A GEOTHERMAL RESERVOIR REVEALED - MAGNETOTELLURICS AND DATA MANAGEMENT TECHNIQUES IN A POTENT COMBINATION

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ABSTRACT

Interpretation of magnetotelluric data from the Berlin geothermal prospect, **El** Salvador, by standard techniques such as apparent resistivity and Bostick resistivity contouring at selected elevations and on profiles failed to delineate the deep geothermal reservoir structure because of small resistivity contrasts obscured by static shift effects and boundary influences However, one-dimensional modelling using finite layers, together with data management tools to select and compare parameters of layers of interest, has resulted in a very clear picture of the depth and extent of the geothermal reservoir, and has tentatively located the upflow and outflow paths and areas of enhanced porosity.

1. INTRODUCTION

A high-quality magnetotelluric survey, comprising *57* stations, was carried out in the Berlin geothermal prospect, Usulutan, El Salvador, in early 1994. A thorough one-dimensional analysis has been undertaken using GDManager, the integrated geothermal analysis and data management system developed by GENZL

The Berlin geothermal field is located within a northwest trending graben, about 4 km in width, on the northern slopes of the Berlin volcano, a large basaltic-andesite composite cone formed during the last 1 to 2 million years. The formation of this volcanic massif was interrupted at least twice about 100,000 years ago by large explosive andesite eruptions (Nairn, 1994), with subsequent collapse forming the outlines of the present Berlin Caldera, extending from the town of Berlin in the west to Alegria in the east (Figure 1). Dacitic pyroclastics were subsequently erupted from within the caldera some 75,000 years ago, followed by basaltic to andesitic lavas and scorias forming the summit cones to the south and overflowing northwards into the Berlin graben.

At present, eight wells have been drilled in the Berlin geothermal field (Figure 1). These all attain high temperatures of at least 250° **C,** although most show a slight temperature inversion at the bottom of the well. The wells are all considered to lie outside the most recent caldera structure, and show low to moderate permeability. There are many areas of steaming ground and fumaroles in the borefield area, and also in the recent craters at high elevation to the south.

2. BOSTICK RESISTIVITY INTERPRETATION

The measured data quality was very high, with many soundings one-dimensional to considerable depth At the graben margins, two-dimensional characteristics were observed, reflecting a strong resistivity boundary **As** an initial interpretation, a one-dimensional analysis was carried out, using the "invariant" resistivity (the geometric average of the two principal apparent resistivities) and the Bostick transformation. This outlined a near-surface conductive layer within the graben and southward through the caldera, bounded by apparent extensions of the mapped graben faults (Figure 1). This layer is presumed to be a zone of argillitic alteration

At deeper levels corresponding to the productive reservoir, however (Figure 2), the picture becomes somewhat confused, with no well-defined boundary because of the lack of resistivity contrast across the graben faults at this elevation. A cross-sectional representation on a profile through the caldera (Figure **3)** also clearly shows the shallow alteration zone but also fails to delineate the reservoir with any precision, due to noise, static shift effects, and possibly two-dimensional boundary distortions.

