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Conceptual Model Review of the Berlín Geothermal System (El Salvador)

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ABSTRACT

The existing data of the Berlín geothermal field has been reviewed and analyzed, in order to achieve a Preliminary Integrated Model of the reservoir. A new numerical TOUGH2 Model of the production performances has been realized, with a special focus on the forecasting of the field exploitation. A convergence between Magnetotelluric and Gravimetric data has been carried out, with an integration of geochemical/geological information.

Introduction

This paper is the result of a joint activity between Enel and LaGeo for the new scheduled development phase of the Berlín geothermal field (Eastern part of El Salvador, Central America).

Many different geoscientific items have been analyzed, with different levels of deepening, according to the availability of reliable data.

Based on the above results of data review, a Preliminary Integrated Model of the Berlín geothermal system is proposed (see Figure 1), as well as a numerical TOUGH2 Model, with forecasting of the exploitation behavior of the Reservoir.

The first exploratory well (TR-1) was drilled in 1968. The exploitation of the reservoir started in 1992 with a 2.5 MW backpressure unit. Subsequently, in 1999, two 27.5 MW condensing unit went on-line. At the moment the operating wells are 9 producers and 15 injectors. The field is currently producing 440 kg/s of fluid (120 kg/s steam and 320 kg/s liquid, separated at 1.1 MPa). The reservoir pressure (at −1200 m asl) is 13 MPa and temperature is 300°C. The pressure is decreased from initial value of 14 MPa to the present one and now is stabilized. 320 kg/s of water is currently reinjected (Monterrosa, 2002)

Geological Settings and Temperature

The 16x12 km study area is located in the central-eastern part of the Republic of El Salvador. Its topography exhibits volcanic

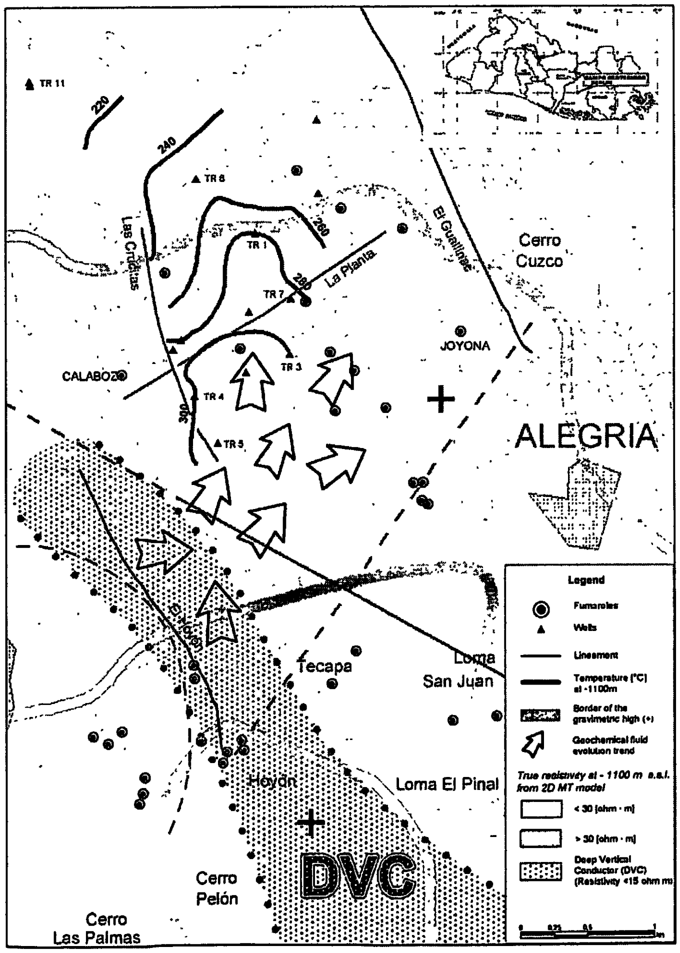

Figure 1. Convergence Map of all the different geoscientific information.

