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Geophysical Reservoir Evolution of Berlin Geothermal field, El Salvador

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ABSTRACT

Based on the 2D Schlumberger analysis and from a geophysical point of view, a resistivity core under a conductive cap was delineated as the first proposed in 1996, for the reservoir of the Berlin geothermal field (BGF). A dense hypocentre cloud registered by the local seismic network was useful for estimating the extension of the production zone, as well as the heat source and the upflow zone in 2001. A 3D of MT resistivity model, calibrated with the temperature and mineralogy of the geothermal wells, in 2008, indicates that the producer reservoir corresponds to a resistivity range of 50 – 90 Ohm- m, inside the resistive dome. The main up flow zone was located around the TR4-TR5 area. New MT resistivity studies conducted in 2010 and 2012 in the southern part indicate a possible extension of the actual reservoir toward the west and southwest of the production zone. A new drilling program focus in this area will confirm the possible extension of the producer reservoir.

1. INTRODUCTION

The subduction of the Cocos Plate under the Caribbean Plate has formed an active volcanic chain that runs E-W through El Salvador (figure 1), the high-temperature geothermal field is located on the northern flank of this young volcanic system.

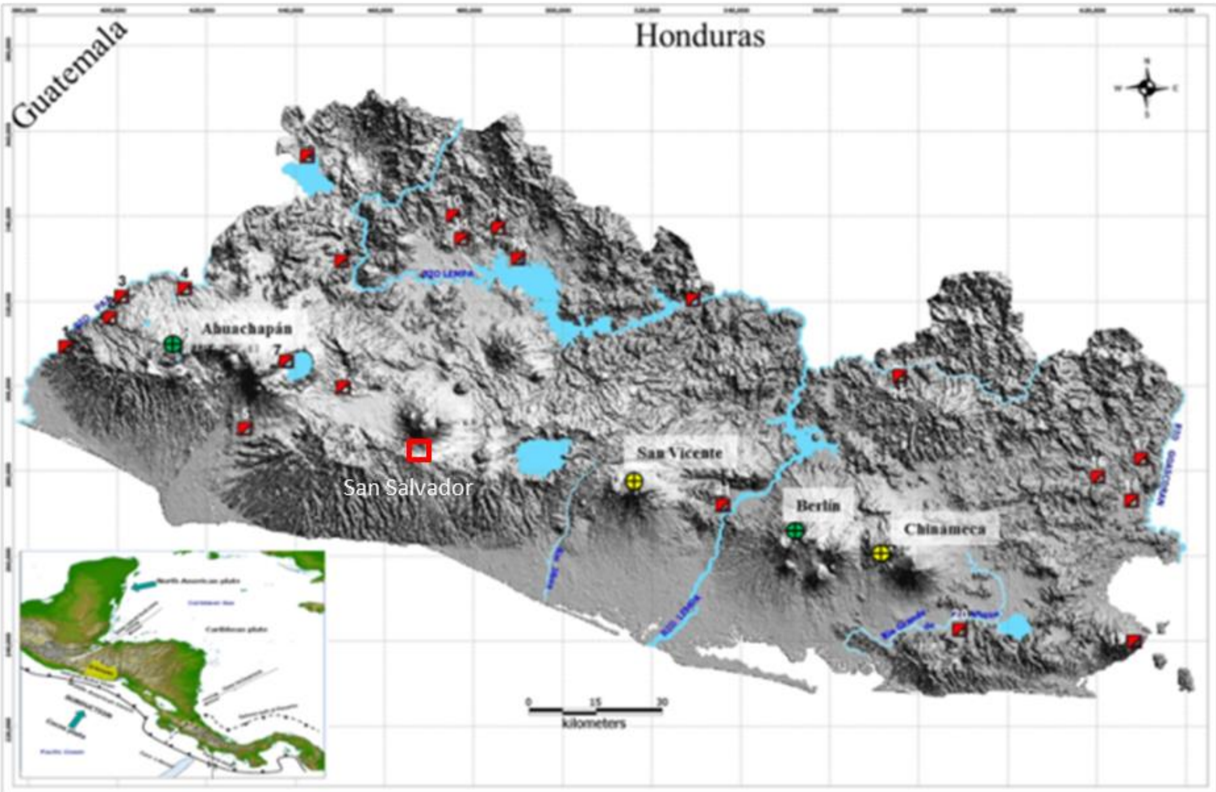

Figure 1. Main high-temperature geothermal field in El Salvador

Berlin geothermal field (BGF) is situated 110 km east of San Salvador (capital city), associated with the Tecapa volcanic complex and the Berlin caldera of Pleistocene age, within an NNW-trending graven structure (Pullinger,1995). A total of 38 geothermal wells have been drilled as shown in figure 3. The producers are shown in red, and the wells for reinjection are in blue.

