AS PLAIN AS THE NOSE ON YOUR FACE: GEOTHERMAL SYSTEMS REVEALED BY DEEP RESISTIVITY

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SUMMARY - A high-temperature geothermal system significantly influences the resistivity of its environment, directly by the physical and chemical properties of the geothermal fluid and indirectly by the chemical changes experienced by the host rocks. Now that deeply penetrating magnetotelluric (MT) surveys are routinely available, this resistivity anomaly should be readily detectable and used to target the geothermal resource. However, interpretation of the resistivity measurements is not always straightforward, especially in steep terrain, and can often mislead investigators and result in failure.

This paper presents MT surveys from four different drilled geothermal fields, and presents an anomaly, namely the shape of the base of the conductive layer overlying the geothermal system, that is directly related to reservoir temperature and often to well productivity. In contrast, conventional resistivity anomalies are shown to be often located in less prospective parts of the field. While the proposed interpretation method is simple and does not require sophisticated analysis techniques or computing power, it does require widespread and reasonably close-spaced MT measurements over the prospect area. As long as the initial survey is well designed and executed, the geothermal system can be revealed - as plain as the nose on your face.

1. INTRODUCTION

Resistivity surveys have been used for geothermal exploration in New Zealand for more than 40 years (Banwell and Macdonald, 1965). The classic method has been to measure and contour apparent resistivity (DSIR, 1985), with the geothermal system delineated by the area of low resistivity. Results from deep wells have confirmed the resistivity predictions, and terms such as "resistivity anomaly" and "resistivity boundary" have entered the geothermal vernacular (Risk, 1986).

This analysis method has not enjoyed the same degree of success in geothermal prospects located in steep topography. Intense resistivity anomalies were often found to delineate cooler "outflow" zones of the geothermal system, while the centre or "upflow" had little characteristic resistivity signature. It quickly became apparent that the location of the resistivity anomaly, caused by a zone of clay alteration formed at cooler temperatures than the target geothermal reservoir, was influenced by local and regional hydrology. The correlation of resistivity anomalies with geothermal systems in New Zealand was fortuitous rather than fundamental, and in steeper terrains this connection could not always be made.

Within the last ten years, the magnetotelluric (MT) resistivity method has come of age. This method measures potential differences generated by naturally-occurring electromagnetic waves, with signal strength information conveniently provided by the accompanying magnetic variations. The wavelength of the electromagnetic signals determines the depth of penetration, rather than the electrode spacing of DC methods. As wavelength is inversely proportional to fiequency, the development of sensitive but stable low-fkequency amplifiers has allowed penetration depths an order of magnitude greater than previous methods.

Unfortunately, the true potential of the MT method was not initially realised. High-quality measurements were difficult to obtain, and interpretation was hindered by troublesome surface effects and by the complexity of the method itself. Furthermore, interpretation methods still focussed on finding resistivity anomalies rather than correlating the sub-surface resistivity structure with the various parts of the geothermal system. These factors all conspired to hide the real message, namely that the conductive zone overlying geothermal systems was now transparent, and the high-temperature geothermal reservoir could be directly "seen" fiom the surface.

This paper presents a number of recent case studies of MT surveys fkom geothermal fields that have also been explored by deep wells. This has allowed comparison and correlation of apparent and interpreted resistivity with directly measured reservoir parameters, such as temperature, fluid salinity, and clay alteration. The most effective anomaly for delineating high-temperature geothermal systems is shown to be the 'shape' of the sub-surface resistivity structure, rather than any conventional resistivity anomaly.

2. GEOTHERMAL RESISTIVITY STRUCTURE

The resistivity structure of a high-temperature geothermal system consists of a number of different zones, primarily depending on temperature (Figure 1, from Johnston et al, 1992). The cooler upper layers are characterised by alteration to smectite, an electrically conductive clay that forms at temperatures above 70°C. At higher temperatures, illite, a less conductive clay, becomes interlayered with the smectite. The smectite content declines with rising temperature, and pure illite commonly appears at greater than 220°C with other high-temperature alteration minerals (chlorite, epidote, etc) in the propylitic alteration assemblage.