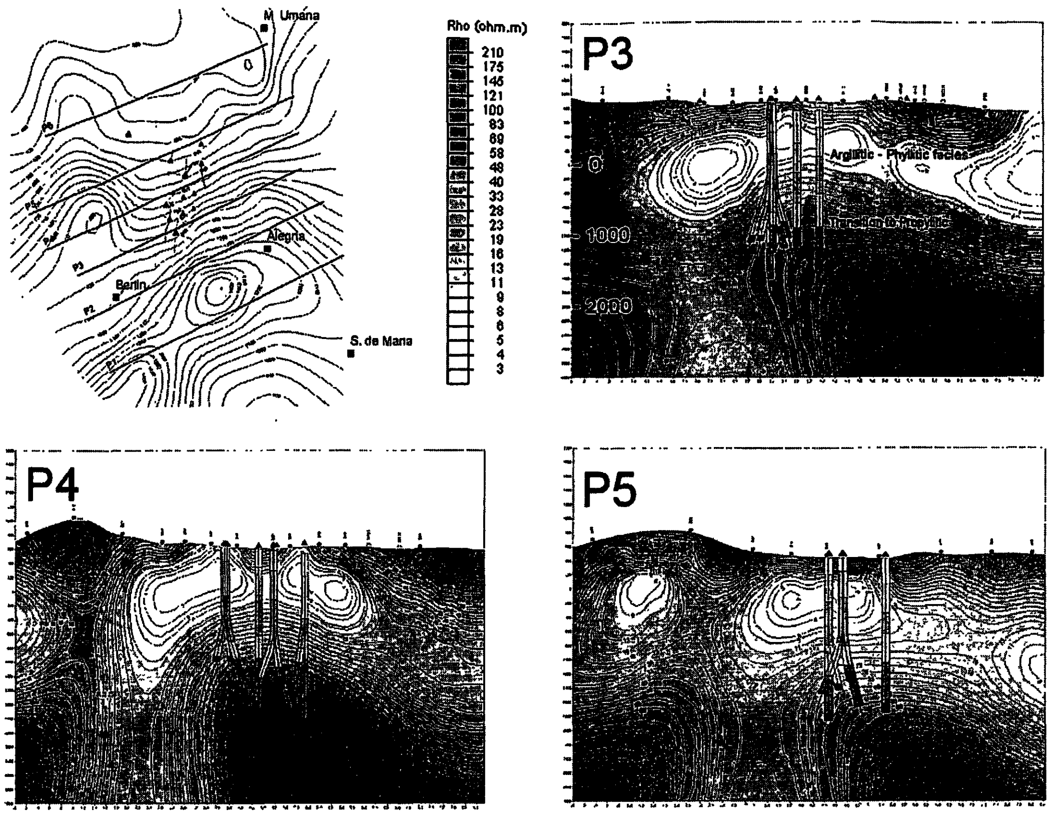

Figure 2. MT sections with hydrothermal alteration facies from wells.

chains in the south, with peaks near 1,500 m, sloping down north to approximately 300 m asl (Tenorio, 1997). The tectonic setting of the region is due to the oblique subduction of the Cocos plate under the Caribbean plate; this seems to be the origin of the main structures of the area, interpreted as a caldera cut through by a fault system running NW-SE.

Berlín's area is affected by quaternary calcalkaline affinity volcanism, alternating effusive (lava) and explosive (tuffs, ignimbrites) events, with andesitic-basaltic composition. The only evidence of differentiation towards more acidic products seems to be provided by the dacite pumice deposit (0.075 M.a.). Dykes are not evenly distributed; they appear most frequent in the northern part of the geothermal field, where most wells are unproductive.

Volcanic rocks are frequently altered by the hydrothermal circulation, exhibiting a band zonation with a typical temperature mineralogic paragenesis (argillitic, phyllitic, propylitic). The stratigraphic succession for Berlín's area includes four units starting from the surface down. The succession of alteration facies generally is not in agreement with the stratigraphic grouping into geological units since it depends on the fluid circulation and temperature experienced by the rock and not just on its lithology.

Above Unit III, made of thin tuffs about 300 m thick, there is a complex sequence of lava and tuffs (Units I and II) which often accommodates thermal aquifers; Unit III comprises the real waterproof covering of the geothermal reservoir.