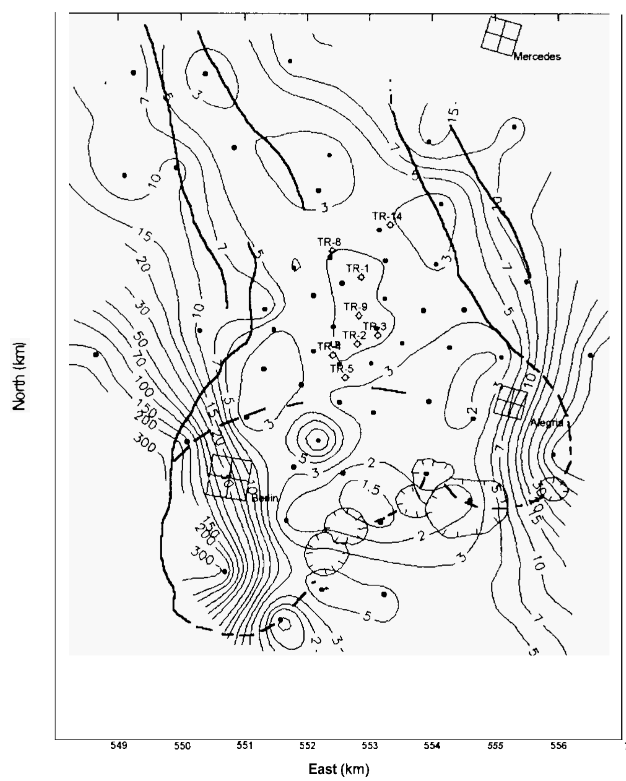

Figure 1 Bostick Resistivity at* 500 *m Depth

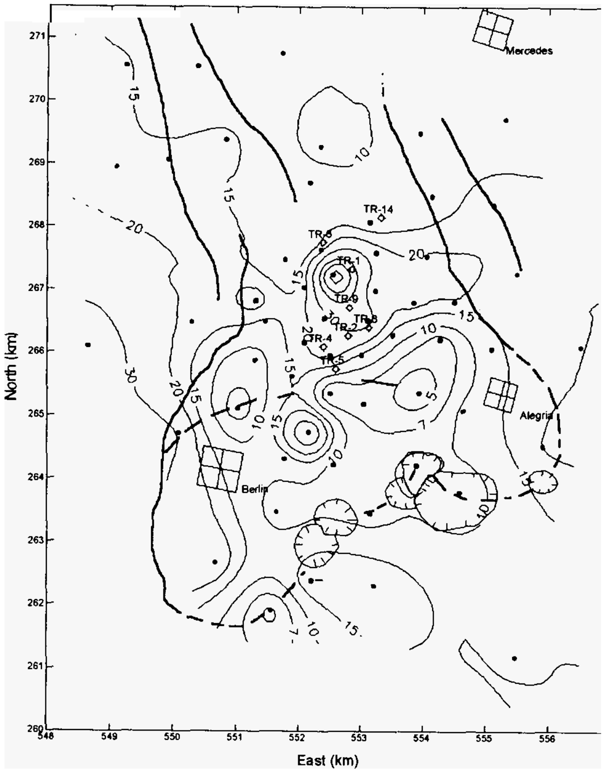

Figure 2 Bostick Resistivity at 1000m below Sea Level

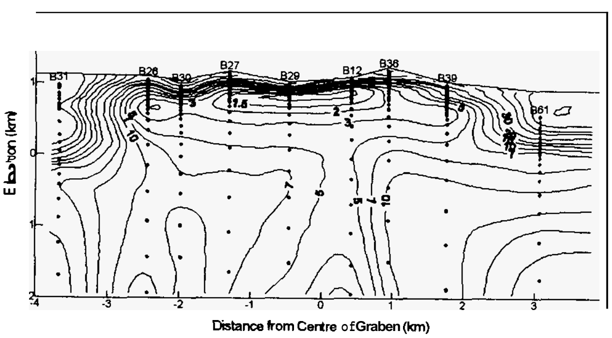

Figure 3 Bostick Resistivity on Caldera Profile

3. INTERPRETATION USING LAYERED MODELS

Making corrections for static shift effects is a rather subjective procedure, requiring the assumption that a particular layer has a constant or known resistivity, and adjusting soundings to conform to this hypothesis. However, the variations in the resistivity of a layer may be real, and give valuable clues as to the location and nature of the geothermal reservoir - information that could be obscured by these adjustments.

It was therefore decided to make layered-model interpretations of all soundings, using the invariant apparent resistivity, and to compare the various layers from sounding to sounding to see if a picture emerged. Data management techniques were essential to facilitate the process of selection of individual layers from each sounding model, and to calculate and contour various parameters relating to each selection, such as depth, elevation, thickness, resistivity and conductance.

All soundings showed a simple three-layer structure in the top 2000 m (although some soundings required more actual layers than this to obtain a good fit). At the surface, a thin high-resistivity layer (or layers) was modelled, representing fresh unsaturated volcanics. Beneath this layer, a conductive layer, several hundred metres thick, was observed everywhere, with very low resistivities within the graben (and its extension through the caldera), and higher values outside. A more resistive layer was observed beneath this conductive layer in all parts of the survey area.

Figure 4 shows the resistivity of the second layer, with a conductive anomaly clearly delineated at the northern boundary of the caldera, and resistivity boundaries to the west and east, although less well-defined than in the Bostick resistivity contour map (Figure 1). Maps of conductance and thickness of this layer (not shown), and correlation with well lithology (CEL, 1991), support the interpretation that this layer, within the graben at least, is the argillitic alteration zone that commonly forms above a high-temperature geothermal system.

