Modelling the complex electrical properties of porous media as a function of frequency

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INTRODUCTION

When a fresh mineral surface is exposed to an aqueous geological pore fluid it is negatively charged and it becomes coated with a layer of adsorbed positive ions from the solution. The development of the positive surface layer causes the bulk solution proximal to the surface to be depleted of positive ions, and hence to become a negatively charged 'diffuse' layer that is fluid by nature. The bulk solution far from the surface remains unchanged. This arrangement is called an electrical double layer or EDL (Revil and Glover, 1997).

Electrical conduction occurs in both the bulk solution and in the EDL. The conduction in the EDL is termed surface conduction. If the characteristic pore or fracture width of a rock is smaller than the thickness of the diffuse layer (i.e., at sufficiently low salinities) the electrical behavior of the rock is dominated by surface conduction, whereas if the thickness of the diffuse layer is small compared to the pore or fracture size, both bulk fluid conduction and surface conduction occur.

When fluid flows through a porous or fractured medium composed of minerals saturated with an aqueous pore fluid, anions in the diffuse layer are moved, generating a so-called streaming potential. Conversely, it is also possible for an external applied electric field to induce relative motion of the free charges in the pore fluid with respect to the solid matrix. These phenomena are called electro-kinetic (EK) processes.

When a seismic wave propagates in the medium, the rock matrix and pore fluids move relatively. The relative motion of ions generates an electrical potential using the same EK mechanism. Hence, we can treat this electro-kinetic-acoustic (EKA) phenomenon as an extension of the EK process. There exists, as before, an opposite phenomenon. The generated seismo-electric signals depend not only on the seismic waves, but also on the conductivity of the pore fluid and the permeability of the formation. We aim to study the mechanisms involved in these processes in order to allow future applications of the EK and EKA phenomena.

The EK phenomenon was described above for a zero-frequency scenario (i.e., a constant applied fluid flow). It is likely that most applications would be low or zero frequency. However, the EKA application is needed to be understood as a function of frequency because the perturbing seismic wave has a given frequency range. Hence, we are required to develop a theory for these processes that is valid as a function of frequency. Such a model is not available currently for two reasons:

1. The coupling coefficients that are used in the current EK theory are always assumed to not be frequency dependent, when in reality they are.
2. There is no AC theory for combined bulk and surface conduction

EXPERIMENTATION

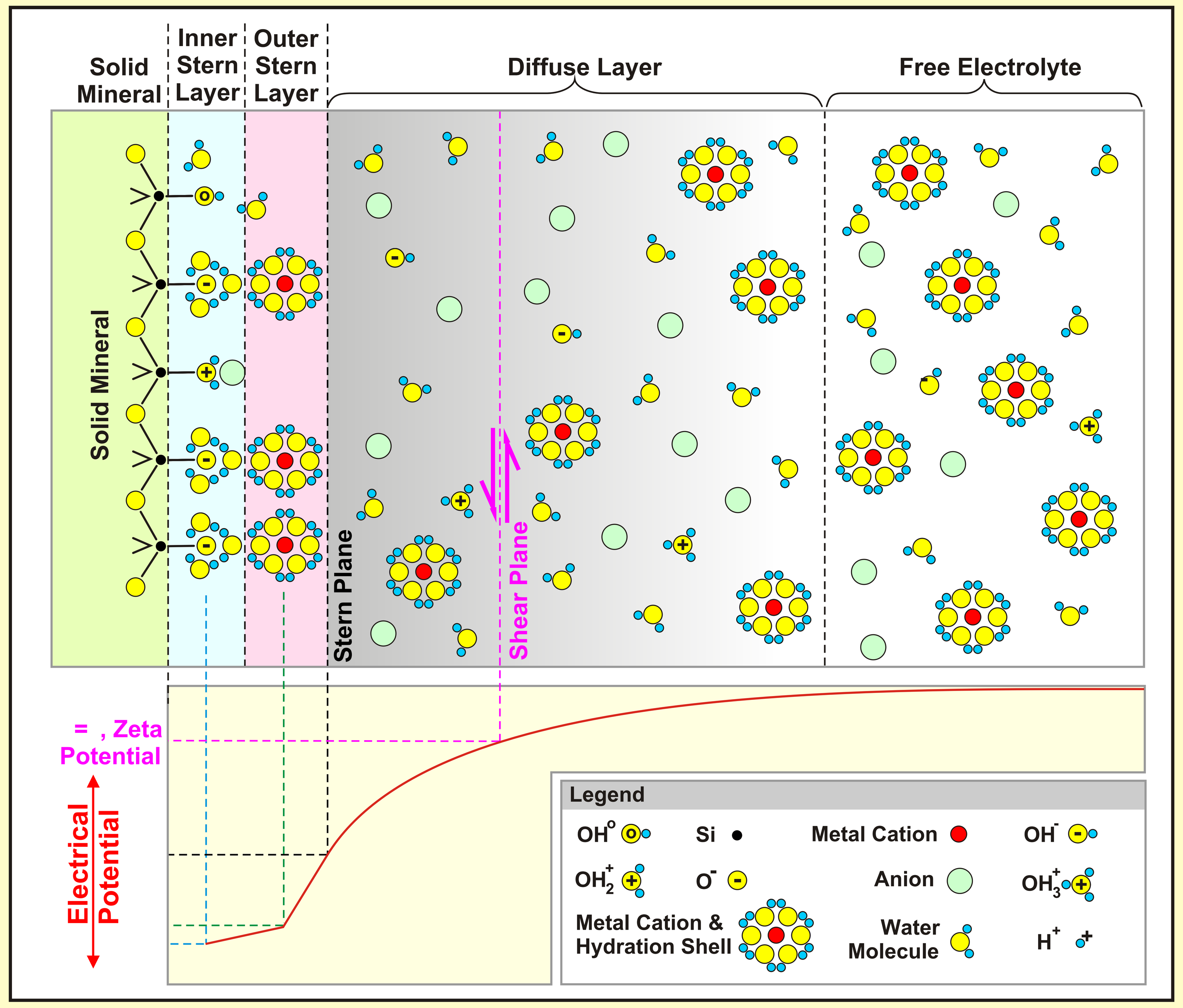
Measurements were made on a number of beadpacks consisting of single bead sizes and multiple bead sizes.

