

# USING COMPLEX CONDUCTIVITY TO PREDICT HYDROLOGY IN THE REGOLITH

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## INTRODUCTION

Whether for agricultural, industrial or environmental purposes, knowledge of the transport and storage of water in the subsurface is a necessity. Acquiring spatially distributed data about the hydraulic characteristics of the aquifer using traditional techniques, such as closely spaced boreholes, can be expensive. In order to address this problem, researchers have sought suitable geophysical analogues for hydraulic characteristics (Purvanca & Andricevic 2000). The relationship between electrical response and sub-surface water makes electrical methods an appealing technique for hydrological investigation. Induced Polarisation (IP) is a common technique in the minerals industry, due to its strong response to disseminated ore. It has also been quite widely used in groundwater investigations due to its ability to discriminate between clay-rich and saline aquifers (Vacquier *et al.* 1957). Over the last decade a number of detailed investigations have shown that the physical properties of mineral grains and pore throats allow an increasingly sophisticated use of IP in environmental investigations, particularly in the prediction of aquifer properties.

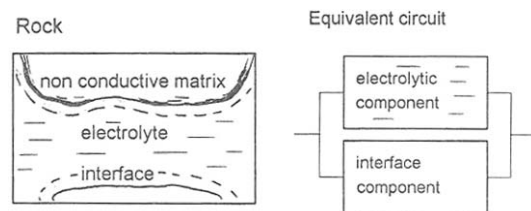
## Electrical Response in Rocks and Sediments

Due to the negligible electronic conduction in most minerals, the majority of charge transport in rocks and sediments occurs in the electrolyte. However, there is also a contribution to conduction at the grain surface (particularly in clay grains), due to the formation of an electric double layer (Schön 1996). These two components can be modelled as a parallel conductor system (Figure 1) where:

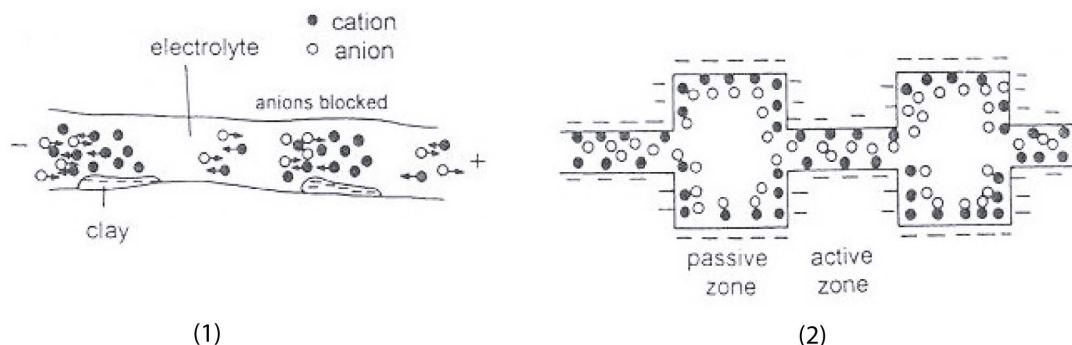
$$\sigma_{bulk} = \sigma_{electrolyte} + \sigma_{interface}$$

However, as well as transport effects in rocks and unconsolidated sediments, there is also a small impedance of charge, known as membrane polarisation. There are two main explanations for this impedance (Figure 2):

1. Variation in surface charge distributions in the pore spaces (this effect is strongest in the presence of clay, but occurs in all rocks); and,
2. Accumulation of charge at constrictions in the medium.



**Figure 1:** Conduction pathways in rocks, and the simple equivalent circuit (Schön 1996).



**Figure 2:** Mechanisms for the IP effect in rocks during the application of current. In (1) the movement of cations is impeded by negatively charged clays. In (2) the movement of cations is impeded by constrictions in the medium. The magnitude of both effects are frequency-dependent.

Thus when a potential distribution is created by introducing a time-varying current into the Earth by galvanic means, the measured voltage can be described in terms of an amplitude and phase relative to the input current.

Following this, the ratio of the voltage to the applied current can be described by a frequency dependent complex number or a complex conductivity:

$$\sigma^*(\omega) = \sigma'(\omega) + i\sigma''(\omega)$$

with a real part  $\sigma'$ , an imaginary part  $\sigma''$ ,  $\omega$  as the angular frequency and  $i$  is  $\sqrt{-1}$  (Börner *et al.* 1996).

Complex conductivity is usually measured using two parameters, conductivity amplitude ( $|\sigma^*|$ ) and phase angle ( $\phi$ ). These measures can be used to determine the real and imaginary parts of the complex conductivity using the relationships:

$$|\sigma^*| = \sqrt{(\sigma')^2 + (\sigma'')^2} \text{ and } \tan(\phi) = \frac{\sigma''}{\sigma'}$$

It has also shown that in high salinity environments that the ratio of chargeability to bulk resistivity (or normalised chargeability ( $M_n$ )) is linearly related to imaginary conductivity (Lesmes & Frye 2001, Slater & Lesmes 2002a).