Outside geothermal systems, quite variable resistivities can occur. Dry and partially-saturated surface volcanic rocks will have resistivities between 200 and 500 ohm m, while values from 50 to 200 ohm m are typical of deeper cold parts of the prospect area. Sediments, however, especially those of a marine origin, can have resistivities of less than 5 ohm m, and the correct assignment of these conductive units is often the most challenging part of resistivity interpretation.

In regions of low relief, the low-resistivity smectite cap may form directly above the high-temperature geothermal reservoir, such that the geothermal system will be reasonably well delineated by the shallow resistivity anomaly. In steeper terrain, however, the hydrological gradient can sweep the geothermal plume away from the upflow area (Figure 2). The conductive smectite layer may be quite deep over the system upflow and much closer to the surface in cooler outflow areas. In these cases, the resistivity anomaly no longer unambiguously locates the geothermal system.

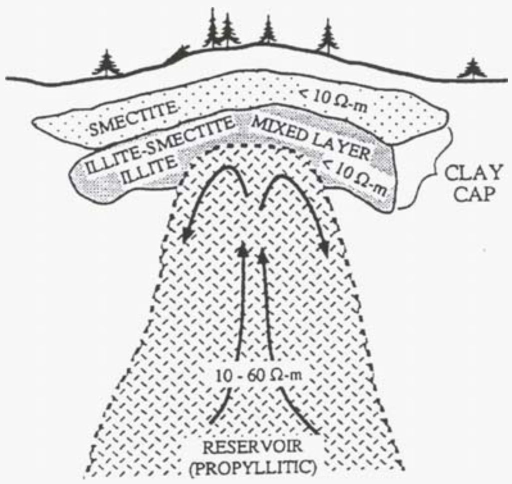

Figure 1. Schematic of a generalised geothermal system (from Johnston et al, 1992)

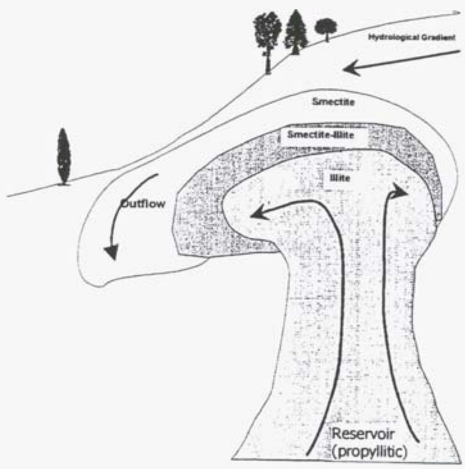

Figure 2. A generalised geothermal system in steep terrain.

The resistivity of the smectite zone is determined by the type and intensity of alteration, modified by the degree of saturation and actual temperature, and is generally between 1 and 10 ohm-m. At higher-temperatures, with lower smectite content, the formation resistivity rises, now depending primarily on porosity, fluid salinity and temperature. Correlations of alteration minerals and abundances with resistivity measurements, both from downhole logging and surface surveys, suggest that the transition occurs when the smectite proportion drops below 30%. This corresponds to a temperature of about 180°C, and typical resistivities in the high-temperature zone lie between 20 and 100 ohm m.

Figure 1 was derived from Johnston et al (1992), a study to evaluate different electromagnetic resistivity methods for geothermal exploration. The authors concluded that detection of the geothermal reservoir, even by the MT method, was marginal at best, given the likely resistivity contrasts, resolution and level of measurement error. However, their analysis assumed a horizontal interface between the conductive layer and the high-temperature reservoir. If constraints imposed by the hydrology of the geothermal system are used in the resistivity interpretation process, a coherent and consistent resistivity model can be developed that reliably delineates the geothermal target.

3. INTERPRETATION AND RESULTS

MT measurements are generally obtained as "soundings", a relationship between signal frequency and "apparent resistivity", a value mathematically derived from the actual magnetic and electric measurements in the field. Survey results can be simply presented as contour maps of apparent resistivity at different frequencies, which may (or may not) indicate resistivity anomalies. More commonly, however, the soundings are interpreted by developing a subsurface resistivity model whose theoretical response best matches the measured data.

