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Connectivity Equation and Shaly-Sand Correction for Electrical Resistivity

Scientific Investigations Report 2011–5005

U.S. Department of the Interior
U.S. Geological Survey

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Abstract

Estimating the amount of conductive and nonconductive constituents in the pore space of sediments by using electrical resistivity logs generally loses accuracy where clays are present in the reservoir. Many different methods and clay models have been proposed to account for the conductivity of clay (termed the shaly-sand correction). In this study, the connectivity equation (CE), which is a new approach to model non-Archie rocks, is used to correct for the clay effect and is compared with results using the Waxman and Smits method. The CE presented here requires no parameters other than an adjustable constant, which can be derived from the resistivity of water-saturated sediments. The new approach was applied to estimate water saturation of laboratory data and to estimate gas hydrate saturations at the Mount Elbert well on the Alaska North Slope. Although not as accurate as the Waxman and Smits method to estimate water saturations for the laboratory measurements, gas hydrate saturations estimated at the Mount Elbert well using the proposed CE are comparable to estimates from the Waxman and Smits method. Considering its simplicity, it has high potential to be used to account for the clay effect on electrical resistivity measurement in other systems.

Introduction

Most electrical-resistivity interpretation methods 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 for clean (clay-free) sands, where formation matrices are poor conductors. However, Archie's law is not accurate in estimating water saturation in shaly sands, where conductive 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 inaccurate if the resistivity from the conducting clay material is not accounted for.

In order to correct for clay conductivity on formation resistivity, a number of clay models have been proposed; 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. 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 claybound water that is spatially separated from the bulk water.

All shaly-sand correction methods presented in Worthington (1985) require additional input parameters such as the clay resistivity for the Simandoux method (1963) or cation exchange capacity and equivalent conductance of the clay counterions for the Waxman and Smits model (1968).

Recently, Montaron (2009) introduced a connectivity theory (or connectivity equation), which is a new approach to model "non-Archie rocks," and applied the theory to correct the effect of clay conductivity on the basis of the dual water model (Clavier and others, 1977). The purpose of this study is to propose a modification of the connectivity equation of Montaron (2009) that accounts for the shale effect on electrical resistivity. In contrast to conventional shaly-sand methods, however, the method presented here requires no additional parameters other than an adjustable parameter that can be derived from the resistivity of water-saturated sediments.

Theory

Archie Equation

The electrical resistivity of water-saturated sediments (R_o) can be expressed using the well-known Archie equation (Archie, 1942) in the following way:

$$R_o = \frac{aR_w}{\phi^m} \tag{1}$$

where R_o is the formation resistivity of water-saturated sediment, R_w is the resistivity of connate water, a and m are Archie constants, and ϕ is porosity. Archie constants a and m can be derived empirically; m is commonly called the cementation factor. Equation 1 indicates that a plot of log ϕ relative to log R_o is linear and the slope is given by m if R_w is constant throughout the sedimentary interval being examined.

The water saturation (S_w) in a formation from resistivity log values for hydrocarbon-bearing sediments is given by Archie (1942) as:

$$S_w = \left(\frac{aR_w}{\phi^m R_t}\right)^{1/n} \tag{2}$$

where n is an empirically derived parameter close to 2 and R_t is the formation resistivity with gas hydrate or other hydrocarbons. 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) and is taken as 2 in this study.

Waxman and Smits Equation

The effect of clay on the formation resistivity can be corrected using various shaly-sand correction methods (Worthington, 1985). The Waxman and Smits (1968) equation (WSE) for the shaly sand correction is given by:

$$\frac{1}{R_t} = \frac{S_w^n \phi^m}{aR_w} + S_w^{n-1}\phi^m BQ_v = \frac{S_w^n \phi^m}{aR_w} + \frac{S_w^{n-1}V_c(1-\phi)}{R_c} \tag{3}$$

where B is the equivalent conductance of the clay counterions, Q_v is the cation exchange capacity per unit pore volume, V_c is the shale volume, and R_c is the resistivity of clay.

