652
Extracting Formation Connate Water Salinity from Multi-frequency Dielectric Measurement

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ABSTRACT

One basic challenge to multi-frequency dielectric logging is the shallow depth of investigation (DOI) from the wellbore. In the case of drilling with a water-based mud (WBM), we anticipate a mixing process of the miscible phases; formation water and the drilling fluid filtrate, making the dielectric data interpretation for water-filled porosity and saturating water salinity not representing the formation values. This work aims to study the impact of mixed salinity water on dielectric data and how to determine formation water salinity from filtrate invaded formations.

In this study we evaluated the effect of mixing different brines with controlled volume proportions on dielectric data of both bulk fluid measurement and saturated core plugs. We used two different outcrops; high permeability sandstone and moderate permeability limestone. The range of salinity studied is between 10 and 200 kppm NaCl. Dielectric measurements are obtained, using a coaxial probe operating between 10 MHz and 1 GHz, on bulk brine fluids and on saturated core plugs with formation water of 200 kppm NaCl flooded by low salinity brines at different pore volumes. We have modeled the dielectric response of the resultant mixed salinity brine using a water dielectric model and simple mass balance equation to compute the dielectric constant of the mixed brine with knowledge of the two brines salinities and their volume ratios. We established a data set for different pair of brines with different salinities using resultant mixed brine dielectric constant versus volume ratio. Such data sets can be utilized with knowledge of the invading brine salinity and obtained dielectric measurement at two or more mixing conditions or invasion ratios to determine unknown formation brine salinity.

From the measurements of fully formation water saturated plugs invaded by a low salinity brine, we found a rapid formation water displacement process of the miscible phases making the dielectric probe only observes the invading brine on the moderate permeability limestone. For the high permeability sandstone, the formation water displacement occurred in slower manner allowing the miscible phases mixing and showing a brine salinity intermediate between formation and invading brines. For the bulk mixing brines experiments, we found agreement between the bulk dielectric measurements and the established data set from applied water models at different volume mixing ratios. We found with the knowledge of salinity of invading brine and incremental invasion proportional volume on at least two set of

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measurement, we could estimate the formation brine salinity using synthetic data sets generated from dielectric water model of different brines mixtures. We applied this method to two wells using dielectric log data where WBM invasion is significant at three different DOIs and the estimated formation brine salinity is reasonable.

This work shows how to estimate formation water salinity on a formation exhibited a mixed salinity water flooding from dielectric logs. This parameter as determined downhole continuously can reduce saturation calculation from resistivity data for enhanced formation evaluation.

EXTENDED ABSTRACT

Introduction

Dielectric logging is well known by its shallow depth of investigation (DOI). It has been shown on the latest multi-frequency dielectric technology development that the DOI could have a range from 1.5 to 8.3 inches. At these depths we are expecting to evaluate the mud filtrate invaded and transition zones in most conditions. In the case of a water-based mud (WBM) system, mixing between connate water and the WBM filtrate will occur, making the connate water difficult to be characterized, Figure 1.

Dielectric measurements are known to be sensitive to the water phase volume, for water filled porosity is the primary deliverable of such measurements. Existing dielectric data interpretation models are used to invert multi-frequency dielectric data in a formation and obtain water-filled porosity, apparent water-phase tortuosity and apparent water salinity. The inverted water salinity was shown to be accurate from almost fresh water salinity up to 70 kppm equivalent NaCl salinity (Forgsang et al. 2019: Zhang et al. 2021). Having the water salinity as an unknown may increase the uncertainty of water-filled porosity estimation especially in a mixed salinity environment where the salt concentration of the drilling fluid is usually different from that of connate brine. Thus, estimating the apparent salinity of mixed brine and connate water is challenging.

In this study, we aim to solve the issue of mixed salinity formation brine with multi-frequency dielectric data and develop a workflow to estimate the apparent mixed brine and connate water salinity and saturation. An experimental study is planned to investigate the effect of mixing different brines salinities of different proportions on bulk fluid dielectric measurements; opening up the research to explore the feasibility of using dielectric data to evaluate mixed-salinity formations at particial reservoir saturations.

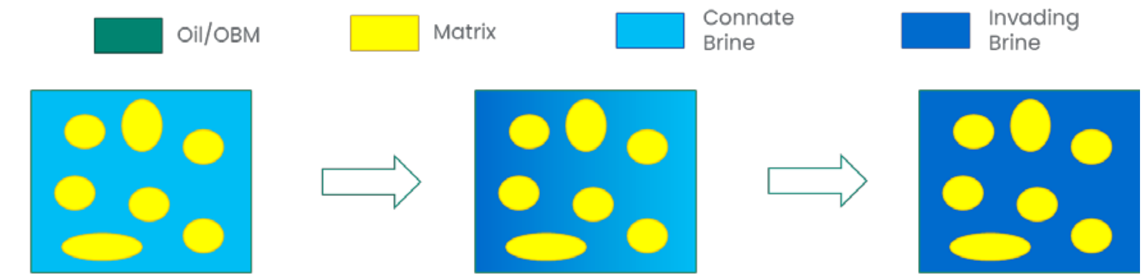

Figure 1 Arbitrary Rock Model with Mixed Salinity Brines Process

Methodology

A. Bulk Brine Dielectric Measurement

Different brines were prepared at different salinities between 10 and 200 kppm NaCl by mixing de-ionized water with NaCl salt powder. Also, different brines with different ions compositions were prepared, CaCl2 and KCl, to assess the ions influence on dielectric measurements. The brine samples were measured by a dielectric open-ended coaxial probe specially designed for fluid measurements at different temperature and pressure conditions, Figure 2.

