

NON-LINEAR COMPLEX RESISTIVITY FOR THE CHARACTERIZATION OF SEDIMENTARY URANIUM DEPOSITS

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Measurement of variations in physical and chemical properties by mapping changes in the electrical resistivity of the ground is a well known technique whereby a known electrical current is used to stimulate the ground while the resultant voltage generated is separately measured. The ratio of the voltage to the current times a geometric constant is then the observed resistivity. If the measurement is done at dc (zero frequency), only one number is obtained, the dc resistivity. At non-zero frequencies, however, the resistivity is a complex quantity and the resultant terms are usually expressed as the real part of the complex resistivity ("real resistivity") and the phase angle between the applied current and the measured voltage. For measurements at several frequencies, there are further parameters such as the percent frequency effect (PFE) which is a measure of the variation of the real resistivity with frequency.

In all of these techniques, it is assumed that the resistivity is a linear function of voltage and a linear reciprocal function of current, in which case we say that the system is linear and obeys Ohm's law. Thus, if we plot current vs voltage at dc the result is a straight line for a linear resistivity material. If the frequency is non-zero and there is a significant phase angle, a plot of current vs voltage will result in an ellipse (with limits of a straight line for 0 mrad (milliradians) phase angle and a circle for 1570.8 mrad phase angle). If the system has any non-linear components, the resultant plot will appear as a distorted line, ellipse or circle. The non-linear complex resistivity measurements described here are the result of driving a pure sine wave current into a sample, and studying the resultant voltage response for harmonic distortion.

Most unaltered materials, such as basalt or quartz sand, have extremely high resistivities when dry and low resistivities when in contact with water; in both cases the response is linear. This is due to the fact that the rock-water interaction in these materials is not very chemically active. In contrast, materials such as sulfides, clays, and zeolites are extremely chemically active at the water-rock interface either through direct oxidation-reduction reactions or through adsorption-desorption reactions (such as in the cation exchange process). The currents which result while these reactions are proceeding cause non-linear responses in such materials.

At very low current densities, when little chemical action is occurring, these materials may be linear. With increasing current density, chemical activity increases and the system becomes non-linear. The nature of the observed non-linearity is a direct function of the type of chemical reaction. Also, as the frequency of the applied current is varied, the non-linear response changes character and eventually disappears as the driving current begins to exceed the rate of the chemical reaction.

Detailed laboratory work has been proceeding on a series of very carefully acquired, handled, and prepared natural and synthetic materials which are representative of sedimentary uranium deposits. Strong differences have been observed between the linear response of quartz sand and the two most common types of non-linear response due to oxidation-reduction reactions (as occurring in sulfides) and due to adsorption-desorption reactions (as in the cation exchange process in clays and zeolites). Although the dry sulfide minerals may have non-linear responses due to their semiconducting nature, all of the observed non-linear responses reported here are due to reactions at the rock-water interface.

A single non-linear response for a typical sulfide such as pyrite is very complicated due to the occurrence of several different reactions. There is a hierarchy in the sequence of reaction as the current is increased and then decreased. This hierarchy allows observance of specific individual reactions. Each reaction occurs at a specific rate and is influenced by the chemical environment (such as the pH, Eh, and so on of the water). Further, some reactions are reversible while others are not. By observing the characteristic non-linear response of a sample as a function of frequency and interpreting that as the presence or absence, rate, and relative magnitude of various chemical reactions it thus becomes possible to identify several types of material (clay vs sulfide, for example), sorbable ions in solution, and to place limits on the oxidation state of the minerals as well as the Eh and pH of the ground water.

The laboratory work has already demonstrated that distinctions may be made between clays, sulfides, shales, and graphites. Also, the relative oxidation state is observable.

Although non-linear complex resistivity is useful as a laboratory tool, it does not appear that it will be successfully applied as a surface exploration technique.

The problems of divergent and widely varying current densities are very great. As a downhole logging tool, however, it shows exceptional promise. This is especially true in areas where an in situ or solution mining process must be tailored to the specific ground water and mineral chemistry of a given site. As a logging tool, non-linear complex resistivity should then be able to delineate and characterize an orebody as to variations in pH and Eh (by observing the changes in various sulfide chemical reactions), as to relative concentrations of clays and sulfides, as to the availability and mobility of sorbable ions, and possibly as to variations in cation exchange capacity.

There is a considerable amount of detailed laboratory work which has yet to be performed. It has already been demonstrated that clays and sulfides have very different non-linear responses, but it has yet to be shown whether or not individual sulfides (pyrite vs chalcopyrite) may be discriminated or whether individual clays (kaolinite vs

montmorillonite) may be discerned. It has been shown that the relative oxidation states of some materials are observable, but absolute calibrations should be possible.

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TOTAL-FIELD MAGNETIC SURVEYING AS AN EXPLORATION TOOL FOR SEDIMENTARY URANIUM DEPOSITS

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Total-field magnetic surveying is a relatively simple and inexpensive geophysical exploration method. In order to test applications in the exploration for sedimentary uranium deposits, ground surveys have been conducted in several areas over known mineralization. Results indicate that magnetic surveying can detect subtle variations in the distribution of magnetic minerals in the sedimentary section. In many cases, these variations can be spatially related to uranium orebodies.

Induced magnetization is usually the primary source of magnetism in sedimentary rocks. The majority of magnetic anomalies are due to changes in the strength of the induced field caused by local variations in the quantity of magnetic minerals distributed in the rocks. The common magnetic minerals are Fe-Ti oxides, the most important being magnetite. Their distribution is controlled by the depositional processes of the sedimentary environment and by their possible alteration due to geochemical processes.

In the fluvial to transitional marine sandstones that most commonly host sedimentary uranium deposits, magnetic minerals can occur both as local concentrations associated with stream channels and as disseminated detrital grains.

The mechanical deposition of these minerals is dependent upon the size, shape, and mass of the grain and the velocity and sorting capability of the environment. Adler (1973); Adams, Curtis, and Hafen (1975); and Reynolds (1975) have discussed how oxidizing and reducing conditions, related to the formation of sedimentary uranium deposits, can alter detrital magnetic minerals. Of particular interest in the application of magnetic surveying techniques is the reported partial to complete destruction of magnetic minerals in the vicinity of some sedimentary uranium deposits and the correlation of low magnetic susceptibility with uranium (Ellis and others, 1968).

The ability of magnetic mapping to detect anomalies associated with sedimentary uranium deposits is dependent upon the contrast of magnetic properties (if any) of mineralized rocks with surrounding rocks and upon the size and depth of that zone of contrast. Increasing depth will decrease the size of an anomaly associated with a given source and increase the possibility of it being obscured by other magnetic sources. This factor limits the usefulness of surface magnetic methods in exploring for deeper uranium deposits. However, even when no anomalies can be directly