Connectivity Equation

Montaron (2009) proposed a connectivity equation (CE) to estimate the pore saturants in sediments instead of using the standard Archie equation, one advantage being that only one parameter is needed to estimate water saturation. The equation is defined as:

$$R_t = \frac{aR_w(1-\chi_w)^\mu}{(S_w\phi - \chi_w)^\mu} \tag{4}$$

where μ is the connectivity exponent (which is equivalent to Archie's equation when $n = m$), a is the conventional Archie parameter, and χ_w is the water connectivity correction index, which is a small number typically ranging from –0.02 to 0.02 (Montaron, 2009). Because χ_w is small, the effect of χ_w in the denominator of equation 4 generally can be ignored. However, in freshwater with high conductivity due to the presence of shale, χ_w could be large and should be retained in equation 4.

Montaron (2009) defined the CE with $a = 1$ in equation 4. Generally, $a = 1$ is accurate for clean sand or in a case where a shaly-sand correction is applied to the measured resistivity (Lee and Collett, 2006). Theoretically, therefore, CE with $a = 1$ appears to be more accurate because the shale effect on the resistivity is accounted for by using the parameter χ_w in equation 4. However, connectivity equation with the parameter a is defined in this report to make the connectivity equation to be more flexible for the real data analysis.

Connectivity Equation and Shaly-Sand Correction

Equation 4 is useful in analyzing the resistivity of the shaly sands as shown in Montaron (2009), in which the dual water model by Clavier and others (1977) was investigated using the CE. The clay effect on the electrical resistivity is through χ_w in the equation, which depends on a particular shaly-sand model. For example, Montaron (2009) used the dual water model of Clavier and others (1977) to derive χ_w, which is given by:

$$\chi_w = -S_{cw}\phi\left[\left(\frac{R_w}{R_{cw}}\right)^{1/\mu} - 1\right] \tag{5}$$

where R_{cw} and are the resistivity and the bulk volume of clay water, respectively.

The WSE can be written as the following, assuming $n = m_c = \mu$ in equation 3:

$$R_t = \frac{aR_w}{S_w^\mu \phi^\mu + S_w^{\mu-1} aR_w BQ_v \phi^\mu} \tag{6}$$

Using equations 4 and 6, the connectivity correction index χ_w can be written as:

$$\chi_w = \frac{S_w\phi(1-\Gamma)}{1-S_w\phi\Gamma} \tag{7}$$

with

$$\Gamma = \left[1 + \frac{aR_w BQ_v}{S_w}\right]^{1/\mu}. \tag{8}$$

If n and m shown in equation 3 are used for Γ in equation 8, that is $\Gamma = [1 + aR_w BQ_v / S_w)]^{1/n}$, then CE is identical to WSE. However, in the case where there is no information about m and n, it is useful to use equation 7 with equation 8 to derive the shaly-sand correction by calculating χ_w using various μ; the results can be examined to assess the accuracy of the method. Note that the effect of clay resistivity is in χ_w; thus, the CE for clean sand is equation 4 with $\chi_w = 0$.

Proposed Connectivity Method

The water-connectivity correction index χ_w was originally based on the percolation threshold of the porous media, and the conductivity exponent was nearly 2 according to numerical simulations (Montaron, 2009). However, numerical simulations demonstrated that a best-fit μ depends on the χ_w value used, which implies the nonuniqueness of the connectivity equation unless χ_w is fixed. Also, different connectivity equations can be developed using different value of χ_w.

When applying the CE to shaly-sand correction, χ_w was derived based on equation 4 with the WSE. Montaron (2009) used the following approximation equation instead of equation 7:

$$R_t = \frac{aR_w}{\left(S_w\phi - \chi_w\right)^{\mu}} \tag{9}$$

However, if equation 9 with χ_w given by

$$\chi_w = S_w\phi\left(1-\Gamma\right) \tag{10}$$

is used to calculate the resistivity, then the calculated resistivities are identical to those from equation 4 with equation 7. In other words, whether using equation 4 or a simpler equation 9 is immaterial χ_w if is calculated according to the corresponding equations.

The nonuniqueness of the CE opens a new way to apply it to the shaly-sand correction. Because an optimum μ depends on χ_w, the following procedures are proposed to apply the CE to the shaly-sand correction.

1. For a given μ, calculate χ_w according to the following equation using an adjustable parameter α:

$$\chi_w = aC_v\phi^{\mu}S_w \tag{11}$$

2. Calculate the resistivity of water-saturated sediments using equation 9 and compare with the measured resistivity. Adjust α until there is a satisfactory agreement between the calculated and measured resistivities of water-saturated sediments.

