ELECTRICAL RESISTIVITY MEASUREMENTS OF CH4 HYDRATE-BEARING SANDSTONE DURING FORMATION

Knut Arne Birkedal*, Geir Ersland, Lars Petter Øren Hauge, Arne Graue
Department of Physics and Technology
University of Bergen
NORWAY

Keith Hester, Jim Stevens, James Howard
ConocoPhillips
Bartlesville, OK
USA

ABSTRACT
Resistivity measurements are acquired during and after drilling wells through hydrate-bearing intervals and are often used in correlation with other logs to determine gas hydrate concentrations. In order to properly interpret the acquired data reliable calibration data are needed. Resistivity changes during hydrate formation can also give insights into how and where the hydrate forms in the pore space, and can be used to build permeability correlations. Electrical resistivity measurements were performed on sandstone cores during methane hydrate formation under differing conditions of initial water saturation and brine composition. A two-electrode sample holder was designed to fit inside a magnetic resonance imager in order to take advantage of its monitoring capabilities. Hydrate saturation was determined from the quantity of liquid water still present in the core. A four-electrode system was used without imaging possibilities, and the agreement between the two setups was good. $R_0$ was measured on this system using a range of salinities. The two-electrode system worked well during hydrate formation with little variation in phase angle that result from changes in electrode contact with the sample. In all cases, an initial decrease in resistivity was observed at the beginning of hydrate formation. This was likely due to ion exclusion during hydrate formation that initially reduced the brine’s resistance. This effect was less pronounced at higher initial water salinity values. As hydrate continued to form, reduced pore connectivity and increased tortuosity through the core led to a significant increase in resistivity. Resistivity values were higher than what have been reported by others. The interpretation of Archie’s Formation Factor and Resistivity Index was problematic. The saturation exponent was found to be lower than expected in all of the experiments performed. Dynamic $R_w$ and $R_0$ values were incorporated into Archie’s equations to account for changes in brine composition during hydrate formation. Based on this study we propose that Archie’s basic model needs to be modified to account for chemical changes during hydrate growth.

Keywords: gas hydrates, resistivity, MRI

* Corresponding author: Phone: +47 55588419, Fax +47 55589440, E-mail: knut.birkedal@ift.uib.no
NOMENCLATURE
A Cross sectional area \([m^2]\)
a Tortuosity factor
C Ion content \([ppm]\)
F Formation factor
L Length \([m]\)
m Cementation exponent
n Saturation exponent
R_t Bulk resistivity \([\Omega m]\)
R_w Resistivity of brine \([\Omega m]\)
R_0 Resistivity of rock filled with brine \([\Omega m]\)
RI Resistivity Index \([\text{fraction}]\)
S_h Hydrate saturation \([\text{fraction of pore space}]\)
S_w Water saturation \([\text{fraction of pore space}]\)
Z Impedance \([\Omega]\)
φ Porosity \([\text{fraction}]\)
ϕ Phase angle \([°]\)

INTRODUCTION
Natural gas hydrate is a solid solution of gas and water formed under high pressure and low temperature where the water molecules connect through hydrogen bonding and encapsulate a guest molecule. Gas hydrates are known to the oil and gas industry to form hydrate plugs in production lines, and significant investments have been made in research on flow assurance. As the global energy demand increases focus is shifted towards gas hydrates as a potential energy resource. Estimates suggest that the energy stored in gas hydrates in the earth is vast and in the same order of magnitude as conventional hydrocarbon resources [1].

Resistivity logging is used, often supplemented with acoustic logging, to determine the presence and estimate saturations of gas hydrate. In order to achieve better field data interpretation and more reliable predictions, controlled laboratory measurements are needed. The electrical properties of hydrate bearing sediments change with mineralogy, porosity, hydrate saturation, brine salinity, and mobility of the formation brine. During hydrate formation water molecules are interconnected through hydrogen bonding and form polyhedral cavities. Extensive hydrogen bonding reduces the water-molecule polarizability which in turn affects the electrical conductivity [2]. During hydrate formation only water and gas are consumed in the hydrate crystal, resulting in displacement of salt previously dissolved in the water. A salinity gradient will therefore be present at the hydrate formation front, where the salt concentration will increase as gas hydrates form. Increasing salt ion concentration increases the conductivity of the remaining pore fluid, but with lower brine saturation the conducting paths become more tortuous and the conductivity decrease.