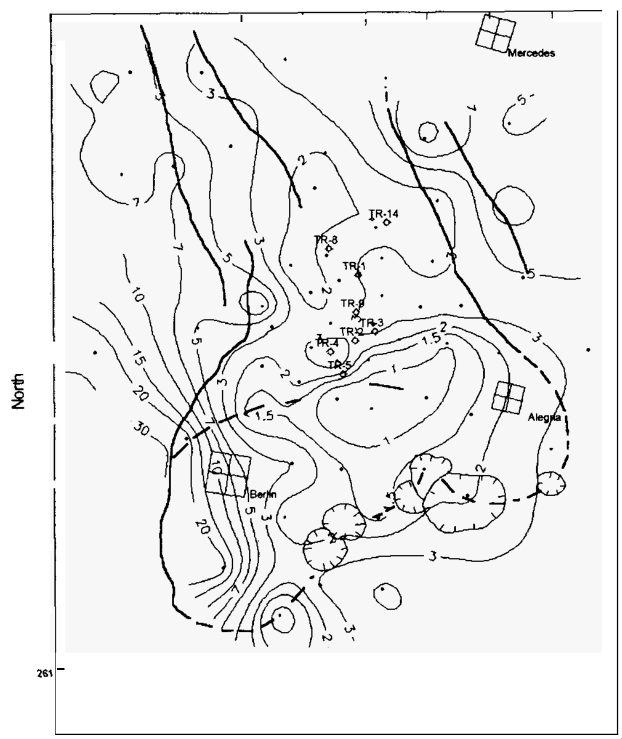

Figure 4. Resistivity of the Conductive Layer

Argillitic or clay (illite and smectite) alteration is produced by geothermal fluids at temperatures between 50° and 150° C. At higher temperatures, these minerals are progressively altered to non-conductive propyllitic minerals such as chlorite and epidote. The upper surface of the third layer, therefore, at least beneath the argillitic alteration zone, would indicate a temperature somewhere in the range between 150 and 180° *C.*

Figure 5 shows the elevation of this third layer, with a broad area above 600 m a.s.l. between the northern and southern boundaries of the caldera, and deepening to the north. The 180" C isotherm in the wells correlates poorly with the elevation of this surface, because of the presence of shallow steam zones and other distortions of the temperature distribution. However, the elevation of the 200° C isotherm parallels the top of this layer but some 200 m deeper! thus supporting the hypothesis that the layer interface is related to a particular temperature.

