

EFFECT OF POROSITY CHANGES ON COMPLEX ELECTRICAL CONDUCTIVITY IN SHALY SANDS

Frank Börner (Technical University Berlin)

Edith Müller-Huber (Technical University Berlin)

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ABSTRACT

The investigation is focused on the determination of compaction of heterogeneous shaly sands. Measurements of the complex electrical rock conductivity in the frequency range from 0.05 Hz to 1 kHz are presented in order to quantify the porosity reduction in shaly sands during the step-wise compression of the samples. The measurements were carried out with a specially designed measuring cell. Overall, 10 unconsolidated shaly sand samples with varying grain size distribution were analyzed. The measured complex conductivity data of the fully water saturated samples show two co-occurring effects:

(1) Real part decreases due to the dominating Archie's law.

(2) Imaginary part increases due to the increasing contribution of interface conductivity.

The effects of compaction observed may be explained using a simple complex conductivity model that relates porosity, surface area and accompanied parameters to conductivity components. The surprisingly significant increase of the imaginary part with decreasing porosity is caused by the increase of internal surface area-to-porosity-ratio. Significance of the effect seems to depend on the cementation exponent and the porosity range under consideration. The proposed interpretation algorithm allows the determination of relative porosity variation, from a base line measurement and a single repeat measurement without knowledge of further rock characteristics, which is associated with changes of compaction and hence changes of hydraulic permeability.

INTRODUCTION

Pore space properties of sedimentary rocks are of general interest for reservoir evaluation but also for special geotechnical applications. Verification and monitoring of slight porosity changes are essential for controlling processes like, e.g., the compaction by pressure drawdown in weakly consolidated reservoirs, the stimulation effects for productivity enhancement of reservoirs, or the compaction of building ground. It is well known that electrical resistivity or conductivity are closely connected with pore space geometry and are very sensitive to slight changes of pore space characterizing parameters.

The degree of compaction characterizing parameters, like porosity, pore or grain size distribution and bulk density, is commonly used for modelling fluid flow but increasingly frequently also e.g. for simulation of geotechnical stability of reservoirs, dams and embankments. A special problem is the determination of naturally or artificially induced porosity changes and accompanied changes of permeability or compaction in very heterogeneous sedimentary rocks. Electrical rock properties can provide valuable

information on porosity change. However, due to various petrophysical influences on electrical rock properties, the attempt to convert electrical conductivity variations into variations of porosity or the degree of compaction often leads to ambiguous results.

Complex electrical conductivity is sensitive to the size of the mineral-water-interface at the grain surfaces and hence, together with porosity, sensitive to changes in pore space geometry. Complex electrical measurements in the low frequency range provide besides conductivity also information on the electrical capacity and relaxation of charge carriers in the pore space. Therefore, complex measurements can reduce the petrophysical ambiguity caused by the influence of textural and state properties.

Complex conductivity phenomena and measuring techniques are reviewed by, e.g. [1], [2] or [3]. [4] presented an overview of the properties and state conditions which influence complex conductivity spectra. The complex electrical properties of shaly sands were investigated e.g. by [5] or [6]. Recently [7], [8] and [9] focused their research on unconsolidated material as well as on the dependency of complex interface conductivity on salinity, pH-value or temperature ([10], [11], [12]). Another topic is the investigation of textural effects on hydraulic and electrical conductivity of sedimentary rocks ([13], [14]) or unconsolidated sediments ([15]) due to a variation in pore radii ([13]). According to our knowledge, the effect of porosity change, especially porosity reduction, on complex interface conductivity was not yet explicitly investigated.

FUNDAMENTALS

The complex conductivity $\sigma^* = \sigma' + i\sigma''$ of a water-saturated shaly sand consists of a real electrolytic conductivity σ_{el} and a complex interface conductivity $\sigma_{if}^* = \sigma'_{in} + i\sigma''_{in}$ (e.g. [5], [6], [9]), if water is the wetting fluid. When oil wets the rock matrix, interface conductivity is insignificant. The key question is to find an applicable parameter model to relate σ_{el} , σ'_{in} and σ''_{in} to pore space characterizing parameters such as, e.g. formation factor F , surface area-to-porosity-ratio S_{POR} and compaction. If frequency dependence is negligible, then the following approach for σ' and σ'' is applicable in the low frequency range (e.g. [5], [10], [16]):

$$\sigma' = \sigma_{el} + \sigma'_{in} = \sigma_w / F + f(\sigma_w)S_{POR} / F \quad (1a)$$

$$\sigma'' = \sigma''_{in} = lf(\sigma_w)S_{POR} / F \quad (1b)$$

The real part σ' consists of the Archie-component σ_{el} and the real part of interface conductivity σ'_{in} . The imaginary part σ'' equals the imaginary part of interface conductivity σ''_{in} . The model is applicable to shaly as well as to clean sands. F , for purposes of simplicity, is the same formation factor for all conductivity components, $f(\sigma_w)$ is a general function considering salinity and pH dependence of interface conductivity dependent on surface charge density and ion mobility in the interface region, and l is the ratio between real and imaginary part of interface conductivity that is assumed to be nearly independent of salinity and varies only slightly with porosity changes.

