UNDERSTANDING THE RESISTIVITIES OBSERVED IN GEOTHERMAL SYSTEMS

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ABSTRACT

The low resistivity geophysical anomalies observed over most geothermal systems have been very useful exploration targets. As better and deeper imaging of the resistivity structure of geothermal systems has become possible with the use of methods such as MT surveying, it has been shown that the lowest resistivity is usually in a zone above the reservoir and that the resistivity of the actual reservoir can be much higher.

To help understand this distribution of resistivity, we have reviewed the factors affecting resistivity in geothermal systems. Conductive clay products of hydrothermal alteration are the most common cause of low resistivity in a zone above the reservoir. Higher temperature alteration products are less conductive so that in systems of low to moderate salinity the reservoir has higher resistivity.

Associations between temperature and clay alteration assemblages have been well established and used as tools for predicting reservoir temperature during drilling. Inferred correlations between alteration type and resistivity can extend this further to enable better prediction of reservoir temperature distribution from surface geophysical measurements. This has the potential to greatly improve reservoir definition and the success rates for exploration drilling.

1. INTRODUCTION

Resistivity is one of the most variable physical properties of materials and has proven to be the most useful geophysical parameter in the search for geothermal resources. Geothermal systems commonly contain saline fluids while hydrothermal alteration processes cause pervasive changes to the natural resistivity of the rocks in which the systems develop. In general, this salinity and clay alteration together with the high temperatures associated with geothermal activity tend to result in lower overall resistivity in geothermal systems. The resultant low resistivity anomalies have generally been the main target for geophysical exploration of geothermal resources.

However, the success of this approach and the observed general correlation of low resistivity with geothermal activity has historically often led our industry to ignore evidence that high temperature geothermal reservoirs may actually be characterised by much higher resistivity.

This paper reviews the factors affecting the resistivity of geothermal reservoirs and surrounding zones. The literature regularly mixes the terms conductive, resistive, conductivity and resistivity and we have found it necessary to similarly use this mixture of terms for appropriate emphasis on the processes being described.

2. FLUIDS, ROCK MATRIX , POROSITY AND TEMPERARURE RELATIONSHIPS

Caldwell et al (1986) provide a very useful analysis of the known relationships between reservoir fluid, matrix resistivity, porosity, saturation and temperature. The bulk resistivity of formations within hydrological systems will be a function of the resistivity of the rock matrix and the resistivity of the saturating fluid. In "clean" porous rocks (no clays and effectively no matrix conductance), the resistivity of the rock will be controlled by the resistivity of the fluid (the saturating fluid). A useful empirical relationship between **bulk resistivity** (ρ), **porosity** (ϕ), **water saturation** (S_w) and **fluid resistivity** (ρ_w) has been widely used (Archies law):

$$1) \qquad \rho = a\, \rho_w\, \phi^{-n}\, S_w^{-m}$$

where a and n are constants (approximately 0.6 to 1.6 and 2 respectively) that are related to the character of the porosity. At saturations greater than 25%, $m \cong n$. It has been practical to measure ρ and ρ_w in the laboratory so the ratio $\rho\, /\rho_w$ (commonly referred to as the **formation factor** - F) is a useful relationship that combines the other terms. A clean sandstone with 10% porosity would have F $\cong$ 100 (ie. the effective measurable resistivity of the rock formation will be 100 times greater than the resistivity of the pore fluid).

Similarly, the bulk resistivity of rocks with conductive minerals in the matrix can be expressed in terms of the **matrix resistivity** (ρ_m) (neglecting any contribution from the fluid resistivity) as :

$$2) \qquad \rho = a\, \rho_m\, (1\text{-}\phi)^{-n}$$

Combining these formulas for the general case with conductive matrix and fluid :

$$3) \qquad 1/\rho = 1/\rho_w F + 1/\rho_m F_m$$

where the matrix formation factor F_m is close to 1 for small values of porosity (Hochstein 1982).