3. Estimate the water saturation using equations 9 and 10 with estimated α.

Because the connectivity correction index χ_w, shown in equation 11, is calculated without any particular shaly-sand models (for example, Worthington, 1985), this approach is universal for the shaly sand correction. The advantage of this approach is that no additional parameters are required other than estimating α by using a trial-and-error method.

Analysis of Formation Resistivity

Laboratory Data

To test the feasibility of the CE for shaly-sand correction, data from Ohirhian (1998) were used. The data by Ohirhian (1998) in the form of values for B (equivalent conductance of the clay counterions) and for Q_v (cation exchange capacity per unit volume) were used, and these values were converted to the equivalent resistivity of clay using equation 12, assuming V_c = 0.2 for all samples. The measured and calculated values for the Ohirhian (1998) data are shown in table 1.

The relation between the resistivity of clay and B and Q_v can be derived from equation 3; it is given by:

$$\frac{V_c\left(1-\phi\right)}{R_c} = BQ_v\phi^{m_c} \tag{12}$$

The measured n value ranges from 1.6 to 2.3, and the Archie cementation parameter, m, varies between 1.6 and 2.0. For all samples, a = 1.0 is assumed. Table 1 includes the saturations estimated from the connectivity equation using $\mu = n = m = 2$ along with those estimated using the WSE by Ohirhian (1998) with different n and m values for each sample shown in table 1. Figure 1 compares the two saturation estimates. Except for samples 2 and 5, the saturations estimated using the CE are more than 80 percent accurate. Observations that can be made from table 1 are:

Where the value of n is close to μ, the estimated saturation is more accurate.

As the saturation increases, the accuracy increases (compare samples 1 and 2).

As expected, if μ is less than n, the CE overestimates, and if μ is greater than n, CE underestimates.

Without a shaly-sand correction, the water saturation from data by Ohirhian (1998) is 1, mainly because the conductivities of clays are higher than those of connate water (table 1). However, the water saturation estimated from the CE with $\mu = 2$ is comparable to that estimated from the WSE. The difference of water saturations between the CE and WSE methods is caused by the difference between the Archie cementation parameter m and the saturation exponent n for data by Ohirhian (1998).

Well Log Analysis

In order to test the proposed connectivity method, well logs acquired at the Mount Elbert well on the Alaska North Slope were analyzed. Details of resistivity log analysis at this well are given in Lee and Collett (2011); figure 2 shows the calculated R_w from the measured salinity and temperature along with the measured electrical resistivity. Note that the average R_w for the interval between 2,000 and 2,500 ft is about 2 ohm-m except for two intervals with much higher resistivities that reflect the effect of low salinity at low temperature

Table 1. Parameters for eight samples from Ohirhian (1998) with calculated resistivity of clay and saturations estimated using the connectivity equation with the connectivity exponent $\mu = 2$.

[Resistivity of clay (R_c), resistivity of water (R_w), and resistivity of formation(R_t) are in ohm meters. S_h, saturation estimated by Ohirhian using the Waxman and Smits (1968) equation; S_h, saturation estimated using the connectivity equation ϕ, porosity; m, Archie cementation parameter; n, Archie saturation exponent]

Sample	R_w	ϕ	R_c	n	m	R_t	S_h^*	S_h
1	6	0.27	3	1.6	1.6	50	0.80	0.64
2	6	0.27	3	1.6	1.6	20	0.32	0.19
3	6	0.25	2.1	2.2	1.9	30	0.51	0.59
4	6	0.25	2.1	1.9	1.9	30	0.60	0.59
5	10	0.2	2.85	2.3	2.0	25	0.25	0.36
6	10	0.25	3.0	2.0	1.9	50	0.65	0.67
7	10	0.3	3.9	2.1	1.8	35	0.32	0.35
8	10	0.25	5.9	2.1	1.8	70	0.49	0.52