The thickness of the reservoir is not known, while its elevation is approximately -1100 m asl. The reservoir is generally located in andesitic lava of Unit IV, with the higher permeability layers (fractured/fissured) in correspondence of the propylitic andesitic lava levels. This lava was put in place in a subaerial environment, presumably cracked by cooling and then altered into propylitic facies. This unit has a mean porosity of 7% measured on core samples. Up to the surveyed well depths (approximately 2500 m), andesitic rocks prevail in the SE portion of the field, while less permeable tufaceous intercalations are more widespread in the NW portion.

Interference tests carried out in 2001 showed that there are differences in permeability of at least one order of magnitude between the northern wells and the southern wells.

All available temperature data were analysed and cross-related. The isothermal trend unequivocally shows a reduction in temperatures and gradients towards the northern area of the field, where the reservoir would therefore get deeper (see thermal data in Figure 1).

The productive area, which is associated with temperatures > 290°C at -1100 m asl, seems to be bordered by faults and lineaments. The known minimum extension of the high-enthalpy field surface (bounded by the 290°C isotherm) is approximately 3x3 km.

Geophysical Analysis

The main geophysical data useful to update the conceptual model of the Berlín geothermal field come from magnetotelluric (MT), electric (DC) and gravimetric (GR) surveys performed since 1977. MT data were corrected for *static shift* effect using the DC data and the MT strike direction was analyzed. A mean strike direction oriented N30°W was identified; this direction reflects the trend of the main structures. Data were 2D inverted (80 TE+TM mode iterations) along profiles normal-oriented to the strike. Figure 2 shows the 2D models along three vertical sections with the alteration characteristics reported in the drilled wells.

A shallow horizontal conductor (SHC) with a resistivity of a few ohm-m and a thickness of some thousands meters can be identified. This conductor appears everywhere above the elevations where productive zone have been found; it looks narrower and arched upwards in the areas of current geothermal exploitation (profiles P3 and P4 in Figure 2).

At a fixed elevation, the geothermal environment is characterized by resistivity values higher than the surrounding environment.

The resistivity of the exploited area increases with depth and reaches values between 30 and 100 ohm-m at the main productive horizon of -1100 m asl (see resistivity data in Figure 1).

At greater depths, resistivity generally increases, although a vertical low resistivity zone (15-20 ohm-m) is visible on the west side of all the profiles. This "deep vertical conductor" (DVC) is believed to have a different significance from the SHC and not to be the expression of the same phenomenon. Given the predicted temperatures at DVC depths (> 250 °C), the low resistivity values of this conductor cannot be explained by rock alterations in the argillitic-phyllitic facies as for the SHC anomaly.

The comparison between the hydrothermal alteration and the temperature data seems to show that the SHC is mainly related to the development of the low-temperature hydrothermal facies (although the contribution to low resistivity of shallow thermal reservoirs can not be excluded).

The passage to medium-resistive areas (between 30 and 100 ohm-m) below the SHC can mark, instead, both the beginning of the propylitic alteration facies and the transition to areas where andesitic lava becomes prevalent (*main reservoir?*). However, the base of such a conductor can not be considered a significant geothermal marker, since it is also found far from the currently exploited areas, where the field seems subject to thermal decay.

On the other hand, the low resistivity values of the DVC could be associated with an interesting zone characterized by a greater contribution of high temperature saline fluids. The effective consistence, shape and geometry of the DVC needs to be investigated by 3D algorithms.

Gravimetric data consist of 329 stations over approximately 100 km^2. The main results of the gravimetric data processing show that the Berlín geothermal field belongs to the regional "gravity high" associated with the volcanic belt and is found in its NW portion. The first-order residual Bouguer anomaly (calculated with density 2.2 g/cm^3) confirms the correspondence between the local gravimetric high and the geothermal reservoir. The possible border of the productive area is shown as the 6 mGal isocontour in fig 1. Outside this gravimetric high, the reservoir probably gets deeper and the wells are prevalently unproductive.