Berlin geothermal field is on the northern flank of the Berlin-Tecapa Volcanic complex. The predominant local system fault is in the NW-SE direction which defines the Berlin graben and cuts the northern part of the Berlin caldera as is shown in figure 2. The reactivation of the NE-SW system follows an alignment of fumaroles, so much in the volcanic area as in the area of the wells. It also stays a fault system with EW direction, that belongs to the regional structure of the Central American graven (figure 1).

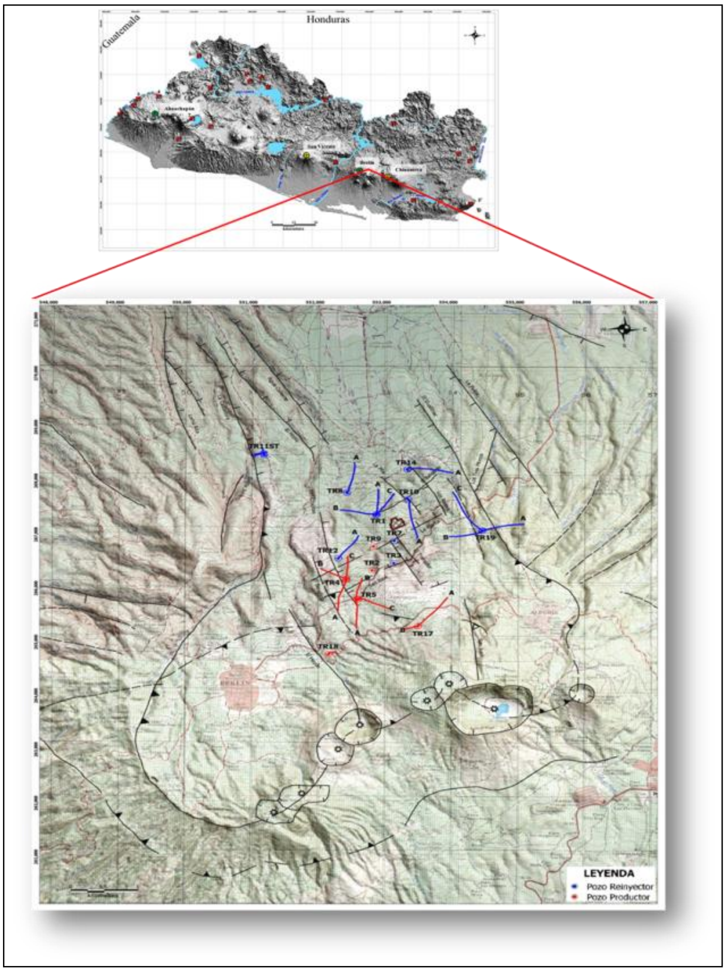

Figure 2: Berlin geothermal field and well location map.

Berlin-Tecapa volcanic complex, formed by the Berlin Caldera, stratovolcanoes and cineritic cones. The quaternary volcanoes are formed by andesites lavas interlayered with scoria, andesite ashes, pyroclastic, and basalt lavas. The cineritic structures are integrated mostly by scoria and basaltic-andesite ashes. As is shown in Figure 3, the main lithology formations of the Berlin area are andesite lavas, ignimbrites, and epiclastic rocks.

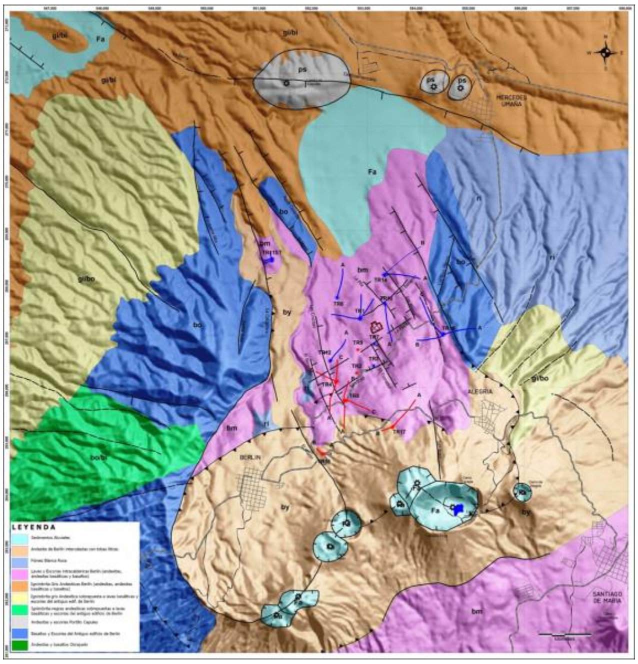

Figure 3: Geological and structural map of Berlin Geothermal Field (taken from BGF Conceptual model, 2008)