In practice, there is no truly "clean" matrix and when saturated with clean water, any free ions will be mobilised and the overall resistivity will be lower than may be expected for the resistivity of the water itself. Because of this effect, estimates of water resistivity, based on measured bulk resistivity and porosity, are seldom greater than 10 Ωm, even when the pore water is known to have a higher resistivity.

More usefully, Caldwell et al (1986) report a modification of Archie's equation that includes a component for conduction by clay minerals within the matrix:

$$4) \qquad \rho = a\, \rho_w\, \phi^{-n}\, S_w^{-m}\ (1 + KC\, \rho_w)^{-1}$$

where S_w is water saturation proportion in pores, C is the proportion of clay minerals in the matrix, and K is a constant according to the type of clay minerals present.

Because conduction within electrolytes is by ionic processes, electrolyte resistivity is directly related to viscosity which decreases with temperature. This is in contrast to metallic conduction mechanisms where resistivity increases with temperature. Consequently ionic and semi-conducting materials both have an inverse exponential dependence of resistivity with temperature of the form:

$$5) \qquad \rho = \rho_0\ e^{\varepsilon / RT}$$

where ε is an activation energy (commonly about 0.2eV in water and for saturated rocks, varying with degree of alteration), R is Boltzman's constant (0.8617×10^{-4} eV/°K), T is temperature (°K) and ρ_0 is the resistivity at theoretically infinite temperature. Although resistivity measurements of a sample at a range of temperatures is needed to estimate ε, the relationship is useful in understanding the expected effect of temperature.

Llera et al., (1990) tabulate decreases in laboratory measurements of resistivity in volcanic rocks by factors of 5 to 40 (commonly 6 to 10) for a temperature increase from 30 to 120 °C.

3. OBSERVED TEMPERATURE - RESISTIVITY RELATIONSHIP

In order to get an understanding of relationship between observed resistivity and temperature in geothermal fields, data from cores, well logs and magneto-telluric (MT) resistivity surveys have been collated. The core resistivities from our own studies were measured at room temperature and adjusted for reservoir temperature using (5). While the relationship between Induction log resistivities and true reservoir resistivity may be questionable due to potential mud infiltration and cooling effects, Llera et al (1990) have shown a very good correlation between resistivity logs and their measured core resistivities (which were measured at actual reservoir temperature).

Representative examples of downhole resistivity logs, core resistivity, modelled subsurface resistivity (from MT surveys) and conductive clay distributions from several exploited geothermal fields are shown in Figure 1. Generally, high resistivities are observed in the cool, upper part of systems where temperatures are less than about 70°C. Much lower resistivities of the order of 1 to 10 Ωm are found in the temperature range of 70 to 200 °C. At temperatures above 200 °C, resistivities increase markedly and are often greater than 100 Ωm, depending on the nature of the primary lithologies.

The high resistivity of the low-temperature zone is no surprise, and can be interpreted as a zone that may tend to have poor water saturation, minimal hydrothermal alteration and little reduction of resistivity by temperature.

The highly conductive zone at intermediate temperatures is widely observed as a characteristic of geothermal systems. The low resistivity in this zone was often in the past regarded as being associated with the hot saline fluids of the geothermal system. This may have been true for high salinity reservoirs such as are common in the western USA, but more generally, low resistivities can be correlated with clay hydrothermal alteration that occurs in that temperature regime.

The higher resistivity found in the hotter parts of systems has been rightly correlated with some vapour dominated reservoirs but is equally a characteristic of most low-moderate salinity reservoirs. In a substantial proportion of geothermal systems investigated in Indonesia, we have observed that the deep reservoir has a significantly higher resistivity than surrounding country rock. This could sometimes be due to the presence of more extensive volcanic lavas in the areas of strong geothermal activity, but we have also seen otherwise conductive sedimentary basements of some systems that appear to have been altered by the geothermal activity in a way that increases their resistivity.