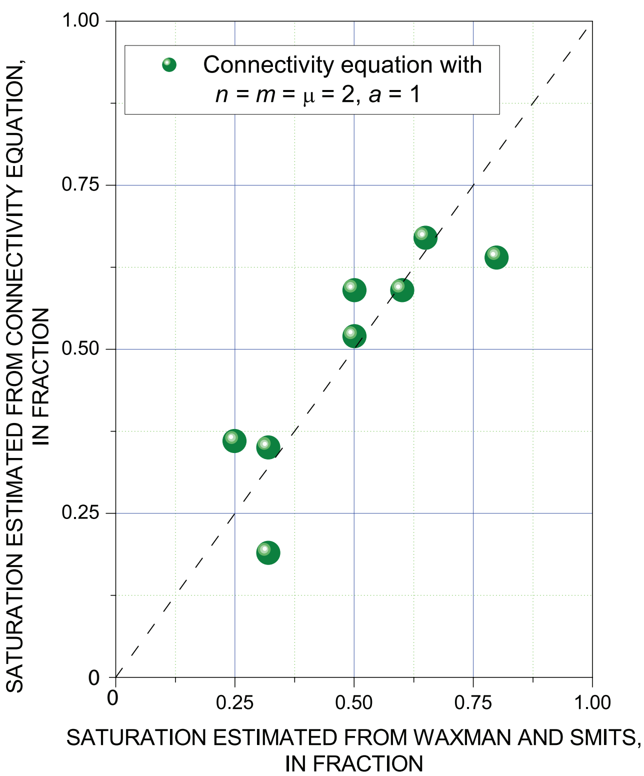

Figure 1. Saturations estimated from the Waxman and Smits equation by Ohirhian (1998) are compared with those estimated from the connectivity equation with the connectivity exponent $\mu = 2$, which is equivalent to using Archie parameter $a = 1$, $m = 2$, and $n = 2$.

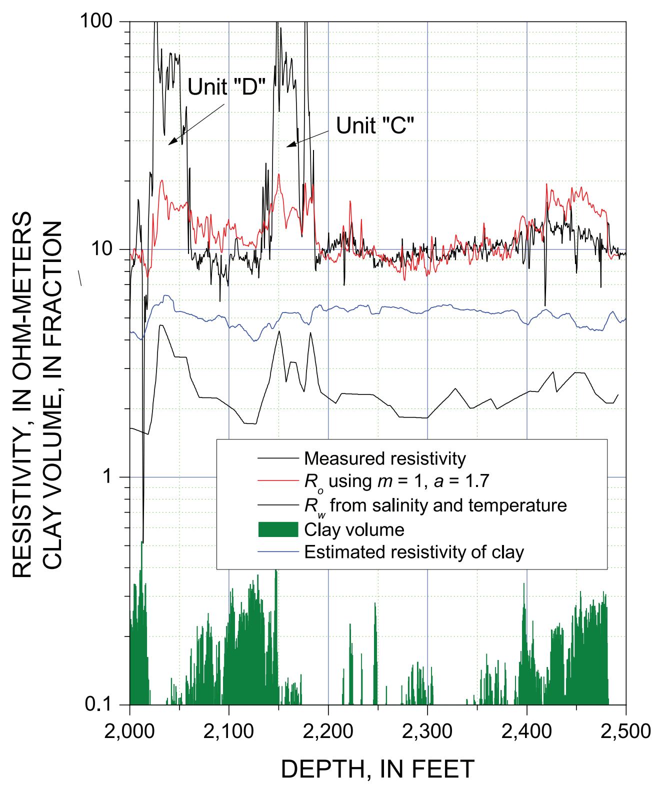

Figure 2. Plot showing measured electrical resistivity with shale volume calculated from gamma ray log, resistivity of pore water calculated using salinity and temperature, and baseline resistivity calculated from porosity and resistivity of connate water (R_w) with the Archie parameters $a = 1.7$ and $m = 1$. R_o, resistivity of water-saturated sediments.

on the resistivity. The resistivity of pore water at the Mount Elbert well is abnormally high. For comparison, R_w at the Mallik 5L−58 well in western Canada, is about 0.45 ohm-m (Collett and Lee, 2005), and at Keathley Canyon in the Gulf of Mexico, R_w is about 0.2 ohm-m (Lee and Collett, 2008). The zones where R_w is greater than approximately 3 ohm-m in figure 2 correspond to hydrate Units "C" and "D" (Collett, 2000), and these zones were caused by the freshening of pore water from the dissociation of gas hydrate. Consequently, the calculated resistivity greater than about 2 ohm-m in figure 2 does not represent the in-situ resistivity of pore water. Because the R_w is the same magnitude of the resistivity of clay, the shale effect on the measured electrical resistivity is significant for gas hydrate Units "C" and "D" (Lee and Collett, 2011).

