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RESISTIVITY OF ROCKS IN GEOTHERMAL SYSTEMS: A LABORATORY STUDY

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ABSTRACT

This paper describes a limited series of laboratory resistivity measurements on a selection of core samples taken from geothermal fields in New Zealand and the Philippines. The resistivities of these cores, selected to include a range of clay contents and porosities, were measured using various saturating fluids (NaCl solutions with resistivities ranging from 0.3 to 3 oh-m) and at temperatures between 20°C and 90°C.

The temperature behaviour of the measured resistivity values implies that ionic conduction is the dominant charge transport mechanism occurring under these conditions. Multiple linear regression analysis of all the data confirms the expected dependence of the resistivity of these hydrothermally altered rocks upon temperature, saturating fluid resistivity. porosity and clay content. This dependence can be described by a variant of Archie's relation, modified to allow for the effect of the clay mineral content and temperature.

INTRODUCTION

Resistivity, particularly the DC resistivity method, plays a key role in exploration for geothermal resources. However, in order to properly analyse resistivity surveys from geothermal areas, interpreters must know what resistivities are appropriate for geothermal reservoir rocks under various conditions. Unfortunately, compared to the vast body of literature available for other lithotypes (Olhoeft, 1981). little published data is available on this subject.

The resistivities in a geothermal environment are likely to be quite different from rocks encountered in other exploration situations, however, because three different conduction mechanisms (ionic transfer through interstitial water, conduction on the surface of clays, and matrix conduction through semi-conducting minerals) may all be important in geothermal reservoirs. This is in contrast with the rocks commonly encountered in oil reservoirs where a very simple relationship (i.e. Archie's law) can be used to relate porosity and water resistivity to rock resistivity.

This paper describes a limited series of laboratory resistivity measurements on core samples taken from several Philippine and New Zealand geothermal fields. Because of the inherent variability of rocks commonly found in geothermal systems and the relatively small number of samples available for analysis, we have analysed our data to determine which underlying charge transport mechanisms are active rather than attempting to develop a predictive relationship.

While the results of these experiments cannot readily be extrapolated to reservoir temperatures, we feel that they are important because they provide insights into the underlying physical processes that control rock resistivities in geothermal situations and because they may be important in directing future research.

CONDUCTION MECHANISMS

The resistivity of rocks in the earth is a function of the resistivity of the rock matrix and the water held in the pore spaces. Pure water has a high resistivity (10^6 ohm-m), but if the water contains dissolved ions the resistivity decreases dramatically (to 10^{-2} ohm-m or less). As a result, conduction through the liquid phase tends to dominate the conductivity. Most of the common constituents of rocks are very highly resistive (with resistivities ranging between 10^4 and 10^{10} ohm-m); although some constituents such as sulphides are quite conductive. As a result, conduction through the liquid phase tends to provide most of the conduction of the total rock sample, even though the liquid phase makes up a small part of the total volume.

In addition to the effect of finite matrix conductivity, chemical interaction between the saturating water and the pore walls can have an important effect on the water resistivities. Surface conduction occurs because exchangeable ions occur near grain boundaries. Because these ions are quite loosely bound, they can contribute to the conductivity of the rock in a manner similar to ionic conductivity in pore water. The number of exchangeable ions varies depending on the minerals present, being greatest in clays (particularly smectites) and zeolites, and nearly insignificant in most network silicates. However, because these constitutents, especially clays, are quite common in geothermal systems, surface conduction can make an important contribution to the conductivity of hydrothermally altered rocks.

In the case of a relatively clean granular aquifer saturated with fairly conductive water (resistivities less than 5 ohm-m) the rock resistivity is found to be directly proportional to the water resistivity. The proportionality can be calculated easily using Archie's (1941) equation.

$$\rho = a \ \rho_w \ \emptyset^n \ S_w^m \qquad (1)$$

where ρ is the rock resistivity, $\emptyset$ is the porosity, Sw is the degree of water saturation, ρ_w is the water resistivity. The constants a, m, and n are empirically derived. If substantial amounts of conductive minerals or clays are present however, is no longer proportional to w because surface conduction becomes important and Archie's equation will substantially underestimate the rock resistivity. The effect of surface conduction due to clays has been examined by several workers (Juhasz 1979), (Waxman and Smits 1968). Following Waxman and Smits, Ohloeft (1981) suggested that Archie's equation can be modified to include the effect of finite matrix conductivity as follows:

$$\rho = \rho_w \emptyset^n Sw^m (1 t KC \rho w)^{-1} \qquad (2)$$

where C is the proportion of clay minerals and K is a constant depending on the clay species present.