4. FLUID CONTRIBUTION TO OBSERVED RESISTIVITY

The resistivity of saline fluids over the temperature range 20-350 °C has been well established experimentally (Ucok et al, 1980). Although geothermal fluids contain a wide range of anions and cations, NaCl tends to be the dominant conductive species in deeper parts of systems and other ions can be considered as Na or Cl equivalents for the purpose of estimating resistivity.

We have compiled the available data for a wide range of NaCl concentrations over the temperature range 20-400 °C and estimated a correlation that is usefully accurate over this data set. This correlation has been used to contour the resistivity of brines over the measured salinity and temperature range (Figure 2). The salinities of reservoir fluids from several well known geothermal fields are shown on this plot for reference.

If Archie's Law (1) is applied assuming a porosity of 10%, then reservoir resistivities would be a factor of 100 greater than the water resistivities shown in Figure 2. On this basis, low chloride fluids (Wairakei) in 10%-porosity, clay-free rocks at 250°C, should result in a bulk resistivity of about 40 Ωm. Similarly the more saline brines of Cerro Prieto should result in a bulk resistivity of about 6 Ωm. Figure 3 further demonstrates the effect of porosity on the bulk resistivity of "clean" saturated rocks.

5. ALTERATION MINERAL CONTRIBUTION TO OBSERVED RESISTIVITIES

The role of clay minerals as sensitive mineral geothermometers in geothermal systems has long been recognised (Steiner, 1968, Jennings and Thompson, 1986, Harvey and Browne, 1991, Harvey and Browne, 2000). The sequence from smectites, through to illites is widely used to provide estimates of formation temperatures during drilling.

Much work on the resistivity of clays has been carried out in shaley-sand oil basins including studies by Hill and Milburn (1950) and Worthington (1985). These workers shows that the conduction path through clay-rich sediments is by two pathways:

- via pore water
- via the double layer, also called the Gouy layer, which is the interface between the clay surface and the water.

An analogue of this is electrical current carried by two parallel circuits.

Waxman and Smits (1968) developed a quantitative relationship such that:

$$6) \qquad \rho = F / (BQ_v + \rho_w^{-1})$$

where *B* is the equivalent conductance of counter ions (a function of solution conductivity), and *Qv* is defined by

$$7) \qquad Q_v = CEC\ (1-\phi)\ \rho_m \phi^{-1}$$

where ρ_m is matrix grain density and *CEC* is the cation exchange capacity of the clay in meq/gm. The product BQ_V in (6) represents the conductivity of the clay portion of the rock and is proportional to the CEC value of the clays present.

Therefore, in clay-rich rocks and where the pore water has low salinity, the rock resistivity will be inversely proportional to the CEC of the clays.

At high salinity, the double layer thickness around clays is suppressed (reduced) and supposedly, this will reduce the number of pathways for conductance.

Typical CEC values for clays commonly found associated with geothermal systems, from Grim (1953) are:

Clay Mineral	*CEC Range*	*CEC Average*
Kaolinite	3 - 15	10
Smectite (montmorillonites)	80 - 150	120
Illite	10 - 40	20
Chlorite	10 - 40	20

Thus rocks containing smectite clays are likely to have resistivities 6 to 10 times lower than rocks with a similar proportion of illite (or chlorite) under the same temperature, porosity and salinity conditions, and 12 times lower than rocks altered to kaolinite.

We have not found in the literature CEC values for mixed-layer clays but they probably fall between the smectite and illite values, becoming progressively lower with increasing illite content.

In Figure 1 a comparison is presented of the sequences of clays, smectite to illite, with increasing temperatures (depths) at the Salton Sea (Jennings and Thompson, 1986) and at Wairakei (Harvey and Browne, 1991) compared with the induction logs for the DRJ-4 well from the Darajat Geothermal field in Indonesia (Whittome and Salveson, 1990) and well WD-1a at Kakkonda, Japan (Muraoka et al. 1998). At Kakkonda pure illite first appears at 220°C, above which there are also interlayered illite / smectite clays (Muraoka et al. 1998).