2. GEOPHYSICAL RESERVOIR EVOLUTION OF THE BERLIN GEOTHERMAL FIELD

A conventional high-temperature geothermal system consists of a volume of anomalously hot porous rock containing geothermal fluid, embedded in country rock of normal temperatures. The physical characteristics of the geothermal system host rock differ from the surrounding rock, thus generating physical "signatures" that may be detected by various geophysical techniques and used to define the nature and extent of the geothermal system (Anderson, 2000). These physical characteristics include the following:

2.1 DC Resistivity reservoir interpretation

One of the first proposals of the reservoir interpretation of the Berlin Geothermal field from the geophysical point of view was based on the 2D interpretation model of the Schlumberger Vertical Soundings (VES) in 1995. The interpretation resistivity reservoir was associated with the resistivity core, overlaid by a low-resistivity cap. Due to low penetration capacity, only the top of this interpreted reservoir was delineated.

The upflow zone is within the caldera close to wells TR-4s and TR-5´S. This is supported by the highest measured temperatures and the highest elevation of the high-resistivity core (Santos,1995), as is shown in figure 4. Further studies supported this interpretation.

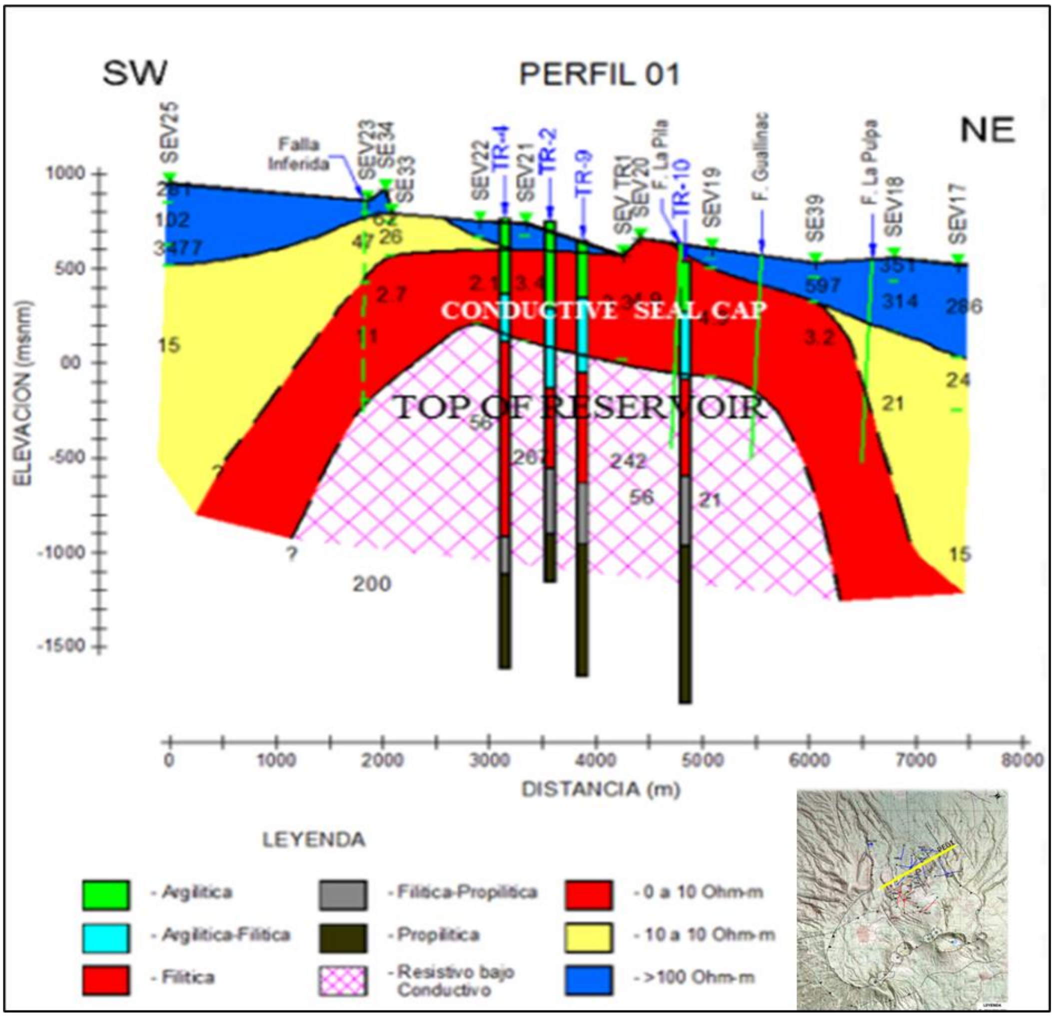

Figure 4: DC resistivity model of Berlin Geothermal Field

2.3 MT Reservoir interpretation for Berlin Geothermal field

2.3.1WestJec MT Resistivity model (2001)

The reservoir interpretation of BGF changed in 2001 when WestJec Company (from Japan) conducted the processing and made the 2D interpretation of 77 MT sounding data collected in 1995 and 2001. This interpretation was based on the belief that a high-temperature reservoir might be present within faults and fractures, as is shown in the figure 5. The fractures are associated with geoelectric anomalies and resistivity discontinuities that may lead to the targeting of high permeable zones (West Jec, 2001).