Recently, the model approach was modified and/or further developed by [7], [10], [11], [17] and others.

All electrical conductivity contributions in equations (1a) and (1b) are dependent on porosity Φ . While the porosity dependence on the electrolytic conductivity in equation (1a) is well known according to the Archie-equation $F = \Phi^{-m}$ ([18]), the relationship between interface conductivity and porosity in equations (1a) and (1b) is less thoroughly investigated. Based on equations (1a) and (1b) and $S_{POR} = S_m d_m (1 - \Phi) / \Phi$ (S_m – surface area per mass, d_m – grain density), a dependency of interface conductivity components σ'_{in} , σ''_{in} on porosity is expected in the form of

$$\sigma'_{in}, \sigma''_{in} \propto (1 - \Phi) \Phi^{m-1}. \quad (2)$$

This means that a porosity variation of a given rock sample with fixed specific surface area S_m results in a change of S_{POR} and consequently in a variation of the interface conductivity. Fig. 1 shows how interface conductivity depends on porosity, on the size of cementation exponent m , and on the related porosity range. The calculated curves show significant differences of the porosity effect on interface conductivity for unconsolidated and consolidated rocks, respectively.

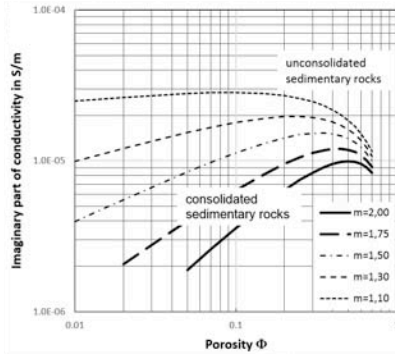


Fig. 1: Calculated curves imaginary part of conductivity vs. porosity for different cementation exponents m .

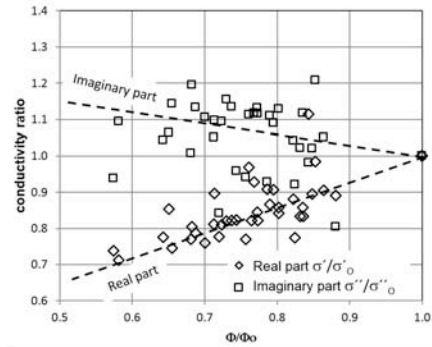


Fig. 2: Imaginary part and real part of complex conductivity vs. porosity (normalized on initial state).

MATERIAL AND METHODS

The relationship between porosity alteration and complex conductivity has been analysed using a series of 10 different unconsolidated shaly sand samples. The mean grain diameter ranges from 0.15 to 1.35 mm. The samples were saturated with NaCl-solution of conductivities between 0.05 S/m and 0.1 S/m at 25°C. The samples were set up in a cylindrical cell with 30 mm diameter and 80 mm length. Complex conductivity was measured with a 4-electrode laboratory system (electrodes made from platinized platinum mesh or wire, respectively) in the frequency range 0.05 Hz to 1 kHz. Data acquisition and data processing was similar to that proposed by [4]. Measurements were carried out at atmospheric pressure and 25 °C. The cell was installed at a tabletop vibrator to produce a step-wise compaction of the sample. The porosity reduction was determined measuring the decrease of sample length and volume of emitted pore water. Porosity reduction was in the order of up to 10%. During compaction the pore water conductivity remained

unchanged. For comparison, data of 8 shaly sandstone samples from [6] were incorporated, which have various porosities but similar specific surface areas S_m .

RESULTS

The expected increase of imaginary part with decreasing porosity or compaction, respectively was found experimentally. All experimental data (real as well as imaginary part), normalized on values for initial porosity Φ_0 , are plotted in Fig. 2. The high error of the imaginary part may be caused by a slight instability of the grain package and additional weak changes in pore water conductivity. Experimental results of selected unconsolidated shaly sand samples are plotted in Fig. 3 together with calculated curves of $\sigma''=f(\Phi)$. Curve parameter is S_m while $m=const.=1.3$. The shaly sandstones with only slightly varying S_m show the different behaviour of consolidated rock with lower porosities and a high cementation exponent (Fig. 4). The model curves were calculated for different S_m but fixed $m=2$.

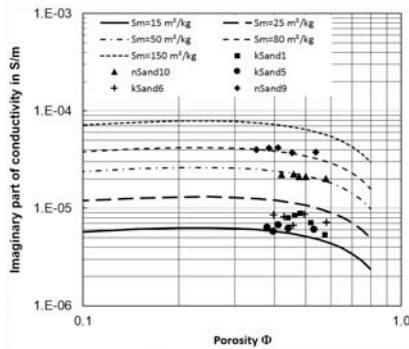


Fig. 3: Unconsolidated shaly sands – imaginary interface conductivity vs. porosity.