The probe is provided by Keysight (model N1501A) and measures the reflection coefficient of the material attached to its aperture. The measurement frequency range is between 500 MHz and 3 GHz. The probe is connected to an acquisition system (Impedance Analyzer with installed software, N1500A materials measurement suite) which converts the reflection coefficient to complex dielectric constant ε^* as:

$$\varepsilon^*(\omega) = \varepsilon_r'(\omega) + i\varepsilon_r''(\omega) = \varepsilon_r'(\omega) + i\frac{\sigma(\omega)}{\omega\varepsilon_0} \qquad (1)$$

Where ε_r' is the real dielectric constant, ε_r'' is the imaginary dielectric constant, ω is the angular frequency in (rad/second), σ ($\sigma = 1/R_t$) is the conductivity in (Siemens/m) and ε_0 is the free-space dielectric constant which is 8.854x10^{-12} (Farads/m2).

In this work, we obtained dielectric measurements at atmospheric pressure and temperature with the probe being calibrated with de-ionized water. During the measurement, the probe is immersed in a fluid with at least 5 mm space between the probe surface and fluid container's wall to avoid any boundary effect to the probe. As a good practice to obtain a reliable measurement, the probe is vibrated to eliminate air bubbles setting at the probe's surface. Such air bubbles could reduce the measured dielectric constant significantly below the expected value. After obtaining the reflection coefficient (S11) from the coaxial probe, the N1500A materials measurement suite utilized the calibration data to compute a dielectric constant for the tested brine. Temperature is also obtained using a thermocouple for comparison with literature sourced modeled or measured values of dielectric constant, as temperature is a critical influential parameter for fluid dielectric constant.

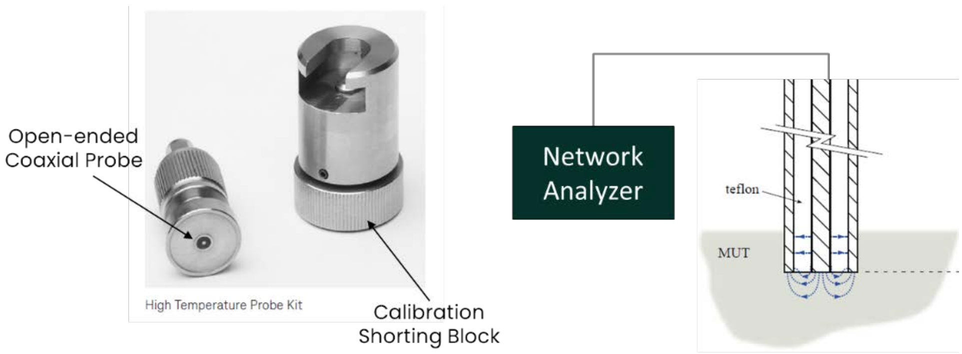

Figure 2 Dielectric Probe for fluid measurement

B. Saturated Plug Dielectric Measurement

Core Preparation and Routine Analysis

For core plugs measurements, different outcrop plugs were prepared. One sandstone sample labeled B2-2, and one limestone sample and labeled IL1-A were also included. The core plug samples were trimmed to have a length of about 5 cm and diameter about 3.8 cm. We measured both helium porosity and N2 gas permeability for both dry core plugs. The matrix permittivity ε_m is also obtained from a dry sample using a coaxial probe.

Core Plug Dielectric Measurement

The dielectric setup comprises a Keysight Impedance analyzer (ENA series E4990A), which has an impeded Operating System (OS) for data acquisition. The samples are placed in a Teflon core holder and gently pressed to a coaxial probe to establish a good contact between the probe and the flat end of core plugs. The quality of contact between the sample and the co-axial probe is essential in reducing any measurement errors. The co-axial probe operates in reflection mode, shown in Figure 3. To perform a reflection measurement, only one port of the impedance analyzer is used. The S11 scattering parameter (S-parameter), also called reflection coefficient, is measured by the impedance analyzer on one flat end of the core plug and then the experiment is repeated on the second flat end. The method is described in detail in (Baker-Jarvis et al. 1994; Zhang et al. 2011).

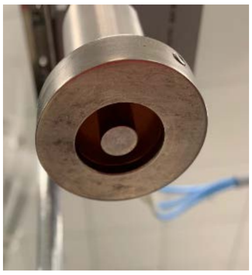

Figure 3 Open-ended Coaxial Dielectric Probe

Brine Salinity Mixing for saturated samples

To mix different brines with different salinities inside core plugs, we relied on conventional core flooding holder to apply a confining pressure of 1000 psi using hydraulic oil and input filtrate brine, 10kppm NaCl, at inlet port with 1 cc/min. The produced water is collected at the open outlet, and after each pore volume injected, the core plug is unloaded to be measured for dielectric constant. A total of 5 pore volumes were injected per core plug as planned, but dielectric constant measurement for two consecutive flooding cycles are compared to monitor change in the measurement. Afterwards, dielectric constant data is inverted for computing petrophysical properties, e.g. water filled porosity, saturating brine salinity and textural parameter (workflow is summarized in Figure 4).

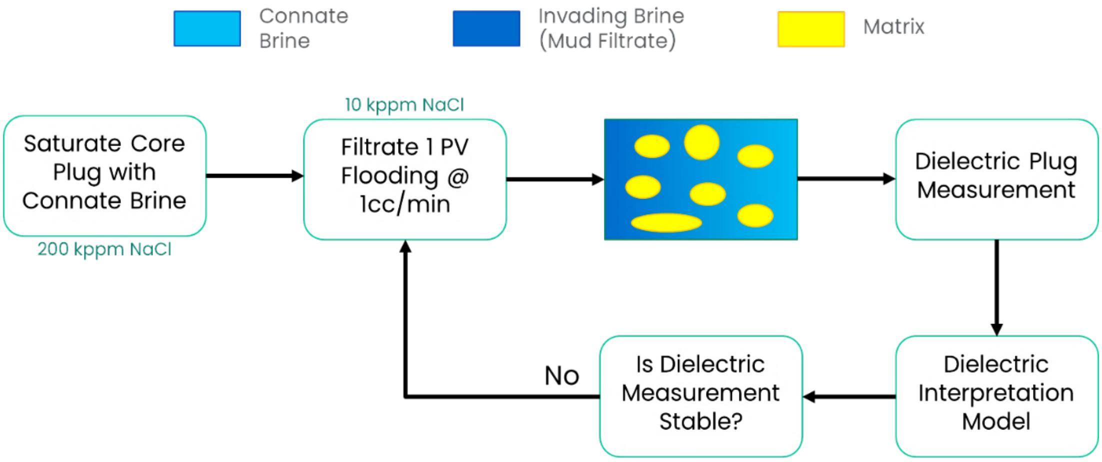

Figure 4 Brine salinity mixing by core-flooding Workflow

Results and Discussions

A. Bulk Brine Dielectric Measurement

Brines were measured at salinities between 10 and 200 kppm NaCl at atmospheric conditions. The results were compared with an established water model (Eq 2) by Messiner and Wentz (2004), where water permittivity ε_w is computed as a function of temperature T[DegC] and salinity S [kppm]:

$$\varepsilon_w = \varepsilon_\infty(T,S) + \frac{\varepsilon_0(T,S) - \varepsilon_1(T,S)}{1 + if/f_1(T,S)} + \frac{\varepsilon_1(T,S) - \varepsilon_\infty(T,S)}{1 + if/f_2(T,S)} - i\frac{\sigma(T,S)}{2\pi\varepsilon_o{}^* f} \quad (2)$$

Where ε_∞ is the high frequency-end permittivity, ε_0 is static permittivity, ε_o is free space permittivity, f is frequency [Hz], σ is conductivity [S/m], and τ is relaxation time [sec], which is used for downhole dielectric log data processing.

The functions; $\varepsilon_\infty(T,S)$, $\varepsilon_0(T,S)$, $\varepsilon_1(T,S)$, $f_1(T,S)$, $f_2(T,S)$ and $\sigma(T,S)$ can be found in Messiner and Wentz (2004). As salinity and frequency increase, real dielectric constant decreases and conductivity increases. The experimental data from this study were compared and matched well with the performance of Eq. 2, especially for low salinity brines or at high frequencies (Figure 5), as well as that of data available in the public domain for low salinity brines (Klien and Swift 1977; Kaatz 1989; Barthel et al. 1991) at 1GHz, Figure 6.

We expect as salinity and frequency increase, real dielectric constant decreases and conductivity increases for the respective water. We compared our experimental data with the water model presented and we found good agreement, Figure 5. We also compared our experimental results with previously published data for low salinity brines (Klien and Swift 1977; Kaatz 1989; Barthel et al. 1991) and we found good agreement at 1GHz, Figure 6. One may use the approximation presented at laboratory temperature, T= 22 DegC, as an example to predict brine's real permittivity at a given salinity compared to freshwater salinity.

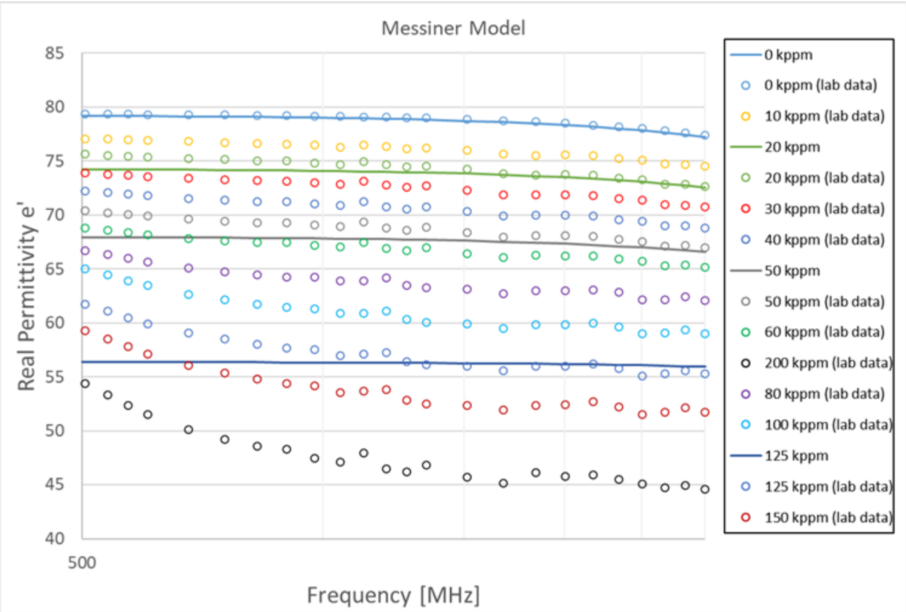

Figure 5 Comparison between brine permittivity experimental data and Messiner and Wentz 2004) model

B. Evaluation of Mixed Salinity with Cores

Fully Saturated Samples

For the saturated core plugs, we obtained dielectric measurements at each saturation condition: fully saturated with connate 200 kppm NaCl brine and at mixed salinity conditions after flooding a 10 kppm NaCl brine (mimicking mud filtrate flushing) with different pore volumes sequentially labeled as: run1, run2, run3 and run4. After that, the samples were cleaned and dried, and re-saturated fully with the fresh filtrate brine. The measured dielectric constants and conductivity are compared in Figures 7 and 8. From these figures, effect of brine salinity on dielectric dispersion and conductivity is clear. Depending on rock quality, IL1-A showed filtrate flushed sample dielectric response just after the first pore volume (PV), whereas B2-2 required two PVs flooding to match the filtrate saturated plug.