There were drilling targets proposed toward these zone of resistivity discontinuities with successful results in the production zone.

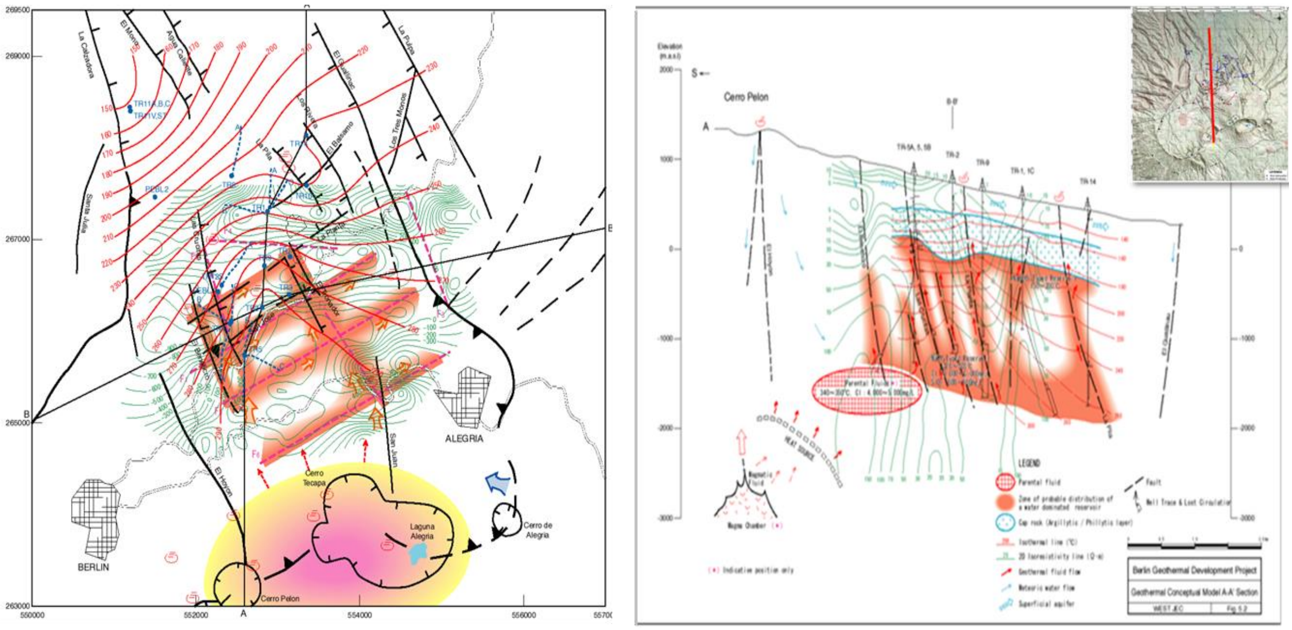

Figure 5: West Jec MT reservoir interpretation (West Jec 2001)

2.3.2 **3D inversion model of MT data**

A total of new 50 MT sounding were conducted in 2005, mostly in the north and west of the geothermal field, and for the first time, a 3D modeling inversion was executed.

The MT interpretation results suggest that the geothermal reservoir is associated with an uplifted resistive zone with a cover of a thin conductive layer.

The calibration of this resistivity model was carried out by correlating with the temperature and mineralogy alteration of the producer wells. The calibrated model suggests that the producer reservoir corresponds to resistivity values ranging between 40 to 90 ohm-m, inside the resistive dome at depth, with a thickness ranging between 600-1000 m, at deeper levels, an inversion in the temperature curves of the producer wells is observed in the extreme south of the geothermal field, as is shown in figure 6. To drill deeper is not recommended.

