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BULLS-EYE! - SIMPLE RESISTIVITY IMAGING TO RELIABLY LOCATE THE GEOTHERMAL RESERVOIR

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ABSTRACT

This paper presents interpretations of MT surveys from a number of geothermal fields in steep terrain, where the geophysical interpretation can be constrained by data from deep exploration or production wells. One particular anomaly, namely the shape of the base of the conductive layer overlying the high-temperature geothermal reservoir, strongly correlates with well temperatures and even well productivity. The proposed interpretation method is simple and does not require particularly sophisticated analysis techniques or computing power. It does not even require particularly high-quality MT measurements, and has given good results with 10-year old data. As long as the initial survey is well-designed and executed, the method gives a clear "bulls-eye" target that reliably locates the geothermal reservoir.

1. INTRODUCTION

Earth resistivity measurements have been used as an exploratory geophysical technique for geothermal resources for more than 40 years (Banwell and Macdonald, 1965). The technique involves measurement of potential differences generated by electric currents in the earth, from which apparent resistivities can be calculated using standard algorithms. The subsequent modelling of the "true" resistivity structure of the earth and the interpretation of its geothermal significance is the major contribution of the geothermal geophysicist.

A variety of direct current (DC) methods have been used in geothermal prospects in New Zealand with conspicuous success (Risk, 1986). Results from deep wells drilled into regions of anomalously low apparent resistivity showed that these 'resistivity anomalies' generally delineated high-temperature geothermal reservoirs. While other parameters such as conductance and true resistivity have been used, the apparent resistivity anomaly was generally accepted as the best indicator of a geothermal target.

Resistivity methods have not been reliable geothermal indicators everywhere, particularly in geothermal prospects located in steep terrain. The most intense apparent resistivity anomalies often identified cooler outflow zones, rather than the centre of the geothermal system. It became apparent that the correlation of resistivity anomalies with the geothermal reservoir in New Zealand was fortuitous rather than fundamental, and in steeper terrains this clear connection could not be made.

Within the last ten years, the magnetotelluric (MT) resistivity method has come of age, because of improved equipment as well as advances in processing and analysis techniques. MT relies on the detection of small potential differences generated by electromagnetic waves propagated from the ionosphere. Depth of penetration is a function of the period of the signals rather than electrode spacing of DC methods. With the development of stable low-frequency amplifiers, depth penetration of an order of magnitude greater than previous methods can now be routinely obtained. In addition, an MT survey costs a fraction of the price of a deep exploration well.

Unfortunately, the full potential of the MT method was not initially realised, because interpretation methods still focussed on finding resistivity anomalies rather than correlating the sub-surface resistivity structure with the various parts of the geothermal system. Also, the complexity of the method, the seemingly large statistical error level, and the presence of troublesome surface effects all conspired to obfuscate the real message, namely that the high-temperature geothermal reservoir could now be directly "seen" from the surface.

This paper presents a number of recent case studies of MT surveys from 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 'shape' of the sub-surface resistivity structure, rather than resistivity or conductance, is demonstrated be the anomaly of choice for delineating high-temperature geothermal reservoirs.

2. GEOTHERMAL RESISTIVITY STRUCTURE

The typical structure of a high-temperature geothermal system is presented schematically in Figure 1. The cooler upper zones are characterised by alteration to smectite, an electrically conductive clay which forms at temperatures above 70°C. At higher temperatures, illite, a less conductive clay, becomes interlayered with the smectite. The proportion of illite increases with temperature, forming about 70% of the mixed-layer clay at 180°C. Above this temperature, the smectite content continues to decline, and pure illite commonly appears at greater than 220°C with other high-temperature alteration minerals (chlorite, epidote, etc) in the propylitic alteration assemblage.

The resistivity of the smectite zone is primarily 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, the formation resistivity rises, depending only on temperature, rock porosity and fluid salinity, with the more crystalline alteration having little effect. Correlations of alteration minerals and abundances with resistivity measurements, both from downhole logging and surface surveys, suggests that the transition occurs when the smectite proportion drops below 30%. This corresponds to a temperature of about 180°C, and typical resistivities lie between 20 and 100 ohm m.

