum porosity of interest, that result in an approximate linear relationship between log R_0 and log ϕ. The values under the curves approximately satisfy the linearity condition. As indicated in figure 3, as the porosity of a sediment increases, the log R_0 versus log ϕ relationship is linear under many different combinations of resistivity and clay content.

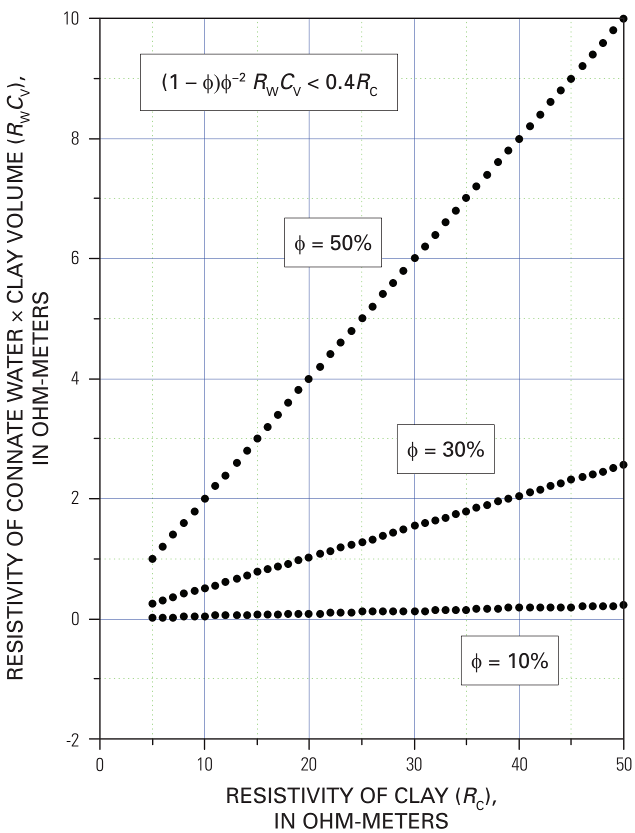

Figure 3. Graph showing relationship between the resistivity of clay (R_c) and the product of connate-water resistivity (R_w) and clay volume (C_v) required to yield an approximate linear relationship between log resistivity and log porosity. The values under each curve satisfy the linearity condition.

Example of Saturation Computation

In order to evaluate the feasibility and the accuracy of the proposed method of computing water saturations with equation 11, the model we used consists of 500 random porosities uniformly distributed over a range of 20–40 percent and random gas hydrate saturations uniformly distributed over a range of 0–80 percent. The resistivity of gas hydrate is assumed to be infinite (similar to hydrocarbons), the resistivity of connate water is 0.4 Ω·m, the resistivity of clay is 20 Ω·m, and the clay content is 25 percent of the total solids. Figure 4*A* shows the computed formation resistivities with respect to porosities with $a = 1$ and $m = 2$. The solid dots, appearing as a thick line in figure 4*A*, denote the resistivities for 100 percent water saturation (base line), and open circles indicate resistivities with variable hydrate saturations.

The Archie parameter for shaly sands can be estimated by applying the least-squares method to the base-line data (solid dots shown in fig. 4*A*). The linear approximation of the base-line values gives $a^* = 1.08$ and $m^* = 1.90$. Note that the effect of clay on the resistivity manifests itself as a^* being more than 1 and m^* being less than 2 (table 1). Through the use of equation 11, the water saturations are computed from the resistivity values shown in figure 4*A*. To evaluate the efficiency and accuracy of the method, the corrected resistivities of sediments with clay are shown as solid dots in figure 4*B*. This evaluation used water-filled porosity (ϕ_w), defined by

$$\phi_w = (1-\phi)S_h , \qquad (12)$$

where S_h is the gas hydrate saturation. Because the solid dots in figure 4*B* represent resistivities of sediments without clay contribution (the contribution of clay on the formation resistivity was eliminated), the Archie constants should be $a^* = a = 1$ and $m^* = m = 2$, which are the Archie parameters for clean sands. The values of Archie constants from the least-squares fitting of solid dots in figure 4*B* agree with the prediction.