In the upper levels of active geothermal systems (temperatures < 200°C) where low salinity groundwaters or mixed groundwater-geothermal fluids are present, the low-temperature, high-CEC smectite clays will dominate over the fluid salinity as the main pathway for conduction. At deeper levels in the systems where higher salinity fluids occur and lower CEC illites prevail, clay conductivity will be less of s fsctor.

Caldwell et al (1986) measured the resistivity of several altered rock samples at temperatures of 20 to 90°C using a range of fluid salinities. The samples had illite as the dominant clay (up to 35% of the matrix) and many had very high porosity (up to 58%). Their multiple regression analysis showed resistivity was most highly dependent on clay content, with water conductivity and porosity being related secondary factors, having effects significantly smaller than indicated by Archie's Law (1). Temperature was a lesser factor still.

Caldwell et al., (1986) included laboratory measurements of an andesite with high illite alteration and porosity of 3.1% - such as may be expected in Indonesian and Phillipines geothermal reservoirs. When saturated with a solution of moderate resistivity (1.2 Ωm) this sample had a measured resistivity of about 100 Ωm at 50°C and about 85 Ωm at 90°C. Extrapolation on the basis of equation (5) would indicate a resistivity approaching 30 Ωm at reservoir temperatures.

If this sample had a high smectite content, then the inversely proportional relationship between CEC and resistivity would indicate resistivities up to 1/10th of those measured where illite is the dominant clay mineral. Such low resistivities are common in the conductive layer over geothermal reservoirs (Figure 1). In the zone between 70 and 200°C the potential increase in resistivity due to reduction in smectite content in the interlayered clays will be partially offset by the effect of increasing temperature.

6. SUMMARY

- The zone between 70 and 200°C in the top of a geothermal system has low resistivity (highly conductive) predominantly because of the temperature and the abundance of conductive clays (predominantly smectites) that are common hydrothermal alteration products at these temperatures. Salinity of the saturating fluid may have very little affect on the resistivity in this conductive zone.
- Temperature is an important (but often ignored) factor in reducing resistivity, particularly over the range 20 to 150°C where a reduction in resistivity by a factor of 10 is commonly observed. Resistivity surveys, therefore, have the potential to differentiate between active and relict areas of a geothermal system. We have observed this in practice.
- The hotter parts of geothermal systems are characterised by higher resistivity than is seen in the overlying conductive zone. The higher resistivity is due to the fact that the rock matrix is much less conductive than the

saturating fluids because low conductivity alteration products dominate mineralisation in this zone. Porosity tends to decrease with depth and this reduces the effect of bore fluid conditions, thus reinforcing the resistivity increase, countering to some extent the effect of higher salinity that is commonly inferred to lie in deeper parts of most systems.

- High temperature alteration processes may increase the resistivity of some rocks by converting smectite clays to illitic or chloritic clays.

7. CONCLUSIONS

The conductive zone that commonly lies above geothermal systems has been shown to have a strong correlation with temperature between 70 and 200°C. The cause of this has been linked with the type of clay alteration that occurs in this temperature range.

In contrast however, the high temperature reservoirs of geothermal systems commonly have much higher resistivity and the delineation of this zone beneath the conductive layer has become our main objective in geophysical exploration of geothermal systems. This approach has lead to surprising success when applied to early exploration or even for refining reservoir delineation during later stages of production drilling.