Geothermal systems are clearly three-dimensional (3D), encompassing a finite volume of the sub-surface rocks and with detectable lateral and vertical boundaries. The corresponding resistivity structure is reasonably expected to be 3D as well, which affects the soundings in a characteristic and detectable manner. To complicate matters, this 3D body is often embedded in an environment with a dominant strike direction - a two-dimensional (2D) structure. This can strongly influence the soundings and obscure the more subtle resistivity variations, especially in the direction of the strike. Furthermore, local surface inhomogeneities can have an effect disproportionate to their size – fortunately, additional measurement techniques (TDEM) have been developed to correct for these so-called static shifts.

Accurate 3D modelling of the resistivity structure is difficult, time-consuming and expensive, requiring sophisticated software and a finely-divided resistivity grid. 2D modelling by contrast is readily accessible and inexpensive, and particularly useful for investigating structure on individual profiles. However, it is less effective at revealing the wider picture, as resistivity variations in the strike direction are ignored. Furthermore, deep or distant structures can often dominate the resistivity model, while finite-element modelling techniques poorly reproduce smoothly-varying changes across the prospect area.

Fortunately, most soundings exhibit a locally one-dimensional structure at shallow penetrations, and in many cases this can extend to depths of 1000 m or more, well into the geothermal reservoir. This is especially true if standard corrections, such as static stripping and static shifting, have been applied to the soundings. Consequently, a one-dimensional (layered) analysis, together with a method of correlating resistivity structures across the field, is sufficient to develop the anomaly of interest (Anderson et al, in press).

First of all, the invariant apparent resistivity is used to generate a layered resistivity model for each sounding (Figure 3). Then, each model is individually examined to select a layer (or a number of contiguous layers) that represent the conductive clay layer. This group of layers from many soundings can then be treated as a single body with "smoothly-varying" physical characteristics, such as the depth to the upper and lower surfaces, the elevation of these surfaces, thickness, resistivity and conductance. Individual sounding models are then iteratively adjusted to ensure the variation across the field of any one of these parameters is no greater than is physically or hydrologically reasonable. While the allowed variation is determined qualitatively at present, by "rule of thumb", a mathematical formulation could no doubt be developed in the future.

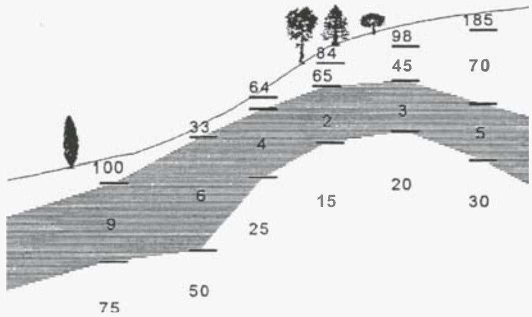

Figure 3. Layered resistivity models and the conductive layer.

The most definitive anomaly generated by this analysis method is the elevation of the base of the conductive layer, corresponding to a temperature of about 180°C within the geothermal system. This is the anomaly presented in all the case studies below. However, the interpretation of this anomaly needs to be supported by other parameters, in particular the resistivity and thickness of the conductive layer, and the resistivity of the layer immediately below this layer.

Unidentified Geothermal Field

A number of different resistivity surveys have been carried out at the first geothermal field example, including DC methods, CSAMT and deeper-penetrating MT. The elevation of the base of the conductive layer (Figure 4) shows a very clear anomaly which correlates extremely well with the elevation of 180°C as interpreted fi-om well measurements (Figure 5). The apparent resistivity anomaly at 1 Hz (Figure 6), however, shows conductive anomalies in the north-east and west of the prospect area. The first of these was the initial drilling target in this geothermal prospect, but wells in this zone proved to be cool and non-productive. It is likely that these anomalies are caused by outflows, and therefore point indirectly towards the upflow area, but do not delineate the geothermal field.