Because the conductivity of clay minerals varies with the number of exchangeable ions available we would expect K to vary with the cation exchange capacity being highest in clay species with high cation exchange capacities (such as smectite) and have a low value in clays with low cation exchange capacities such as illite, chlorite and kaolinite. All of the samples reported here contain low cation exchange capacity clays with illite and chlorite being the only significant clay types present.

In addition to ionic conduction and surface conduction, matrix conduction, which arises because of the presence of conductive minerals such as sulfides may also be important in some geothermal rocks. In this case, conduction occurs by the movement of electrons within the body of mineral grains.

TEMPERATURE DEPENDENCE OF RESISTIVITY

All conduction in the earthis caused by one of three mechanisms: metallic conduction, electronic semi-conduction and ionic conduction. Metallic conduction (which is very rare in the crust, being confined to native metals and graphite) is linearly related to temperature, resulting in an inverse relationship between resistivity and temperature. The other two mechanisms both have exponential temperature dependence as follows:

$$\rho = \rho_o e^{E/KT} \qquad (3)$$

Here, **E** is the activation energy for the conduction process, **K** is Boltzemann's constant and ρ_o is the resistivity at infinite temperature.

Because the value of E is determined by the underlying conduction mechanism. it can be used to determine which of the several possible conduction mechanisms is most important.

Of the conduction processes which might be important in hydrothermal systems, matrix conduction in sulfides is known to follow the exponential temperature dependence very closely. Activation energies typically range from 0.5 to 1eV (Olhoeft 1982).

The resistivity of ionic solutions is a function of the mobility of ions which in turn is proportional to the viscosity of water. The viscosity of water does not exactly follow a simple exponential temperature dependence because of a thermally activated breakdown of hydrogen bonds but, as shown in Fig. 4, in the temperature range from 20°C + 90°C the resistivity does approximately follow equation 3. The activation energy for both viscosity and resistivity is 0.16 eV in this temperature range.

The temperature dependence of conductivity in clays is not well understood. Drury and Hydam (1979) report that charge transport in smectites is thermally activated with activation energies higher than those for water. They do not present quantitative estimates of the activation energy however and implications of their work for the temperature dependence of other types of clay is not clear.

EXPERIMENTAL METHOD

Because we suspected that rock resistivity is a function of several variables (i.e. degree and type of alteration, porosity, temperature and water resistivity) we started with a suite of samples which had a range of porosities and clay contents (see Table 1). The samples were then repeatedly saturated with increasingly saline pore waters and their resistivities were measured at a range of temperatures from room temperature to 90°C. The resulting dataset, which included a total of 60 measurements was thus fairly well designed for analysis by multiple linear regression.

Resistivity measurements were conducted using the four electrode. method which is described by Hunt et al 1979. In this configuration the electric current is applied across the ends of the sample while the voltage drop is measured using two parallel ring electrodes located near the centre. Before any measurements are made the sample is shaped into a column with a regular sectional area approximately 25 mm in diameter with parallel ends and saturated under a vacuum. The sample was then tightly jacketed with shrink tubing after any surface water adhering to the sample was removed in order to eliminate any leakage of electric current around the sides of the sample. When conducting the measurements, metal plates are used for the current electrodes and the potential electrodes are stainless steel wire loops which sit in shallow grooves cut in the sides of the sample. Good contact between these electrodes and the sample is ensured by painting the sides of the .grooves with silver paint. The input signal during these experiments was a square wave with a period of 3s in order to approximate DC conditions. Fig. 1 shows a typical signal recorded across the potential electrodes.

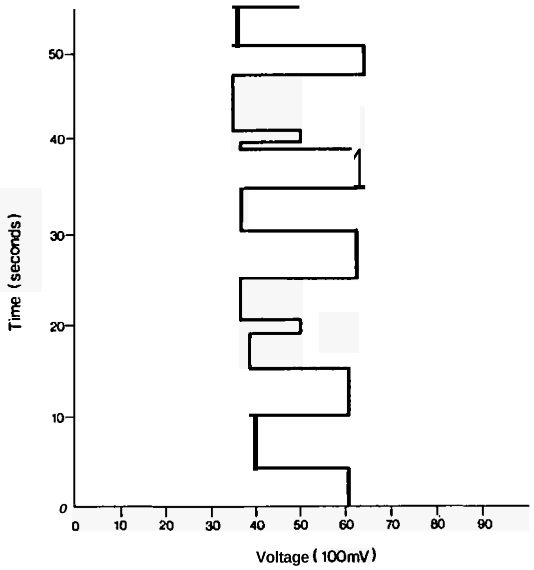
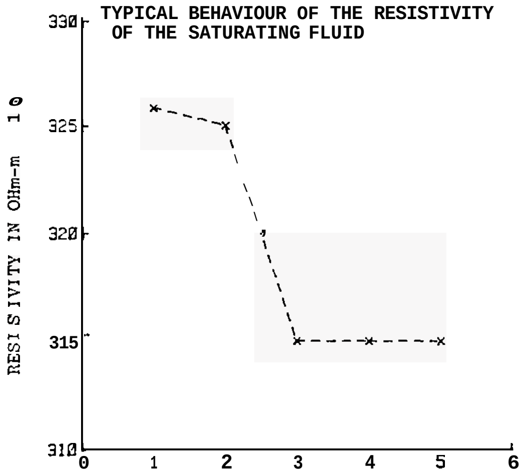