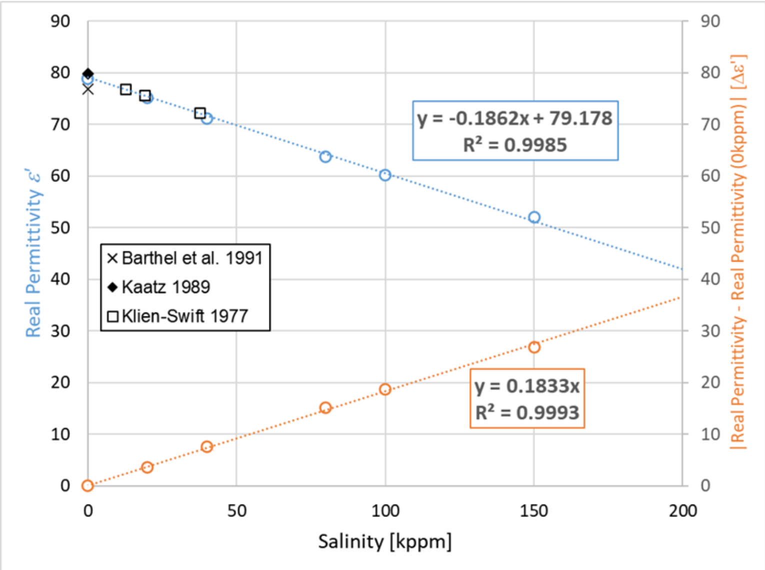

Figure 6 Experimental data of brine real permittivity values compared with published data

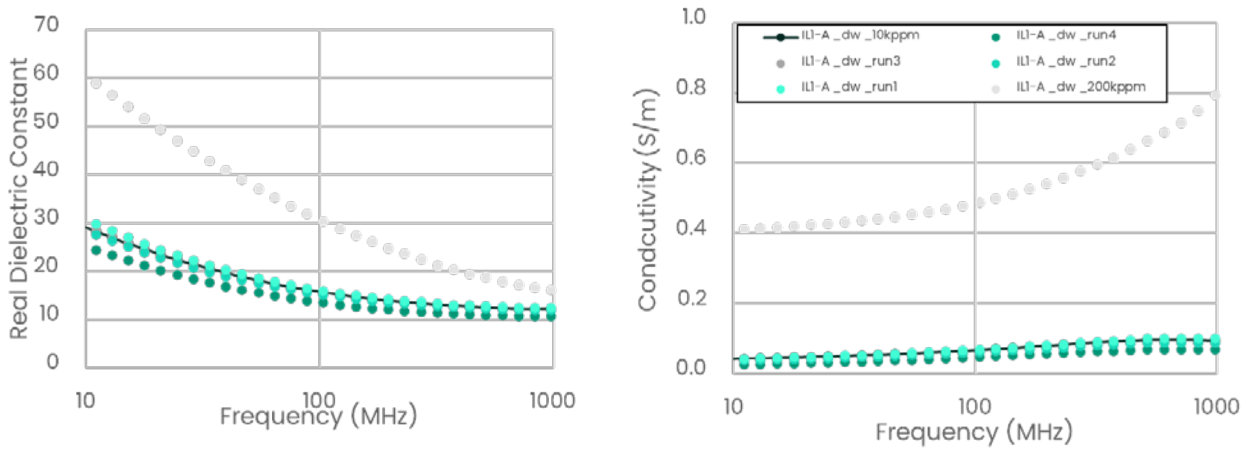

Figure 7 Real dielectric constant and conductivity of IL1-A at different brine saturation conditions

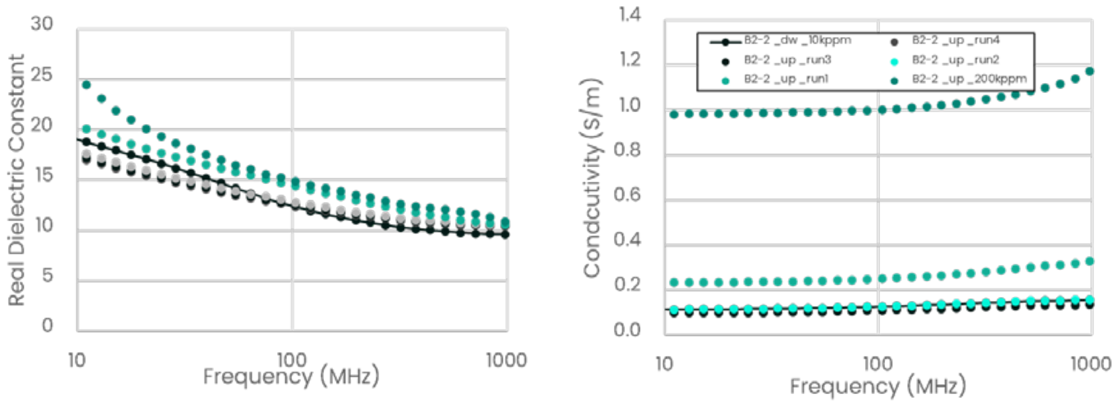

Figure 8 Real dielectric constant and conductivity of B2-2 at different brine saturation conditions

Cores Saturated with Mixed Salinity Brines

To quantify this effect of mixed salinity from dielectric data, we need to apply the measured dielectric dispersion data at each saturation condition to an interpretation model such as in (Stroud et al. 1986) which express the formation effective permittivity ε_{eff} as follows:

$$\varepsilon_{\text{eff}} = \emptyset_w^m \varepsilon_w + (1 - \emptyset_w^m)\varepsilon_m - \varepsilon_m h(s) \tag{4}$$

Where m is the apparent Archie's law cementation exponent, which can be precisely expressed as water-phase tortuosity, $\emptyset_w$ is water-filled porosity, s is equal to $\varepsilon_m/(\varepsilon_w - \varepsilon_m)$ and $h(s)$ can be evaluated numerically (Stroud et al. 1986). Water salinity can be obtained using ε_w and water model as reported in Eq. 2.

For the core flooding experiments, we inverted the SMD model for parameters of $\emptyset_w$, S and m. Figures 9 and 10 show the results of samples IL1-A and B2-2 after each PV of 10 kppm filtrate injected. We labeled each test corresponding to each PV injected from 1 to 5. Data corresponding to label 0 represents measurements done at saline connate brine condition, and label 6 indicates the measurement at fully filtrate brine condition. We presented the results of dielectric data obtained at both ends of each plug and their average to highlight the spatial heterogeneity of our experimental data between sample's two ends.