The GR modeling has been carried out to verify and to integrate the resistivity model. The 2D MT structure (SHC base, interpreted as top of the reservoir) was used as input for the 2D gravimetric forward modeling. A good fit was obtained demonstrating the consistency of these geophysical data (Fig 3).

The top of the reservoir seems to be marked by the convergence of the gravimetric high and the top of a medium-resistive body (see Figure 1).

Geochemistry

The review of chemical and physical data from wells and fumaroles led to an improvement of the geochemical interpretation with important relations with reservoir engineering (D'Amore, 1998).

Temperatures measured in the wells (around 300°C) are in agreement with the values calculated by the most reliable chemical ionic geothermometers.

The N_2/Ar molar ratio in the wells (15-22) is very close to ground water balanced with air at 25°C (27-34). The meteoric origin of the fluid reservoir in Berlín is also proven by its stable isotope content.

The chloride content of productive wells, at reservoir conditions, ranges from a minimum of almost 3200 mg/l in the south-western area to a maximum of over 5500 mg/l in the north-eastern area. The same liquid phase (natural groundwater at the origin) feeds the fumaroles and wells located at Berlín. The various gas concentrations found in the fumaroles depends on the percentage of steam condensation as they rise to the surface. In general, the farther the manifestation from the main upflow, the highest the gas content. More favorable drilling was experienced in the southern area than in the western or eastern areas.

The low CO_2 content of the productive wells cannot be accounted for by a boiling process, but could be explained by a poor gas flow from depth or by the absence of complete equilibrium (as could be inferred by the values computed on the basis of CO_2, H_2 and Ar concentrations; about 50% lower than the measured ones). This is confirmed also by the observed trends in the gas, chloride and isotope contents of the produced fluids. Probably, due to different permeability boundaries, several fluid circulation patterns, providing different levels of water-rock interaction, should be taken into account (see arrows in Figure 1). The circulation seems to originate in correspondence of the DVC with meteoric water and develops within the reservoir towards the NE and

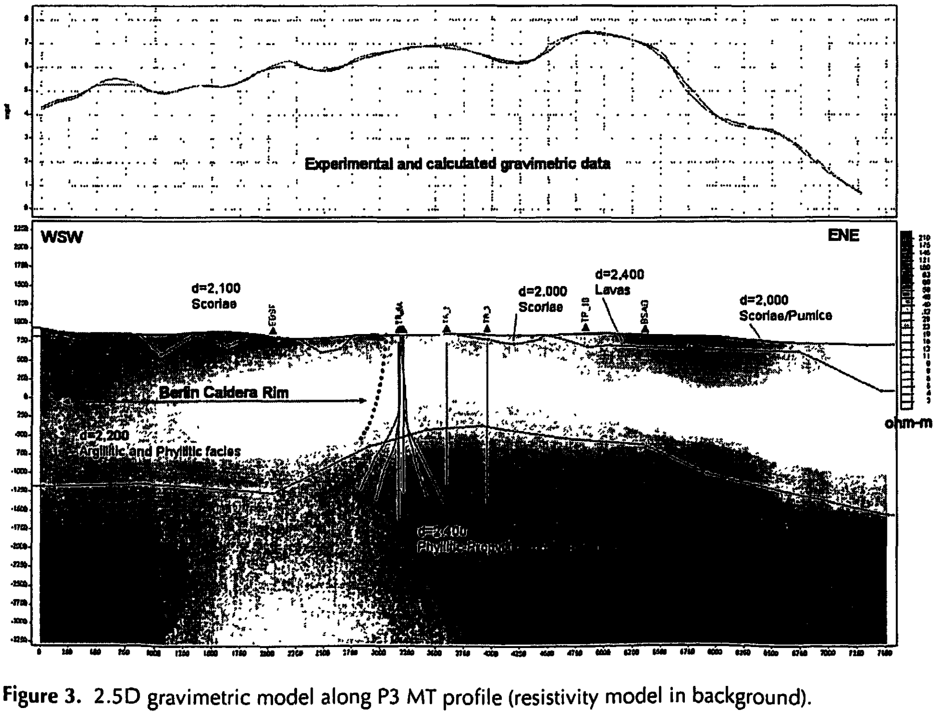

Figure 3. 2.5D gravimetric model along P3 MT profile (resistivity model in background).