Fig 1 TYPICAL VOLTAGE RECORD

In order to investigate the effect of water resistivity on the bulk resistivity of the rock, samples were repeatedly saturated using increasingly saline NaCl solutions. Between these sequencies of measurements; each core was allowed to equilibrate with a more, concentrated NaCl solution until the water conductivity stabilised. Because the salinity increased by at least a factor of three between repeat saturations, the effect of residual ions left in the pore spaces was usually found to be minimal. However, because measured conductivities were used in the analysis, residual ions will not add additional error. A sample plot of water resistivity vs time is shown in Fig. 2.

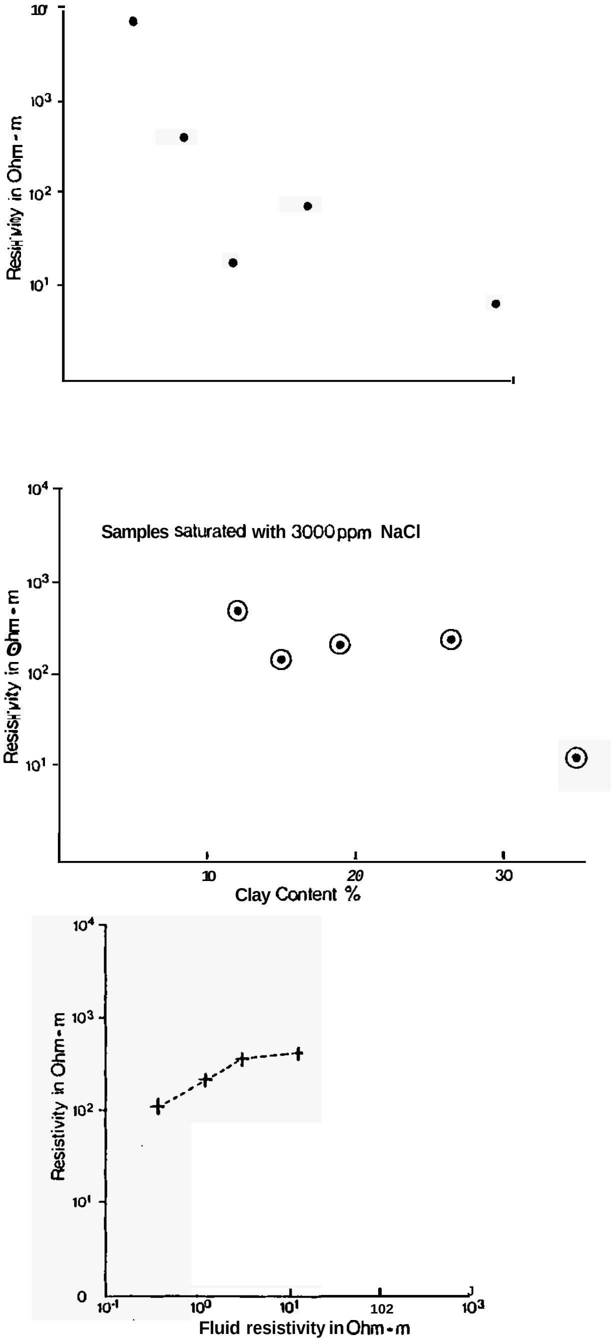


The content of various clay species was determined using semi-quantitative XRD analysis where the quantity of clay in a sample is determined from the heights of peaks in an x-ray diffraction spectrum of a random mounted powder sample (see Brindley and Brown 1980 for a more complete discussion). In order to include first and second order diffraction peaks from all the common clay minerals, the XRD spectrum was recorded from 4°20'. Samples were prepared by mixing known quantities of clays with silica powder. Using the peak areas of the standard samples and the known clay content, it was possible to determine the appropriate conversion factors between peak areas and clay content in the sample. Unfortunately, the primary XRD peaks for Biotite and Illite overlap; however this problem can be overcome by using the second order peaks to estimate the content of these minerals. X-ray diffraction studies are at best only semi-quantitative with a precision of ±25% of the estimated 'clay percentages. In order to guard against significant errors, all estimates of clay percentages were checked optically using thin sections and a petrographic microscope.