The purpose of a clay correction for the electrical resistivity is to accurately estimate the amounts of nonconducting constituents in the pore space, such as gas, oil, or gas hydrate. Therefore, it is desirable to analyze the proposed method relative to gas hydrate saturation. Figure 5*A* shows the estimated gas hydrate saturation ($1 - S_w$) without the clay correction relative to true saturation based on the Archie equation for shaly sand using equation 10a with $a^* = 1.08$, $m^* = 1.9$, and $n = 1.9386$. As indicated, the estimated gas hydrate saturations are less than the true hydrate saturation (about 7 percent less). Figure 5*B* shows the comparison of gas hydrate saturation after applying a clay correction to the resistivity and reveals that the estimated gas hydrate saturations are accurate. Thus, this model study indicates that the method of using equation 11 for the correction of clay on the electrical resistivity is feasible.

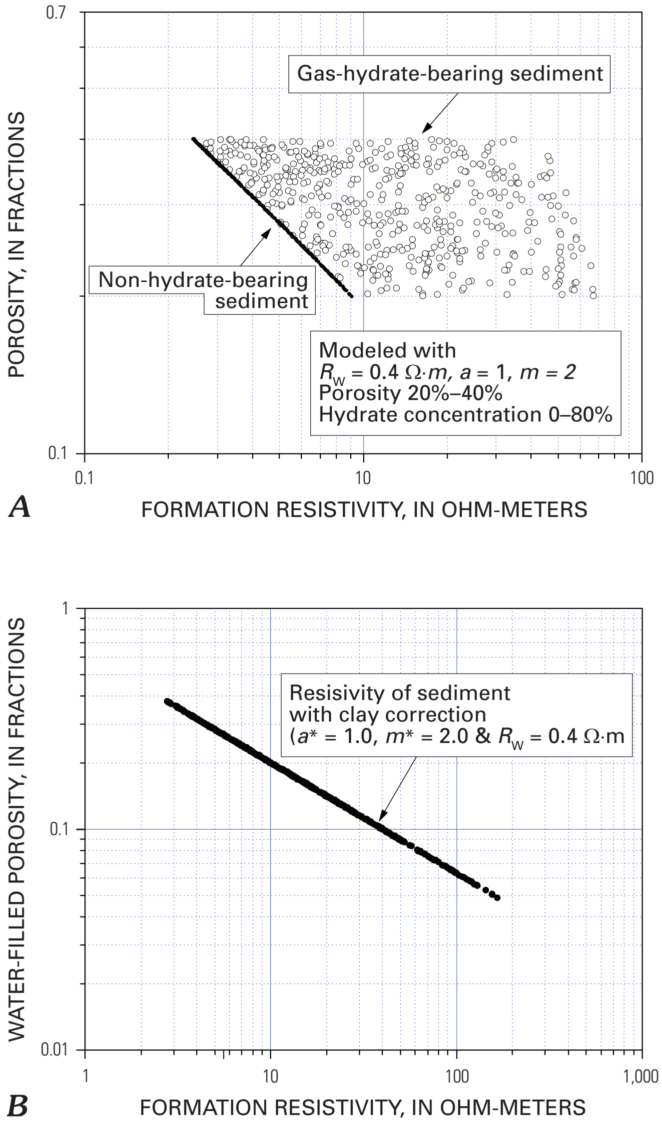

Figure 4. Plots showing relationship between formation resistivity and porosity. *A*, Resistivities versus porosities calculated by using $a = 1$, $m = 2$, water resistivity (R_w) = 0.4 Ω·m, clay volume (C_v) = 25 percent, and clay resistivity (R_c) = 20 Ω·m. Porosity is uniformly distributed over a range of 20–40 percent. Solid dots (mainly merged into a line) represent resistivities for the base line (no gas hydrate saturation), and open circles are for the resistivities for gas-hydrate-bearing sediments with random hydrate saturation distributed over a range of 0–80 percent. *B*, The resistivity versus water-filled porosity after application of a clay correction.