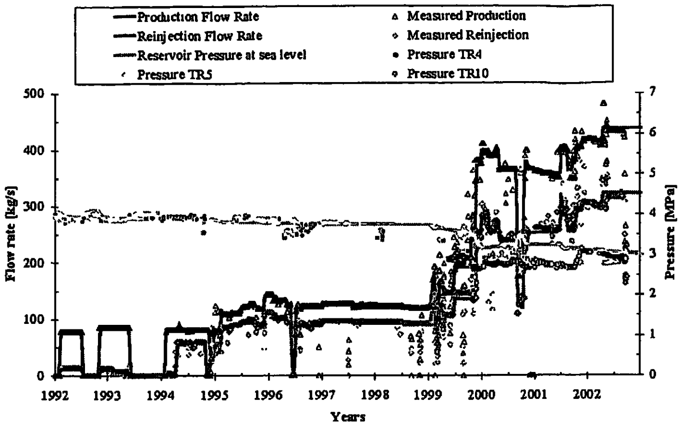

Figure 4. Reservoir drawdown simulation for 1992-2002 data.

then beyond the northern boundary of the field, with increasingly degraded thermal characteristics. The chemical composition of the fluids sampled in the wells corroborate this assumption. Boiling phenomena, if any, are negligible.

Reservoir Engineering

The reservoir boundary was established on the basis on the basis of the temperature distribution (290°C isotherm) and geophysical indications (see Figure 1); the geochemical and MT data suggest a possible anisotropy of permeability between the southwest/north-east direction and the orthogonal direction (Montalvo, 2001). Geochemical data show that the reservoir east-west extension is limited by the "Calaboz" and "Joyona" manifestations (they are located 2.6 km away, and are a clear indication of the lateral extent of the high permeability area, see Figure 1).

According to the probable reservoir geometry and the observed pressure decline data, a possible mechanism for pressure control of the system is given by the «falling liquid level». In the uppermost layer to the south, under the Tecapa volcano (see Figure 1), the liquid interface level is gradually decreasing at a rate in accordance with the measured hydrostatic pressure behaviour in the reservoir. Different values of permeability (60 mD in the reservoir area, 6 mD on the north zone), as well as a permeability anisotropy (reduction of a factor of 10 East-South/West-North direction for the reservoir area) has been utilized (Barrios, 2002).

The first stage of production/reinjection (from the beginning up to year 2002) has been used for a proper tuning of the model parameters. The standard trial-and-error procedure for matching the reservoir pressure drawdown as a function of the mass withdrawn was followed. The system geometry was modified, reducing the number of reservoir cells in the south area, where the controlling pressure evaporation surface is located, in order to increase the pressure drawdown of the system. The final value of 4.73 10^6 m^2 (with an overall reservoir volume of 1.79 10^{10} m^3) achieves a very good match (see Figure 3).

The well flow rates were imposed on the simulation. Reinjection well enthalpy was fixed at 76 MJ/kg for hot and 33 MJ/kg for cold reinjection

With the tested model, the future reservoir exploitation was forecast (from today to year 2025). The existing reinjection and production wells flow rates were maintained at the present values. Five new production wells to the south and five new reinjection wells to the east, were added to the model, increasing flow to a total of 650 kg/s of extracted mass (180 kg/s steam, for additional 30 MW) and a reinjection flow rate of 460 kg/s.

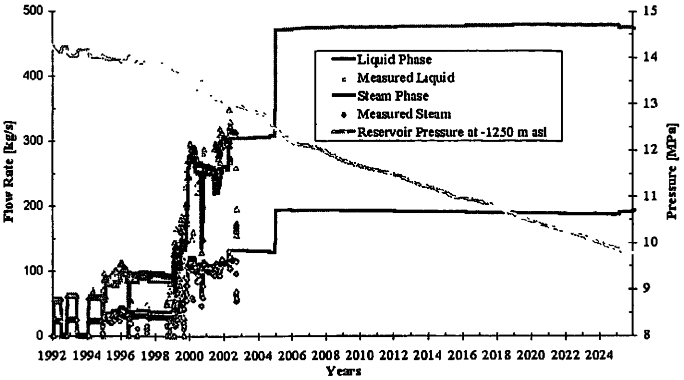

Figure 5. Exploitation forecasting with a new 30 MW unit for 20 years.