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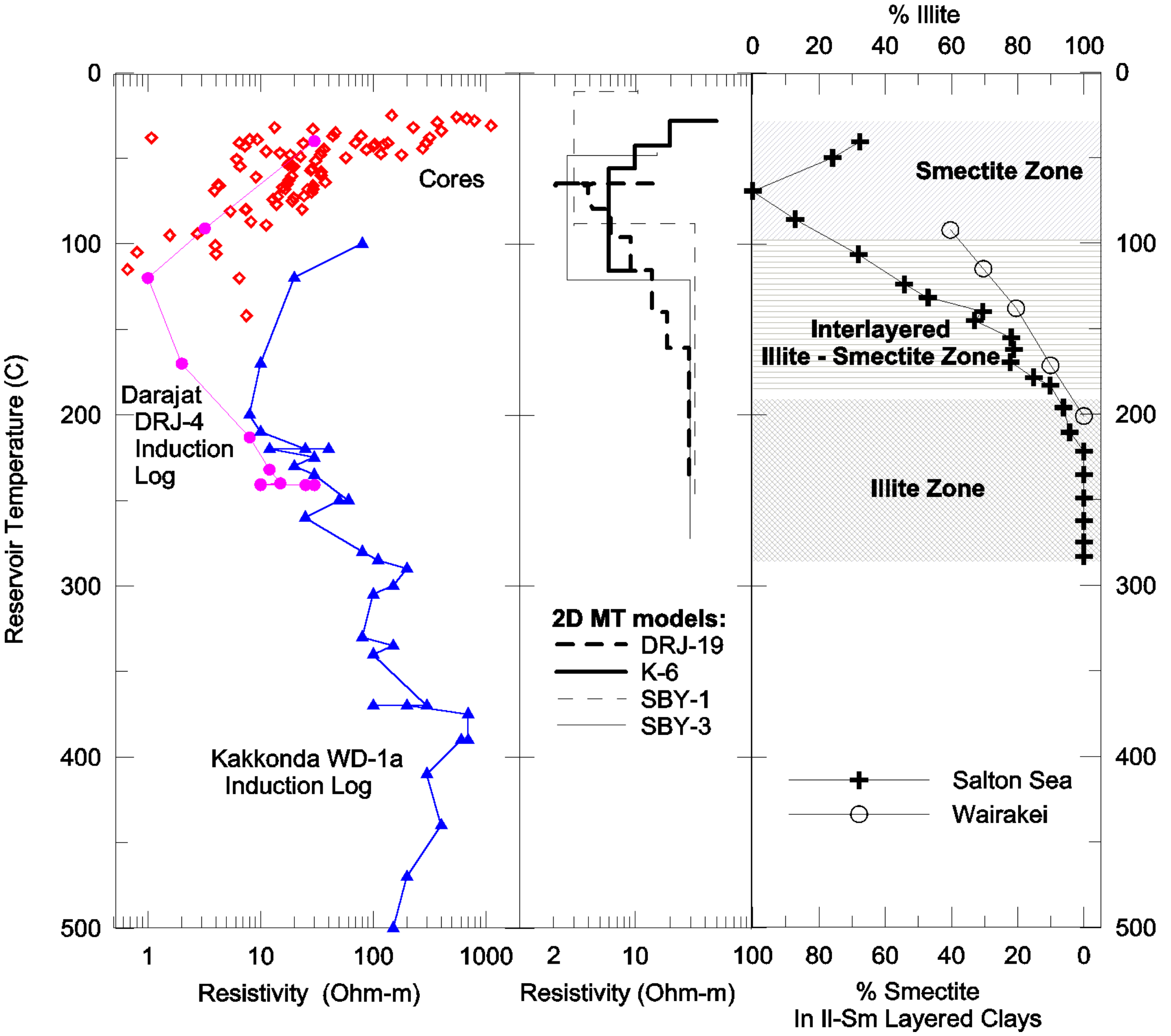

Figure 1. Measured core and Induction Log resistivities plotted against the estimated reservoir temperature at the depth sampled. The Darajat log is from Whittome and Salveson (1990) and the Kakkonda log is from Muraoka et al (1998). Core samples were summarised from our own records and were measured at room temperature but have been corrected for resistivity at reservoir temperature. The right graph shows observed proportions of illite and smectite in layered clays with respect to reservoir temperature as found in two different geothermal environments at Salton Sea (Jennings & Thompsom, 1986) and Wairakei (Harvey & Browne, 1991).