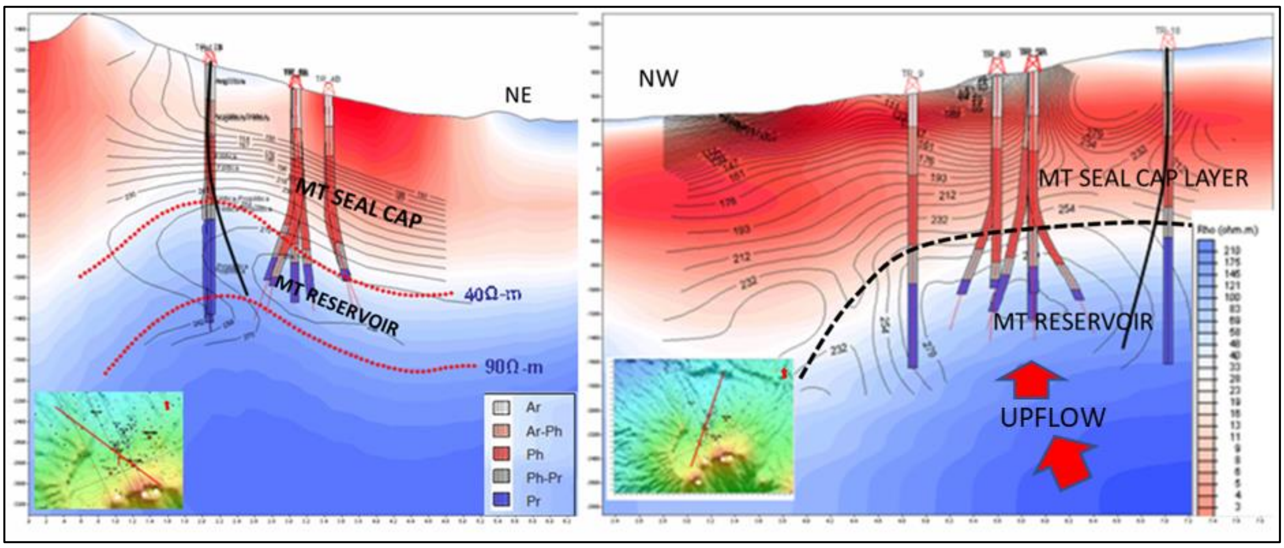

Figure 6: LaGeo MT Reservoir interpretation Alteration, based on the correlation of mineralogy, resistivity, and temperature of the geothermal wells (LaGeo 2008)

In 2012 a new MT survey was carried out in the south and southwest part of the Berlin geothermal field, a total of 32 MT sounding were realized and a new updated 3D inversion model was created, which included the previously collected data.

The obtained result suggests that the MT propylitic reservoir is extending toward the south, southwest of the actual production zone.

As discussed before, the MT propylitic reservoir is associated with a resistivity cupule at depth. The map of the elevation to the top of this resistivity anomaly (cupule) is shown in figure 10, which suggests that the MT reservoir is extending toward the south, southwest, and west of the actual production zone, as is shown in figure 7.

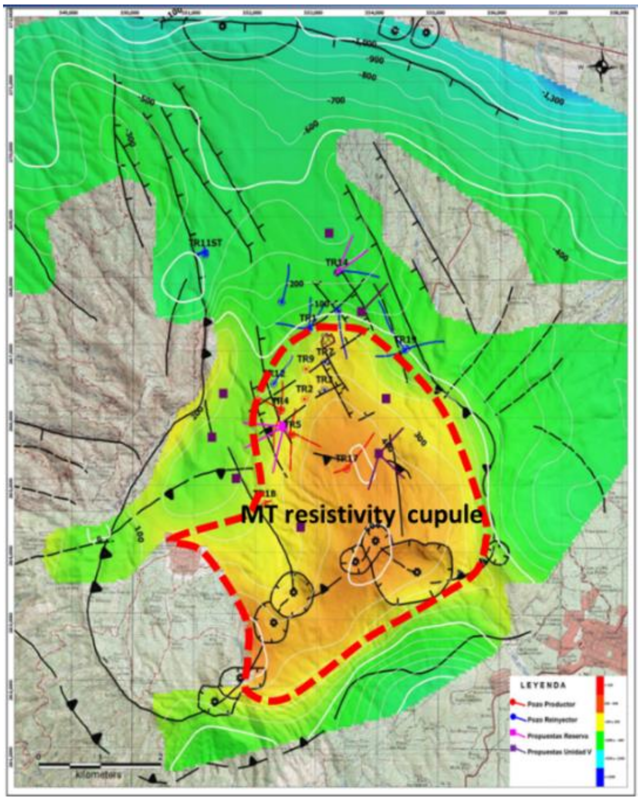

Figure 7: *Map of the elevation of the top of the MT resistivity core*

2.4 Gravity analysis data and the producer reservoir

A total of 560 gravity stations have been measured in the Berlin Geothermal field in three different surveys carried out in the years 2000, 2005, and 2008, as is shown in figure 8.