The final reservoir pressure will be 9 Mpa (see Figure 4). Neither significant boiling effects nor two phase transitions are expected. The pressure drawdown of the reservoir is affected only by the amount of production-reinjection, and not by its areal location.

The enthalpy will be constant for all the forecasted production, with an indication of onset of slight boiling in years 2024-2025. Reinjection induced cooling does not affect reservoir performance. The radial extension of the cold water front at -1250 mbsl in 2025 will be about 250-500 meters around the main reinjection sites. A detailed study was carried out on a standard production well, using a well-simulator program. At the production pressure of 1.1 MPa, the well is still capable of producing 45 kg/s of fluid at the depleted pressure of 9 MPa in year 2025.

Conclusion

The interpretation of geological, thermal and geophysical data helped us develop the conceptual model of the field and to highlight its main features useful to prioritize future drillings.

The reservoir cover is represented, overall, by alternating volcanic rocks with argillitic-phyllitic alterations (approximately 1500 m thick) containing shallow thermal aquifers. (Units I, II and III). Unit III, consisting of thin tuffs, is 200-300 m thick and forms the real waterproof covering of the geothermal reservoir. Cover is characterised by high electric conductivity (resistivity < 30 ohm m) due both to the prevalence of pyroclastic rocks over lava and to their widespread argillitic alteration.

The reservoir is made of propylitic andesitic lava (Unit IV), having a mean porosity of 7% and a primary permeability <0.45 mD (core measurements) and a secondary permeability of 60 mD (from the well production tests). Up to the surveyed well depths (approximately 2500 m), andesitic rocks prevail in the SE portion, while tuffaceous intercalations, which are less permeable, are more widespread in the NW portion.

The reservoir seems to be bounded by the main lineaments, roughly trending NW-SE (El Guallinac, El Hoyon, Las Crucitas and Tecapa) and a NE-SW (La Planta). In the southern portion, towards the volcanic belt, this border looks more uncertain (see Figure 1). There are not enough data to correlate these lineaments to faults.

The reservoir seems to be identified by the convergence between the gravimetric high (values >6 mGal in the first-order residual) and a medium-resistive body (30÷100 ohm-m); it extends on the southern side of the volcanic belt. The low resistivity of the andesitic rocks of the reservoir is due to the circulation of saline geothermal fluids (TDS ~ 10,000 ppm).

The reservoir top is situated on average at -1100 m asl, while its base is not known. The likeliest high-enthalpy field surface is approximately 9 km^2, but it might spread further southward. The temperature distribution, as reconstructed from the few available well data, exhibits convective circulation. The field extends into a structural high, with temperatures of approximately 290°C.

In correspondence of El Hoyon fault area, a deep conductor (DVC with resistivity < 15÷20 ohm m), has been located. This has a vertical development, a SE-NW direction, and is likely to be the way through which primary geothermal fluids flow back upward.

The chemistry of the fluids sampled in the wells corroborate this assumption. They show a geochemical evolution, especially in water-rock interaction (decrease in gas/steam ratio and increase in ^{18}O and chloride content) when moving from SW (area of origin) to NE. Boiling phenomena, if any, are negligible.

The circulation seems to originate in correspondence of the DVC and develops within the reservoir towards NE and then beyond the northern boundary of the field, with increasingly degraded thermal characteristics.

The numerical model is rather satisfactory, in term of simplicity and historical data matching. The possibility of pressure control due to the falling liquid level (4.7 km^2 of evaporating surface in the south) in a closed system is rather conservative, but nevertheless the field should be able to sustain another 30 MW for 20 years, with a final pressure of 9 MPa, and no significant boiling effects or two-phase transitions are expected.

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