During flooding the samples with filtrate, it is observed that the inverted salinity follows the filtrate salinity, close to 12 kppm for IL1-A after the first PV of injection. However, for sample B2-2, the inverted salinity indicates a gradual filtrate penetration by showing a 20 kppm after 1st PV injection, and then converges to 11 kppm. For water filled porosity, some discrepancy is observed for IL1-A, the reported $\emptyset_w$ during core flooding with filtrate differs by about 2-3% from the single brine saturated data. As for sample B2-2, inverted $\emptyset_w$ is more consistent, within about 1% comparing to single brine saturated data.

Similarly, it is observed that the variation of the inverted cementation exponent m for IL1-A is more than that of B2-2. As a possible reason for that, the current interpretation model assumes a single fluid property in the entire pore space having similar electrical properties. With pores filled by different brines, the interpretation model attempts to fit the experimental data with approximate brine properties that might not be representative of existing brine inside the sample. The variation of cementation exponent m during core flooding also potentially indicates that electrical current distribution is not consistent probably due to variation of brine's ions concentration (salinity) inside the sample. Although, the variation is small, but still we can't arrive at a clear conclusion to confirm this phenomenon. Further study is required.

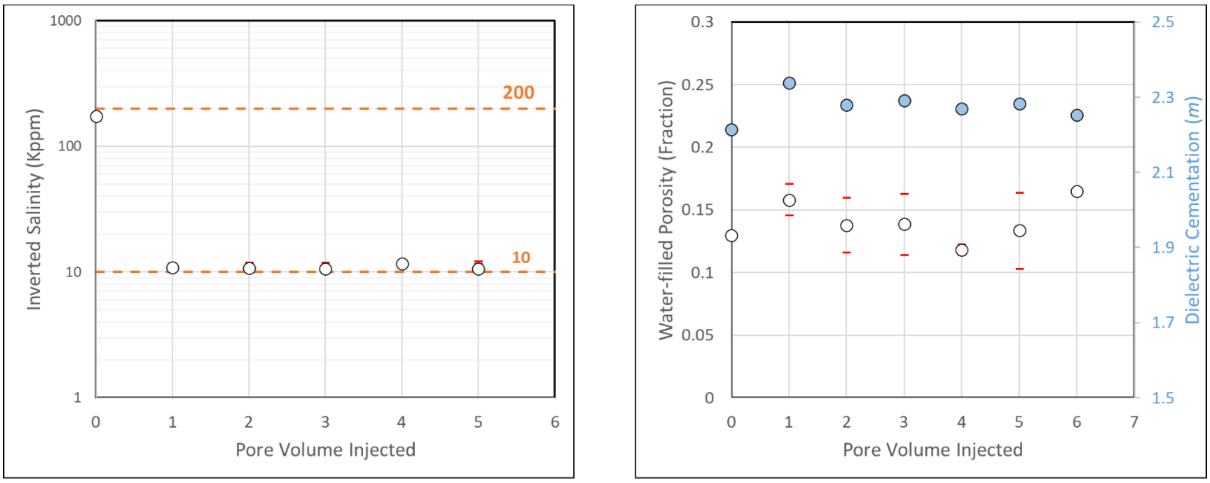

Figure 9 Dielectric interpretation results using SMD model on sample IL1-A for filtrate core flooding experiment: inverted water salinity (Left), water-filled porosity and cementation exponent (Right).

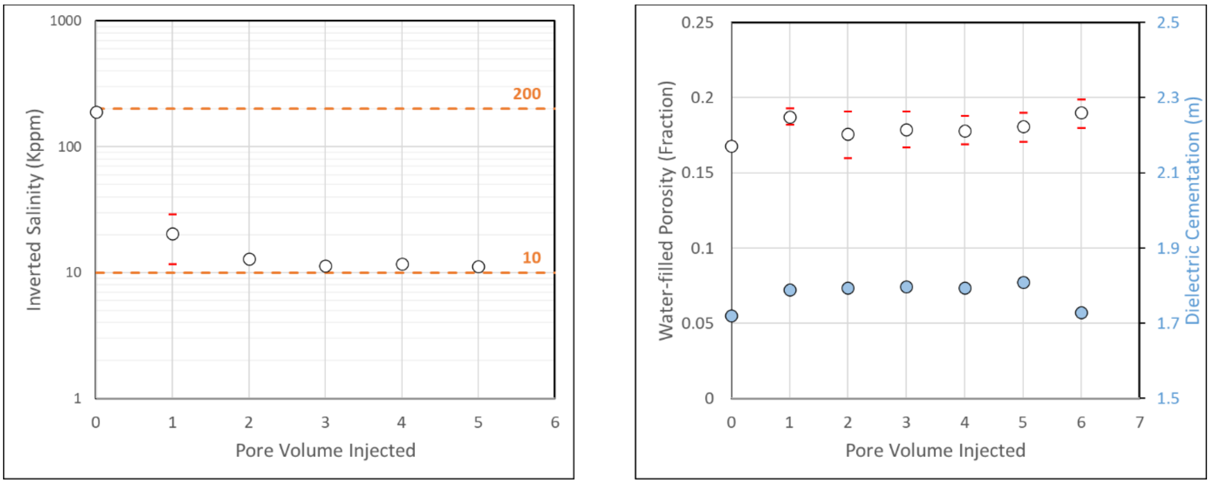

Figure 10 Dielectric interpretation results using SMD model on sample B2-2 for filtrate core flooding experiment: inverted water salinity (Left), water-filled porosity and cementation exponent (Right).

C. Estimation of Formation Water Salinity with Known Filtrate Salinity

Mixed-Salinity Brine

In this section, we evaluate a new workflow relating to establishing look-up tables based on the calculated dielectric constant (using Eq. 2) for the mixture of two brines with different volume ratios and different filtrate and connate water salinities. Such look-up tables are useful to track the change of dielectric constant due to change of volume ratio between unknown connate water and known filtrate water using bulk dielectric measurements at different mixing proportions. This technique will help to estimate the dielectric constant of connate water and salinity using the change of mixing proportion of the two brines without knowing the instantaneous volume proportions of each at a single measurement.

