Resistivity Structure of the SE Sector of the Miravalles Caldera

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ABSTRACT

After several years of production in the Miravalles Geothermal Field, there has been clear aspects of the fluid flow assessment that impacts its sustainability. To better understand the hydrodynamics and extension of the resource a more detailed study of the resistivity structure was carried out for the SE of the Miravalles caldera based on MT soundings. We had to deal with issues, such as quality and availability of the soundings along with a complex geology in terms of a caldera structure, as critical factors for evaluating the resource. We proceeded with a traditional approach for the interpretation to determine the dimensionality and the induction vectors by identifying TE and TM modes separately. A pseudosections analysis was also conducted with 1D TE profiles and the interpretation of 2D sections. Towards this sector the morphological evidences of the caldera rim has been unclear. A conductive body that extends beyond and a shallower NS NNE-SSW structural trend that crosses the inferred caldera rim might become a drilling target.

1. INTRODUCTION

Miravalles geothermal field is at the NW of Costa Rica, 200 km away from the capital city, San José (Figure 1). It is associated with an andesitic strato-volcano inside an evident caldera structure with a diameter of 11 to 14 km and a highest topographic elevation difference of about 200 meters toward the north (Figure 2). The first condensing unit has produced since March 1994, and now, there are four more generating units reaching an installed capacity of 163 MWe.

The production has caused pressure declines and chloride returns due to injection and implies that Miravalles field has actually reached its maximum extraction rates. Therefore, for its sustainable utilization, evaluation of the E-SE and N-NE areas of the field is required. The area has been partially explored. Once a geothermal resource is identified, it will support the production in the main area at the center.

![Figure 1: Miravalles field, location.](image-url)

The re-assessment of these two areas should be done given that: these areas match with aquifers of different composition (one rich in bicarbonates at the E-SE area, and the other an acid aquifer to the N-NE), and they can help (and actually do) to solve the production decline observed in the main aquifer, hence making feasible to consider a field expansion if it is established that they are...
independent. Now we are oriented to characterize the S-SE aquifer as a partial fulfillment of the re-assessment asked, it was started with the reviewing of the available geophysical data in particular MT. Among the first geophysical works in the history of Miravalles field are: a geophysical summary reported by ICE (1982 updated in 1984) and a first integration of the geology and geochemistry with geophysics by Herrera D. (1994) as benchmarks for the conceptual modeling considered nowadays. All data referred to have been processed from geophysical surveys since in 1986. But between 1993-1995 additional data were collected in parallel to the drilling program aiming to update the geological information with geophysics.

However it was not until the year 2000 that the first electromagnetic surveys were carried out. Some of this data was obtained with the V5 unit from Phoenix Geophysics, in general the time series are not traceable, and the EDI files do not contain the spectra information. Therefore its quality was difficult to assess. However an effort was made to look over variables like the dimensionality, tipper strike, Z strike, maps and profiles of apparent resistivity, for proposing a resistivity scenario.

2. GEOCHEMISTRY AND GEOLOGICAL SETTING

Miravalles volcano resulted from a Miocene activity, with effusive to explosive deposits, under a NE, NW tectonic environment. The heat source of the system is considered to be related to the last cone of Miravalles volcano. Locally the depth to the 220°C isotherm and the alteration mineralogy in the northern sector supports this model (Eduardo, 2005).

The main reservoir at the center is characterized as a two phase flow mixture from 230-250°C at 700 meters depth, with a thickness that varies from 0.8 to 1 km. The temperature decreases to the south and west (Vallejos, 1996). The dominants fluids are sodium chloride with TDS of 5300 ppm, almost neutral pH, and a silica content of about 430 ppm. Additionally at least there are two more types of aquifers; and acid one to the N and NE, and other one rich in bicarbonate, coming from east and southeast close to the caldera border, which is the subject of this investigation.

This area (E-SE) is nowadays under exploitation by a single flash wellhead unit. The main differences of its fluids are: the high bicarbonates content, the Na/K relationship, which interferes with geothermometry calculus, and likewise the differences in calcium and magnesium content. These fluids manifest a trend to form calcium carbonate scaling as well as to have a high NCG content in the steam phase (Sánchez et al 2010).

