

Rocks' Electromagnetic Properties

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1. INTRODUCTION

It is possible to use electrical properties of rocks in mineral exploration by using methods such as induction polarisation and resistivity, as well as electromagnetic methods (Keller and Frischknecht in 1966), crustal sounding (Hermance in 1973), lunar and planetary sounding (Banks in 1969; Brown in 1972; Dyal and Parkin in 1973; Simmons et al. in 1972), glacier sounding (Rossiter and coworkers in 1973), and many more. Other factors like oxygen fugacity and water content have been taken into account while analysing the electrical properties of rocks in laboratory settings (Keller, 1966; Ward and Fraser, 1967; Parkhomenko, 1967; Brace and Orange, 1968; Fuller and Ward, 1970; Alvarez, 1973b; Dvorak, 1973; Hansen et al., 1973; Katsube et al., 1973; WatT, 1973; Gold et al., 1973; Schwerer et al., 1973; Marshall et al., 1973; Olhoeft et al., 1974b; Duba et al., 1974; Hoekstra and Delaney, 1974; and others). An overview of the electrical characteristics of rocks, focusing mostly on frequency, temperature and water content in relation to possible processes will be presented here. In geological materials, the best procedure usually involves a combination of techniques involving the observation of electrical properties as functions of applied field (to test for voltage-current non-linearity) and frequency (Collett and Katsube, 1973). There are many experimental techniques available and a discussion of them will not be attempted here (see von Hippel, 1954; Collett, 1959; ASTM, 1970; Hill et al., 1969; Suggett, 1972); (temperature, water content, etc.).

2. ELECTRICAL PROPERTIES

Maxwell's equations are used to determine electrical characteristics. Standard textbooks (such as Stratton, 1941) provide a propagation constant for an electro magnetic wave.

FREQUENCY DEPENDENCE

The complex permittivity or complex resistivity is used to characterise all frequency-dependent electrical characteristics here (see discussions in Fuller and Ward, 1970, or Collett and Katsube, 1973). Only the value at zero frequency is taken into account for calculating conductivity, and this value is regarded independent of any other frequency. Keep in mind that except for the limit of $\omega \rightarrow 0$ or when $\omega = 0$ we, conductivity is not the reciprocal of resistivity. The complex dielectric constant is the ratio of the material's permittivity to the open space's permittivity. The free space permittivity, $8.854 \times 10^{-12} \text{ F/m}$, is equal to $K' - jK''$ in this equation. Diameter of a real dielectric

$$\rho' - j\rho'' = \frac{1}{\omega \epsilon_0 K'} \frac{(D - j)}{(1 + D^2)}$$

waveguide An imaginary dielectric constant known as "K"

where D is the loss tangent

$$D = \tan \delta = \frac{K''}{K'} + \frac{\sigma}{\omega \epsilon_0 K'} = \frac{\rho'}{\rho''}$$

It is used to indicate an electromagnetic wave phase shift (Olhoeft & Strangway, 1974b) as well as an energy dissipation measurement. Figure 1 (explained below) shows the basic behaviour of electrical characteristics as a function of frequency and may be simulated by a circuit like Figure 2. The DC conductivity channel is represented by the conductance G, the low frequency limit of the dielectric constant is determined by the capacitance CL and the resistor-capacitor pair RCL, and the high frequency limit of the dielectric constant is determined by the capacitance CH. There is a single time constant in this circuit, but in general, there is a distribution of time constants (see Ghausi and Kelly, 1968; Shuey and Johnston, 1973; and others). Dielectric constants that are distributed in time may be

described as having a complex dielectric constant form (Gevers, 1945)

$$K' - jK'' = K_{\infty} + (K_0 - K_{\infty}) \int_0^{\infty} \frac{G(\tau)(1 - j\omega\tau)d\tau}{1 + \omega^2\tau^2}$$

$K_0 = \lim_{\omega \rightarrow 0} K' = \text{low frequency dielectric constant}$, $\omega \rightarrow 0$

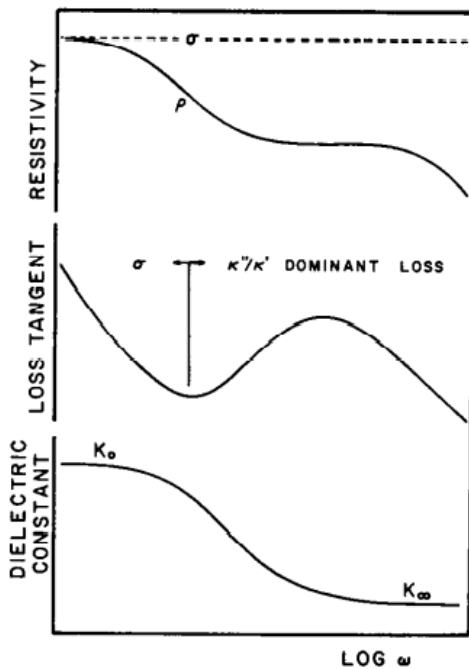


Figure 1. Schematic behaviour of the complex dielectric constant, loss tangent, and resistivity versus log frequency.