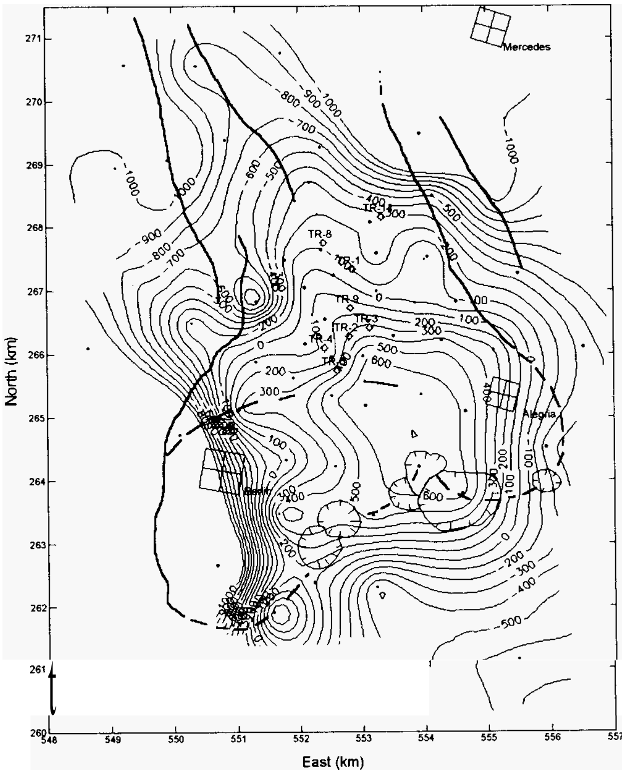

Figure 5 Elevation of Layer beneath the Conductive Layer

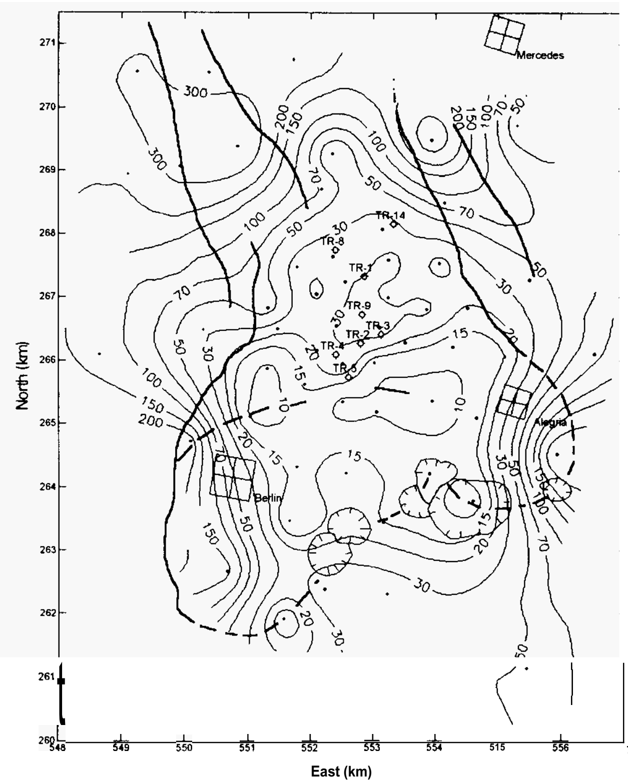

Figure 6 Resistivity of the Layer below the Conductive Layer

The resistivity of this layer (Figure *6)* exhibits a subtle but distinct anomaly, centred on the northern caldera boundary, and extending as far north as the northern-most wells. Within the caldera, the resistivity is about 15 ohm-m, whereas in the borefield a typical resistivity of about 30 ohm-m is observed. These resistivities are similar to those proposed for typical propyllitic alteration expected within a reservoir (Johnstone et al, 1992). **A** calculation based on Archie's Law, using the salinity and temperature of the geothermal fluids and assuming a non-conductive rock matrix in both zones, indicates that this difference in resistivity can be generated by a change in porosity from *6%* in the borefield to about 8.5% in the caldera

Analysis of these maps together with the map of the depth to the top of this layer (not shown), as well as information from geology, chemistry and the wells, suggests that this layer, within the zone outlined by hatching in Figure 7, represents the geothermal reservoir. Upflows are probably located on both the northern and southern caldera boundaries, with an outflow to the north through the borefield. Minor outflows are also observed to the west and to the southwest, with continued tectonic action keeping the flow paths open. Wells TR-8 and **TR-14** are at the northern limits of the productive zone. The lower resistivity in the caldera probably reflects enhanced porosity in the ignimbrites infilling this zone.

5. DISCUSSION

Analysis and interpretation of magnetotelluric data is not an easy task, in view of the effects of shallow inhomogeneities, two and three-dimensional structures, and the ever-present noise in the data. Bostick resistivity analysis points to the existence of a geothermal resource but fails to delineate the reservoir, because of the lack of resistivity contrast between the reservoir and the surrounding rocks. This paper shows that a convincing model, with a believable structure and realistic boundaries, can be obtained with one-dimensional layered analysis (assuming that data quality is adequate) as long as tools are available to select, manipulate and transform data rapidly, to aid in the search for meaningful and self-consistent interpretations.

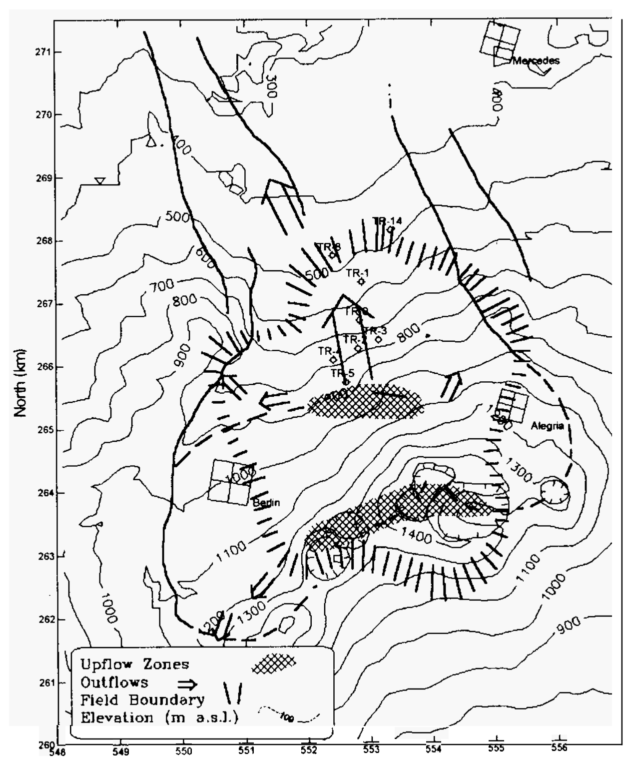

Figure 7 Conceptual Model of Reservoir

6. ACKNOWLEDGEMENTS

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