The non-condensable gases content (NCG) has been evolved starting from 0.6 to 0.9% weight/weight (w/w) of steam. They are mainly composed of three species; CO₂ (between 97 to 99% w/w), nitrogen (of about 1.4 to 2% w/w), and hydrogen sulfide content less than 1% w/w (ICE and ELC, 1986). After exploitation, an increasing trend was observed. The current data showed the values of 0.2 to 2.4% (w/w) in the main aquifer, from 0.9 to 1.75% w/w for the acid aquifer and approximately 3 to 18% w/w in the bicarbonate aquifer (Sánchez et al, 2010) being the latter of our immediate interest.

A 48 km² area of proven capacity was assumed, which is well constrained by conductance values from magnetotelluric soundings. The predominant permeability probably arose from fractures according to the wells logging. The fractures and faults are shown in Figure 2. The well distribution (in red) reflected the proven area.
Evidences from geology and geochemistry together with the measured temperatures showed an up-flow zone from the north, and three different fluids zones.

The more important morphological features are the caldera structure of Guayabo, with the diameter between 11 and 14 km at least after three activity stages (c.f. Figure 2). Its NE and E limitation were covered, while the west, the south, and the northern borders are well expose.

These craters were cut by the N-S normal faulting system that caused a depression along the caldera. It is inferred that the faulting N-S and NE-SW has had recent activity. These conspicuous fault systems, that is, NW-SE, N-S, NE-SW, and E-W are key parts of the hydrogeology and the hydrothermal system. The permeability has been defined as secondary in nature, controlled by these fracture systems. The E-W trend is associated with a series of horst and graben, well expressed in the lithologic units found in the deep wells.

3. EXPANDING THE TERMOHYDRAULIC CHARACTERISTICS

Temperatures and pressures around the field have changed over years due to the continuous exploitation for 20 years.

The formation temperature and the reservoir pressure before exploitation indicates that the geothermal fluid flowed initially to the NE-SW direction, and changed to N-S in the central part of the field afterwards. A fluid flow appeared to come from an area in the vicinity of wells PGM-10 and PGM-11, at the north where the highest temperatures and pressures on the field were observed. The temperature and the pressure then decreased gradually from the north to the south: the maximum was around 250°C near a well PGM-11, and the lower is around 220-230°C in wells PGM-26 and PGM-16 near the southern caldera rim. The reservoir was clearly bounded to the west due to the low temperatures and pressures observed at wells PGM-04, 15 and 22. The change in the temperature and the pressure to the E were not completely identified due to lack of data. There was a gradual pressure decrease of about 3-4 bar from the north to south.

The wells PGM-28 and PGM-29 located at the SE were characterized by its NCG and carbonate content. The undisturbed reservoir pressure was considered to be about 70-71 bar at -500 m.a.s.l. Those values were similar to the ones observed at the central part of the field, but this can be considered as an indication of another deep recharge zone coming from the NE or the E of the field revealing a geothermal subsystem.

The porosity of the field in rock samples varied around 9.8% ± 4.9%, but for numerical modeling purposes, the porosity was set to 5.0% (Osvaldo, 2013).

4. ELECTROMAGNETIC DATA – MT SOUNDINGS AVAILABLE

A review of geophysical data available in the geothermal field of Miravalles was requested. Issues such as geophysical methods, coverage, and quality were reviewed from several exploration campaigns. Subsequently, a more detailed analysis of the MT soundings located to the E-SE (green ellipsis, Figure 3) was done, given the great potential of information provided. This paper is considered as a first approach to this reviewing of geophysical data, in partial fulfillment of a sustainability assessment in order to expand the resource toward the E-SE.

The data were scarce especially after filtered by noisy bands or galvanic distortions like the static shift. Rather, its distribution was asymmetric especially regarding TE or TM modes and 2D constrains. It is recommended to realize more MT soundings for sake of completeness of the scenario with a proper static shift modeling. The obtained data thus will guide and support us for a more comprehensive integration before any further investment.

