SIMULTANEOUS DETERMINATION OF WATER SATURATION AND SALINITY BY COMBINING ELECTRIC WITH DIELECTRIC MEASUREMENTS DURING MULTIPHASE DISPLACEMENT IN SANDSTONES

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Objective

The objective of the multiphase displacement experiments made in this study was the determination of residual water saturation and residual gas saturation in heterogeneous sulphide bearing sandstones. In order to obtain representative parameters large scale samples have been investigated. During the water imbibition process the water composition and hence the water salinity changes in space and time. The salinity changes as a consequence of the imbibition of water of another chemical composition compared with that of the remaining water in the pore space. E.g. rock-fluid interaction between sulphide minerals in the sandstone and dissolved oxygen in the water results in a significant decrease in pH and an increase in salinity. The dissolution of hydrocarbon components in injected fresh water results also in an increase of water conductivity.

In such rock-fluid-systems the determination of only one saturation dependent electrical parameter without knowledge of salinity can give rise to gross uncertainties in the estimation of water saturation. Therefore, the developement of a method is of interest that allows the simultaneous measurement of water saturation and water salinity.

Petrophysical background

A simple way to solve the problem is the combination of a low frequency conductivity measurement and a dielectric measurement to obtain the two independent rock parameters electrical conductivity and dielectric permittivity (Boerner 1997). Both parameters are strongly water saturation dependent and somewhat dependent on water salinity. The system of two equations (one for dielectric constant and one for conductivity) is determined (number of equations = number of unknowns) in case of constant pore space properties.

The relationship between relative dielectric constant $\varepsilon_{r,mess}$, water saturation S_W and salinity σ_W is based on a mixing law. It has the simple shape

$$e_{r,mess} = e_{r,S_W=0} + e_{r,W}\Phi^* S_W^{n^{**}} = e_{r,S_W=0} + bS_W^{n^{**}} \quad \text{with} \quad b = f(s_W) \qquad (1)$$

Porosity Φ^* and dielectric constant of the pore water $\varepsilon_{r,W}$ are dependent on chemical water composition (salinity). The quantity b is a nonlinear function of water conductivity. The dielectric constant of the dry rock is $\varepsilon_{r,Sw=0}$, n^{**} the dielectric saturation exponent. The relationship between the real part of electrical conductivity and the two variables water saturation and water conductivity (salinity) is a simplified version of the conductivity equations from Vinegar and Waxman (1984) or Riepe et al. (1979):

$$s_{mess} = (s_W \Phi^m + s_{gr}) S_W^{n^*} \qquad (2)$$

σ_{gr} is the interface conductivity, σ_W the water conductivity, m the cementation exponent and n^* the electrical saturation exponent. Gruhne (1999) found that the same saturation exponent n^* may be used for interface and electrolytical conductivity component.

Experimental work

The experiments have been carried out on rectangular designed sandstone blocks with a volume of 36 L and 600 L. Each block was part of an experimental set up that allows the control of water imbibition and drainage of the sandstone block. The capillary pressure variation was measured with tensiometers. The local water saturation was measured noninvasively using electrical and dielectrical techniques:

(1) Dielectric constant $\varepsilon_{r,mess}$: The radar wave velocity v between a 1 GHz-transmitter and receiver was detected. Then the relative dielectric constant of the rock $\varepsilon_{r,mess}$ was calculated from the measured radar wave velocity v (see fig. 1), the free space velocity c_0 and the permeability μ_r using the equation

$$e_{r,mess} = c_0^2 / m_r v^2 \qquad (3)$$

(2) Electrical conductivity σ_{mess}: A conventional electrode arrangement with two current and two separate potential electrodes was used. The system works in the frequency range between 0.1 and 10 Hz.

In a first step all pore space related parameters in equation (1) and (2) are obtained from systematic core analysis on small sandstone core samples. The sandstone has a total porosity between 0.19 and 0.23. The internal surface area measured with the nitrogen adsorption method varies between 0.22 and 0.35 m^2/g. Then the multiphase displacement experiments on sandstone blocks were monitored and controlled by the application of the described petrophysical measuring and interpretation technique. The block was divided into volume elements of similar size. During the experiments water saturation and salinity in each volume element were calculated on the basis of equation (1) and (2) using an iterative algorithm.

