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Novel laboratory methods for determining the fine scale electrical resistivity structure of core

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ABSTRACT

High-resolution electrical resistivity measurements are made on saturated rocks using novel laboratory instrumentation and multiple electrical voltage measurements involving in principle a four-point electrode measurement but with a single, moving electrode. Flat, rectangular core samples are scanned by varying the electrode position over a range of hundreds of millimetres with an accuracy of a tenth of a millimetre. Two approaches are tested involving a contact electrode and a non-contact electrode arrangement. The first galvanic method uses balanced cycle switching of a floating direct current (DC) source to minimise charge polarisation effects masking the resistivity distribution related to fine scale structure. These contacting electrode measurements are made with high common mode noise rejection via differential amplification with respect to a reference point within the current flow path. A computer based multifunction data acquisition system logs the current through the sample and voltages along equipotentials from which the resistivity measurements are derived. Multiple measurements are combined to create images of the surface resistivity structure, with variable spatial resolution controlled by the electrode spacing. Fine scale sedimentary features and open fractures in saturated rocks are interpreted from the measurements with reference to established relationships between electrical resistivity and porosity. Our results successfully characterise grainfall lamination and sandflow cross-stratification in a brine saturated, dune bedded core sample representative of a southern North Sea reservoir sandstone, studied using the system in constant current, variable voltage mode. In contrast, in a low porosity marble, identification of open fracture porosity against a background very low matrix porosity is achieved using the constant voltage, variable current mode. This new system is limited by the diameter of the electrode that for practical reasons can only be reduced to between 0.5 and 0.75 mm. Improvements to this resolution may be achieved by further reducing the electrode footprint to 0.1 mm × 0.1 mm using a novel high-impedance, non-contact potential probe. Initial results with this non-contact electric potential sensor indicate the possibility for generating images with grain-scale resolution.

Contents

Abbreviations: AC, alternating current; ADC, Analogue to Digital Converter; DAQ, PC Data Acquisition Control; DC, direct current; EPS, Electric Potential Sensor; PCMCIA, Personal Computer Memory Card International Association.

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1. Introduction

The electrical resistivity of a porous rock depends primarily on the nature of any conducting pore fluid, the proportion of conducting fluid occupying the pore space, and the distribution of fluid (Archie, 1942, 1950; Eq. (1)).

$$R_t = aR_w\phi^{-m}S_w{}^{-n} \tag{1}$$

where R_t is the electrical resistivity of the rock, R_w is the resistivity of the conducting fluid (most commonly saline water or an aqueous solution), ϕ is the porosity of the rock and S_w is the saturation (or proportion of pore space) occupied by the conducting fluid (water). The values of "*a*, *m* and *n*" are typically constant for a specific pore morphology and may commonly be determined by experimental laboratory methods or through numerical modelling. Archie assumed that "*a*" is equal to one, whilst Winsauer et al. (1952) suggested that it may deviate from this value. If the rock is fully saturated with the conducting fluid (saline water) then the water saturation takes a value of unity and the equation reduces to:

$$R_o = aR_w\phi^{-m} \tag{2}$$

where R_o indicates that the rock is fully water-saturated as in the experiments conducted here.

Electrical flow takes place primarily by ionic or electrolytic conduction through the pore fluid, in the absence of metallic conductors such as pyrite or clay minerals, although the pore fluid properties are affected by salinity, temperature and pressure. In siliciclastic rocks containing significant proportions of clay minerals the presence of a cation-rich layer of electrochemically bound water at the mineral surface can add additional conductivity (e.g. Worthington, 2011); this effect is due to the negative charge on silicate minerals attracting positive ions and water to the surface, but is negligible in the so-called "clean" sandstones. In "shaly sands", however, with a significant amount of clay minerals this effect can be large due to a large surface area to volume ratio, and can reduce the resistivity (e.g. Waxman and Smits, 1968; Winsauer et al., 1952). There are two primary groups of the so-called shaly sand models that can be used in these circumstances. Vshale models are based on shale volume fraction where the excess conductivity is represented by derived shale fraction, typically determined from downhole natural gamma ray or neutron-density log separation, together with the shale conductivity. Cation exchange models are based on ionic double layer or clay bound water where the excess conductivity is represented by cation exchange properties of clays and electrolyte conductivity. In both cases Archie's equation is modified accordingly, but in each case the resulting equations reduce back to that of Archie where no additional conduction paths are available (i.e. there are insufficient clay minerals). Worthington (1985) provides an overview of the various models. Here we consider rock formations with relatively small surface conduction effects where Archie's equation is applicable.