Figure 3 shows the results of the proposed CE approach. The resistivity of water-saturated sediments shown in figure 3*A* is calculated with a =1 and for equation 9 and $\alpha = -9.5$ for equation 11; the calculated resistivity appears to be satisfactory. The gas hydrate saturations estimated using the above parameters are shown in figure 3*B* and compared with those estimated from the nuclear magnetic resonance (NMR) porosity. Gas hydrate saturations for Units "C" and "D" estimated from the CE are comparable to those from NMR porosity. Also shown in figure 3*B* are gas hydrate saturations estimated from the WSE method using R_c = 5 ohm-m. Estimates from the CE in figure 3 are comparable to those from the WSE method.

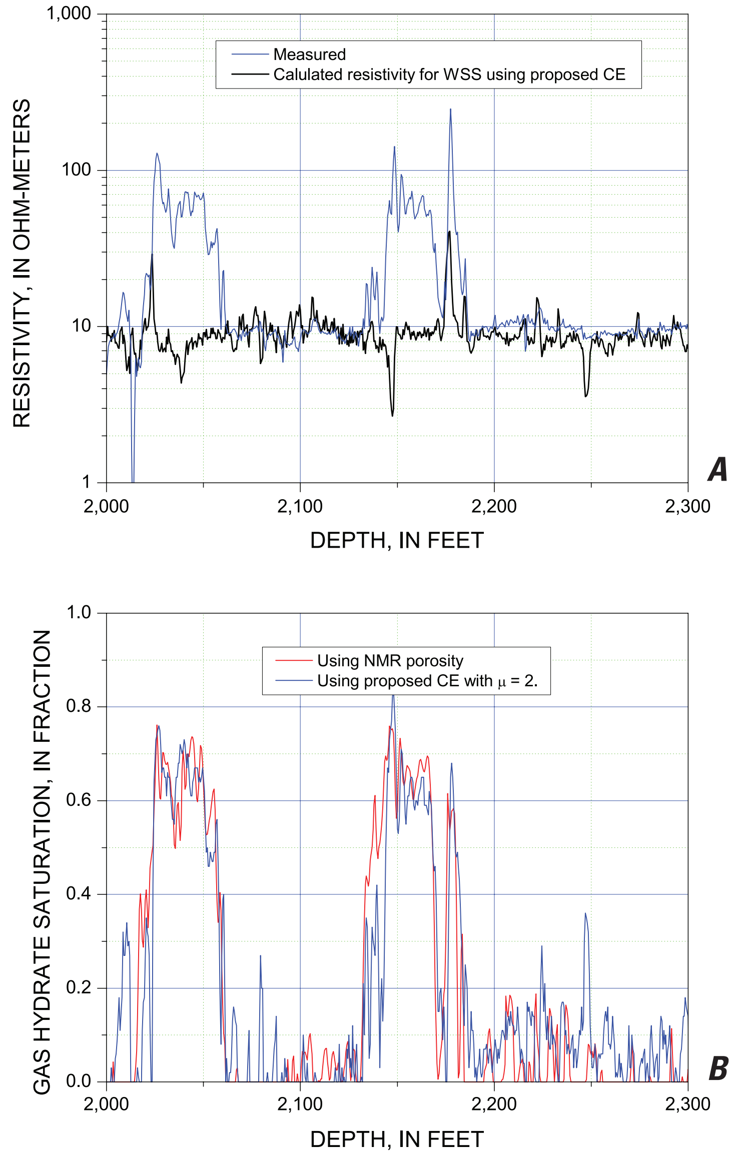

Figure 3. Results from the proposed connectivity equation (CE) at the Mount Elbert well on the Alaska North Slope. *A*, measured resistivity and calculated resistivity of water-saturated sediments (WSS) using proposed CE with connectivity exponent $\mu = 2$. *B*, gas hydrate saturations estimated from the nuclear magnetic resonance (NMR) porosity log, proposed CE, and Waxman and Smits equation (1968).

Considerations for the Application of Connectivity Equation

Archie Parameters and Connectivity Exponent

Theoretically, the Archie parameters for clean sands are $a = 1$ and $m = 2$. However, many core measurements require $a \neq 1$ to fit the observations (Carothers, 1968; Porter and Carothers, 1970). If $a \neq 1$, then equation 1 yields inconsistent R_w at $\phi = 1$. However, Lee and Collett (2006) suggested that $a \neq 1$ is due to the effect of shale on the measured resistivity.