$K_{\infty} = \lim_{\omega \rightarrow \infty} K' = \text{high frequency dielectric constant}$, $\omega \rightarrow \infty$, $\tau = \text{time constant}$, $G(\tau)$ is the time constant distribution function with the normalization

$$\int_0^{\infty} G(\tau)d\tau = 1.$$

Temperature and water content have little effect on the high frequency dielectric constant, which is mostly determined by density. For frequencies up to optical, the high frequency dielectric constant is valid, and it is roughly comparable to the index of refraction squared (see von Hippel, 1954). Due to the buildup of charge at crystal boundaries and defects, the low frequency dielectric constant will be studied further below. The distribution function of the time constant may get narrower as the temperature rises, but it usually becomes wider when the water content, salinity, and fault structure increase. In the literature (Poole and Farach, 1971; de Batist, 1972; and others), there are many unique distributions, one of which is the Cole-Cole distribution (Cole and Cole, 1941)

The high frequency dielectric constant is mostly unaffected by temperature or water content, and is instead primarily influenced by density. When discussing high frequency dielectric constant in this context, it can be used only up to optical frequencies, when it is roughly comparable to the square of refraction's index (see von Hippel, 1954). The buildup of charge at crystal boundaries and defects is the primary reason of the low frequency dielectric constant,

which will be described in more detail below. As temperature rises and water, salt, and fault structure are added to a system, the time constant distribution function tends to widen. In the literature, we may find many particular distributions (Poole and Farach, 1971; de Batist, 1972; and others), with the Cole-Cole distribution being the most relevant (Cole and Cole, 1941)

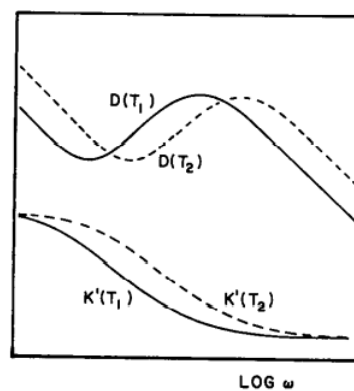
3. TEMPERATURE DEPENDENCE

When it comes to electrical characteristics, time constants and activation energies may be used to describe the frequency-dependent nature of their properties. There is a generalised Boltzmann temperature dependency for both

$$\tau = \sum_i \tau_i e^{E_i/kT}$$

the time constants in the above distribution and the DC conductivity

R = infinite temperature time constant (conductivity) E_i = activation energy (positive for time constants, negative for



conductivity and perhaps temperature-dependent)

Schematic behaviour of: dielectric constant, loss tangent, and activation energy distribution for two temperatures T_2 larger than T_1 . T against frequency for a distribution of time constants and activation energies, Figure 4 (Kelvin). Using the Cole-Cole distribution (5), the behaviour of a single word expression like (6) is depicted in Figure 3. Relaxation occurs more often as the temperature rises. In general, however, each time constant in the distribution (4) may have a distinct expression (6), resulting in the behaviour seen in Figure 4. Temperature affects both the frequency of relaxation and the form of the time constant distribution. Equation (5) would show this as a change in 1 - cx's temperature.