Formation resistivities outside geothermal systems are quite variable. Values of 200 to 500 ohm m are commonly encountered in dry and partially-saturated surface volcanic rocks, and 50 to 200 ohm m are typical of deeper cold parts of the prospect area. However sediments, especially of a marine origin, can have resistivities of less than 5 ohm m. The correct assignment of these conductive units is often the most challenging part of resistivity interpretation.

A geothermal field in a region of low relief will form the low resistivity smectite cap directly above the high-temperature geothermal reservoir. In such cases, shallow resistivity anomalies are reliable indicators of the general location of geothermal fields, although less definitive in boundary areas. In steeper terrain, however, where a significant hydrological gradient is present in the sub-surface, the overall structure of the geothermal system is rather more complex (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 reservoir.

Figure 1 was derived from Johnston et al. (1992), a study to evaluate different electromagnetic resistivity methods for geothermal exploration. The authors concluded that delineation 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, and ignored constraints imposed by the hydrology of a geothermal system. When this is considered, and as long as measurements penetrate through the conductive layer, a coherent and consistent model of the geothermal reservoir can be developed.

3. INTERPRETATION AND RESULTS

A magnetotelluric sounding provides a wealth of information about the sub-surface resistivity in its vicinity. In particular, it can indicate whether the resistivity structure is one-dimensional (layered), two-dimensional (with a dominant strike) or three-dimensional. Geothermal systems clearly have a three-dimensional (3D) structure, but are often embedded in a regional two-dimensional (2D) environment. However, most soundings exhibit a locally one-dimensional structure at shallow penetrations, which can often extend to depths of 1000 m or more, which is well into the geothermal reservoir. Consequently, a one-dimensional (layered) analysis is generally adequate to develop the anomaly of interest.

Various studies (Swift, 1970, Dobrin and Savit, 1988) have shown that, for 2D resistivity structures, analysis of TE-mode resistivity (electric field parallel to strike) generally gives a better 1D model of the sub-surface than TM-mode. However, geothermal systems generally have a 3D structure, and the 2D characteristics are simply imposed by current-channelling on a regional scale. In this case, the invariant apparent resistivity is least influenced by these *external* 2D effects, and is therefore the most reliable data set to use when developing a layered resistivity model for each sounding (Figure 3). Furthermore, TE-mode is relatively insensitive to resistivity changes which means that this component is less effective at detecting the subtle 3D variations that mark a geothermal system. In contrast, the TM-mode is too strongly affected by lateral resistivity changes.

The interpretation procedure is described in detail in Anderson et al (these proceedings). Briefly, each model is individually examined to select one or more layers that represent the conductive clay layer. This group of layers is then treated as a single body with varying physical properties, such as depth to the upper and lower surfaces, elevation of these surfaces, thickness, resistivity and conductance. Sounding models are iteratively adjusted to ensure that the variations in any of these properties are not greater than is physically or hydrologically reasonable.

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.

3.1 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 Bostick transformation can be used to generate "true" resistivities as a function of depth from frequency-dependent apparent resistivities. The Bostick resistivity anomaly at 500 m depth (Figure 4) is located within the graben, and encompasses all the deep geothermal wells drilled to date. However, the wells in the north of the prospect are significantly cooler and less productive than wells further to the south. This resistivity interpretation clearly does not delineate these variations within the field.

The elevation of the base of the conductive layer (Figure 5), shows a striking anomaly centred over the southern part of the graben, coinciding with the Berlin caldera. Assuming this represents the geothermal upflow, the non-productive wells in the north are now clearly on the margins of the system. The elevation of the 180°C isotherm interpreted from well measurements is shown in Figure 6. Even with the limited spatial separation of these wells, the correlation with the base of the conductive layer is good. A recent well, deviated south towards the centre of the anomaly, has been very successful, thus confirming the proposed interpretation.

3.2 Unidentified Geothermal Field

A number of different resistivity surveys have been carried out at the second geothermal field example, including DC methods, CSAMT and deeper-penetrating MT. The apparent resistivity anomaly at 1 Hz (Figure 7) shows a major conductive anomaly in the northeast of the prospect area. Wells drilled in this area, however, were not productive. This area may indicate an outflow, and therefore point indirectly towards the upflow area, but does not delineate the geothermal reservoir. However, the elevation of the base of the conductive layer (Figure 8) shows a very clear anomaly which correlates extremely well with the elevation of 180°C as interpreted from well measurements (Figure 9). Furthermore, wells drilled where the base of the conductive layer was most elevated showed enhanced productivity.