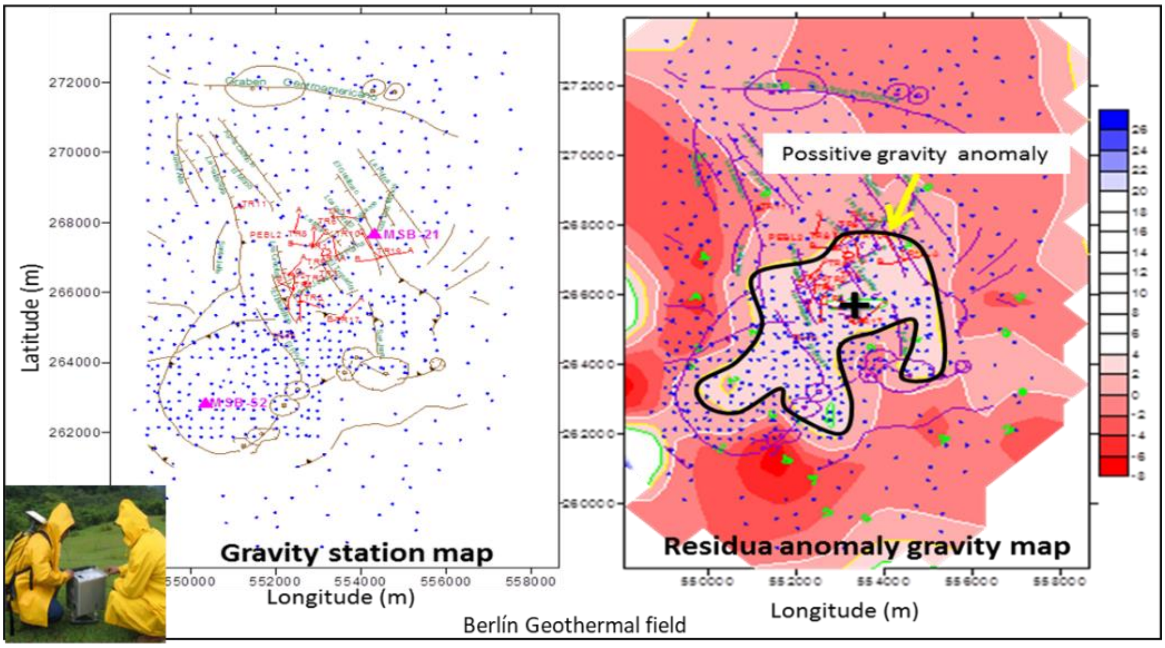

Figure 8: G*ravity station and residual anomaly map related to producer reservoir.*

The main geothermal reservoir area is associated with a high positive gravity anomaly related to propylitization caused by the mineral deposition during the path of geothermal fluid and the consequent reduction of porosity (Rivas, 2005). This anomaly covers the main producer geothermal wells and it is extending toward the south and southwest area, suggesting that possible extension of the reservoir in this direction, in good agreement with the MT resistivity cupule interpreted as a propylitic reservoir (Figure 9)

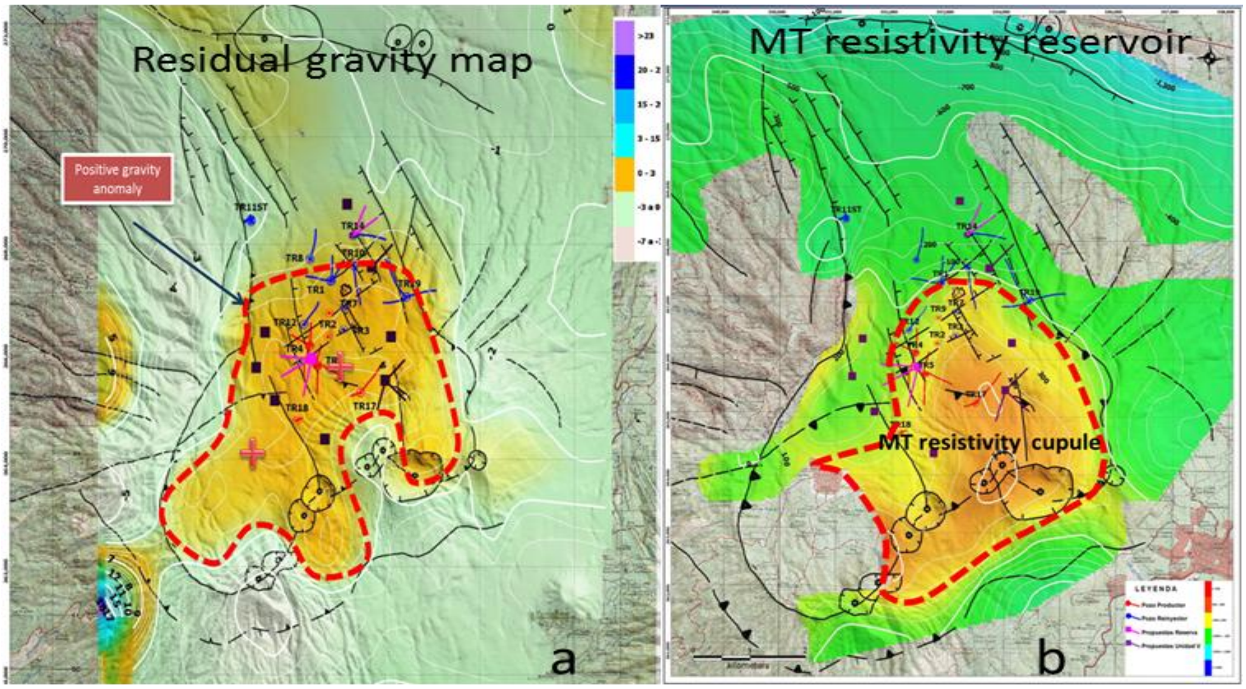

Figure 9: *Comparison between the gravity and MT resistivity anomaly associated with the geothermal reservoir.*