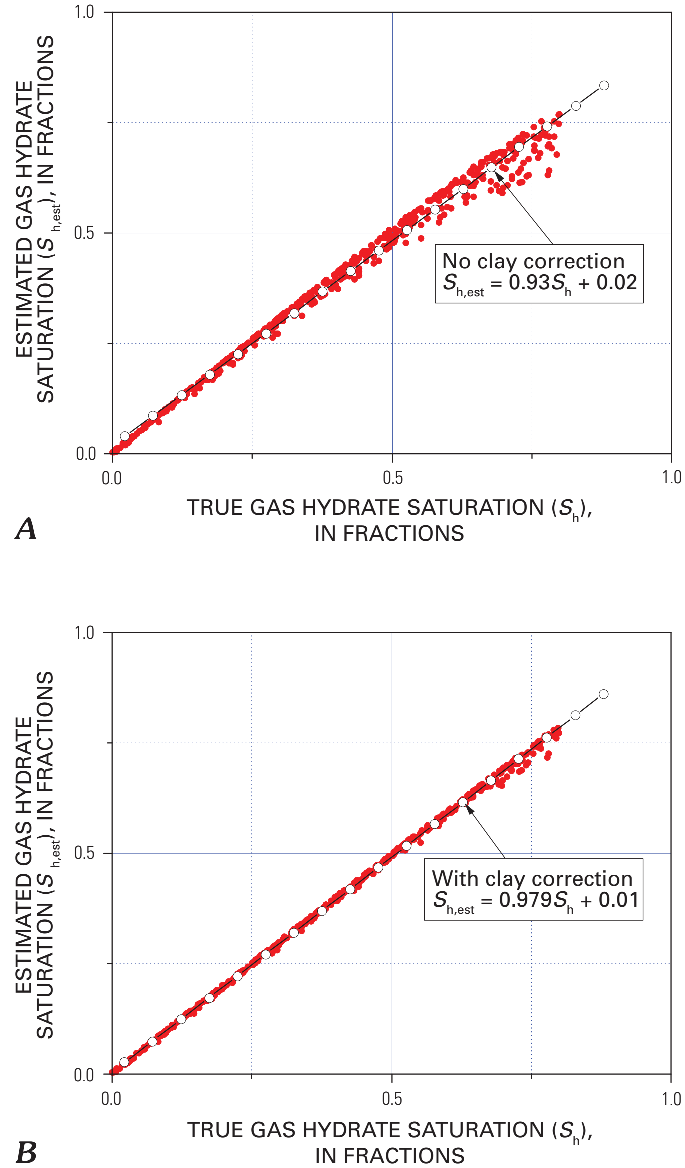

Figure 5. Plots showing estimated gas hydrate saturation ($S_{h,est}$) versus true gas hydrate saturation (S_h) for the model shown in figure 4*A*. *A*, Without clay correction. *B*, With clay correction.

Real Data Example

Figure 6 shows the clay-corrected resistivity versus the observed resistivity from the well log acquired at the Mallik 2L-38 gas hydrate research well, Mackenzie Delta, Canada. The Archie constants for shaly sand used for figure 6 are a^* = 1.02 and m* = 1.95, and R_w is 0.25 Ω·m; for clean sands, the constants are a = 1 and m = 2. Figure 6*A* shows the result when using a constant clay content of 30 percent. As indicated in equation 8, the effective clay conductivity (Q_c) is a function of porosity if R_w, a^*, and m^* are constant. Therefore, when using a constant clay content, the estimated Q_c provides an average electrical conductivity for the clay. The average Q_c for the result shown in figure 6*A* is 0.021±0.005 mho·m. By using an average porosity of 0.31 and an average clay content of 0.324, the average resistivity of clay of about 10 Ω·m can be calculated from equation 3. The resistivity of clay estimated in our study is comparable to the value that Miyairi and others (1999) used in their well-log analysis at Mallik 2L-38 (that is, 5 Ω·m). The clay-corrected resistivity was greater than the observed resistivity, and the difference between the two increased as the measured resistivity increased (overcompensation). These results occurred because a constant clay content was used even though sediments having high resistivities are cleaner than sediments having low resistivities at this well site.