3.3 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 elevation of the base of the conductive layer, (Figure 10) 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 11) correlate closely with Figure 11, and strongly support the resistivity model. In contrast, apparent resistivity contours at 10 Hz (Figure 12) 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.

3.4 Wayang Windu, Indonesia

The Wayang Windu geothermal prospect is located on the southern flanks of G. Malabar, also in West Java, Indonesia. Initial exploration and drilling focussed on the area around G. Wayang and G. Windu, relatively small parasitic cones immediately south of G. Malabar. However, geothermal manifestations on G. Malabar, as well as pressure and temperature trends from well measurements, soon indicated that the geothermal reservoir extended northwards, which was confirmed by exploration wells.

Total conductance to basement, an anomaly readily derived from MT measurements, was initially used to delineate the Wayang Windu system (Sudarman et al, 1986). This showed a strong anomaly to the west of the Wayang Windu peaks, in a similar location to the closely related conductance of the conductive layer (Figure 13). The elevation of the base of the conductive layer (Figure 14), however, encompasses these volcanic cones and extends northwards onto the slopes of G. Malabar. The location and orientation of the 180°C isotherm (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.

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. The wells drilled within the “bulls-eye” target 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 target 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.

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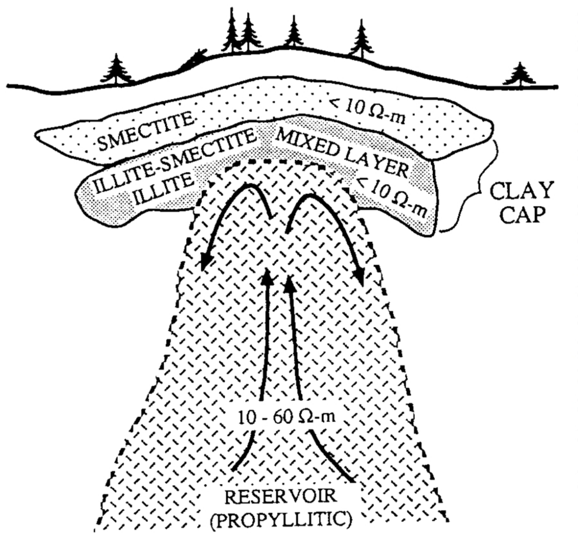

Figure 1. Schematic of a generalised geothermal system (from Johnston et al, 1992)

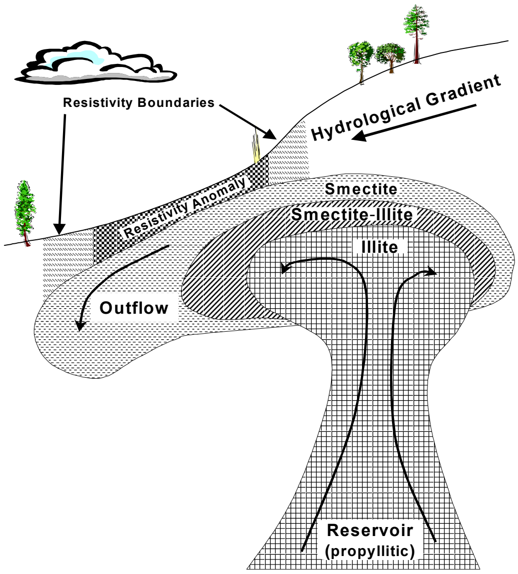

Figure 2. A generalised geothermal system in steep terrain.

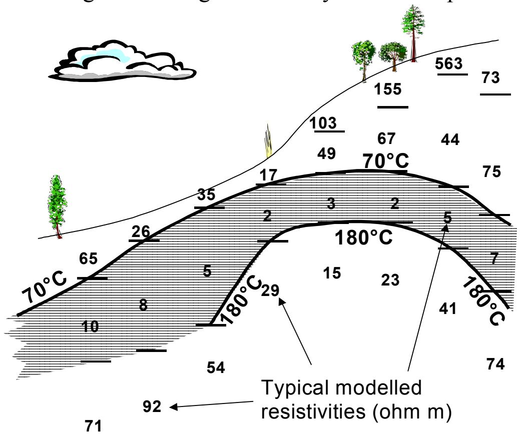

Figure 3. Layered resistivity models and likely temperatures above and below the conductive layer.