The resistivity is found from

\[ R_t = \frac{Z A}{L} \cos(\phi), \quad (1) \]

where \( R_t \) is the bulk resistivity \((\Omega m)\), \( Z \) is the measured impedance \((\Omega)\), \( A \) is the cross sectional area of the sample \((m^2)\), \( L \) is the distance between electrodes \((m)\), and \( \phi \) is the phase angle. A series of empirical rules are used to evaluate the fundamental correlation between porosity and saturation for porous media partial or entirely filled with brine [3]. The formation factor \( F \) relates empirically to porosity through

\[ F = \frac{R_0}{R_w} = a \phi^{-m}, \quad (2) \]

where \( R_0 \) is the resistivity of a fully water saturated sample, \( R_w \) is the resistivity of the brine, \( \phi \) is the porosity of the sediment, \( m \) is the cementation exponent and \( a \) is the tortuosity factor. \( R_w \) can be calculated using a standard conversion [4]

\[ R_w = 0.0123 + \frac{3647.5}{[C]^{0.955}}, \quad (3) \]

where \( C \) is the ion content of brine \((ppm)\). The \( R_w \) value can be corrected for temperature change using Arps formula [5]

\[ R_w(2) = R_w(1) \frac{(T_1 + 21.5)}{(T_2 + 21.5)}, \quad (4) \]

where \( T_1 \) is room temperature \((°C)\) and \( T_2 \) is sample temperature \((°C)\).

Another useful empirical relation from Archie applies to sediments partially saturated with a nonconductive material (such as oil, gas, or hydrate). The Resistivity Index is defined as
where $R_t$ is the measured bulk resistivity, $S_w$ is the water saturation, and $n$ is the saturation exponent. During hydrate formation the ion content $C$ changes in the remaining pore water. The basic Archie resistivity model does not consider changes in brine composition. In order to relate resistivity to saturations during hydrate growth one has to correct for chemical changes of the formation water. $R_w$ was calculated based on initial salt content and saturation changes and was used to calculate the formation factor at each saturation step.

**EXPERIMENTAL DESCRIPTION**

In laboratory electrical resistivity measurements two- and four-electrode systems are typically used to monitor resistivity changes. Both configurations have been used to monitor the performance of samples partially saturated with gas hydrate in this study. According to Bona et al. [6] a two contact system is preferable for higher frequencies (10-100 kHz), while a four-electrode system is preferable at 1 kHz.

**Experimental setups**

The first setup took advantage of a superconducting 2T MRI that could spatially resolve hydrate growth pattern and water saturation. A custom-made core holder with fiber glass housing was used to ensure compatibility with the high magnetic field. Silver filter paper, contacting both trans-axial core faces, was used as electrodes in the MRI system (Figure 1). Polyoxymethylene (POM) spacers were used to increase the contact area between the core and the injected fluids. The electrodes were connected to an LCR meter which logged resistivity and phase angle every 11 seconds with frequencies ranging between 100 Hz and 100 kHz. An accurate high-pressure pump controlled injection of methane. Fluorinert FC-40 was used as the confining fluid as it contains no hydrogen and minimizes RF loss due to its low dielectric properties. The system temperature was held constant at 4.0 ± 0.1 ºC by circulating cooled confining fluid under pressure in lines inside a low-pressure PVC jacket that worked as an additional cooling loop outside the MRI. During the experiment, the confining pressure was kept near 10.5 MPa and pore pressure at 8.37 MPa.

Hydrogen in methane and water was detected by a standard MRI spin echo sequence. Hydrate formation was detected as drop in MRI intensity as signal from hydrogen in solid hydrate has a very short lifetime which is not captured by spin echo measurements. MRI provided a tool for 3D monitoring of water saturation and hydrate growth pattern with time. The MRI acquired a full 3D saturation image in 2 hours and 17 minutes and ran continuously during days or weeks of hydrate formation.