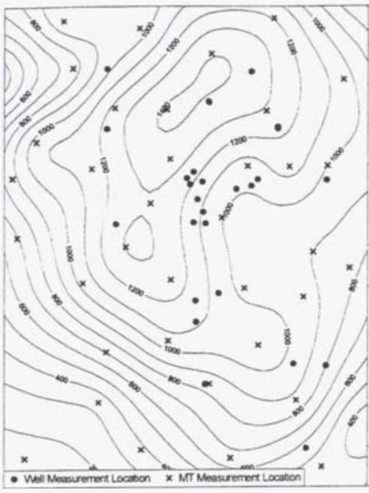

Figure 4.
Elevation of the Base
of the Conductive Layer (m asl)

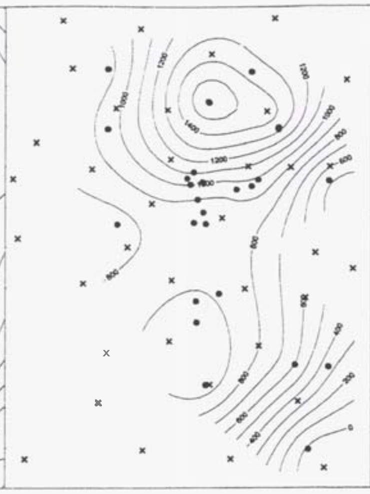

Figure 5.
Elevation of 180°C
Isotherm (m asl)

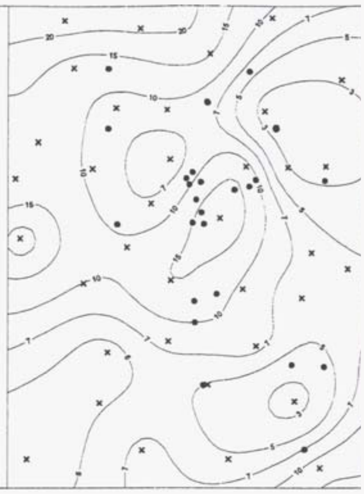

Figure 6.
Apparent Resistivity at
1 Hz (ohm-m)

Berlin, El Salvador

The Berlin geothermal field is located on the northern flanks of the Berlin-Tecapa volcanic complex, within a NNW-trending graben structure. A total of **57** MT soundings, over a prospect area of about 50 km^2, were carried out in 1994 (GENZL, 1994). The elevation of the base of the conductive layer (Figure 7), shows a striking anomaly centred over the southern part of the graben, coinciding with the Berlin caldera. This correlates closely with the elevation of the 180°C isotherm interpreted from well measurements (Figure 8). The centre of the anomaly appears to delineate the geothermal upflow, and a recent successful well, deviated south towards the centre of the anomaly, confirms this interpretation.

The wells drilled to the **north** of the prospect are cooler and less productive, and are clearly on the margins of both the geothermal system and the conductive layer anomaly. In contrast, the Bostick resistivity anomaly at 500 m depth (Figure 9), while located within the graben, encompasses all the deep geothermal wells drilled to date and does not highlight these variations within the **field.**

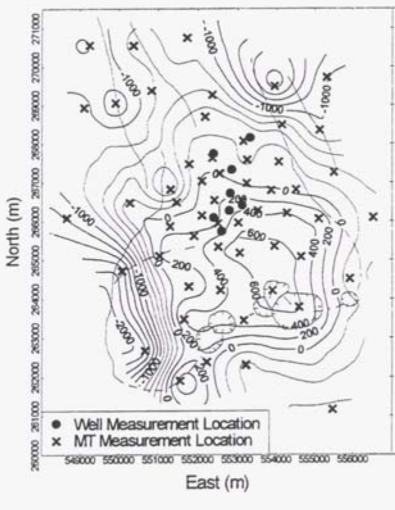

Figure 7. Berlin
Elevation of the Base
of the Conductive Layer (m asl)

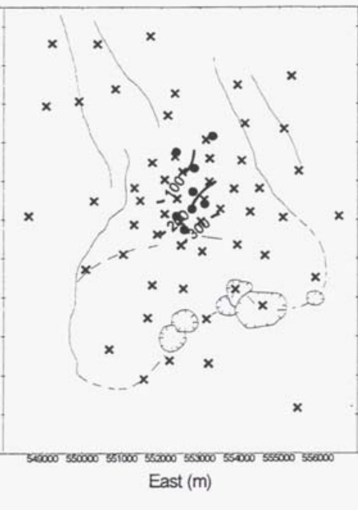

Figure 8.
Elevation of 180°C
Isotherm (m asl)