The value of m is estimated from the cross plot between porosity and the formation factor of shaly sands. Therefore, if the shale effect is not accounted for, the estimated m may be different from m for clean sands. Laboratory measurement of m for shaly sands with clay correction ranges from $m = 1.8$ to $m = 2.1$ (Waxman and Thomas, 1974), whereas m can be as low as $m = 1.4$ without clay correction for the same dataset. Smaller m for shaly sand compared to m for clean sand agrees with the prediction of the shaly-sand model by Lee and Collett (2006). The m values for the shaly sand by Ohirhian (1998) range from 1.6 to 2.0. Therefore, $a = 1$, $m = 2$, and $n = 2$ are reasonable parameters to use where there is no information for these parameters.

The application of the CE is intended for use in the case that there is no information for the shaly-sand model such as the resistivity of clay, clay counterions, the cation exchange capacity, and others. Therefore, the proposed CE can be considered as a kind of blind application of the shaly-sand model based solely on the measured resistivity. Because $a = 1$, $m = 2$, and $n = 2$ represent a reasonable model for sand, $\mu = 2$ is appropriate to use unless more information for the shaly-sand model is available.

Saturation Differences

The saturation difference estimated from the connectivity and Archie equations can be assessed from the following clean (clay-free) sand equations. For clean sand, the WSE (R_t^{ws}) can be written as

$$R_t^{ws} = \frac{aR_w}{S_w^n \phi^m} \tag{13}$$

and the CE (R_t^{ce}) as

$$R_t^{ce} = \frac{aR_w}{S_w^\mu \phi^\mu} \tag{14}$$

From equations 13 and 14, the relation between the conductivity index (μ) and the saturation exponent (n) can be written as:

$$\mu = n + \frac{(m_c - n)1n\phi}{1nS_w} \tag{15}$$

Equation 15 indicates that:

1. Saturations estimated from the CE differ from those from the Archie equation unless $m = n$.

2. The difference between n and μ increases as ϕ decreases and S_w increases. Consequently, the saturations estimated from the CE are similar to those from the Archie equation for sediments with high porosity and low water saturation.

3. If $m_c < n$, then the CE overestimates the saturation in comparison to the Archie equation irrespective of water saturation and porosity.

4. Depending on the sign of the second term of equation 14, the CE overestimates or underestimates the saturation in comparison to the Archie equation.

Original and Proposed Connectivity Methods

As shown previously and in Montaron (2009), the water-connectivity correction index for shaly sand correction depends on shaly-sand models such as those represented by equation 5 for the dual water model and by equation 7 for the Waxman and Smits (1968) model. According to Lee and Collett (2011), the Archie parameters appropriate for the electrical log at the Mount Elbert well are $a = 1$, $m = 1.6$, and $n = 2$. Because n differs from m, there are two options for μ: $\mu = m = 1.6$ or $\mu = n = 2$. Figure 4*A* shows the calculated resistivity for water-saturated sediments (WSS) using $\mu = 1.6$ and $\mu = 2$; the CE with $\mu = 1.6$ closely predicts the resistivity, whereas the CE with $\mu = 2$ overestimates the resistivity. On the other hand, the gas hydrate saturation estimated, shown in figure 4*B*, indicates that the CE with $\mu = 1.6$ highly overestimates the gas hydrate saturations, and the CE with $\mu = 2$ slightly underestimates the saturation. If there is no saturation estimated from the NMR log, it would be concluded that the CE with $\mu = 1.6$ is more accurate than the CE with $\mu = 2$ because the calculated resistivity of water-saturated sediments with $\mu = 1.6$ agrees more closely with the measured resistivity even though the saturations are actually highly overestimated.