The second experimental setup was a four-electrode system that bypasses the contact impedance between the current electrodes and sample. The core holder (Figure 2) was equipped with a floating distribution plug which allowed radial and axial confining stress. The inner end piece faces were coated with a high conductivity silver layer contacting the trans-axial core faces. Due to high conductance the capacitive reactance...
Figure 2: Four electrode core holder used for hydrate resistivity measurements. Experiments conducted on this setup did not have the benefit of additional MRI data. Two wires are situated in the sleeve where the electrical potential was measured. By using a four-electrode system it was possible to bypass the capacitive reactance. (the imaginary part of the impedance) is low and does not affect the measured resistivity. The sleeve is equipped with two electrode rings with one inch spacing. These were connected to an LCR meter that measured resistivity every minute using 1 kHz and 1 V, which should give low error in the measurement [6]. Resistivity measurements on four-electrode systems have been further described in detail elsewhere [7]. The core holder was equipped with a cooling jacket where cooled antifreeze circulated to maintain temperature at 4 ± 0.3 °C. High sensitivity pumps were used to maintain pore pressure. PVT data were logged and provided volume information to calculate water saturation based on methane consumption during hydrate formation.

Properties of porous media
Bentheim sandstone samples were used for all experiments due to its homogeneity, uniform porosity (22-24%) and high permeability (1.1D). Bentheim sandstone has a grain density of 2.64 g/cm³, and the mineralogy showed 99% quartz content with trace of the clay mineral kaolinite.

Experimental procedure
Each core was saturated with brine with a NaCl concentration ranging between 0.1 wt% and 3.5 wt% ranging from fully saturated (1.0) to partial water saturations of 0.3 (see Table 1). In the latter case methane gas occupied the remaining pore volume. The experiments are therefore all excess gas experiments, except for the R₀ measurements and one hydrate formation experiment that began with an initially fully water saturated core. The sample was placed inside a high pressure cell and the contact electrodes were saturated with water to minimize contact impedance. Experiments in the MRI confirmed fairly uniform initial water saturation. While no confirmation of uniformity was possible in setup 2 due to lack of imaging, the cores were saturated with a similar technique (spontaneous imbibition and/or vacuum desaturation). The confining and pore pressures were incrementally increased from atmospheric to about 10.5 MPa and 8.37 MPa respectively. The system was then cooled to 4 °C, well within the hydrate stable region. Hydrate growth was detected by a drop in MRI intensity, loss in pump volume as methane was consumed, and changes in resistivity.

RESULTS AND DISCUSSION
R₀ measurements
A series of R₀ measurements experiments were conducted, using 5 different salinities: 0.1, 1, 2, 3 and 3.5 wt% NaCl (see Figure 3). The main purpose was to acquire resistivity data at 4 °C for later calculation of formation factor and resistivity index. At lower initial salinities the measurement was more sensitive to heterogeneities in the core, as less free ions are available to conduct charge. For 1 and 2 wt% NaCl, the reproducibility between measurements was very good. Archie’s laws assume that the rock matrix is non-conductive, which is not the case for samples with high clay content where surface chemical effects will affect the conductivity. The zero intercept and linear trend in Figure 4 shows a clean and well-behaved Bentheim sample. Presence of clay would result in a curved shape due to charge transport contribution from the sediment itself (i.e. [8]).

Figure 3: Resistivity for fully saturated samples at 4 °C.
Figure 4: Conductivity of fully saturated samples at 4 °C plotted as a function of calculated formation water conductivity. A linear trend and zero intercept indicates clean and well-behaved core sample.

**Impedance**

The next step was to map how hydrate formation affects the resistivity of the sample. The resistivity is given by Equation 1, where impedance and phase angle were determined through measurements. The measured impedance ranges from 170 to 185,000 Ω and is dependent upon both the resistance and the inductive reactance. Inductive reactance will shift the voltage and current out of phase. If the impedance and phase angle are known, both resistance and inductive reactance can be calculated. Impedance and phase angle were logged continuously for the two-electrode setup, as shown in Figure 5. Based on these values resistivity is calculated using Equation 1. Core data and resistivity values for all seven experiments are displayed in Table 1. Some experiments were run with similar initial conditions to determine the reproducibility and strength of resistivity as an imaging tool. Part of the motivation was also to determine how differing initial conditions (salinity and saturation) would affect the resistivity. Experiments supported by MRI data are emphasized in this paper in the analysis due to accurate saturation data. However, the general agreement between all experiments was good.