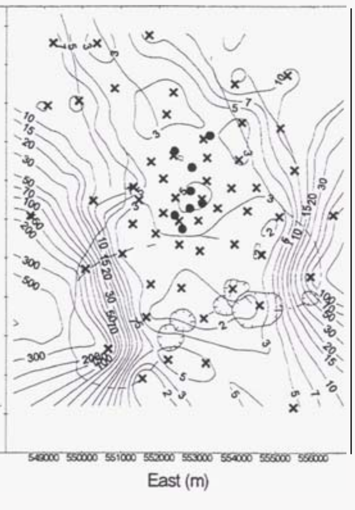

Figure 9.
Bostick Resistivity (ohm-m) at 500
m Depth of Conductive Layer (masl)

Karaha Telaga Bodas, Indonesia

The Karaha Telaga Bodas geothermal prospect is located within the Karaha volcanic complex, in West Java, Indonesia. Geothermal manifestations exist in the north of the prospect area on G. Karaha, and also in the south near Telaga Bodas. A total of 182 soundings have been recently carried out in the prospect, 113 on close-spaced profiles and the remainder spaced in a pseudo-random manner (GENZL, 1996).

The apparent resistivity contours at 1 Hz (Figure 10) show one conductive anomaly in the northern zone and a larger anomaly in the south. These two regions are separated by higher resistivities, and appear to have no connection. In contrast, the elevation of the base of the conductive layer, (Figure 11) indicates an elongate ridge running north-south between the two areas of geothermal manifestations. The pattern suggests that the surface features are located on the edges of the geothermal system rather than at the centre. The contours of the 180°C isotherm in exploration wells (Figure 12) correlate closely with Figure 11, and strongly support the resistivity model

Wayang Windu, Indonesia

The Wayang Windu geothermal prospect is located on the southern flanks of G. Malabar, also in West Java, Indonesia. The total conductance to basement, an anomaly readily derived from MT measurements, was initially used to delineate the Wayang Windu system (Sudarman et al, 1986). The conductance of the conductive layer (Figure 13) gives a similar pattern, showing a strong anomaly to the west of G. Wayang and G. Windu, relatively small parasitic cones immediately south of G. Malabar. Initial exploration and drilling focussed on the area around and to the west of the Wayang Windu cones. Mixed results were obtained, and wells within the conductance anomaly were generally cool and non-productive.

Pressure and temperature trends from well measurements, together with the presence of geothermal manifestations on G. Malabar, indicated that the geothermal reservoir extended northwards, which was confirmed by exploration wells. The location and orientation of the 180°C isotherm (Figure 14) clearly demonstrates this. The elevation of the base of the conductive layer (Figure 15) shows a very similar pattern. Differences in detail can be ascribed to a lack of wells in the north-west, and elevated well temperatures in the north-east, possibly higher than formation temperatures.

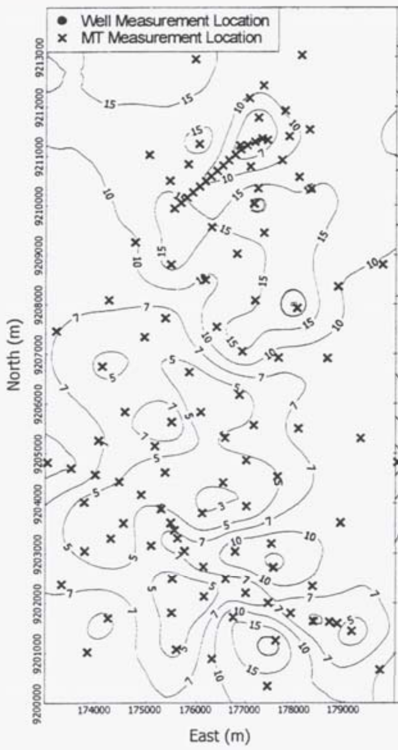

Figure 10. Karaha Bodas.
Apparent Resistivity
at 1 Hz (ohm-m)