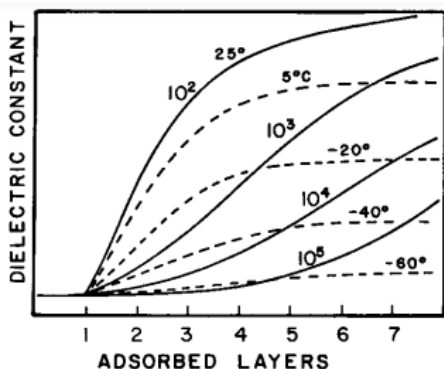
4. VOLTAGE-CURRENT DEPENDENCE

Electrical conductivity is often measured by applying a voltage across an object of specified size. If the linear VI (voltage-current) relationship of Ohm's law is used, the resulting current flow is given by the equation: $a = AIIV$ (7) where I denotes current, V indicates voltage, and A is a geometric constant. It isn't true that all materials are linear VI compatible. A semiconductor diode with a V I relation of the type $I = I_s(e^{qV/kT} - 1)$ (8), where kT is as in (6), q is the electronic charge, and I_s is the saturation current, is the greatest example of one that doesn't (see Gray et al., 1964, for details). This nonlinearity is compounded by the fact that it is also asymmetrical (positive and negative voltages produce different magnitudes of current). Nonlinearity of the second kind is created by the buildup of charge in locations where the electrical characteristics of the material rapidly change, as in the diode shown above. In addition to the margins of crystal lattices, fractures and other defects, and sudden changes in material energy, these areas (also known as space charge layers, or SCL) may be found in other places. Contact potentials, the Maxwell-Wagner frequency response, and the complicated interfacial effects between electrodes and samples are all caused by these space charge layers, which are also the source of VI nonlinearity (Alvarez, 1973b) (Covington, 1970, 1973; Baker and Buckle, 1968; Buck, 1969; Hampson, 1972, 1973; Hever, 1972; and others). The relaxation rate of a charge distribution is determined by the electrical characteristics of a space charge layer. Consequently, a heterogeneous material will have a wide range of time constants due to the presence of space charge layers in many

distinct materials. Dielectric constants are also affected by space charge layers, and the impact is more obvious in wet materials where the water forms the electrochemical double layer (space charge layer in a liquid; see Delahay, 1965; Schiffrin, 1970, 1972, 1973; Payne, 1973). In experiments with wet materials, it may be especially difficult to tell the difference between the electrode-sample low frequency response and the response that is a result of the sample's interfacial characteristics. As a well-known and acknowledged fact, nonlinearity of $V I$ in rocks has not been well investigated. Studies in the laboratory using conductors such as conductive minerals conducted by Scott and West (1969) and Katsube et al. Very low conductivity lunar materials have been studied by Schwerer et al. (1973) and Olhoeft et al. (1974b) 268 l, who both found nonlinear VI phenomena in their work. In field surveys, Halverson et al. (1973) reported nonlinear polarisation responses. All of these phenomena have been reported at frequencies below 1000 Hz.

5. MOISTURE DEPENDENCE

Dielectric constants in bulk materials are not altered by a monolayer of water adsorbed onto a dielectric surface in the dry state, as has been demonstrated by Baldwin (1958), Yon Ebert and Langhammer (1961), and McCafferty and Zettlemoyer (1971). The time constant activation energy increases, the frequency of relaxation increases, and the time constant distribution widens as a result of successive adsorption layers. Free pore water formation and pore fluid conduction take over electrical characteristics after around seven layers. An increase in low-frequency dielectric constant and time constant distribution is achieved by adding alteration products and electrolytes to water. In addition, the DC conductivity is increased by many orders of magnitude with additional monolayers and layers. Strangway and et al. (1972), Hoekstra and Doyle (1971), Alvarez (1973a), and others have addressed examples of the aforementioned. The electrochemical double layer is formed as a result of water modifying electrical characteristics. Adsorbed Gouy-Chapman layers form the monolayer, which is on the order of 10 angstroms thick and is the strongest layer. Additions of water to the Gouy-Chapman layer's space charge layer have a significant impact on the electrical characteristics of the layer (which may influence general physical properties to 1000 angstroms from the solid-liquid interface). Clark (1970), Schiffrin (1970, 1972, and 1973), Sing (1973), and Payne (1973) all address and examine these. Davies and Rideal (1963), Rangarajan (1969), and Everett and Haynes (1983) all highlighted the extra issues presented by porous system geometries (1973). Fine parallel capillaries in rocks have been linked to abnormal dielectric characteristics, according to Marshall et al. (1973). In the domain of geology, Shankland and Waif (1973) and Madden (1974) examined the specific topic of connectedness with reference to electrical conductivity in porous media. Hasted (1972), Rao and Premaswarup (1969), and Pottel (1970) all examine electrolytes in water (1973). Additional to the double layer, such solutions must take into account chemical reactions and Faradaic mass transport mechanisms (see att and Rys, 1973a, b; Schmidt, 1973a, b, c; DeVlie and Pospisil, 1969; Reinmuth, 1972a, b, c; Armstrong and Firman, 1973a, b). Baldwin (1958), Yon Ebert and Langhammer (1961), Dransfeld et al. (1962), McCafferty and Zettlemoyer (1964), and McCafferty and Zettlemoyer (1964) have studied the effects of temperature and water content on electrical characteristics (1971). In addition to Hoekstra,



Water's dielectric constant varies with frequency at different frequencies at ambient temperature (solid lines) and with temperature at 100 Hz (dotted lines) (dashed lines).

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