To derive the new brine mixture salinitiy, we assume both filtrate and connate brines are homogeneously mixed with $V_{mixture}$ is constant and $V_{filtrate}$ is varying with P is between 0% and 100%, thus with the knowledge of filtrate and connate brines densities, $\rho_{filtrate}$ and $\rho_{connate}$, one can derive the new mixed brine salinity $S_{mixture}$ which we use to calculate dielectric profiles look-up tables as follows:

$$S_{mixture} = P\frac{S_{filtrate}\rho_{filtrate} + S_{connate}(\frac{V_{filtrate}}{P} - 1)\rho_{connate}}{\rho_{mixture}} \tag{5}$$

where $S_{filtrate}$ and $S_{connate}$ are the salinity of filtrate and connate brines respectively, $\rho_{mixture}$ which can be calculated using mass balance of the two brines mixture and respective volume ratio. To establish different look-up tables of dielectric constant profiles of filtrate and connate brines mixtures, we need the two brines salinities, $S_{filtrate}$ and $S_{connate}$ and temperature of the mixed fluid T.

As an example, we show the profile of real dielectric constant and conductivity at different volume ratios ($P = V_{filtrate}/V_{mixture}$) for two filtrate salinities; 10 and 30 kppm NaCl, and three connate water salinities; 100, 150 and 200 kppm NaCl at room temperature 23 DegC, Figure 11. We can observe for different filtrate salinities, we have distinct dielectric profiles for different connate brine salinities. If one has knowledge of filtrate brine salinity and a set of measurements represents different volume ratios. To assess this workflow, we designed an experiment for mixing 30 kppm NaCl and 200 kppm NaCl brines at different ratios, Table 2. We conducted dielectric measurements on 5 bulk fluids with constant volume of 50 cc. The incremental volume ratio x is used as a dilution volume ratio to reduce the salinity of the tested brine and defined as: $x_k = P_k - P_{k-1}$.

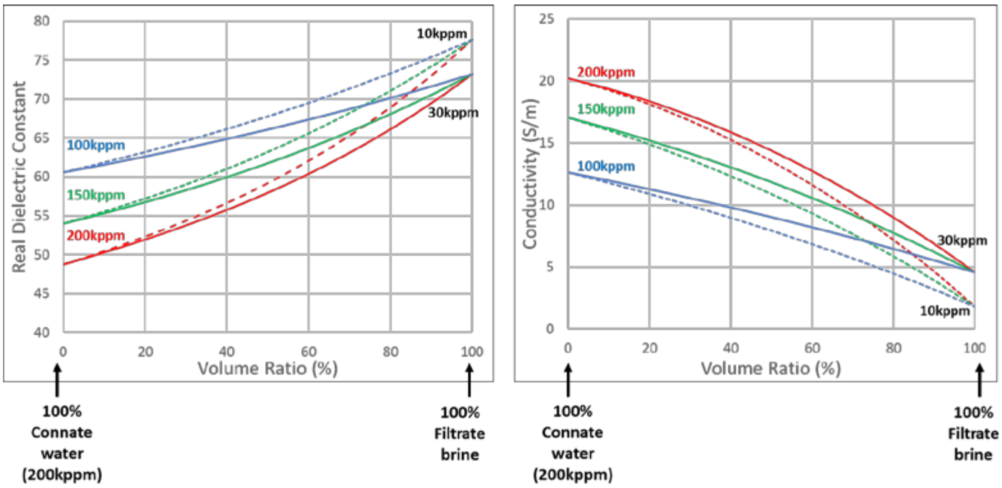

Figure 11 Real dielectric constant and conductivity profile generated from water dielectric model (Eq. 2) using a mixture of two different brine salinities, i.e. filtrate and connate water using different volume ratios

Table 1 Experimental Data Set for Mixed Salinity Bulk Brines

Sample $\boldsymbol{k}$	$\boldsymbol{V_{200ppk}}$ [cc]	$\boldsymbol{V_{30ppk}}$ [cc]	$\boldsymbol{x_k}$	$\boldsymbol{P_k}$	$\boldsymbol{\varepsilon_r}$ @1GHz	$\boldsymbol{\sigma}$ [S/m]
S1	50	0	0%	0%	48.954	21.422
S2	40	10	20%	20%	52.816	19.459
S3	30	20	20%	40%	56.363	16.754
S4	10	40	40%	80%	66.412	9.555
S5	0	50	20%	100%	72.666	4.902

When we overlap the test data in terms of (P_k,ε_k) against dielectric profile generated from a mixture of 30 kppm filtrate and different connate brines, we can observe the data points closely match the profile trend generated from mixing 30 and 200 kppm NaCl brines, Figure 12. More interestingly, if we have knowledge of the incremental volume ratios with unknown initial volume ratio of the mixed brine, we can move the measured data points simultaneously to the left or the right, but we can't have a match between the data points and a dielectric profile based on 30 kppm NaCl filtrate, except for connate brine salinity of value between 190 and 200 kppm, Figure 13. From this finding, we observe what's significant is the knowledge of the dilution incremental volume ratio more than the initial mixture's volume ratio in addition to filtrate brine salinity. Thus, the dielectric data points with known incremental volume ratios which matches single connate water dielectric profile can lead us to estimate the unknown connate water salinity.

Dielectric Log Data from Radial Invasion Profile

For downhole logging data, commercial dielectric logging tool has three different depths of investigations: short, medium and long, Figure 14. Throughout drilling process, we expect some mud (Water-based-Mud) invades the formation and volume of mud filtrate displaces the original formation brine. While it's not on the scope of this study to define the invasion characteristics and profile through the formation, we aim to present a simple workflow to utilize standard multi-frequency dielectric interpretation answers to evaluate the saturating water salinity change among the three DOI's.