Figure 6*B* shows the clay-corrected resistivity when using a variable clay content based on the well logs. Clay contents were calculated from the gamma log by using the formula pertinent to Tertiary clastic sediments (Western Atlas International Inc., 1995). Archie constants depend on the clay content in sediment, as demonstrated in table 1. In cases where the clay content varies, the Archie constants a^* and m^* are linearly interpolated with respect to the clay content. When using variable clay contents, the clay-corrected resistivity is almost linearly related to the observed resistivity (fig. 6*B*), but is about 20 percent higher.

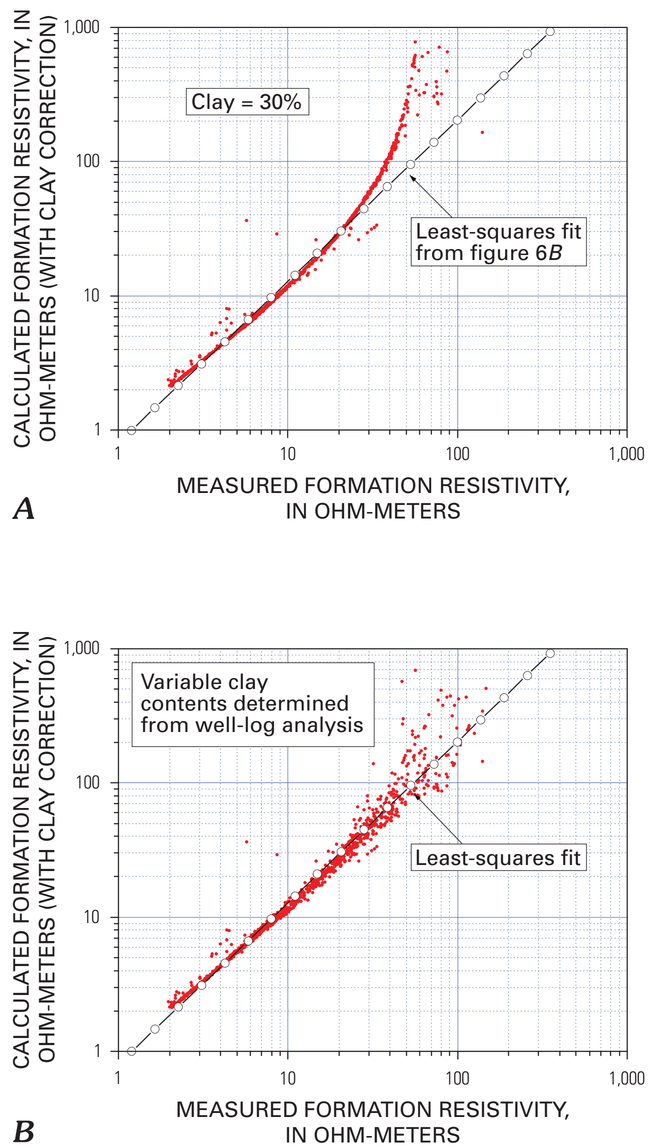

Figure 6. Plots showing clay-corrected resistivity versus observed resistivity at the Mallik 2L-38 well, Mackenzie Delta, Canada. Archie constants for shaly sand are a^* = 1.02 and m^* = 1.95, and for a clean sand they are a = 1 and m = 2. The resistivity of connate water was set to 0.25 Ω·m. *A*, Using constant clay contents (average of 30 percent). *B*, Using variable clay contents from well-log analysis.

Analysis of the Method

Reliable estimates of the clay contribution to formation resistivity are dependent on a number of important factors, such as clay types, the nature of pore space (connected or isolated), the degree of lithologic heterogeneity of the reservoir, and the accuracy of resistivity measurements. In this section, elements relevant to using equation 11 for determining the clay correction are discussed.

Condition for the Linear Approximation

There are many models accounting for the clay effect on the resistivity of sediments (for example, Simandoux, 1963; Waxman and Smits, 1968; Poupon and Leveaux, 1971; Clavier and others, 1977). In our study, we used the Simandoux model, which considers the conductivity of the formation to be the sum of conductivity of water in clean sand and the conductivity of clay. The contribution of clay (that is, the effective clay conductivity, Q_c) to the total conductivity is proportional to the total clay content in the matrix and the conductivity of clay. Although the explicit expressions of other models are different from the Simandoux model, the essence of the expressions is similar. For example, Q_c in the model of Waxman and Smits (1968) is expressed by the product of cation exchange capacity per unit volume and equivalence of conductance of the clay, which is equivalent to the conductivity of clay material in the formation.