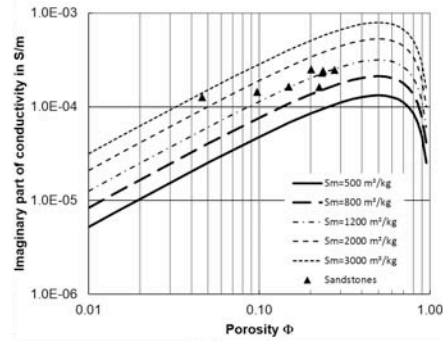


Fig. 4: Shaly sandstones – imaginary part of conductivity vs. porosity.

Imaginary interface conductivity calculated with a modified capillary tube model (see [13] or [15]) indicates that compaction of sediments leads to a decrease in the ratio of pore throat to pore body radius r_b/r_t , while pore throat radius r_t remains constant (see Fig. 5). In comparison to shaly sands, shaly sandstones seem to be characterized by lower ratios r_b/r_t and lower radius r_t (see Fig. 6).

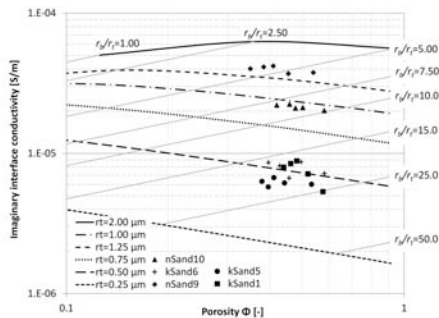


Fig. 5: Unconsolidated shaly sands – Modeled imaginary interface conductivity vs. porosity.

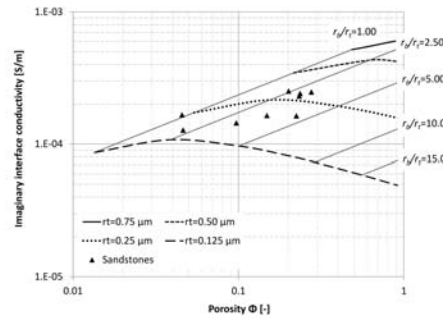


Fig. 6: Shaly sandstones – Modeled imaginary interface conductivity vs. porosity.

Porosity of the shaly sands calculated from complex conductivity data according to

$$\Phi = \left(\frac{\sigma_w}{\sigma' - \sigma''_{if}/l} \right)^{\frac{1}{m}} \quad (3)$$

versus independently determined porosity is presented for all unconsolidated samples in Fig. 7. The relative porosity change C relates the porosity Φ to the initial porosity Φ_0 :

$$C = \frac{\Phi}{\Phi_0} = \left[\left(\frac{\sigma'_0 - \sigma''_{if,0}/l}{\sigma' - \sigma''_{if}/l} \right)^{\frac{1}{m}} \right]^q \quad (4)$$

Using equation (4), C was then calculated from complex conductivity data alone for all unconsolidated shaly sand samples. The result is shown in Fig. 8. The exponent q was found to be about 2. It takes account of all remaining effects of changing m and l .

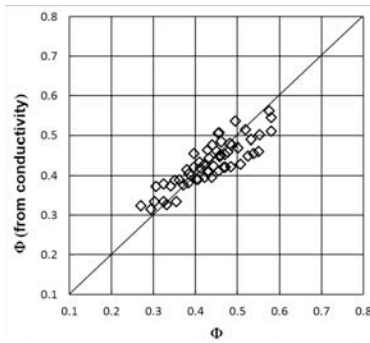


Fig. 7: Porosity from complex conductivity vs. porosity from volumetric measurement.

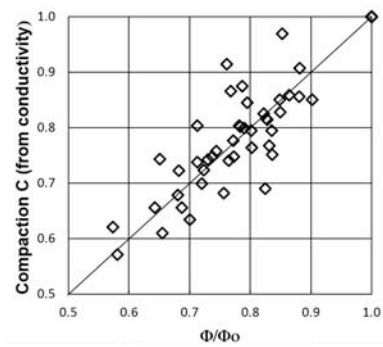


Fig. 8: Compaction C from complex conductivity vs. compaction from relative porosity decrease.

CONCLUSION

The observed significant increase of the imaginary part with compaction is caused by the increase of internal surface area-to-porosity-ratio S_{POR} with decreasing porosity. The increase was found to be restricted to unconsolidated shaly sands with high porosities and therefore low cementation exponents. In contrast to that, a decrease of the imaginary part with decreasing porosity occurs in the case of consolidated shaly sandstones characterized by lower porosities and cementation exponents of about 2. If the surface area effect is ignored, the calculated porosity changes are reduced or not detectable due to the influence of interface conductivity. The proposed formula predicts the porosity change, which is associated with changes in permeability and bulk density (compaction), from a base line measurement and a repeated measurement without knowledge of further petrophysical properties.

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