**Resistivity**

Significant resistivity increase was observed as gas hydrates formed and the conductive brine saturation decreased. Salt is excluded from the more organized hydrogen bonding associated with hydrate formation as there is no space to accommodate the salt ions. At the initiation of growth a noticeable drop in resistivity was observed for all experiments. This is believed to be due to increased salt concentration of the remaining brine. Similar resistivity drops were reported by Liu et al. [9] where a following steep resistivity increase was observed for hydrate saturations above 0.2. In Figure 6 resistivity initially drops at the onset of hydrate formation (after 1.2 hours) and increases after reaching a hydrate saturation of approximately 0.15. This effect was detectable but less pronounced for higher initial salinities, where an almost immediate increase was observed, as shown in Figure 7.

<table>
<thead>
<tr>
<th>Test</th>
<th>Length [cm]</th>
<th>Diam. [cm]</th>
<th>Salinity [wt%]</th>
<th>Sw</th>
<th>Initial $R_t$ [$Ωm$]</th>
<th>Final $R_t$ [$Ωm$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2-1</td>
<td>9.99</td>
<td>3.78</td>
<td>0.1</td>
<td>1</td>
<td>169.5</td>
<td>456.3</td>
</tr>
<tr>
<td>2-2</td>
<td>9.99</td>
<td>3.78</td>
<td>0.1</td>
<td>0.80</td>
<td>175.3</td>
<td>563.1</td>
</tr>
<tr>
<td>2-3</td>
<td>9.99</td>
<td>3.78</td>
<td>0.1</td>
<td>0.80</td>
<td>267.6</td>
<td>467.7</td>
</tr>
<tr>
<td>2-4</td>
<td>10.01</td>
<td>3.74</td>
<td>3.5</td>
<td>0.49</td>
<td>19.5</td>
<td>177.5</td>
</tr>
<tr>
<td>4-1</td>
<td>15.00</td>
<td>5.09</td>
<td>0.1</td>
<td>0.29</td>
<td>493.3</td>
<td>2486.8</td>
</tr>
<tr>
<td>4-2</td>
<td>14.48</td>
<td>5.04</td>
<td>3.5</td>
<td>0.67</td>
<td>7.4</td>
<td>45.0</td>
</tr>
<tr>
<td>4-3</td>
<td>14.20</td>
<td>5.06</td>
<td>3.5</td>
<td>0.52</td>
<td>12.5</td>
<td>123.4</td>
</tr>
</tbody>
</table>

Table 1. Core data and resistivity experiments

Figure 6: Progression of impedance and phase angle with time during hydrate formation for experiment 2-4. Phase angle remained low during the experiment. This indicates that the measured impedance is not as affected by the inductive reactance and the conductivity at the end surfaces is good.

---

1 Number prefix indicates the electrode arrangement of the experimental setup.
Figure 6: Hydrate formation causes a drop in resistivity and methane delivery from the pump at the onset of hydrate formation (after 1.2 hours). This is believed to be an effect of salt exclusion during hydrate formation, increasing the conductivity of the formation water at early stages of formation.

Figure 7: Hydrate formation causes a temporary resistivity drop at the onset of hydrate formation (after 1.22 hours). The resistivity then increase and stabilize at similar value as prior to hydrate growth.

Figure 8: Comparison of CH₄ consumption, resistivity and inverted MRI intensity for experiment 2-4 with S_w=0.49 (3.5 wt% NaCl). Resistivity remained relatively low until the hydrate saturation reached 0.13. The connectivity of the conductive water film was not as affected by hydrate growth prior to ~18 hours. This may be explained by initial hydrate growth on the gas/water-interface that not significantly altered the conducting water path. For increasing hydrate saturation the saturation and tortuosity changed, which caused a resistivity increase. The general agreement between trends of MRI, resistivity and methane consumption was good after 30 hours.

One of the benefits of MRI is that it is possible to isolate selected regions of the core and monitor phase transitions on a smaller scale. Figure 9 shows how a wormhole-like water path appeared during hydrate formation in experiment 2-3. The hydrate growth pattern will affect the bulk resistivity measurement and vary between samples with different growth pattern, as discussed in later sections.