The only constraint in using equation 11 for the estimation of clay contribution is the linear nature of log R_0 versus log ϕ. As long as the plot of log R_0 versus log ϕ can be approximated by a linear equation, this clay-correction method can be applied irrespective of the clay model. As indicated in the previous section, the plot of log R_0 versus log ϕ for 100 percent water-saturated sediments is approximately linear, if the quantity FR_wQ_c—which is the ratio of the formation conductivity contributed by the clay to the conductivity contributed by the fluid—is less than approximately 0.4. The ranges of water conductivity, clay conductivity, and volume of clay that satisfy the linear condition for various porosities are shown in figure 3. The values under the curves satisfy the linear condition. As shown in figure 3, it is difficult to satisfy the linear requirement for low-porosity sediments, particularly those with less than 10 percent porosity. Bussian (1983) showed that, on the basis of real resistivity measurements, the linear condition breaks down when porosity is less than 4 percent. Equation 2 shows that at 4 percent porosity, R_wC_v should be less than $(6.67 \times 10^{-4})R_c$ to meet the linearity condition. On the basis of the assumption that R_c is 20 Ω·m and R_w is 1 Ω·m, C_v should be less than about 1.3 percent, which demonstrates that the proposed method using Archie constants a^* and m^* may not work well for sediments with less than 10 percent porosity.

Constraint on Cementation Constant *m*

Because clay increases the conductivity of composite material irrespective of m values, the resistivity of shaly sand is always less than the resistivity of clean sand at the same porosity. Because of the contribution from clay to the resistivity, the slope of the log R_0 versus log ϕ plot decreases as the clay effect increases, as shown in figure 1. Therefore, the Archie constant m, which is given by the slope of the log R_0 versus log ϕ plot, for shaly sand is less than m for clean sand as long as the clay content is constant. Consequently, $m - m^*$ in equation 8a is always positive in this clay model, and equation 9 predicts that when a^* is greater than 1, m is greater than m^*. Equation 9 also predicts that when a^* is less than 1, m is less than m^*. Although the clay model we propose cannot predict m^* greater than m or a^* less than 1.0, it is generally true that a^* is less than 1.0 for real data. For example, a^* for the Humble equation (Labo, 1987) is 0.62, so m should be less than m^*.

Equation 9 provides the lower bound for m. The upper bound for m can be derived from equation 11, expressed as $1 - R_tQ_c \geq 0 \Rightarrow R_tQ_c \leq 1$. This relationship can be written as

$$m < m^* + \frac{\ln\left[(aR_t\phi^{m^*} - a^*R_w)/(R_t\phi^{m^*}a^*)\right]}{\ln\phi}, \quad (13a)$$

or, alternatively, by using the water saturation shown in equation 11a:

$$m < m^* + \frac{\ln(a/a^* - S_w^n/a^*)}{\ln\phi}. \quad (13b)$$

Where uncertainty exists, a bound for m can be calculated from equations 9 and 13. In the case that $a = 1$ and $S_w = 1$ (water-saturated sediments) or high water saturation, the upper bound is large, and only the lower bound is important. Because both upper and lower bounds of m depend on porosity as well as Archie's parameters, an accurate estimation of m is not practical. However, equations 9 and 13 provide some guidelines for choosing m. For example, if $a = 1.0$, $a^* = 1.6$, $m^* = 1.6$, $\phi = 0.4$, and $S_w = 0.5$, equations 9 and 13 yield $2.11 < m < 2.42$. This inequality indicates that if $m = 2$ is used for the clay correction, Q_c is negative. Therefore, m should be greater than 2.11 to apply the proposed method for the clay correction.