Along with the clay content and electrical resistivity, we also measured the density and porosity of the samples. The densities and porosities were determined by saturating each specimen under a vacuum until the sample weight stabilised. The densities were then calculated from the difference between the saturated and immersed weight and the porosity was calculated from the difference between the dry and saturated weight. Densities thus determined were accurate to about 5% and porosities to ± 10%.

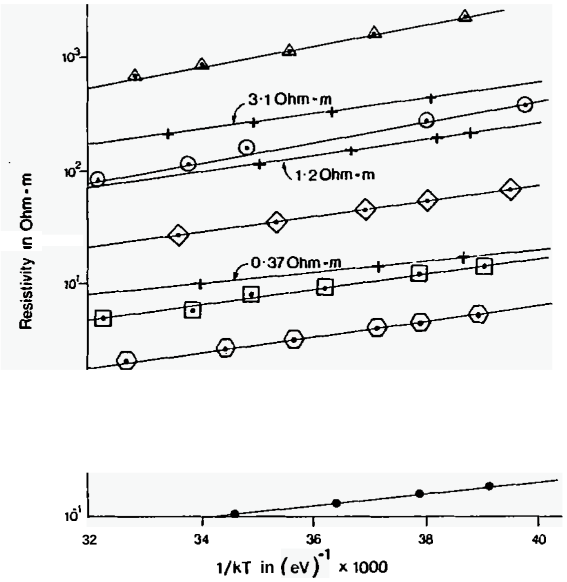
RESULTS

Experimental results illustrating the effect of clay content, porosity and water resistivity are shown in Figure 3. Note that water resistivities appear to be related to the rock resistivities by power law relations as the log-log plot shown in Fig. 3 is approximately linear above a cutoff value. Clay content and porosity also appears to have an effect on rock resistivities however it is difficult to separate the effects of clay content and porosity without the use of multiple linear regression, which is discussed in a later section.



3. Bulk rock resistivity plotted vs water resistivity and clay content.

The effect of temperature on rock resistivities is illustrated in Fig. 4. Note that an exponential dependence of temperature on resistivity, as suggested above, holds for a wide variety of geothermal rocks. This appears to be true irrespective of the degree of alteration, salinity of the saturating water or porosity of the sample. While the slope of the straight line segments, which are proportional to the activation energy show some variability, the majority of samples have activation energies near 0.14 eV. In fact, all of the samples measured have activation energies between 0.08 ev and 0.20 ev, i.e. within 50% of the value appropriate for ionic conduction in water. This observation is important as it suggests that ionic conduction is the dominant charge transport mechanism in geothermal rocks whether the conductivity is due to a high concentration of clay minerals or the presence of a highly mineralised pore water.



Br/11 Silicified Rhyolite (porosity 16%)
○ **Ohaaki** Geothermal Field

K5 Slightly Altered Rhyolite (porosity **33%)**
◇ Kawerau **Geothermal** Field

Br/9 Altered **Rhyolite;** (porosity 23%) Main alteration minerals: **Montmorillonite / Illite**
□

Oh/4 Altered Ignimbrite: (porosity *58%)* Main **alteration** minerals: Kaolinite **/ Alunite**
⬡

Im/3 Highly altered Andesite saturated with various saline waters (porosity 3.1%)
+

Oh/1 Silicified Ignimbrite (porosity 8·5%)
△ Ohakuri Fossil Geothermal Field

● Data for **3%** NaCl **solution** after Ucok 1979

4. Bulk rock resistivity plotted vs temperature.

DISCUSSION

A qualitative look at the data shows that the rock resistivity is a function of at least four variables, i.e. temperature. clay content, water resistivity and porosity. For this reason we use multiple linear regression as a technique to analyse the resistivity data.

Regression analysis requires a simple. preferably linearisable equation relating the dependent and independent variables to act as the regression model. For the regression model we used the following equation

$$\rho = a \; \rho_w^m \; \Phi^n \; e^{bC} \; \frac{e^{E/KT}}{e^{E/K\,300^\circ}} \qquad (4)$$

Where ρ is the rock resistivity, ρ_w is the water resistivity, C is clay content, Φ is porosity, T is temperature and a. m, n, E and b are empirical constants whose values are to be determined by the regression process. Note that equation 4 incorporates both the exponential temperature dependence and power law porosity dependence noted earlier. An exponential relationship between resistivity and clay content has been assumed largely for convenience as. in this form, the equation is readily linearisable by taking the log of both sides. Note that, while the assumed exponential dependence on C is quite different from the Waxman and Smits model (eq 2) both factors have the same assymtopic behaviour in that both factors approach zero as C approaches 100% if the empirical constant b has a negative value. and both approach unity as C approaches zero.

