

Gas-hydrate concentration and uncertainty estimation from electrical resistivity logs: examples from Green Canyon, Gulf of Mexico

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Summary

Many gas-hydrate systems from deepwater, near-seafloor strata in the Gulf of Mexico have limited availability of data because the targeted logging intervals from these regions are deep reservoirs. The usual well-log information acquired over the gas-hydrate stability zone is restricted to gamma-ray and resistivity logs. Also sparse geotechnical data are available. Therefore, in estimating gas-hydrate concentration in these environments we should take into account the inherent uncertainty associated with our predictions.

In this paper we present a methodology for estimating gas-hydrate concentration and its associated uncertainty using resistivity logs. Our methodology combines rock-physics theories and empirical relations with stochastic simulations. We also present a technique that helps calibrate Archie's Equation (1942) for estimating gas-hydrate concentration based on resistivity logs using the theoretical Hashin-Shtrikman (1962) Lower Bound on electrical resistivity. This method is especially useful when there is limited availability of resistivity and porosity data for calibrating the empirical parameters in Archie's Equation. We show examples of estimating gas-hydrate concentration and the associated uncertainty for well-data from the Green Canyon area of the Gulf of Mexico.

Empirical approach: Archie's Equation

Gas hydrates are electrical insulators, in the same way as hydrocarbons are. Therefore, in principle, we can use the same techniques to estimate hydrate saturation as those used to estimate hydrocarbon saturation in the oil industry. The most common empirical technique is the Archie Equation. This equation has been used to analyze resistivity responses of fluid-filled porous rocks for more than six decades in the form (Archie, 1942):

$$R = (aR_w\Phi^m)(S_w)^{-n}, \quad (1)$$

where R = resistivity of the logged interval (ohm-m), a = dimensionless parameter related to the grain shape, R_w = resistivity of the pore fluid (ohm-m), Φ = porosity (dimensionless fraction), m = dimensionless parameter related to grain cementation, S_w = water saturation (dimensionless fraction), and n = saturation exponent (a dimensionless parameter).

Parameters a , m , and n have to be empirically derived and adjusted to create optimal agreement between resistivity readings and independent knowledge of R_w , Φ , and S_w for a specific rock-fluid system. In typical oil and gas reservoir applications, a is ~ 1.0 , $n \sim 2$, and m usually ranges from 2.0 to 2.56.

There is limited experience in applying Archie's Equation to high-porosity, unconsolidated marine sediments found in deepwater, near-seafloor strata containing hydrates. For example, the values for cementation exponent m appear to be significantly lower

(as low as 1.2) in these environments than values used in the oil industry for sandstone reservoirs (2.56). Therefore, caution should be used when applying Archie's Equation for gas-hydrate concentration in unconsolidated, high-porosity sediments. Finding appropriate values for the empirical parameters of Archie's Equation can be challenging for deep-water sediments.

Theoretical approach: Hashin-Shtrikman bounds

In addition to the empirical Archie Equation, we can also use a theoretical approach to estimate the electrical properties of sediments containing gas hydrates. One approach is the Hashin-Shtrikman (1962) theoretical bounds on the electrical resistivity for composite materials.

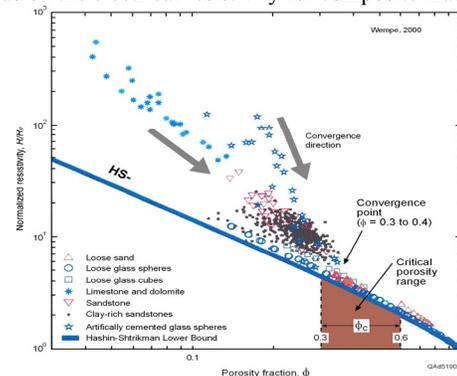


Figure 1: Crossplot of normalized resistivity (R/R_w) and porosity for laboratory tests and field-data observations that involve a wide range of conductive media (after Wempe, 2000). R is measured resistivity; R_w is the resistivity of the pore-filling fluid. The shaded interval Φ_c is the range of critical porosity for grains of different geometrical shapes. Note all data converge to the Hashin-Shtrikman Lower Bound as porosity increases and enters the critical-porosity range.