Rock electrical properties are thus sensitive to the mineralogy and the pore morphological characteristics as well as the nature of the pore fluid, degree of saturation, temperature and pressure (e.g. Archie, 1942; Llera et al., 1990; Mualem and Friedman, 1991). Most dry rocks are excellent insulators in vacuo, but even saturation with distilled water can decrease resistivity by several orders of magnitude due to the mobilisation of ions for electrical conduction (e.g. Duba et al., 1978). Archie (1942) published the first quantitative use of electrical resistivity in a petrophysical context and developed a series of empirical yet quantitative relationships linking the resistivity of the water-saturated rock to the pore fluid resistivity through a formation factor previously defined by Sundberg (1932). Archie also related his experimentally-defined formation factor to porosity and in turn to saturation by incorporating the resistivity of the hydrocarbon bearing rock as well as the resistivity of the water-saturated rock. Today, some 70 years after Archie, these equations still form the generally accepted basis for the deterministic evaluation of water saturation using electrical methods within petrophysics (e.g. Archie, 1950; Burdine et al., 1950; Doll et al., 1952; Riedel et al., 2005; Spangenberg, 2001; Worthington, 2011; Worthington and Griffiths, 1975). Archie's equations rely on the rock matrix being non-conductive and the pore water being relatively saline. Where either of these conditions is contravened, then alternative methods can be employed, based on Archie's equation but with modification to take account of the excess conductivity due to an additional, different mode of conduction beyond the ionic conduction we consider here (e.g. Worthington, 1985, 1991, 2010) whilst the combination of shale effects and low salinity may also lead to the electrical resistivity being frequency dependent. In this study we confine ourselves to water-saturated rocks and the relationship between pore fluid distribution as controlled by sedimentary fabric and stress-induced fractures. This understanding forms the basis of electrical resistivity investigations and monitoring at a range of scales, in the laboratory, in the field and in boreholes.

The electrical resistivity distribution is dependent on micro-scale (sub-millimetric) heterogeneity of properties such as porosity, controlled by grain size distribution and cementation, which are strongly related to sedimentological fabrics of millimetric geometries. Thus, small-scale heterogeneity controls the morphology of the pore space and in turn, fluid flow and migration within reservoirs, and this is reflected in the petrophysical properties such as electrical resistivity. Clennell (1997) published a classic paper on the tortuosity of electrical flow in rocks, whilst studies of electrical resistivity and heterogeneity include Bernabe et al. (2011), Bernabe and Revil (1995) and more recently Fitch et al. (2013). Downhole logging tools and techniques have been developed to evaluate and record the heterogeneity within the formation as part of subsurface formation evaluation. Conventional downhole logs use current focussing from multi-electrodes, and can identify bedding and fractures with vertical resolutions of about 600 mm (Rider and Kennedey, 2011) whereas, downhole electrical imaging devices comprising multi-electrode-button pads on several pads contained on radial arms provide images with approximately 5 mm resolutions (e.g. Gaillot et al., 2007). Images provided by the high resolution downhole tools, however, require quantitative calibration and whilst possible by integrating the borehole images with resistivity measurements made downhole using conventional resistivity logs, the latter often have a poor resolution and calibration can be problematical (e.g. Boyeldieu and Jeffreys, 1988; Ekstrom et al., 1986). Calibration may be feasible using laboratory measurements on core samples taken from the borehole. Thus, assessing the resistivity of core at the millimetre scale achieved in downhole image logs would be beneficial (Lovell et al., 1997, 2006).

This paper concerns the development of laboratory techniques that are capable of making resistivity measurements with the required resolutions to capture the fine sedimentological fabric within reservoir rocks. Both galvanic or contacting and non-contacting techniques for high-resolution rock core resistivity measurements have been developed. By measuring the voltage gradient parallel to a switched DC current across fixed, multi-electrode grids Jackson et al. (1992, 1995) and Jackson and ODP Leg 133 Shipboard Party (1991) produced resistivity images with a 5 mm resolution of the fabric in samples of the Penrith Sandstone, building on earlier work