TABLE 1: VALUES OF EMPIRICAL CONSTANTS GIVEN BY REGRESSION (MULTI-LINEAR)

a = $(1.4 \pm 0.2) \times 10^2$
m = -0.9 ± 0.2
n = -0.8 ± 0.2
b = -11 ± 2
E = -0.14 ± 0.06

Uncertaintities calculated to the 95% confidence level.

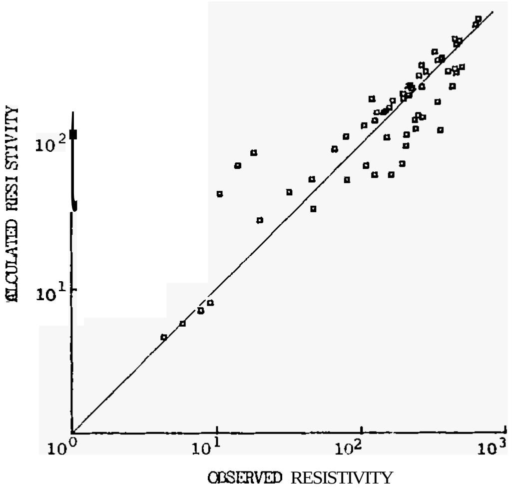
TABLE 2: GENERAL LINEAR TEST RESULTS

Variable	F Test Value
Clay Content C	123
Water Resistivity	87
Porosity	69
Temperature T	19

(Minimum significant value of F test at 95% confidence level is 1.6)

The statistical significance of variables in a regression model can be tested using the general linear test statistic. In this test, variables are removed from the model one at a time. and the significance of the variable is estimated by the increase in the total square error of the points about the model. Results of the general linear test are summarised in Table 2. Note that all of the variables in the model are significant at the 95% level of confidence.

As shown in Figure 5, multiple linear regression. using equation 4 as a statistical model, does an excellent job of fitting the data. Values of the empirical constants in eq 4 resulting from the multiple regression process are listed in Table 1. Note that m, the exponent for water resistivity does. not differ from 1 at the 90% level of confidence. This result is not unexpected as Archie's law relationships for sedimentary rocks usually assume that p and pw are directly proportional (Archie 1942). The exponent of porosity has a value of -0.8. in contrast to values of about -2 which are commonly observed in Archie's law relationships for sandstone. This difference is not related to the clay variable as the exponent remains largely unaffected if clay is removed from the model. It may possibly be explained by different pore geometries in the two samples. The constant a which usually is equal to unity, takes a value of 140 ± 20 in our regression model. This dfference, which at first may seem surprising, can be explained by the presence of an exponential clay term in equation 4. If this factor (which has a major effect on the calculated resistivites) is removed from the regression model, values of a decrease by a factor of five (to a value of 29 ± 11).



5. Scatter diagram illustrates the fit of the regression model.

CONCLUSIONS

Important conclusions from this study are:

1. The resistivities of the rock samples are a function of temperature, porosity, clay content and water resistivity. Clay type, another potentially important variable was not studied because all of the samples contained illite as the predominant clay species. Because other clay species such as montmorillinite have higher cation exchange capacities, we would expect the effect of clay content to be even more pronounced when they are present.

2. Porosity and water resistivity are related to the rock resistivity by simple power law relationships which suggests that an equation similar to Archie's law may be valid for geothermal rocks.

3. The temperature dependence of resistivity follows Arrhenius equation with an activation energy of about 0.14 mV, a value which suggests that ionic conduction is the dominant charge transport mechanism. This conclusion appears to hold both when the conduction is due to a saline saturating fluid and when conduction is due to the presence of clay minerals.

4. A generalised version of Archie's equation does an adequate job of fitting our admittedly limited data set. This equation which has been extended to include temperature and clay content as variables, has a form quite similar to versions of Archie's equation from sedimentary rock sequences, however the empirical constants are quite different, suggesting that the simple extrapolation of normal Archie's law relationships from sedimentary to geothermal environments is unwise. All of the variables included in the extended Archie's law are statistically significant, so explorationists must consider the effect of clay minerals and temperatures as well as porosity and water resistivity when interpreting resistivity data from geothermal areas.

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