The saturating brine's dielectric constant (ε_w) can be computed from dielectric dispersion logging data using one of the interpretation models, e.g. SMD as in Eq. 4. The inverted ε_w will be considered as the mixed salinity brine dielectric constant, and the volume ratio P at each DOI can be calculated as follows:

$$P_1 = \frac{\emptyset_{w\_M}}{\emptyset_{w\_S}};\ P_2 = \frac{\emptyset_{w\_L}}{\emptyset_{w\_S}}; \tag{6}$$

where $\emptyset_{w\_S}$ is the inverted water-filled porosity of short DOI, $\emptyset_{w\_M}$ is the inverted water-filled porosity for medium DOI and $\emptyset_{w\_L}$ is the inverted water-filled porosity for long DOI.

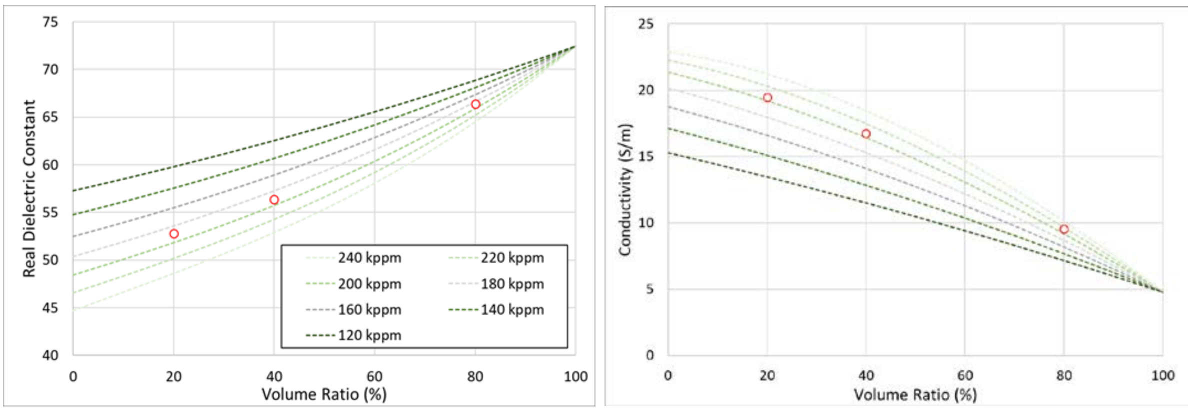

Figure 12 Overlaying experimental bulk dielectric data against dielectric profiles of different mixed salinity brines using 30 kppm NaCl filtrate and different connate brine salinities

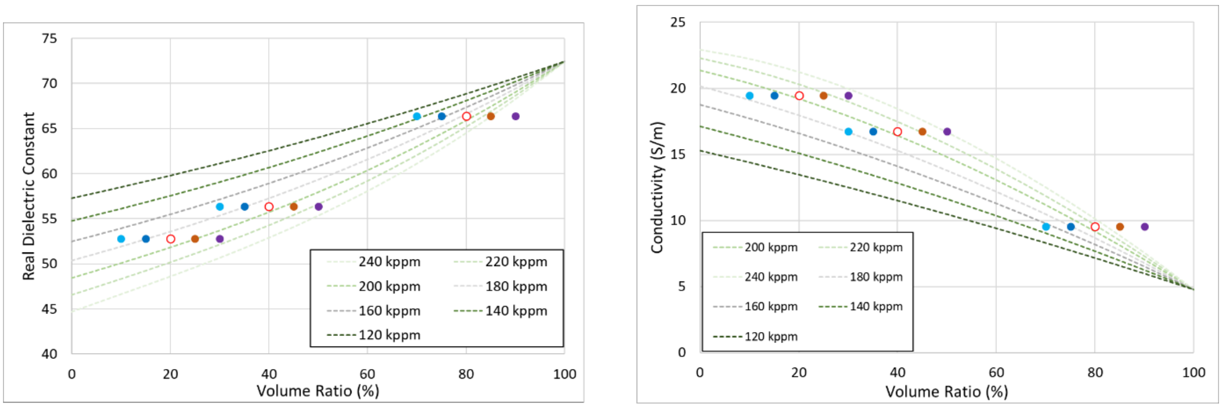

Figure 13 Overlaying experimental bulk dielectric data with unknown initial mixture volume ratios but known incremental dilution rates against dielectric profiles of different mixed salinity brines using 30 kppm NaCl filtrate and different connate brine salinities

Thus, the points to be plotted against the mixed-salinity dielectric profiles will be: (P_1, ε_{w_M}) and (P_1, ε_{w_L}), where ε_{w_M} is the inverted saturating brine dielectric constant at medium DOI and ε_{w_L} is the inverted saturating brine dielectric constant at long DOI.

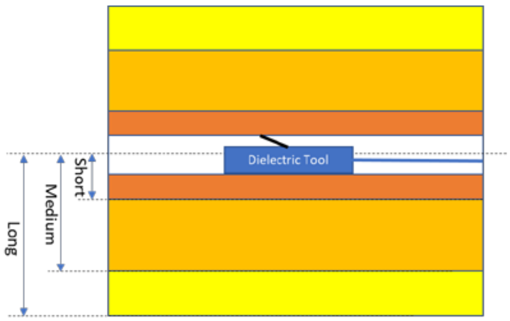

Figure 14 A schematic for downhole dielectric logging tool and its different DOI

D. Field Testing

Well A

This well penetrated a clastic formation, and we have a prior knowledge of filtrate salinity between 3 and 5 kppm NaCl and formation water salinity between 30 and 35 kppm NaCl. When we establish the mixed salinity dielectric constant profiles from a water model as of Eq. 2, we considered filtrate salinity of 5 kppm NaCl and connate water salinities between 10 and 90 kppm NaCl at reservoir temperature of 49 DegC. After computing water-filled porosity and saturating water dielectric constant at each DOI using SMD model, we were able to define the points (P_1, ε_{w_M}) and (P_1, ε_{w_L}) as shown in Eq. 6. Then, we overly the measured data against the generated mixed salinity dielectric constant profiles, Figure 15. Our findings show that the measured data used from different DOI's match the profile curves associated with connate water of salinity between 30 and 40 kppm NaCl and agree with our knowledge of this well. Due to uncertainties associated with the log data and the inherited assumption of this approach, we may not get an accurate answer of connate water. However, out of the three data sets used, one data set match well the dielectric profile generated from 5 kppm NaCl filtrate and 30 kppm NaCl connate water.