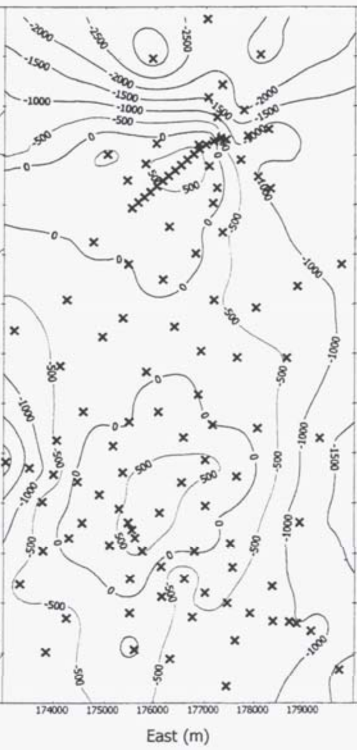

Figure 11.
Elevation of the Base
of the Conductive Layer (m asl)

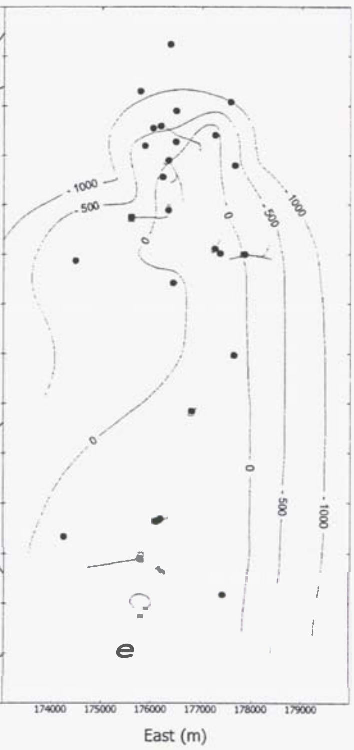

Figure 12.
Elevation of 180°C
Isotherm (m asl)

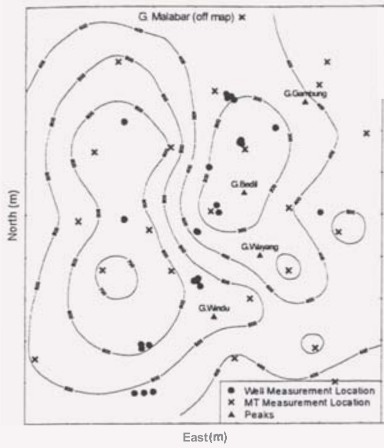

Figure 13. Wayang Windu. Conductance of the Conductive Layer (S)

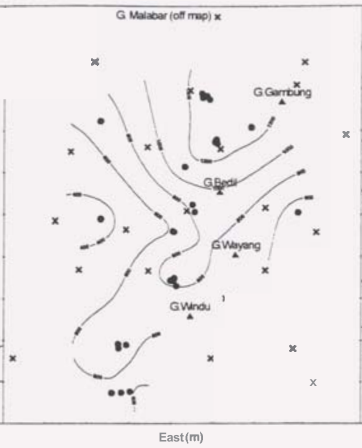

Figure 14. Elevation of the 180°C Isotherm (m asl)

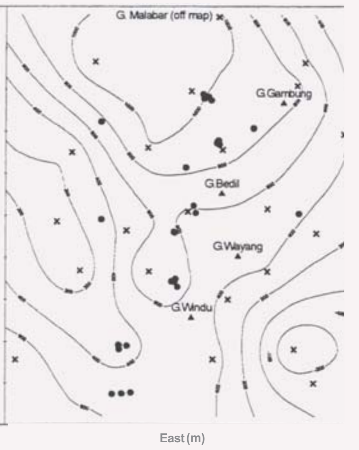

Figure **15.** Elevation of the Base of the Conductive Layer (m asl)

4. CONCLUSIONS

This paper demonstrates excellent correlation between the base of the conductive layer and the 180°C isotherm, for four geothermal fields explored by deep wells and MT surveys. Wells drilled within the target anomaly have reliably encountered high temperatures; furthermore, many of them also found good permeability. The authors have applied this MT interpretation method to many other geothermal prospects, most of which show a clear base-of-conductive-layer anomaly. While good permeability can never be guaranteed, the success rate of exploration wells centred on the target is likely to be higher than in any other locations within the prospect area. The cost of MT measurements has fallen markedly over the past few years, such that a comprehensive MT survey coupled with this interpretation method is an essential and cost-effective precursor to any green-field geothermal development.

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