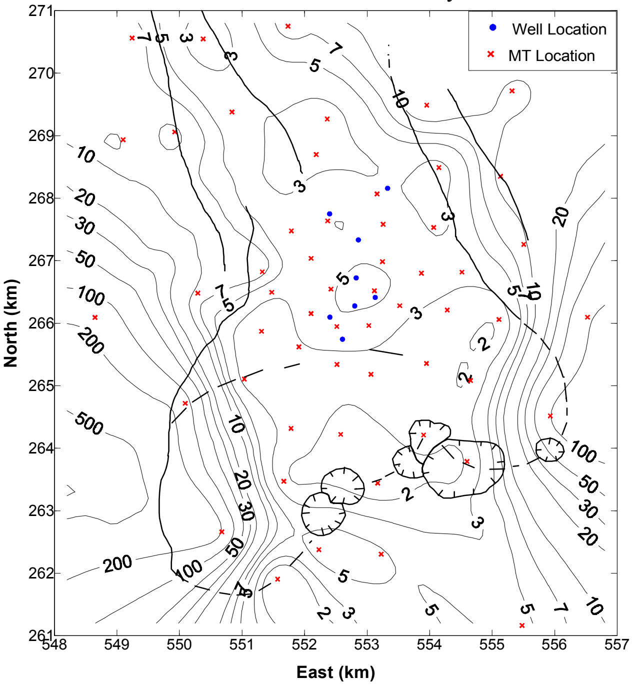

Figure 4. Berlin. Bostick resistivity at 500 m depth (ohm m)

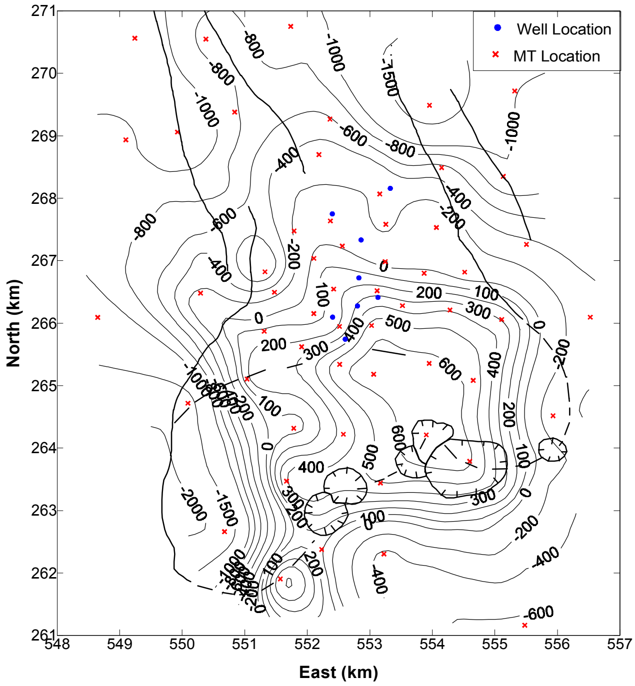

Figure 5. Berlin. Elevation of the base of the conductive layer (m asl)

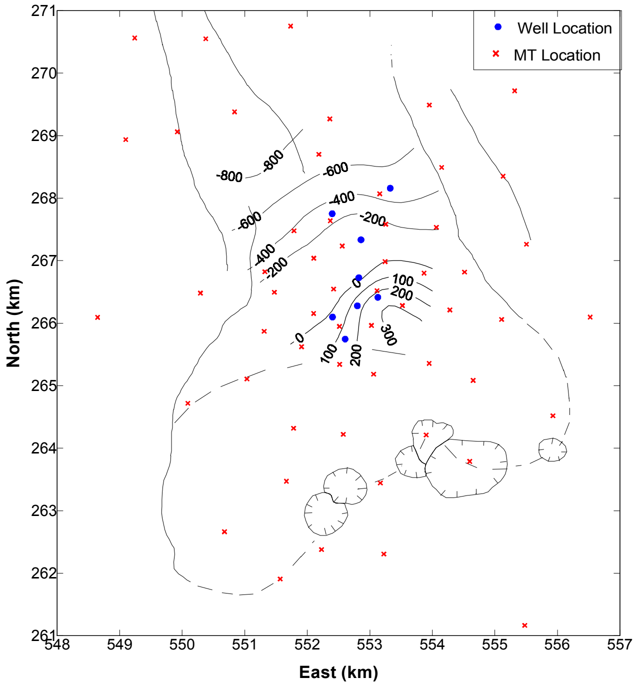

Figure 6. Berlin. Elevation of 180°C isotherm (m asl).