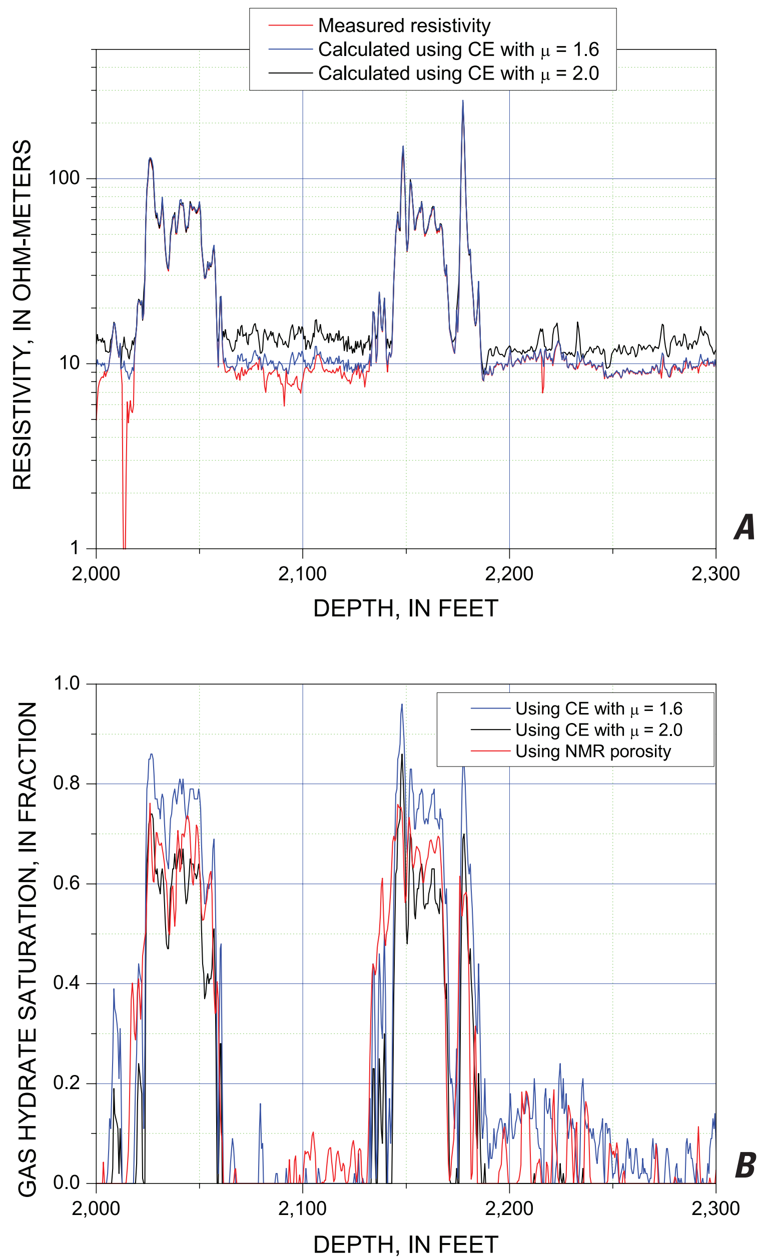

Figure 4. *A*, measured and calculated resistivity at the Mount Elbert well on the Alaska North Slope, using the connectivity equation (CE) (Montaron, 2009) with Archie constant $a = 1$, and two values for connectivity exponent $\mu = 1.6$ and $\mu = 2$. *B*, gas hydrate saturations estimated from the nuclear magnetic resonance (NMR) log and using the proposed CE.

The results from the proposed the CE with $\mu = 2$ indicates that calculated resistivities of water-saturated sediments and gas hydrate saturations agree well with those measured and those estimated from the NMR log, respectively, as shown in figure 3. This comparison indicates a great potential for the proposed connectivity method for the shaly-sand correction, and further investigations are warranted.

Conclusions

Based on the nonuniqueness of the connectivity equation (CE), a simple CE is proposed to account for the effect of conductive clay on the electrical resistivity of sediments. The proposed CE was applied to account for the effect of shale on electrical resistivity by using laboratory data and well logs acquired at the Mount Elbert well on the Alaska North Slope. By incorporating gas hydrate saturations estimated from the nuclear magnetic resonance (NMR) porosity log, it can be concluded that if all parameters such as the Archie constants and characteristics of clay are available, then a specific shaly-sand model (for example, that of Waxman and Smits [1968]) is optimal in estimating saturations (for example, hydrocarbon or gas hydrate). However, this approach requires additional information such as the resistivity of clay or cation exchange capacity. In cases where there is no available information for the electrical properties of shale, the proposed CE can be used to model the resistivity of the sediments.