The cells (right) were used to make the measurements.

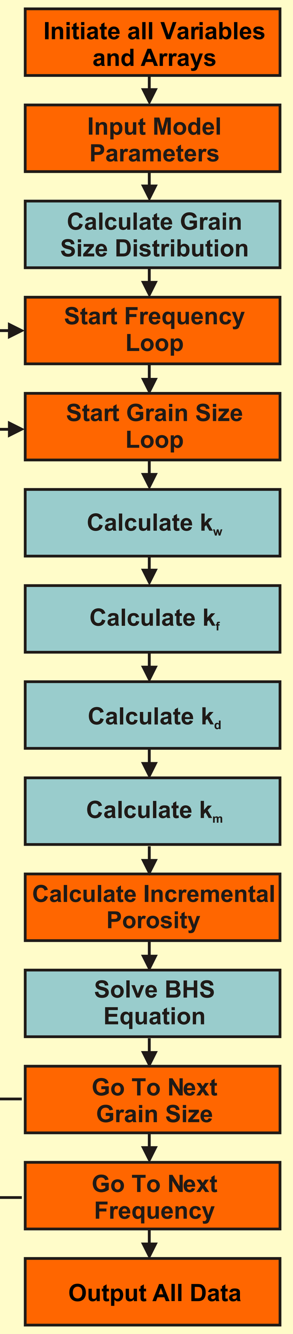
Electrical data was logged using a PC-controlled impedance spectrometer in a temperature controlled cabinet. The temperature was regulated to 25°C with an error of 1°C. All electrodes were platinum-blacked platinum gauze and all connections were 50 ohm coaxial cables.

Quoted Bead Diameter	Measured Bead Diameter	Lower Standard Deviation	Upper Standard Deviation	Mean Porosity by Saturation (%)	Mean Porosity by He (%)	Sphericity (-)
49 microns	48± 1 microns	9.60 microns	4.80 microns	0.43	0.42	1.01
137	135± 5	26.86	13.43	0.41	0.42	1.02
412	410± 10	80.78	40.39	0.42	0.41	1.03
1500	1450± 50	294.11	147.06	0.40	0.40	1.05
2000	2000± 50	392.15	196.08	0.40	0.39	1.02
3000	2900±100	588.24	294.12	0.38	0.39	1.02