Part of the motivation of this study was to determine the robustness of resistivity as an additional measure of saturation duringhydrate formation. Figure 8 compares data from pump log, normalized and inverted MRI intensity and resistivity for sample 2-4. Because MRI Intensity drops as water form a solid hydrate it is inverted for direct comparison with resistivity and methane consumption data. Hydrate formation was detected as methane consumption and drop in resistivity. The MRI magnetization is sensitive to temperature and the inverted intensity therefore drops as the temperature continues to decrease, despite hydrate growth. Further hydrate growth is detected in both methane consumption and MRI intensity, while
Figure 9: The MRI is sensitive to hydrogen and is therefore a useful tool for monitoring hydrate phase transitions inside the sample. a) shows sample 2-3 with $S_{wi}=0.8$ prior to hydrate formation. As hydrate forms the relaxation time is reduced and hydrogen spins in the crystal lattice is no longer detected. At the end of hydrate formation a wormhole was clearly visible, as shown in b). The two circular shapes in b) is bulk methane occupying the POM spacers.

Impact of frequency

As $R_t$ is essential when determining the resistivity index and saturation exponent $n$, it is important to keep in mind how different frequencies impact the measurement, especially in a logging scenario. Six different frequencies were used to measure resistivity on the two-electrode setup. Figure 10 compares the resistivity of the different frequencies. The fluctuation level for lower and higher frequencies increased during hydrate formation, but remained relatively small for 1 kHz. Resistivity dispersion was observed as the saturation and shape of non-conductive hydrate changed. Dielectric dispersion is frequency dependent and often divided into two domains; the sub 1 kHz domain and the higher frequency domain above 1 kHz. Lower frequencies are used to indicate fractures, while higher frequencies are affected by pore shape and non-conductive phases occupying the pore space [10]. For lower frequencies the charge travels for a longer period of time. The probability of pore wall interactions of ionic charges therefore increases, thus increasing the bulk resistance to flow. For higher frequencies the ions travel a shorter distance before the current alternates and will therefore collide less frequently [7]. Resistivity dispersion was observed after hydrate saturation reached a level where it significantly affected the size and shape of the conductive pathway. A general but relatively minor resistivity decrease was observed for increasing frequencies. This was most pronounced at 100 kHz, where the resistivity was 7.73 $\Omega$m (4.4 %) lower than for 1 kHz. Frequencies between 100 and 20 kHz gave the same $R_t$ within 1.1 %.

Resistivity comparison

A selection of resistivity data are presented and compared in Figure 11. The experiments differ in initial conditions (see Table 1 for core details), which is also reflected in the graph. Initial brine composition was shown to have a more significant impact on the resistivity than initial saturations. The two experiments with 0.1 wt% NaCl had approximately similar initial resistivities, but the lower saturation core was less affected by hydrate growth. This is believed to be a result of differences in hydrate growth pattern. No significant resistivity impact was observed for hydrate saturations below 0.2.

The measured values are quite high, especially when compared to previous reported values in hydrate bearing sediments, but it is important to...
keep in mind that most samples in this study are occupied by excess free gas. Earlier reported values differ by two orders of magnitude, most in the lower 1-13 Ωm range [11-16]. These values are based on in situ measurements and sandpacks. Resistivities exceeding 100 Ωm have also been reported [17-19]. Although the measured values in this study are high compared with past studies, they are consistent.

Resistivity measurements during hydrate formation are often described as replacement of conductive brine by non-conductive hydrate. Resistivity will therefore be affected by changes in saturation and tortuosity. One key assumption in Archie’s law is that the pore volume remains constant and conductive brine is replaced by non-conductive fluids such as oil or gas. During hydrate formation the conductive brine is replaced by gas hydrate which will cause a decrease in pore volume if we assume that the solid hydrate has similar properties as the matrix. In addition we have to keep in mind that the chemical composition of the remaining brine will change as gas hydrates form. This will have a significant impact on the measured resistivity and should therefore be considered in hydrate resistivity measurements.

Physical properties of the hydrate bearing sediment is sensitive to the hydrate growth pattern [20]. Differences in saturation method may cause a different growth pattern. In nature, hydrate formation typically takes place as methane saturated water migrates into the hydrate stable region. Considering the hydration number of methane hydrate (5.99) [21] and the solubility of methane in water (750 moles of water per mole of methane at 4 °C [22]) it is evident that this is a slow process. Most samples in this study were partially saturated with water and methane. Water is the wetting phase and resides along the pore walls, preferably occupying smaller pores due to capillary forces. Presence of methane in larger pores will therefore increase the effective charge travel length, resulting in high initial resistivity. Hydrate formation will mainly occur at the interface between the two fluids in this scenario [23].