### COMPLEX CONDUCTIVITY AND PHYSICAL PARAMETERS

Darcy's Law relates fluid flow ( $Q$ ) to the permeability ( $k$ ), cross-sectional area ( $A$ ), fluid viscosity ( $\mu$ ) and the pressure ( $p$ ) using the formula:

$$Q = -\frac{kA}{\mu} \nabla p$$

Ohm's law can be described with a similar form:

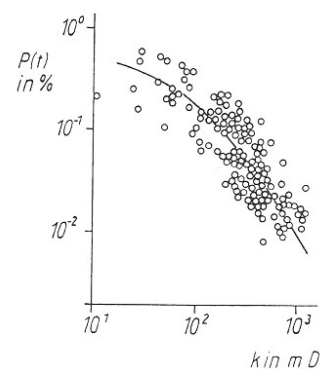
$$I = -\frac{A}{F\rho} \nabla v$$

where  $I$  is electrical current,  $A$  is the cross-sectional area,  $\rho$  is the resistivity ( $\sigma^{-1}$ ) of the fluid,  $v$  is the voltage and  $F$  is the formation factor (the ratio of the rock resistivity to the resistivity of the conducting fluid).

The formation factor is indicative of connected pores in the medium and therefore is seen as the means of deriving fluid permeability values from electrical data. However, due to the effect of surface conduction in many porous media, the true formation factor has been difficult to determine from bulk conductivity measurements (Schön 1996).

A general relationship of increasing chargeability (a measure of polarisation) with decreasing fluid permeability has been noted (Figure 3) and the IP effect has been used qualitatively for many years to determine the location of clays in areas with high fluid conductivities (Bleil 1953, Vacquier *et al.* 1957). Recently, however, investigations of low frequency ( $10^{-3}$ - $10^4$  Hz) complex conductivity responses have shown the possibilities of this measure in revealing information about physical parameters of fluid filled rocks and sediments.

The real component of conductivity ( $\sigma'$ ) is actually made up of  $\sigma_{electrolyte}$  and the real component of the interface conductivity ( $\sigma'_{interface}$ ). In most rocks  $\sigma_{electrolyte} \gg \sigma'_{interface}$ , but in clay-rich rocks  $\sigma'_{interface}$  becomes more important, as clays are very good conductors. Traditional methods of porosity estimation, such as Archie's Laws, often fall down when used in clay-rich or organic-rich areas where surface conduction can be significant. It can be considered, however, that there is now a sufficient accumulation of empirical and analytical evidence for the assumption that the imaginary part of the complex response is dependant on lithology (Börner *et al.* 1996, Chelidze & Gueguen 1999, Dias 2000, Schön 1996, Slater & Glaser 2003, Slater & Lesmes 2002b, Titov *et al.*



**Figure 3:** The relationship between chargeability (PFE in %) and hydraulic permeability in milliDarcy (mD) (Schön 1996)

2002, Vinegar & Waxman 1984, Weller & Börner 1996, Weller *et al.* 1996). Figure 4 shows some of the of the hydraulic/electrical relationships that complex conductivity measurements have the potential to reveal, but how to quantify this relationship for hydraulic parameters is problematic.

With debate over whether the IP effect is primarily due to grain surface or pore throat mechanisms, there is great scope for research into both fundamental mechanisms and the effect of variation in conditions, such as saturation, grain size distributions and clay content.

The majority of models that quantify the relationship between imaginary conductivity and hydraulic permeability use the grain surface model, with the Börner model (Börner *et al.* 1996) relating the imaginary conductivity to a value known as  $S_{por}$  (the surface area to porosity ratio) and the formation factor (F). These are then used to estimate the hydraulic conductivity and cation exchange capacity (CEC) of clays. This model relies on the fact that there is a constant phase angle (CPA) in the electrical response of rocks at different frequencies.

Theoretical models of IP response (Marshall & Madden 1959, Titov *et al.* 2002) predict, and empirical evidence has shown (Pelton *et al.* 1978, Scott & Barker 2003), that there is a length scale to the impedance of current, or a relationship between grain size and frequency response. This means that Börner's assumption is not necessarily valid outside of simple grain-size distributions (Slater & Lesmes 2002b).

Slater & Lesmes (2002b) use this relationship to relate the imaginary conductivity to  $d_{10}$ , or the diameter of the grain that is larger than 10 percent of the sample, which presents as a linear relationship with hydraulic conductivity (Figure 5). However, this model also falls into problems with grain sorting.

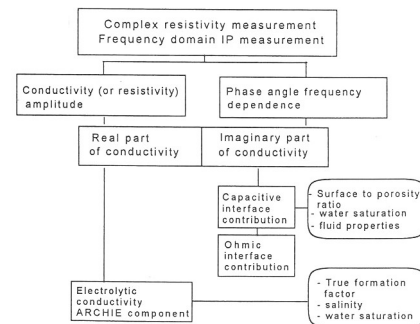
In more complex regolith environments the use of complex relaxation models, such as the Cole-Cole models developed by Pelton (1978) for mineralised systems, may present themselves as a means of describing grain size distributions.

## CONCLUSIONS

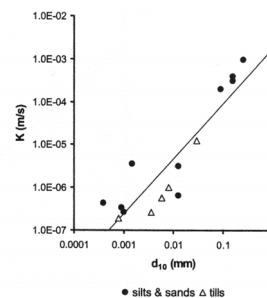
The association of the imaginary part of complex conductivity with structure and grain-size in porous media has a demonstrated potential for characterisation of the hydraulic parameters of the regolith. The development of further evidence, theory, useful arrays and tools, as well as interpretation techniques, will reveal more information from electrical data which is already easily and routinely collected.

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**Figure 4:** Börner's flowchart describing the parameters available from complex conductivity measurements.



**Figure 5:** The relationship between the  $d_{10}$  measure and hydraulic permeability (Slater & Lesmes 2002b).

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