Error Analysis

Archie constants $a = 1$ and $m = 2$ were assumed for clean-sand reservoirs in our study. Theoretically, a is always 1 for the clean sand, but m can vary from 1 to infinity according to the shape of the sediment's particles (Bussian, 1983). The cementation factor $m = 2$ corresponds to the electrical resistivity of the infinitely long rod perpendicular to the electric field. One drawback in applying a clay correction using Q_c is uncertainty in the value for m, when it differs from 2 for clean sands. The relative error associated with this uncertainty can be written by the following formula, derived from equation 8a:

$$\frac{\Delta Q_c}{Q_c} = \frac{-a^*(\ln\phi)\phi^{m-m^*}}{(a - a^*\phi^{m-m^*})}\Delta m. \quad (14)$$

Because $(a - a^*\phi^{m-m^*})$ is a small number, the relative error of $\Delta Q_c/Q_c$ for a given error in m (that is, Δm) is large. Figure 7 shows relative errors, Q_c/Q_c, associated with an error in m so that $\Delta m = 0.1$ for the clean sand with respect to the porosity for the three clay models (clay content = 25, 50, and 75 percent) shown in figure 1*A*. For most cases, the error is greater than 100 percent for a 25 percent clay model. To reduce this error to less than 10 percent for a sediment with 30 percent porosity, Δm should be less than about 0.01.

The error in water saturation owing to the error in Q_c can be derived easily from equation 11 in the case of $a = 1$ and $m = 2$. By using S_w as the estimated water saturation determined from the erroneous Q_c and by using S_w as the estimated water saturation determined from the correct Q_c, then

$$\frac{S_w^*}{S_w} = \sqrt{1 - \frac{R_t\Delta Q_c}{1 - R_tQ_c}} \approx 1 - \frac{R_t\Delta Q_c}{2(1 - R_tQ_c)}. \quad (15)$$

Figure 8 shows the ratio of water saturation for two relative errors in Q_c—one is for a relative error of 100 percent, and the other is for a relative error of 50 percent. When the relative error $(\Delta Q_c/Q_c)$ is less than 50 percent, the error in estimating water saturation is less than about 20 percent.

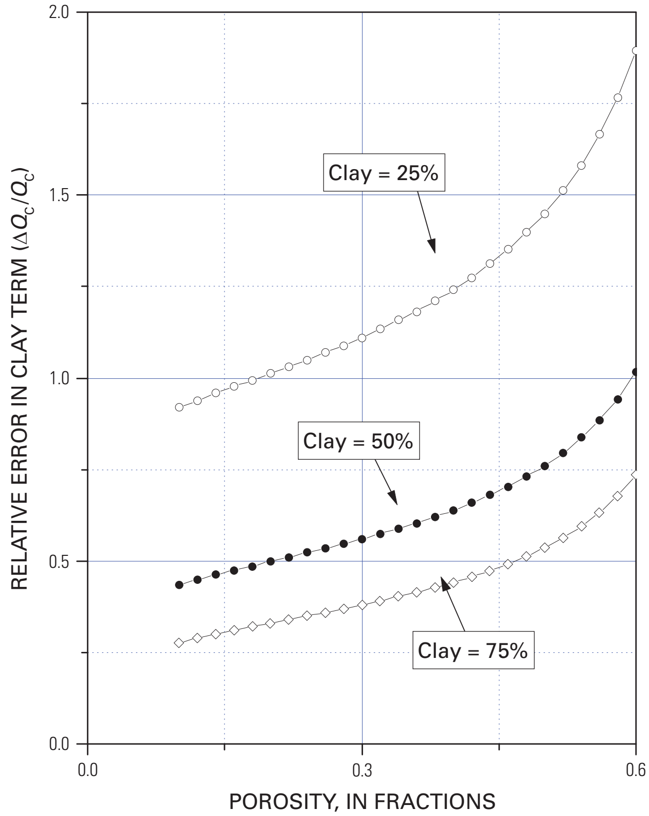

Figure 7. Graph showing relative errors in estimating the conductivity contributed by clay versus porosity. The parameters for various clay contents are identical to those for figure 1*A*, and the error in *m*, $\Delta\mu$, is 0.1.