It is demonstrated that the proposed CE can be used for shaly-sand correction without any parameters, assuming that the Archie parameters for clean sand are $a = 1$ and $m = 2$ and the connectivity exponent $\mu = n = m = 2$. The water connectivity-correction index is derived independently from any particular shaly-sand models, and the proposed CE requires one adjustable parameter α. The parameter α can be estimated by a trial-and-error method by fitting resistivity of water-saturated sediments calculated from the CE to the measured resistivity. The gas hydrate saturations estimated from the proposed CE are comparable to those from the NMR porosity log acquired at the Mount Elbert well on the Alaska North Slope. Saturations estimated from the proposed CE become more accurate as the porosity increases and water saturation decreases.

Because the proposed CE is simple and requires no additional parameters except an adjustable parameter, more investigations involving the application of the proposed CE to shaly-sand correction are warranted for estimating gas hydrate saturations or any other hydrocarbons from the resistivity logs.

References Cited

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Journal of Petroleum Technology, v. 1, p. 55–62.

Carothers, J.E., 1968, A statistical study of the formation relation: The Log Analyst, v. 9, p. 13–20.

Clavier, C., Coates, G., and Dumanoir, J., 1977, The theoretical and experimental bases for the “dual water” model for the interpretation of shaly sands: 52d Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Denver, Colo., October 9–12.

Collett, T.S., 2000, Quantitative well-log analysis of in-situ natural gas hydrates: Golden, Colorado School of Mines, Ph.D. dissertation, 535 p.

Collett, T.S., and Lee, M.W., 2005, Electrical-resistivity well-log analysis of gas hydrate saturations in the JAPEX/JNOC/GSC et al. Mallik 5L-38 gas hydrate production research well, *in* Dallimore, S.R., and Collett, T.S., eds., Scientific results for Mallik 2002 gas hydrate production research well program, Mackenzie Delta, Northwest Territories, Canada: Geological Survey of Canada Bulletin 585, 10 p.

Lee, M.W., and Collett, T.S., 2006, A method of shaly sand correction for estimating gas-hydrate saturations using downhole electrical resistivity log data: U.S. Geological Survey Scientific Investigations Report 2006–5121, 10 p.

Lee, M.W., and Collett, T.S., 2008, Integrated analysis of well logs and seismic data at the Keathley Canyon, Gulf of Mexico, for estimation of gas hydrate concentrations: Marine and Petroleum Geology, v. 25, p. 924–931.

Lee, M.W., and Collett, T.S., 2011, In-situ gas hydrate saturation estimated from various well logs at the Mount Elbert Gas Hydrate Stratigraphic Test Well, Alaska North Slope: Marine and Petroleum Geology, v. 28, p. 439–449.

Montaron, Bernard, 2009, Connectivity theory—A new approach to modeling non-Archie rocks: Petrophysics, v. 50, no. 2, p. 102–115.

Ohirhian, P.U., 1998, An explicit form of the Waxman-Smits equation for shaly sand: The Log Analyst, May-June, p. 54–57.

Pearson, C.F., Halleck, P.M., McGuire, P.L., Hermes, R., and Mathews, M., 1983, Natural gas hydrate deposit—A review of in-situ properties: Journal of Physical Chemistry, v. 97, p. 4180–4185.

Porter, C.R., and Carothers, J.E., 1970, Formation factor-porosity relation derived from well log data: Society of Professional Well Log Analysts, Transactions, 11th Annual Logging Symposium, Los Angeles, May 3–6, p. A1–A19, Simandoux, P., 1963, Dielectric measurements on porous media; Application to the measurement of water-saturations: Revue de L'Institut Français du Pétrole 18, supplementary issue, p. 193–215. (Translated text in shaly sand reprint volume, Society of Professional Well Log Analysts, Houston, p. IV 97–124).

Waxman, M.H., and Smits, L.J.M., 1968, Electrical conductivities in oil-bearing shaly sand: Society of Petroleum Engineers Journal, v. 8, p. 107–122.

Waxman, M.N., and Thomas, C.E., 1974, Electrical conductivities in oil-bearing shaly sands—I. The relation between hydrocarbon saturation and resistivity index. II. The temperature coefficient of electrical conductivity: Society of Petroleum Engineers Journal, v. 14, p. 213–225.

Worthington, P.E., 1985, The evolution of shaly-sand concepts in reservoir evaluation: The Log Analyst, January–February, p. 23–40.

Wyllie, M.R.J., and Southwick, P.F., 1954, An experimental investigation of the S.P. and resistivity phenomena in shaly sands: Journal of Petroleum Technology, v. 6, p. 44–57.

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