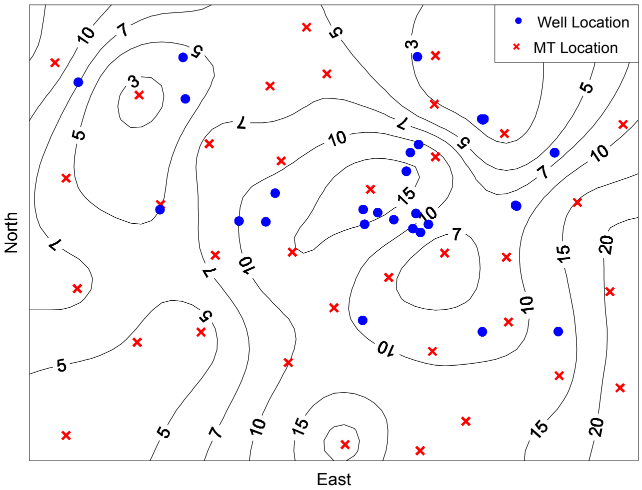

Figure 7 Unidentified geothermal field. Apparent resistivity at 1 Hz (ohm m)

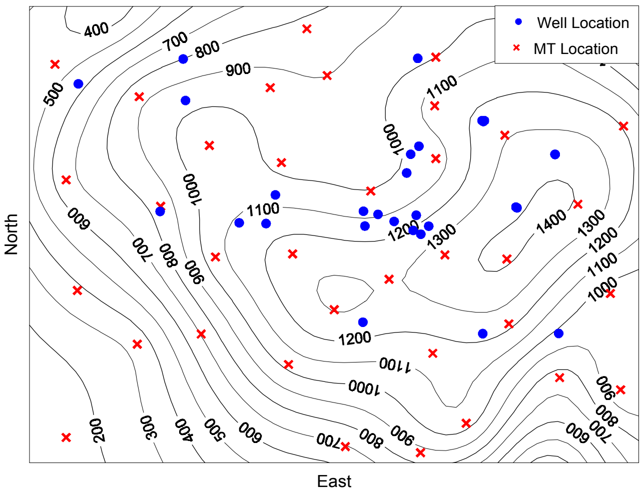

Figure 8. Unidentified geothermal field. Elevation of base of conductive layer (m asl)

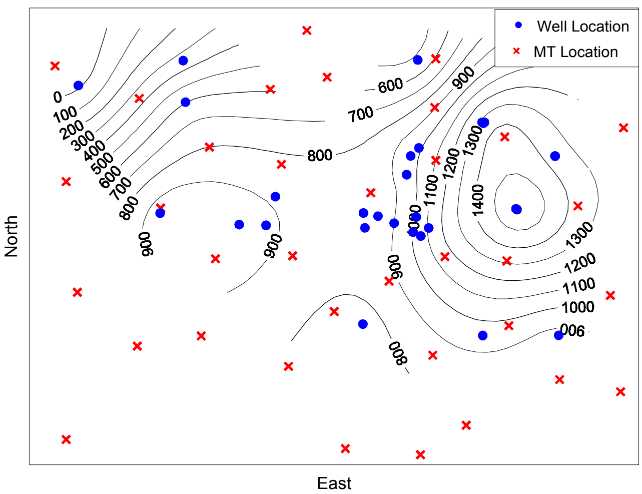

Figure 9. Unidentified geothermal field. Elevation of 180°C isotherm (m asl)