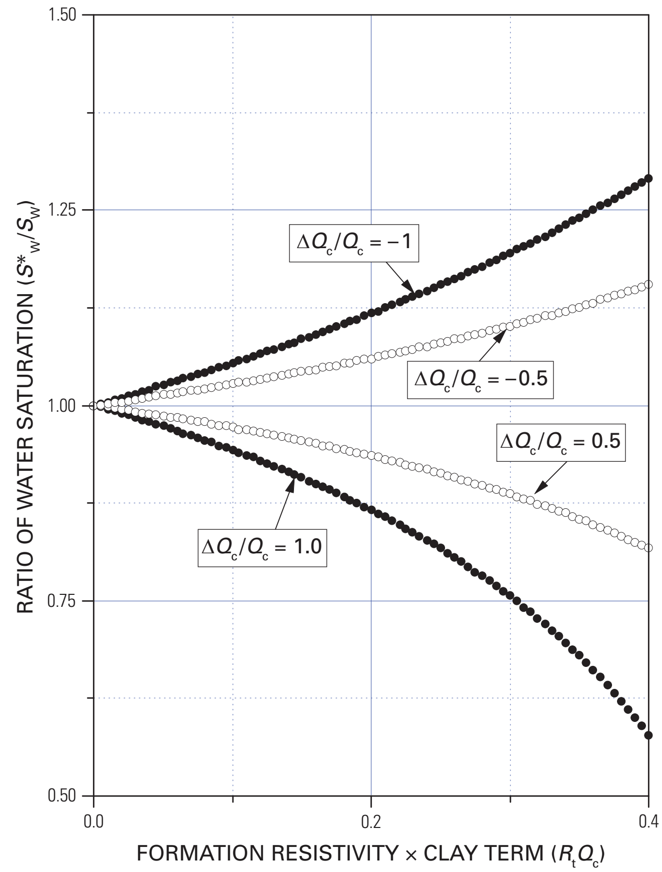

Figure 8. Graph showing the ratio of water saturation versus the formation resistivity times the clay term (R_{tQc}) for different relative errors in the clay term (Q_c). S_w is the water saturation estimated from the resistivity when there is no error in Q_c, and S_w* is the estimated water saturation when there is a relative error in Q_c. Solid dots indicate an error of 100 percent, and open circles are errors of 50 percent.

Summary of the Proposed Method

Equation 11 is a general formula in the sense that it can be applied to any kind of clay model that satisfies the linear condition, because the equation does not depend on the explicit expression of the clay model. Rather, it uses only the effective clay conductivity term Q_c irrespective of the clay model. The details of how to calculate the conductivity of clay and how to estimate the effect of clay on the resistivity of the formation depend on the specific clay model. However, our proposed method—which is based on Archie parameters *a** and *m** for estimating the effective clay conductivity in order to estimate water saturation—is independent of any explicit clay model. This aspect is different from other methods. For example, that used by Waxman and Smits (1968) requires parameters specific to the clay model such as cation exchange capacity and equivalent conductance of the clay.

Archie constants *a** and *m** for shaly sand, calculated from resistivity versus porosity data with 100 percent water saturation, represent average values for the sedimentary interval analyzed. As the clay content in sediments changes, the dependence of *a** and *m** with respect to clay content should be incorporated in equation 8 to estimate a reliable Q_c. Table 1 indicates that *a** and *m** are nearly linear with respect to the clay content. The difference between a clay correction using a constant clay content and that using a variable clay content is shown in figure 6. Therefore, it is possible to use variable Archie constants for clay corrections by linearly interpolating the Archie parameters between clean and shaly sand.

Conclusions

From model studies based on the Simandoux equation, we propose a method of correcting the clay contribution to resistivity measurements. In this method, Archie constants *a** and *m** for shaly sands are used to compute clay conductivity from the resistivity log under the assumption of known Archie parameters for clean sands. To apply the method, the plot of log R_0 versus log ϕ should be approximately linear, a condition that is satisfied if the conductivity contributed by the clay is less than about 40 percent of the conductivity contributed by the fluid. Because of the linear condition, however, the method is inadequate for low-porosity reservoirs (those with approximately less than 10 percent porosity). The linearity requirement also implies that with (1) high water salinities and high sediment porosities and (2) low clay contents and low clay conductivities, the proposed method is more effective in estimating gas hydrate saturation.

The proposed method has been tested only in the case that a^* is greater than a and m^* is less than m. Even though applicable to a wide range of reservoir conditions, further study is required to evaluate the method's accuracy and effectiveness in all cases of Archie parameters.

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