This theoretical approach helps us define the upper and lower bounds for electrical resistivity of sediments containing gas hydrate in various concentrations. A disadvantage of the method is that these bounds are widely separated, resulting in a large uncertainty about the electrical resistivity of the sediments. A study by Wempe (2000) shows that high-porosity, unconsolidated sediments near the critical-porosity regime are well described by the Hashin-Shtrikman Lower Bound. The data plotted in Fig. 1 include laboratory measurements and field data gleaned from 11 studies referenced by Wempe (2000). A key concept demonstrated by these data is that the resistivity behavior of all porous media converges to the Hashin-Shtrikman Lower Bound (HS-) when the porosity of the medium equals or exceeds critical porosity. Because the porosity of the deepwater, near-seafloor sediments that span the hydrate stability zone in our study area is close to critical porosity (Fig. 2), we are led to an important conclusion: *the Hashin-Shtrikman Lower Bound can be*

Electrical resistivity of sediments with gas hydrates

used to estimate the resistivity of deepwater, near-seafloor sediments.

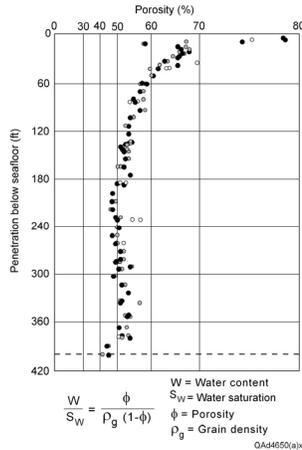


Figure 2: Porosity as a function of depth below seafloor derived from geotechnical data for one of the wells in the Green Canyon area, GOM.

Calibrating Archie's Equation using HS Lower Bound

As we have seen in the previous section, we propose that the electrical resistivity of the high-porosity sediments be modeled using the Hashin-Shtrikman Lower Bound. Therefore, for highly unconsolidated sediments close to the suspension regime, we can calibrate the empirical Archie Equation using the Hashin-Shtrikman Lower Bound.

The parameters in Archie's Equation should be chosen such that the electrical resistivity predicted by this empirical law agrees with the Hashin-Shtrikman Lower Bound. As Archie (1942) suggested, the internal geometric parameter "a" is approximately 1, while the cementation exponent "m" increases with the degree of cementation and compaction. Therefore, we keep the geometric parameter "a" fixed at a value of 1, and the saturation exponent "n" fixed at a value of 2 (Tiab and Donaldson, 1996), and then we determine the cementation exponent "m" such that the resistivity predicted by Archie's Eqn. is the same as the resistivity predicted by the HS Lower Bound for sediments 100% saturated with brine.

Once we introduce hydrates into the system, the initial porosity of the sediment will decrease with increasing gas-hydrate concentration, and the resistivity behavior of the sediment with hydrates will depart from the Hashin-Shtrikman Lower Bound. Our calibrated form of Archie's Equation is then used to estimate the gas-hydrate saturation.

Figure 3 shows the resistivity of sediments having uniformly dispersed hydrate as a function of gas-hydrate saturation in the pores. In this example, the sediments are represented by pure quartz grains, initially with a porosity of 40% and fully saturated with brine. We then theoretically add gas hydrates into the sediments and compute the resistivity of the composite using Hashin-Shtrikman Lower Bound and two Archie Equations based on two different choices for the cementation exponent "m." We observe that at 0% gas-hydrate saturation and for a value of cementation exponent $m=1.3$, the Archie Equation

(red curve) agrees with the Hashin-Shtrikman Lower Bound. However, if $m=2.56$, a value commonly used for sandstone reservoirs, then the Archie Equation (green curve) significantly differs from the Hashin-Shtrikman Lower Bound.

For a resistivity of 2 ohm.m (the horizontal dotted line), an Archie Equation with $m=2.56$ would predict 0% gas-hydrate concentration. However, if we use the value $m=1.3$ for the cementation exponent, which makes the Archie Equation agree with the Hashin-Shtrikman Lower Bound, then the gas-hydrate concentration is 43% of the pore space. Small values for the cementation exponent "m" for unconsolidated sediments are also observed by other authors who have studied marine sediments (Jackson et al., 1978; Mendelson and Cohen 1982).