ELECTRICAL DOUBLE LAYER



METHODOLOGY



DISPERSIVE EQUATIONS

Relative permittivity of solid grains (Lesmes & Morgan, 2001)

$$k_g \quad k_{go} \quad \frac{g}{o}$$

Relative permittivity of the pore fluid (Ruffet, 1993)

$$k_w \quad k_{wo} \quad \frac{k_{ws} \quad k_w}{1 \quad i \quad _{w1} \quad ^{1}} \quad \frac{k_w \quad k_{wo}}{1 \quad i \quad _{w2}},$$

$$k_{ws} \quad 295.68 \quad 1.2283\,T_w \quad 2.094 \quad 10^{3}\,T_w^2 \quad 1.41 \quad 10^{6}\,T_w^3 \qquad _{w1} \quad 5.62 \quad 10^{15} \exp \frac{0.188}{8.6171 \quad 10^5\,T_w}$$

Relative permittivity of the fixed layer

$$k_{fs} \quad \frac{e^2 R \quad _f}{_o k\,T_w} \qquad k_f \quad \frac{k_{fs}}{1 \quad i \quad _f} \quad i\,\frac{k_{fs} \quad _o}{_f} \qquad _f \quad \frac{R^2}{2\,D_f}$$

Relative permittivity of the diffuse layer

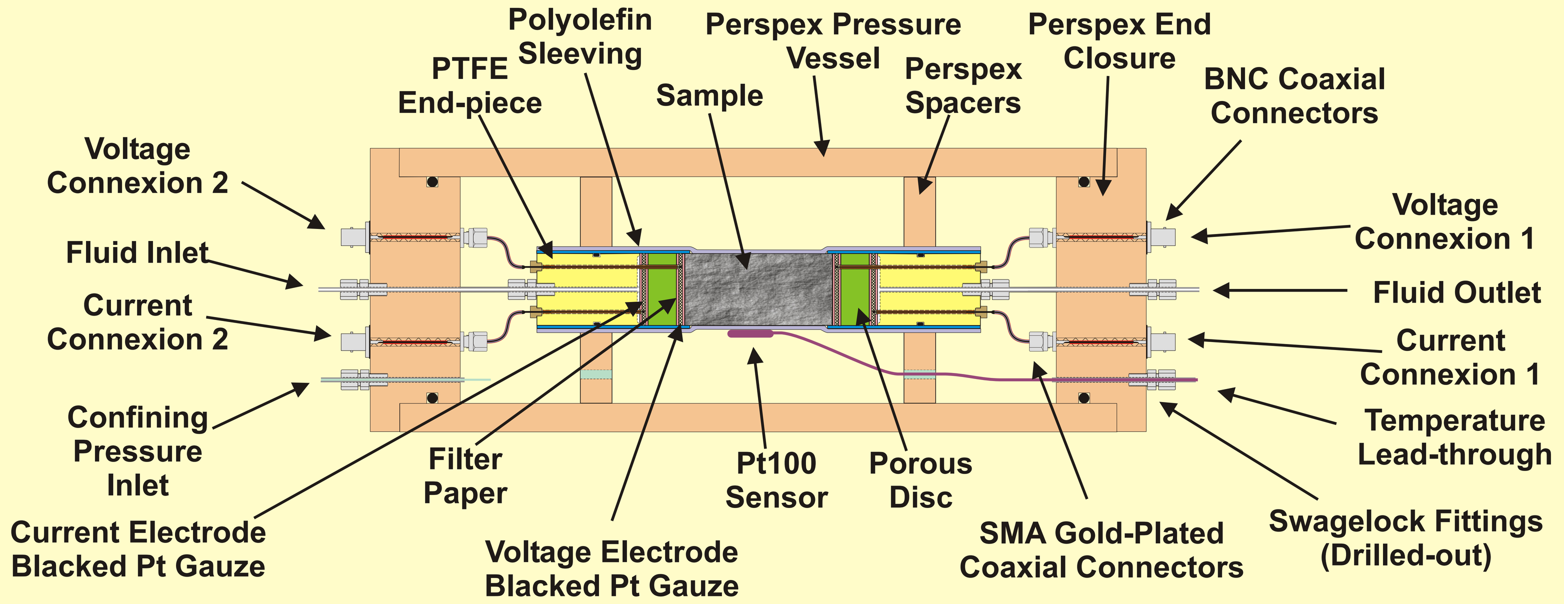
$$k_{d1} \quad k_w \; 1 \quad A \quad \frac{^2 B \quad _w / \quad _o}{1 \quad A^2 \quad ^2 B^2} \qquad k_d \quad k_{do} \quad i \quad _d \qquad _d \quad _w \; 1 \quad A \quad \frac{^2 B k_w \quad _o}{1 \quad A^2 \quad ^2 B^2}$$