Archie’s laws are only applicable as long as the matrix is non-conductive. The $R_0$ measurement indicated clean and well-behaved samples, but also revealed that the $R_0$ resistivity is higher than what is generally reported for $R_t$. This may be explained by differences in sediment properties. Gas hydrates are typically found in unconsolidated sediments where presence of hydrate has inhibited further consolidation and cementation. The initial cementation factor is therefore low, resulting in low resistivity. Shale layers are also reported in hydrate bearing sediments. Hydrate formation in shale is typically inhibited due to extensive capillary pressure. Charge transport in brine and the contribution of negative surface charge of clay minerals will therefore increase the conductivity.

**Effective porosity from Formation Factor**

Porosity and hydrocarbon saturation are usually the target for different logging suites. Porosity is related to the ratio of $R_0$ and $R_w$, which is referred to as the formation factor (Equation 2). Hydrate formation is commonly described as replacement of conductive saline pore fluid by non-conductive material with similar properties as the matrix itself [14, 24]. The effective porosity will therefore decrease due to hydrate formation. This is reflected in increased formation factor. However, one has to keep in mind that salt exclusion will have a significant impact on $R_w$ and $R_0$. Because both porosity and $R_w$ is affected by hydrate growth the latter has to be incorporated in the equation for formation factor. Figure 12 shows a comparison for experiment 2-1, where formation factor has been calculated based on both static and dynamic $R_w$ values. $R_w$ was not measured in this study and was therefore calculated based on initial salt content. The dynamic $R_w$ also considered changes in $S_w$, based on changes in MRI intensity. The
effective porosity \( (\phi_{\text{eff}} = \phi (1 - S_h)) \) was calculated based on changes in MRI intensity. The residual effective pore volume remained occupied by brine, and the measured resistivity was therefore \( R_0 \). From these results it is obvious that the apparent resistivity is impacted by increased salt concentration of the formation water. This effect becomes more significant as the effective porosity and amount of free water is reduced. In order to isolate the effect of gas hydrate on resistivity it is necessary to correct for brine changes. These results indicate that Archie needs to be modified to incorporate chemical changes occurring during hydrate formation.

The empirical Archie parameter was unknown in this study and for practical reasons set to unity. The cementation factor \( m \) in Equation 2 will vary with the interconnectivity of the pores and is believed to change as gas hydrates form. The average \( m \) based on the dynamic formation factor was 1.92. Figure 13 compares effective porosity based on data from MRI and porosities calculated through Equation 2 for three different cementation factors. Formation factor porosities based on dynamic and static \( R_w \) data are shown for comparison. The dynamic approach shows better correlation with the actual effective porosity (within 1.7%). The static approach has high error, in particular for highhydrate saturation (low effective porosity). Because the tortuosity and cementation factor change during hydrate growth, the static values either under- or overestimate the effective porosity. A future resistivity model should therefore also adopt a dynamic cementation factor \( m \) in order to display better correlation between formation factor and effective porosity.

### Saturation from Resistivity Index

In order to establish the fraction of pore space occupied by hydrocarbons it is essential to determine the water saturation. If the sediments are partially occupied by non-conductive fluids, such as gas or hydrate, the measured resistivity is often converted into the more convenient Resistivity Index (RI). RI from this study is plotted in Figure 14. The experimental results can be divided into two groups, where the first group includes data from experiments 2-1, 2-2, 2-3 and 4-1. The first group is consistent despite differences in initial saturation and salinity. Experiments 2-4, 4-2 and 4-3 show a different trend. The initial RI is within the range of the first group, but as hydrate form a steep resistivity increase was observed. The resistivity reaches a plateau, where little further resistivity increase was observed despite continued hydrate formation. The reason for this sharp resistivity increase is similar to what is observed for oil-wet cores where oil starts to block pore throats at low saturations (i.e. [8]). The equivalent in a hydrate system would be hydrate plugging of pore throats. MRI data in
Figure 15 show substantial differences in growth habit between the two groups. Hydrate formation had a front-like movement where almost all of the free water was converted into gas hydrates behind the front. The impact on local resistivity is therefore extensive, even though residual water is still present in other parts of the core. Accurate estimates of saturation from RI measurements will therefore be hard to establish in regions with a heterogeneous saturation distribution.