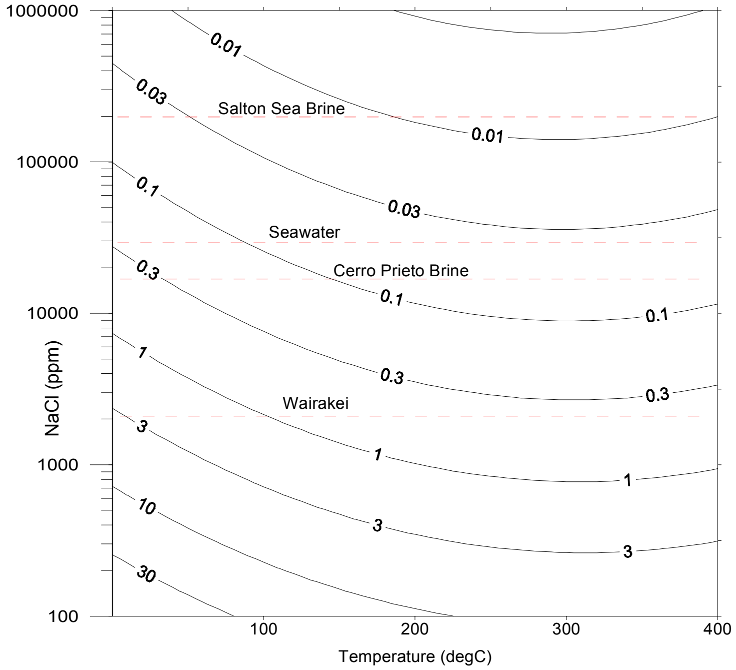

Figure 2. Variation of resistivity (in Ωm) of NaCl solutions from measurements of Ucok et al. (1980). The salinity of several well known geothermal fields are shown for reference.

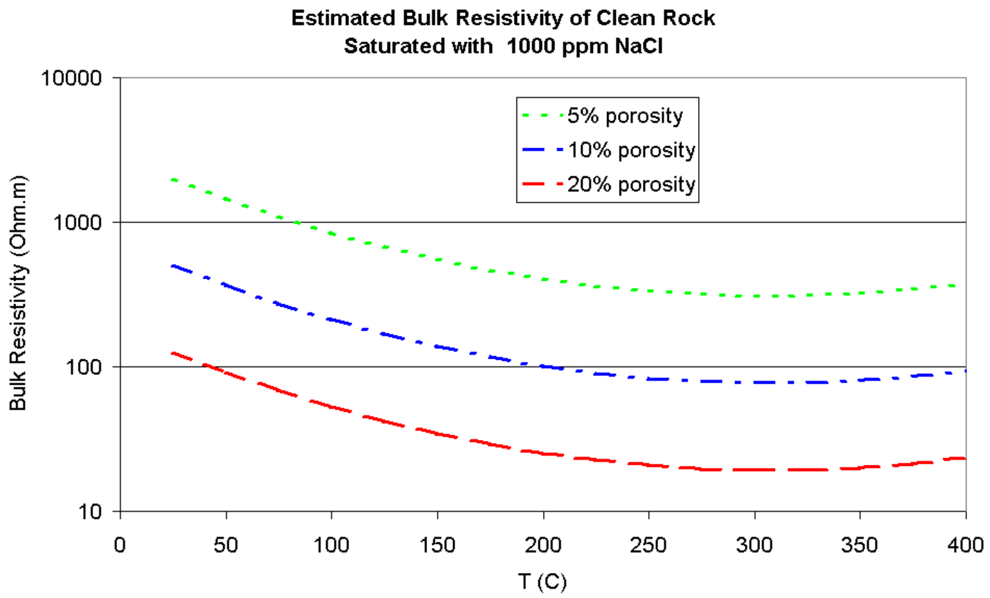

Figure 3. Bulk resistivities for “clean” rocks containing saturated with 1000 ppm NaCl brine (using Archie’s Law).