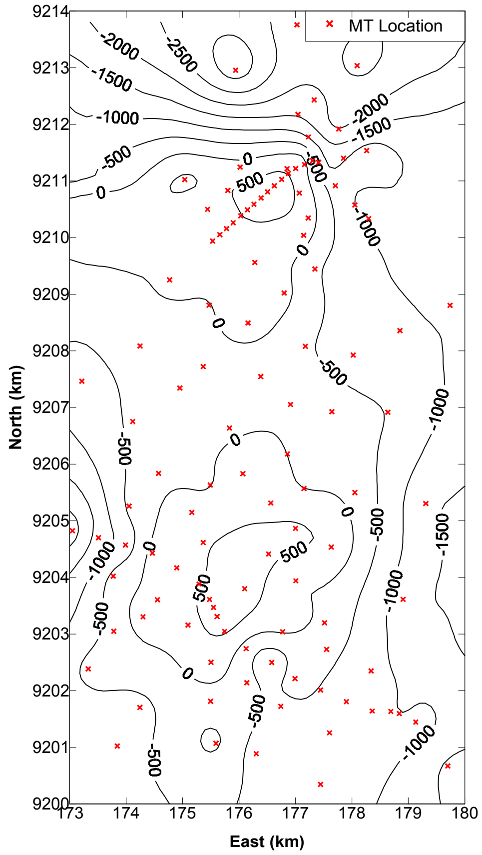

Figure 10 Karaha Bodas Elevation of base of conductive layer (m asl)