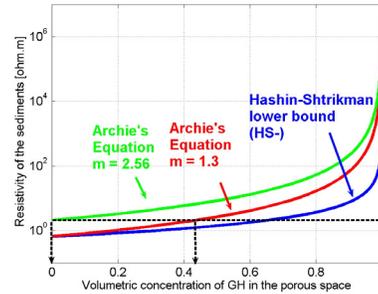


Figure 3: The Hashin-Shtrikman Lower Bound (HS-) and two formulations of the Archie Equation displayed as functions of resistivity of the sediment and the gas-hydrate fraction in the pore space.

From Figure 3 we observe that the resistivity response of sediments with gas hydrates is non-linear. At gas-hydrate concentrations up to 60% of the pore space, the increase in resistivity is relatively small.

Modified Archie Equation for volume of clay

Archie's Equation is an empirical law that was developed to determine water saturation in clean sands from measurements of resistivity and porosity across a sand-fluid mixture. When clay minerals are present in the sediments, Archie's Eqn. is no longer accurate. Because clay minerals may have significantly lower resistivity than clean sands, clays can have a large impact on the resistivity of a rock formation. If the presence of clay minerals is ignored and the simple form of Archie's Equation (Eq. 1) is applied to clay-rich sands, water saturation is overestimated. As a result, the saturation of any nonconductive phase in the pores will be underestimated.

Schlumberger Wireline & Testing (1998) proposed a simple modification to the Archie Equation that takes into account the presence of clay (Eq. 2). Key parameters required for implementing this modified equation are the volume of clay (V_{cl}) present in the sediments and the resistivity (R_{cl}) of the clay minerals. The volume of clay can be estimated from gamma-ray log data, and the resistivity of clay minerals can be measured in the laboratory. If no core samples are available for lab testing, we must use resistivity data measured across pure-clay intervals from nearby fields or rely on published resistivity measurements for clays in similar environments. These

Electrical resistivity of sediments with gas hydrates

information sources confirm R_{cl} spans a large range of 1 to 1000 ohm-m (Rider, 1986).

$$\frac{1}{R} = \frac{\phi^m}{aR_w(1-V_{cl})} S_w^n + \frac{V_{cl}}{R_{cl}} S_w^{n-1}. \quad (2)$$

Since marine sediments are usually clay-rich, we need to adjust the Archie Equation to account for the volume of clay. In our analysis we use Equation 2 to do this adjustment because the modified Archie Equation is claimed to be valid for several types of clay distributions (disseminated, structural, or layered).

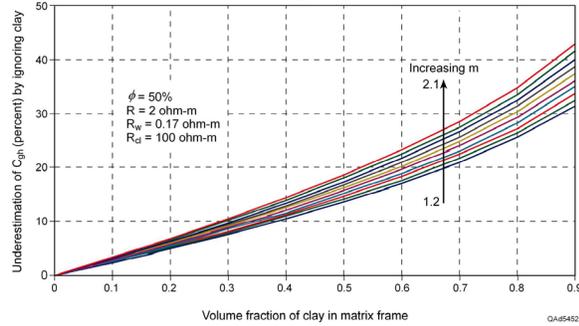


Figure 4: The difference between gas-hydrate concentration determined from the Archie Equation modified for clay content and gas-hydrate concentration derived using Archie's Equation for clean sands. The curves correspond to different values of the cementation exponent m . The arrow indicates the direction in which m increases from 1.2 to 2.2 in increments of 0.1. The figure shows the underestimation of gas-hydrate concentration that occurs when clay content is ignored. The sediment has a porosity of 50% and a log-measured resistivity of 2 ohm-m.

Figure 4 illustrates the difference between the gas-hydrate concentration estimated with the modified, clay-volume Archie Equation (Eq. 2) and the gas-hydrate concentration derived using Archie Equation for clean sands (Eq. 1). Each curve on the figure represents a different value for the cementation exponent “ m ”, from 1.2 (unconsolidated sediments) to 2.2 (more consolidated and compacted sediments). The difference between the two estimates shown in Figure 4 is due only to the presence of clay. This difference between the two estimations represents the magnitude of underestimating gas-hydrate concentration that will occur in porous seafloor sediment when we ignore clay. The results show that the error that results by ignoring clay increases with increasing volume of clay and with increasing cementation exponent. This behavior occurs because small values of “ m ” imply a highly unconsolidated medium for which the electrical current travels freely through the conductive brine phase. In such a medium, the conductivity of the clay in the matrix plays a less important role. When “ m ” increases (i.e. when the rock becomes better compacted and consolidated), the pathways for current through the brine are more obstructed, and the clay in the matrix plays a more important role in conducting the electrical current.