Results

Fig. 2 shows the water imbibition curve measured on a sandstone block with a volume of 36.0 L. During the experiment the water salinity has changed slightly by rock-fluid interaction. The data in fig. 3 show the significant effect of saturation and salinity on both the conductivity and dielectric constant of the rock. These data where measured on the large sandstone model with a volume of 600 L. The measured residual water saturation in the block models changes between 0.2 and 0.3. Residual gas saturation was found to be between 0.29 and 0.15. The water salinity varies between 0.03 and 5 S/m. The residual gas saturation decreases with increasing water salinity.

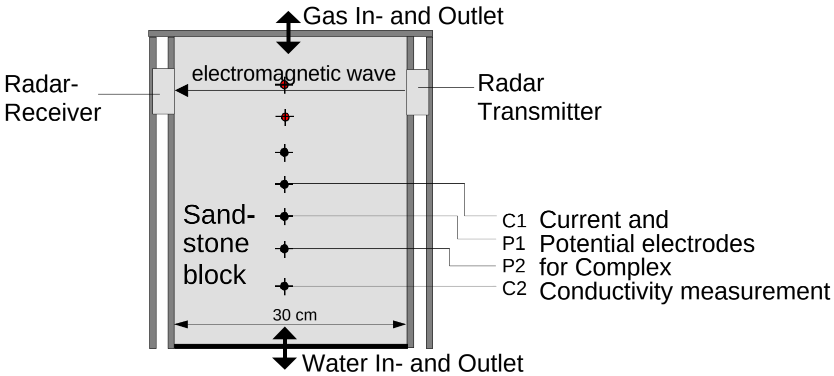

Fig. 1:
Scheme of an experimental set up for simultaneous determination of water saturation and salinity in a sandstone block model using combined conductivity and dielectric measurement.

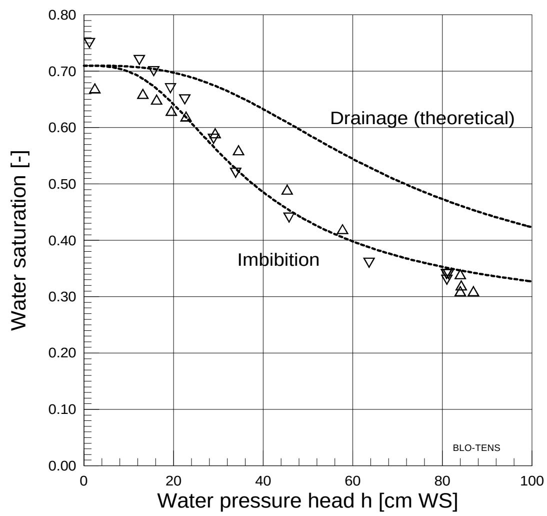

Fig 2:
Example of an experimentally determined imbibition process using combined conductivity and dielectric measurements for improved water saturation determination.

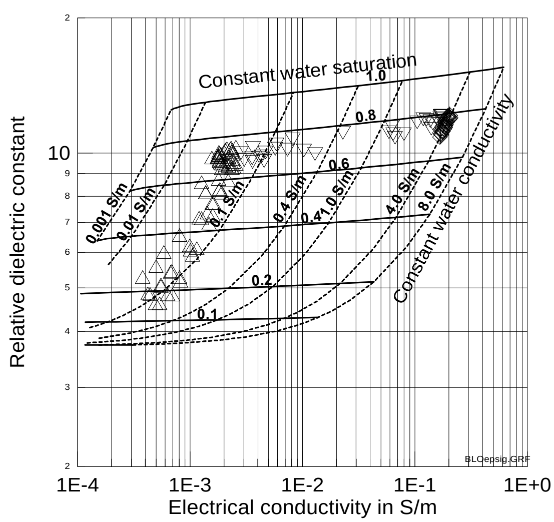

Fig. 3:
Relationship between relative dielectric constant and real part of conductivity for varying water saturation and water salinity. Each data point represents a volume element of the block. The curves were calculated using equations (1) and (2).

Conclusions

The investigation demonstrates that the combined technique allow a representative determination of water saturation in large scale multiphase displacement experiments. The simultaneous monitoring of water saturation and geochemical alterations in core analysis or large block samples seems to be possible.

A good agreement of the water saturation results with independently determined water balance was found. As a result of the investigation it is established that the simultaneous measurement of conductivity and dielectric constant provides improved saturation data during the water imbibition of sandstone formations with significant geochemical rock-fluid interaction. Subject of further petrophysical investigation is the surprising strong increase of dielectric constant with increasing salinity of pore water.

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