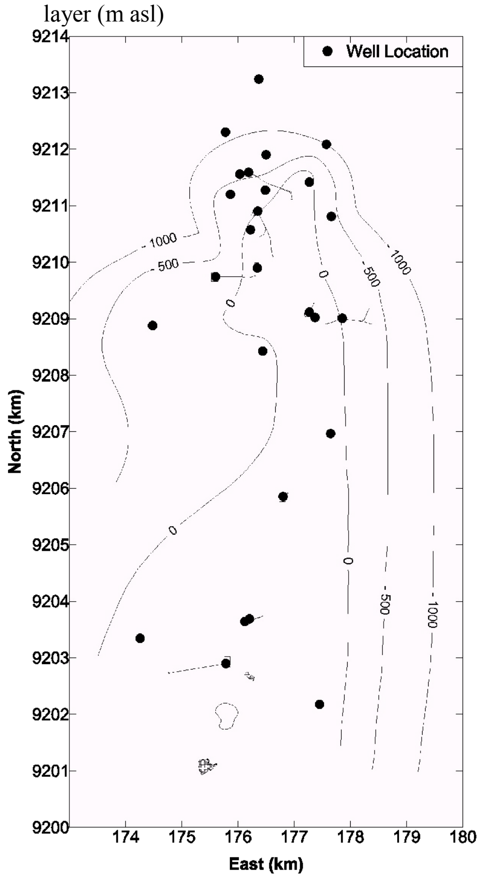

Figure 11 Karaha Bodas. Elevation of 180°C isotherm

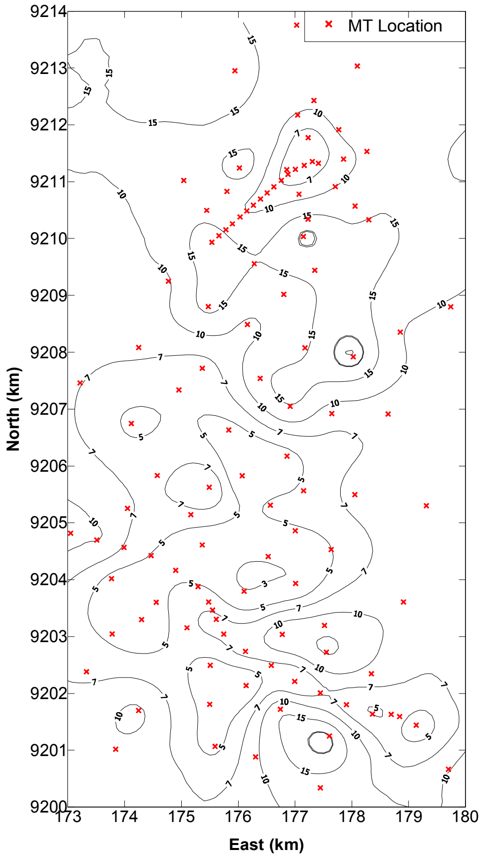

Figure 12 Karaha Bodas. Apparent resistivity at 1 Hz

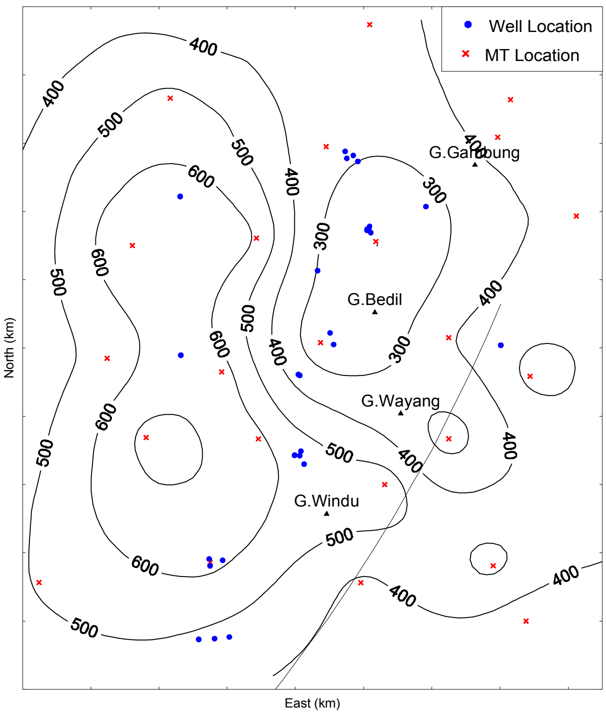

Figure 13. Wayang Windu geothermal field. Conductance of conductive layer (S)

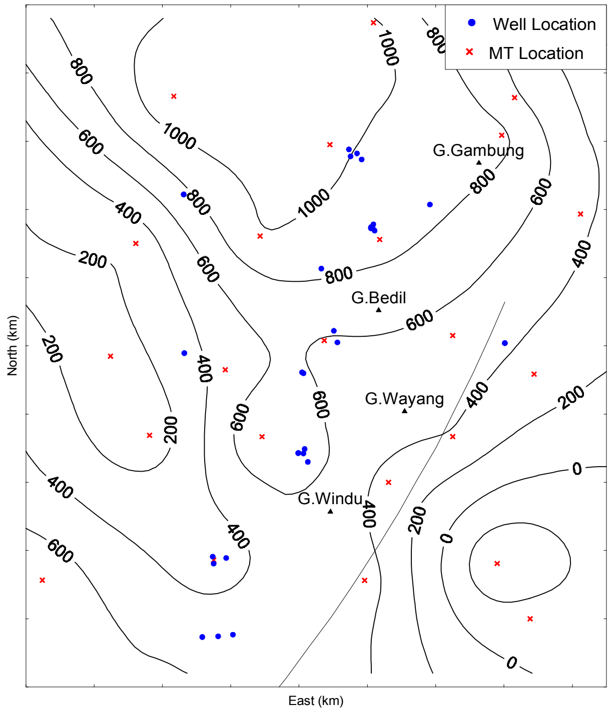

Figure 14. Wayang Windu geothermal field. Elevation of base of conductive layer (m asl)

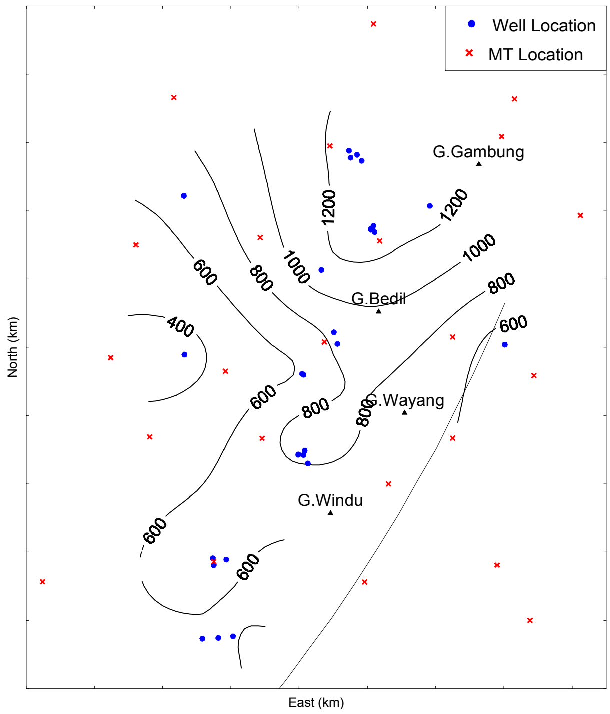

Figure 15. Wayang Windu geothermal field. Elevation of 180°C isotherm (m asl)