2.4 Seismic monitoring and the producer reservoir of Berlin Geothermal field

From July 1996 to April 2005 a seismic network was monitoring the microseismic activity of the Berlin geothermal field. More than 3,600 seismic events were located. As is shown in figure 10 a, the areal distribution of the epicenters is constrained to the Berlin local Graben.

Based on the epicenters and hypocentres location of the local seismic events, a simplified conceptual model is proposed in figure 8 b, where the reservoir is characterized by a high concentration of seismic events (cloud) in the production zone. The heat source is associated with a very deep seismic anomaly zone, between 6 and 7 km depth, where there is a sudden interruption of the seismicity, probably due to the ductile condition of the rocks. A structural barrier is suggested in the extreme north of the study area, associated with the change in the seismicity behaviour in this area.

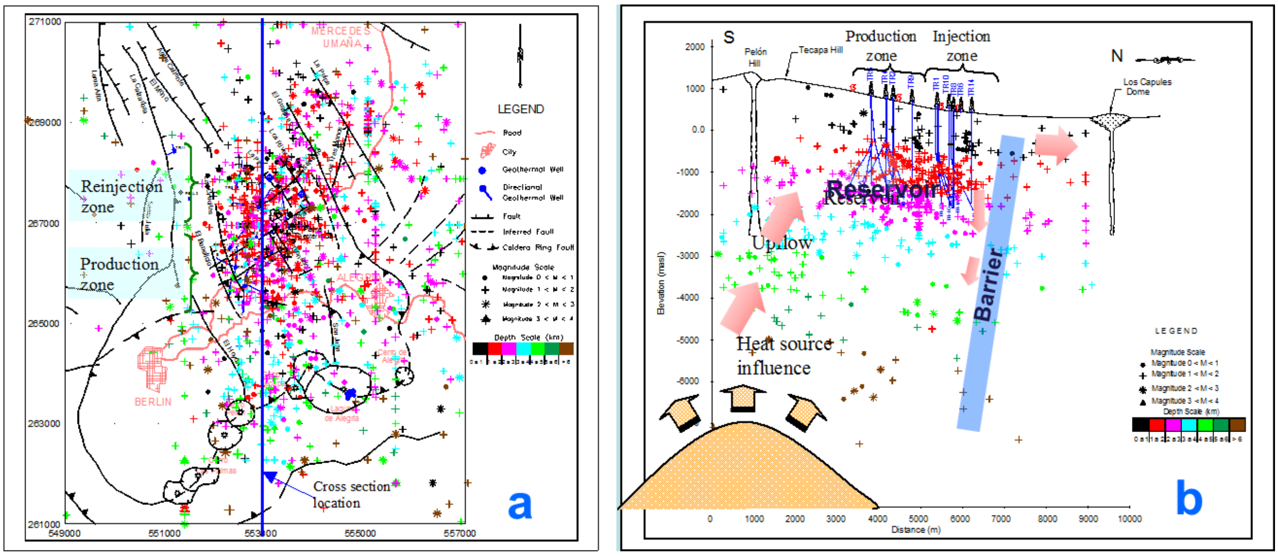

Figure 10: *Micro seismicity distribution and conceptual model proposal*

The tomographic analysis was achieved by Geosystem company in 2005, on a selected dataset covering the period from 1996 to 2005. Three-dimensional distributions of the P-velocity, S-velocity, and Vp/Vs ratio parameters were computed and analysed together with the 3D density distribution deriving from the inversion of the gravity Bouguer anomaly data (Geosystem, 2006).

Evidence of differential effects on Vp and Vs (hence on Vp/Vs) caused by pore fluid phase changes (water versus steam or CO2) have been observed in geothermal fields which have been continuously monitored for a microseismic activity for several years. These include The Geysers (Gunasekera et al.2003), Mammoth Mountain and Long Valley caldera, and Coso geothermal area (Foulger and

Julian, 2004). In all these cases significant decreases over time of Vp/Vs have been observed because of steam substituting water in the reservoir porosity or anomalous CO2 concentrations displacing water (Geosystem, 2006).

The seismic tomography analysis results provide elements contributing to delimiting the producing reservoir, characterized by the presence of an anomaly Vp/Vs ratio, with values lower than 1.7, as is shown in figure 11 (area with red dots line). All the producer wells are located inside this area, while the reinjection wells are located toward the north of this zone.