For larger values of “ m ,” ignoring clay in sediments introduces large errors in the estimation of gas-hydrate concentration in the pores. Even for small values of “ m ,” the errors in gas-hydrate estimation when clay content is ignored are significant, and increase with volume of clay.

Stochastic simulations for quantifying uncertainty

Most of the input parameters in Archie's Equation vary over a wide range and can be challenging to estimate. Many published gas-hydrate concentrations predicted from resistivity logs using Archie Equation's are represented in the literature by a single number, usually without a measure of uncertainty associated with the calculation. Also, these single-number results for gas-hydrate concentration can sometimes be inaccurate because the values of the input parameters used in the analyses may not be optimal choices. Therefore, estimates of gas-hydrate concentration should be based on a careful analysis of the possible range of variability of each input parameter, and the estimate should always be accompanied by a measure of uncertainty.

Our approach to estimating the uncertainty in gas-hydrate concentration from resistivity logs is based on stochastic simulations. We represent the input parameters used in the deterministic Archie Eqn. and in its modified version for clay content, by various probability distribution functions (PDFs). These PDFs express mathematically the fact that the parameters can vary and have uncertain values. The probability distribution functions that we use are either uniform distributions over the possible range of variability for each parameters, or Gaussian distributions. A uniform distribution assumes that any value for an input parameter is equally likely over the range of variability that is allowed, and it is appropriate when no other information is available to constrain the PDF. A Gaussian distribution suggests that the most likely value for the parameter is the mean of its Gaussian distribution, and that the variance of its distribution function is a measure of the uncertainty about that mean value. Therefore, each input parameter in Archie's Equation is represented not by a single number, but by a PDF (Fig. 5), which allows us to incorporate the inherent uncertainty about the inputs into the calculation of hydrate concentration.

After we express each of the input parameters through a PDF based on any available data and physical constraints, we run Monte Carlo simulations over these probability distribution functions. We randomly draw a set of values of R , R_w , Φ , a , m , V_{cl} , and R_{cl} and compute the gas-hydrate concentration using both Archie's Equations (Eq. 1 and 2). We repeat this procedure many times ($N > 5000$), and we obtain many realizations for gas-hydrate concentration at a certain sub-seafloor depth. The variability of our estimate for gas-hydrate concentration is caused by the inherent uncertainty of the parameters used in the Archie Equation. From this PDF for gas-hydrate concentration we derive our best estimate, expressed as the expected (mean) value.

Results

Figures 6 and 7 show results for gas-hydrate concentration estimated in two different wells. Gamma-ray and resistivity logs across these targeted intervals are displayed on the left panels. In each figure, the specific interval over which hydrate concentration was estimated is indicated by the bracket drawn along the right edge of the resistivity curve. Two estimates of hydrate concentration

Electrical resistivity of sediments with gas hydrates

were calculated for each interval. One estimate used the clay-free form of the Archie Equation (Eq. 1), and the other used the clay-dependent form (Eq. 2). The clay content was estimated from the Gamma-Ray log. The PDF of hydrate concentration produced by each form of the Archie Equation is identified on each figure on the right panels.

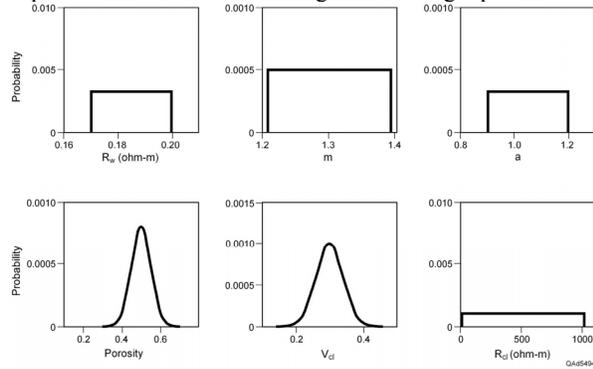


Figure 5. Example for the Probability Distribution Functions used to define the uncertainty of each parameter involved in the modified Archie Equation. Top panels: R_w , m , a . Bottom panels ϕ , V_{cl} , R_{cl} .