Sediment wettability will have a significant impact on resistivity in conventional reservoirs, and the saturation index $n$ therefore needs to be determined. $n$ may be determined based on the slope of the curve in Figure 14 or by using Equation 5 for each saturation step. According to this data $n$ was less than 1 for the different experiments. For a clean and uniformly water-wet sample the saturation index is expected to be 2 ($\pm 0.5$) even as the core is drained to $S_w$.

**Figure 14:** Resistivity Index plotted as a function of water saturation. The data can be divided into two groups. The first group followed an approximately linear trend where the value of the saturation exponent $n$ was less than 1. The second group had a varying saturation exponent with a dramatic resistivity increase over a small saturation range. Based on MRI data this may be explained by front-like growth, where local hydrate growth contributed to significant resistivity increases even for smaller saturation changes.

**Figure 15:** Comparison of hydrate growth pattern for experiment 2-4 (upper) and 2-2 (lower). The upper images are sagittal slices of the core while the lower circular images show transverse slices at different positions along the core’s length. Red represents higher MRI intensities (more brine), while blue is low. It was observed that the 2-4 experiment had piston-like growth pattern, moving from left to right. This was observed throughout the experiment. In the lower experiment hydrate formed in a relatively uniform pattern.
Modifying Archie’s Equation

The chemical composition of the formation water will change continuously during hydrate formation. This change inflicts significant impact on the resistivity, as established in the formation factor section. Archie’s Resistivity Index does not account for salt concentration changes occurring during hydrate formation. This may explain the low saturation exponent values. A function that considers the specimens response to salinity change was acquired through the $R_0$ experiments. A dynamic $R_0^*$ was implemented into the Archie equation, where chemical composition and subsequent resistivity changes for each time step. The expression used for a dynamic Resistivity Index is given as

$$R_0^* = \frac{R_t}{R_0} = \frac{R_t}{16.176 \left( \frac{C}{10000} \right)^{1.04}}$$  \hspace{1cm} (6)$$

and plotted in Figure 16. Using a dynamic $R_0^*$ caused a general increase in calculated RI. The saturation exponent was consequently shifted from below 1 to more reasonable values ranging between 1.6 and 2.

![Figure 16: Resistivity Index plotted using a dynamic $R_0$ to account for changes in salinity during hydrate formation. The saturation index was shifted from below 1 to a more reasonable value between 1.6 and 2.](image)

CONCLUSIONS

Two different experimental resistivity setups have been designed and built. The agreement between the two systems was good. According to literature, four-electrode setups are preferable, especially at 1 kHz. We found that the two-electrode setup provided less noise, especially data acquired at 1 kHz.

A resistivity drop was detected at the onset of hydrate formation. Resistivity therefore provides an additional means of detecting initiation of hydrate growth.

Resistivity data were compared to MRI intensity and methane consumption. The agreement between trends was generally good.

Porosity from formation factor was plotted as a function of effective porosity from MRI, and indicated that a dynamic $R_w$ should be included in the Archie model to account for changes in salt concentration during hydrate growth. The measured cementation factor changed during hydrate growth, but within earlier reported values for sandstone. In a future resistivity model a dynamic $m$ should be incorporated. The effective porosity was either under- or overestimated for different static cementation factors.

Resistivity index measurements may provide an additional approach of determining brine saturation. A dynamic relationship for $R_0$ was incorporated for water saturation estimates. However, large differences in resistivity progression were observed during hydrate formation. This is assumed to be an effect of inhomogeneous growth which causes large resistance locally. Resistivity measurements may therefore not be suitable for saturation estimation in regions with heterogeneous water saturation and/or distribution within pores.

ACKNOWLEDGEMENTS

Several of the authors are indebted for financial support from the Norwegian Research Council and ConocoPhillips. The authors acknowledge the permission from ConocoPhillips to publish this work. We also acknowledge the contribution from David Kennouche and Jérôme Lelong on the $R_0$ experiments.
REFERENCES
[16] Collett, TS & Ladd, J. Detection of gas hydrate with downhole logs and assessment of gas hydrate concentration (saturations) and gas volumes on the Blake ridge with electrical resistivity log data, College Station, TX: 2000.