Well B

Well B penetrated a carbonate formation with high salinity formation water. The only knowledge we have is that mud filtrate equivalent salinity is around 33 kppm NaCl and borehole temperature is 102 DegC. We selected four different depths which has significant filtrate invasion and overlayed them against mixed-salinity dielectric profiles with filtrate salinity of 33 kppm NaCl. Figure 16 shows how the measured data set are scattered but it is clearly observed they can be extended towards connate water salinity range between 210 and 220 kppm NaCl. One data set at particular depth matches very well the mixed salinity profile of filtrate 33 kppm NaCl and connate water 220 kppm NaCl. Although some data are very scattered and finding a proper data set matching one of the mixed-salinity dielectric profiles is challenging, it’s convenient to bound our predication of connate water salinity with -/+ 20 kppm NaCl at very high salinity formation water such as this case.

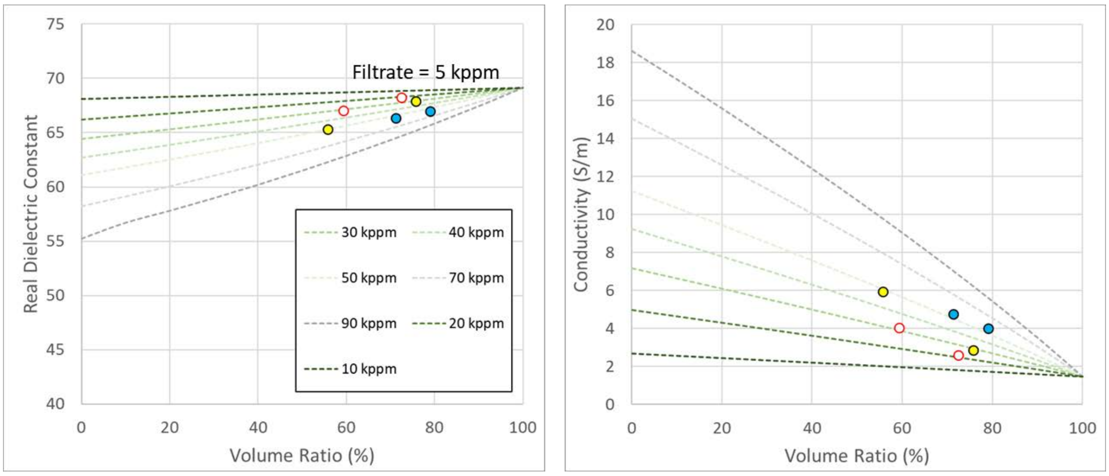

Figure 15 Application of the proposed workflow to predict connate water salinity on Well A using three different depths; (red) depth 1, (yellow) depth 2 and (blue) depth 3

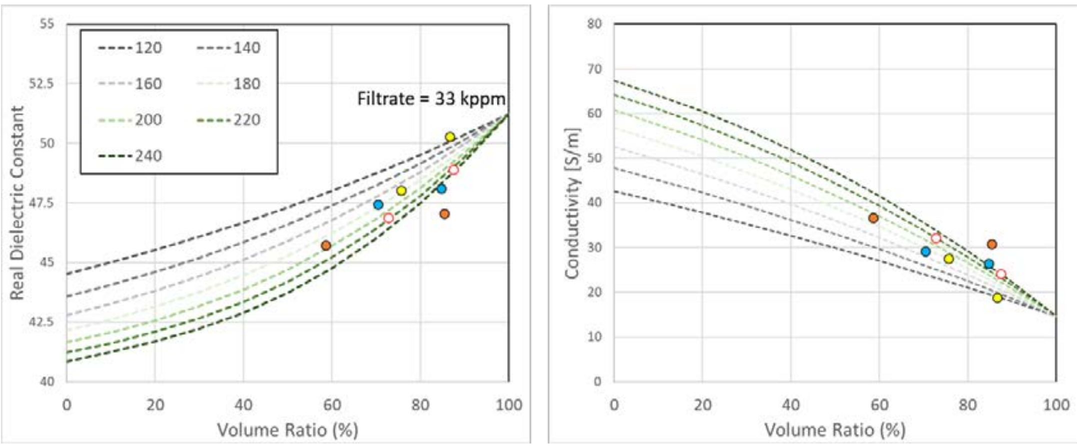

Figure 16 Application of the proposed workflow to predict connate water salinity on Well B using four different depths; (red) depth 1, (yellow) depth 2, (blue) depth 3 and (orange) depth 4

Conclusion

- Multi-frequency dielectric measurements are highly sensitive to the saturating brine’s salinity and our experimental data demonstrated how raw dielectric dispersion measurements and SMD model inversion can estimate brine salinity of unknown or mixed salinity brines during the filtrate invasion process. With limited data of two outcrop core samples, results may be summarized as
  - The carbonate sample. Some discrepancy in dielectric interpretation of water-filled porosity and apparent cementation exponent were observed. This

discrepancy must be further investigated, and more data are needed to confirm our findings in carbonate formation samples.

  - The sandstone sample. Results are consistent and no variation of petrophysical inversion answers was observed during filtrate invasion process.

- Note that different interpretation models could be investigated or developed to assess the effect of having different brines in the pore space, as current models account only for having single brine property inside the pore space.
- As our findings from laboratory data showed how filtrate rapidly mixes with formation water at pore level of a rock, we presented and assessed a method to estimate an unknown connate water salinity from a knowledge of filtrate salinity using generated look-up tables of mixed salinity dielectric constant profile versus volume mixing ratios.
- Such method can be applied on bulk fluids for reservoir fluid analysis from downhole multi-DOI dielectric logging. The results of the proposed technique showed promising applicability for reservoir connate water characterization using informaiton derived from logs, though more work is needed to well understand the mixed-salinity invasion mechanism.

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