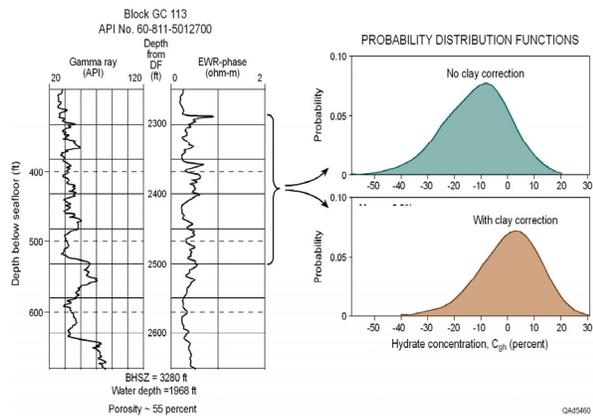


Figure 6: Hydrate concentration calculated in well A across depth interval 2,270 to 2,500 ft. The upper PDF results when the clay-free form of the Archie Equation (Eq. 1) is used. The lower PDF results when the clay-dependent form (Eq. 2) is used. The mean of the resistivity log readings across the interval is 0.35ohm-m. The average porosity is ~55%.

The example presented in Figure 6 corresponds to an interval in which the resistivity of the sediments is low ~ 0.35 ohm.m, where we do not expect gas hydrates to be present. In this example, the clay-free form of the Archie Equation yields a negative mean estimate of -12% for the hydrate concentration. In contrast, the clay-dependent form of the equation predicts a realistic value of less than 1 % concentration, suggesting no hydrate is present. The negative value predicted by the original Archie Equation is due to the fact that the clay content was ignored and illustrates the importance of accounting for clay content.

Figure 7 shows an example with a resistivity as high as 2 ohm.m in the interval selected. This increase in resistivity is assumed to be due to the presence of hydrate. Using stochastic simulations, we compute the probability

distribution functions for both no-clay and clay-dependent Archie's Equations. We see that for this relative small increase of resistivity, the gas-hydrate concentration is significant. For the simple Archie Equation (ignoring clay), the mean value for gas-hydrate concentration is 51% with a standard deviation of 4%. If we take into account the clay content, the mean gas-hydrate concentration is larger, equal to 59%, with a 3.7% standard deviation.

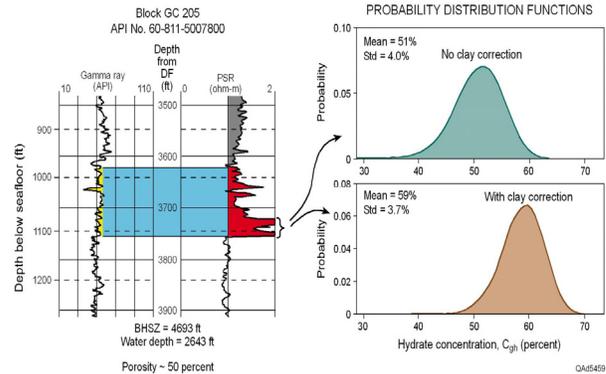


Figure 7. Hydrate concentration calculated in Well B across depth interval 3,720 to 3,760 ft. The upper PDF results when the clay-free form of the Archie Equation (Eq. 1) is used. The lower PDF results when the clay-dependent form (Eq. 2) is used. The mean reading of the resistivity log across this interval is 2 ohm-m. The average porosity is ~ 50 %.

Conclusions

We have presented a method of stochastic simulations and empirical laws for estimating gas-hydrate concentration and its associated uncertainty, based on resistivity logs acquired across unconsolidated, deepwater, near-seafloor strata. We show that for high-porosity, unconsolidated sediments, we can calibrate the Archie Equation using the Hashin-Shtrikman Lower Bound. We also present examples from deep-water near-seafloor strata from Green Canyon, GOM, and we emphasize the importance of using the clay-dependent form of the Archie Equation in clay-rich marine sediments. We also show that the resistivity behavior of the sediments with hydrates is highly nonlinear, and even for a relatively small increase in well-log resistivity (up to 2 ohm.m), the gas-hydrate concentration in such intervals can be as high as 60%. The stochastic approach helps us to understand and quantify the inherent uncertainty about gas-hydrate estimates.

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