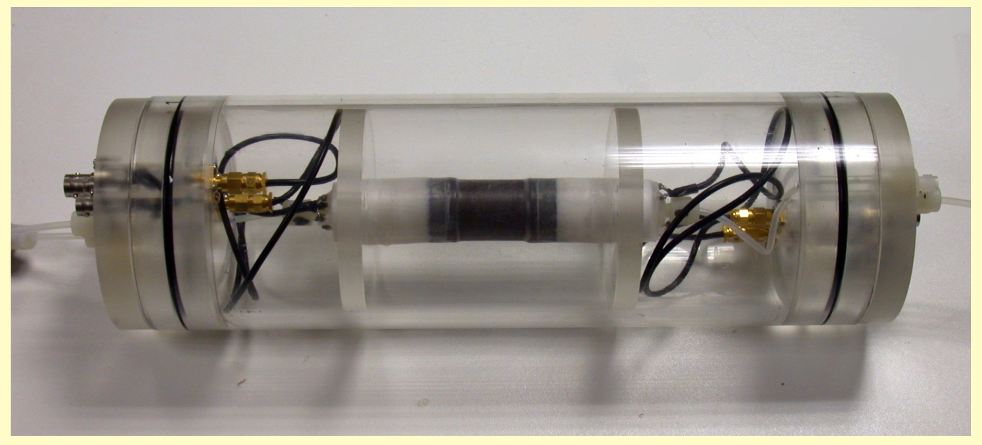
$$A \quad \frac{1 \quad ^{3/2} \quad _d^{3/2}}{2\,1 \quad ^2 \quad _d^2} \qquad B \quad \frac{_d \quad ^{3/2} \quad _d^{3/2}}{2\,1 \quad ^2 \quad _d^2}$$

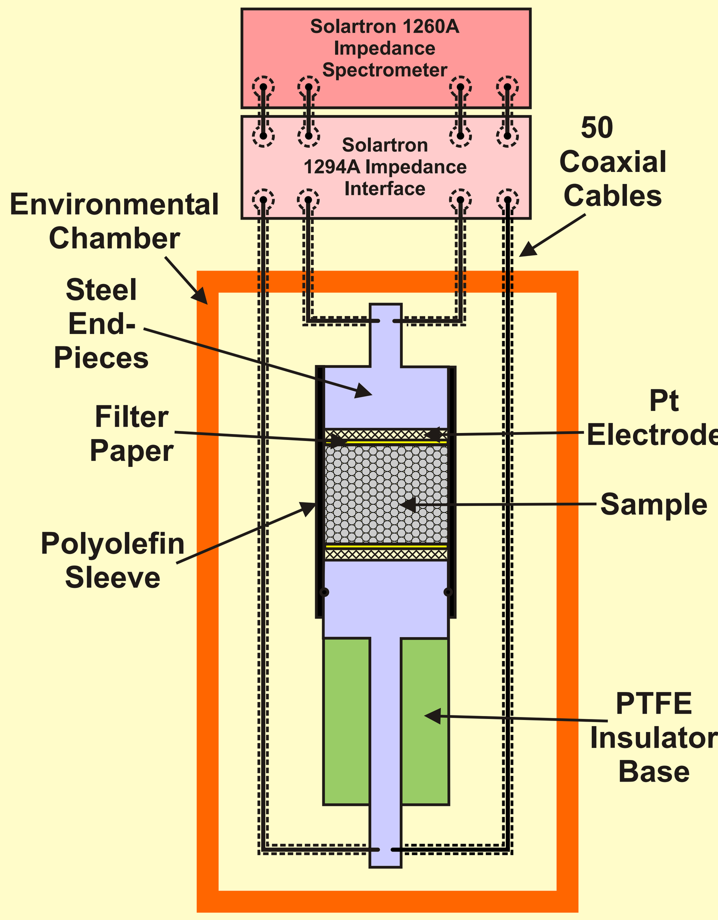
BHS Equation and Conformable mapping

$$k^* \quad k_w \quad ^m \quad \frac{1 \quad k_m / k_w}{1 \quad k_m / k^*} \quad \longrightarrow \quad k^* \quad \frac{k_m}{f^{\,1} \quad f \quad \frac{k_m}{k_w}}$$