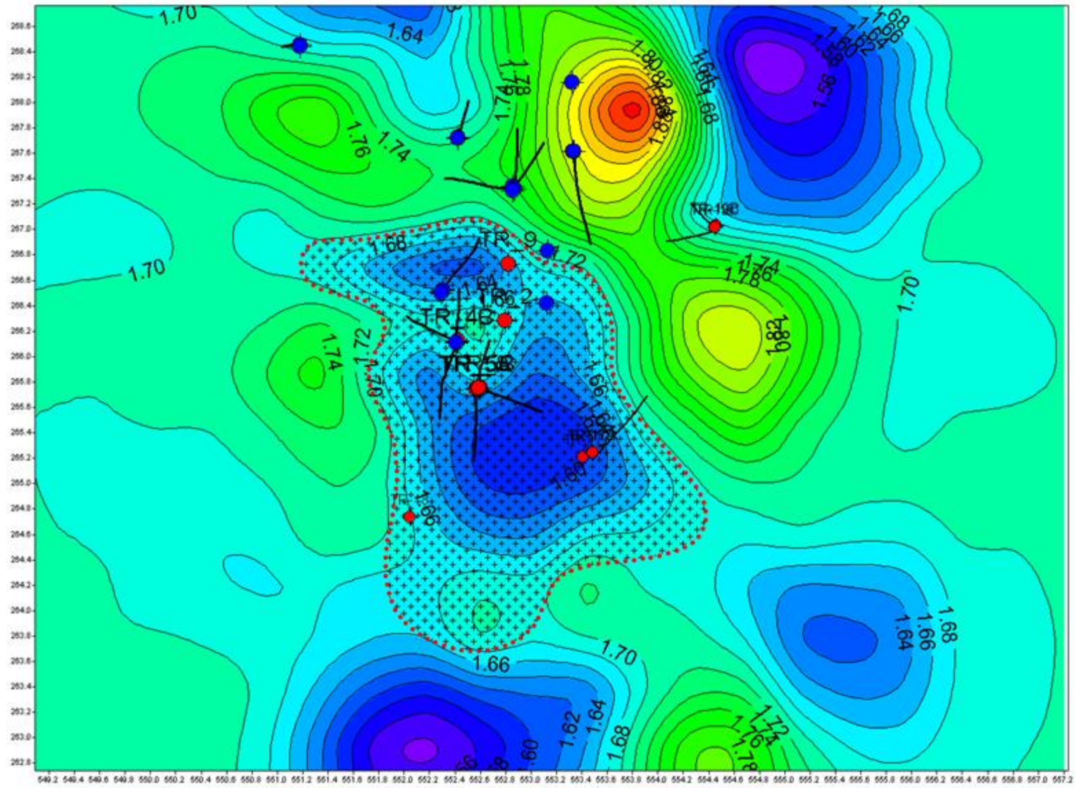

Figure 11: *Vp/Vs ratio anomaly associated with the producer reservoir, modified from Goesysgtem 2006.*

3 CONCLUSIONS

Based on 2D Schlumberger sounding interpretation, in 19955 the reservoir of Berlín Geothermal Field (BGF)was associated with a low-resistivity cap which is underlain by a high-resistivity core. Despite the limited penetration capacity of this method, due to the presence of a shallow and thick conductive layer, was possible to identify the top of the producer reservoir associated with the high resistivity core at depth.

The 2D interpretation of MT data carried out in 2001 by West Jec company, defined that the producer reservoir of BGF might be present within faults and fractures, associated with geoelectric anomalies and resistivity discontinuities that may lead to the targeting of the high permeable zone. There were drilling targets proposed toward these zone of resistivity discontinuities with successful results in the production zone.

In 2008 LAGEO calibrate the 3D resistivity model of MT data by correlating it with the temperature and mineralogy alteration of the producer wells. The calibrated model suggests that the producer reservoir corresponds to resistivity values ranging between 40 to 90 ohm-m, inside the resistive dome at depth, with a thickness ranging between 600-1000 m, at deeper levels, an inversion in the temperature curves of the producer wells is observed in the extreme south of the geothermal field.

The seismic monitoring of BGF, allowed the associate the geothermal reservoir with a high concentration of seismic events (cloud) in the production zone, as well as the probable heat source estimated between 6 and 7 km depth, where a sudden interruption of the seismicity occurs, probably due to the ductile condition of the rocks.

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The main geothermal reservoir of BGF is associated with a positive residual gravity anomaly related to a propylitization caused by the mineral deposition during the path of geothermal fluid and the consequent reduction of porosity. This anomaly covers the main producer geothermal wells and extends toward the south and southwest area, suggesting the possible extension of the reservoir in this direction, in good agreement with the MT resistivity cupule interpreted as a propylitic reservoir, carried out by LAGEO in 2012.

4 ACKNOWLEDGEMENTS

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