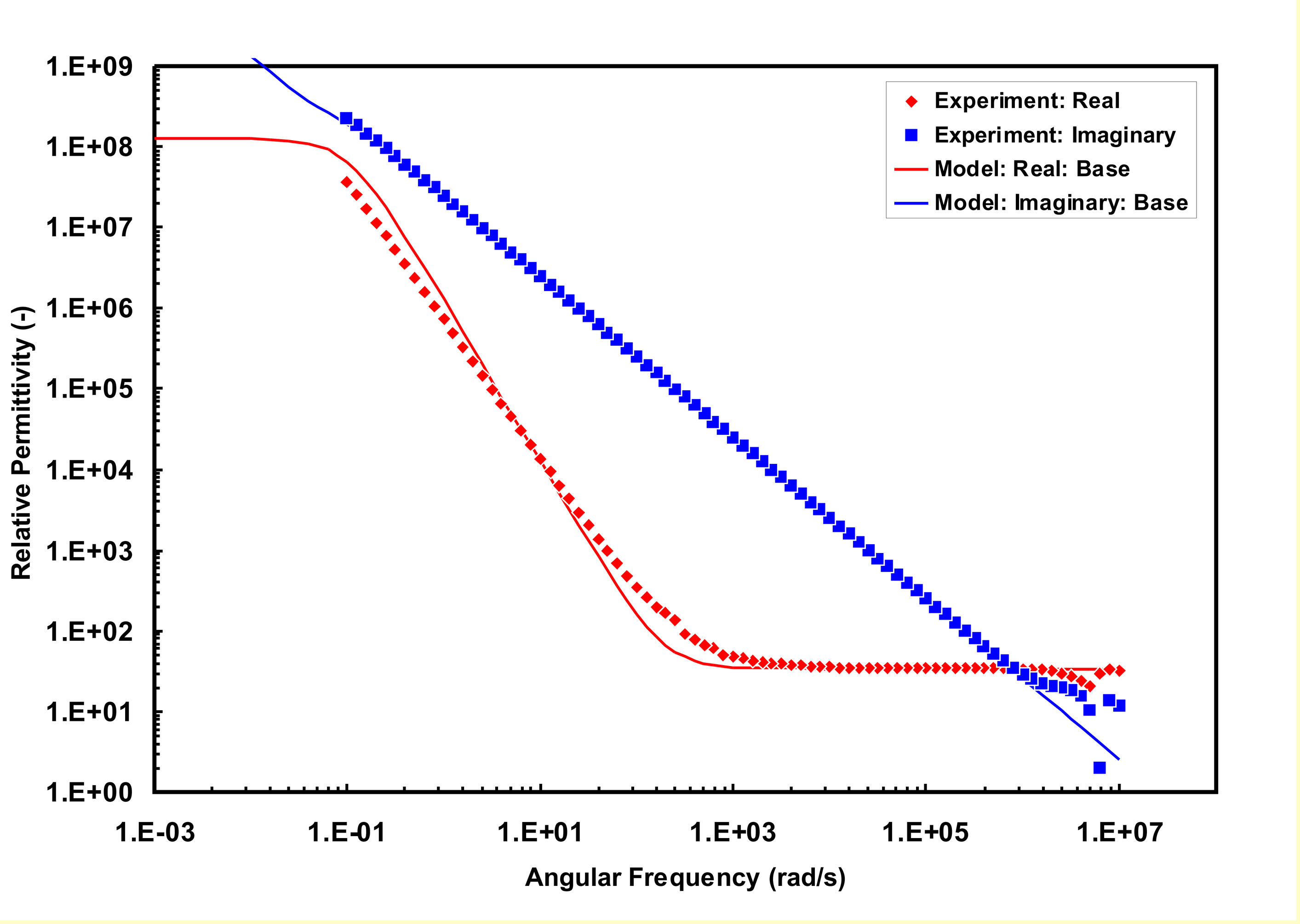
MEASUREMENT CELLS







INITIAL RESULTS



The relative permittivity of a random pack of 0.418 mm diameter glass beads saturated with 0.1 M KCl as a function of frequency measured using an impedance spectrometer together with the modeled response. The model response is the solution of the BHS equation for a 4 permittivity system (grains, adsorbed layer, diffuse

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