We can mention that the area (E-SE) is partially covered by blocky lava flows with big blocks that make difficult any measurement over them. Furthermore, a buried caldera border is also inferred to the south. An evaluation of the dimensionality and directionality for the area with apparent resistivity maps supported the 2D profiles modeled as the end product (after an extensive assessment of 1D, TE profiles). This kind of work has reduced the ambiguity due to processing and complex geology. We used approximately 42% of the available soundings for Miravalles, distributed in 3 profiles oriented perpendicular to the tipper strike. Only two of them (the extremes) are shown in Figures 6 (REC4) and 7 (REC1).
5.1 Processing and interpretation

As pointed out in Cummings (2001), there is a possibility of artifacts due to the processing with a so-called robust algorithm. In our case, some of the soundings were rejected or were unusable; these kinds of decisions were specially taken regarding the unclear traceability of its reference station.

The dimensionality, directional analysis as well as distortions were considered in sequence. Then 1D sections were prepared for having a complete scenario of the resistivity structures, and finally a 2D modeling was valued, which was oriented by the 1D results.

5.1.1 Dimensionality

Dimensionality and directional information can be extracted from the impedance tensor using several methods. For noise free MT data, the diagonal components of the impedance tensor (Z) were zero or close to zero when rotated to the regional strike angle. Deviations from an ideal 2-D situation required a search of the appropriate strike angle that minimizes the diagonal elements (Zxx and Zyy) or maximizes the off-diagonal (Zxy and Zyx) elements of the impedance tensor (Swift, 1967). This angle is called the Swift strike, S. However, it does not always give the same regional strike angle. Therefore, we should evaluate how the MT impedance tensor satisfies the Swift criteria accurately. This quantity is known as the Swift skew, (K=Zxx+Zyy/Zxy-Zyx), and the value less than 0.3 can indicate 2-D (Swift, 1967).
Figure 4 shows the skew value per frequency per sounding and profile. In all cases information, such as a variation of induction vectors and regional strike angles (impedance polar diagrams) along the profile and per range in frequencies, should be inspected (Bahr, 1988 and 1991; Simpson and Bahr, 2005).

To assess this parameter, soundings from the 1D profiles modeled were used. These profiles were parallel, heading toward the NE direction with a length of 10.7 km, with 11 and 13 soundings according to the largest sounding sample. For comparison, soundings k results were placed in equispaced columns in the abscissas while the ordinates are the frequencies in which the impedance tensor components occur. Values between 0.2 - 0.3 are shown in yellow, under the values are in green, and above the values are highlighted in orange color. Therefore, a 2D analysis at least seems feasible.

5.1.2 Directionality – Tstrike and Induction Arrows Analysis

Geoelectrical strike analysis indicates directions of lateral resistivity contrasts, some of which could be faults or fractures, and could enrich a local structure and yield a resistivity model (Gylphy 2013). Sometimes these are related to structural trends that are not “visible” by other techniques. In our 2D earth the strike depends on the site and the frequency. In addition, sometimes it contains artifacts from laterally displaced structures unless a rotation, be done for decoupling E and B polarizations. In some cases, more than one strike influenced the same data (Simpson, Bahr 2005), which is well known how the geoelectrical strike is different at different depths.

The tensor decomposition methods can be applied as hypothesis tests of the preferred 2-D regional geoelectric subsurface in addition to removing effects caused by near surface inhomogeneities. If the subsurface is 2-D, after decomposition, r.m.s misfit between the observed and calculated impedance tensor should be small. If using single site decomposition, small r.m.s misfit values may be obtained at the expense of different strike angles computed for each period.

Induction arrows are vector representations of the complex ratios of vertical to horizontal field components. Since magnetic fields are generated by lateral conductivity gradients, they can be used to infer the occurrence of lateral variations in conductivity. In our case we adopted the vectors pointing to the conductors. Nonetheless, as Simpson and Bahr (2005) pointed out, its absence in a single site does not confirm an absence of a conductivity boundary, as they are sensitive to distortions.

Rose histograms were prepared for induction arrows and tipper strikes (Figure 5) in the ranges of 1 Hz and 0.1 Hz, corresponding to a sampling of 240 and 280 frequencies calculated by Winglink corresponding likewise to 0.39811-2.51189 Hz for a central value of 1 Hz, and 0.003981-0.02512 Hz for a central value of 0.1 Hz.

For around 1 Hz there was a poor control of the induction vectors (Figure 5), which was very likely influenced by heterogeneities of the cap rock. Therefore, an ample distribution was seen especially regarding the tipper. The geoelectric strike was not showing a preferential strike.

On the other hand, for around 0.1 Hz two strikes were predominant: a SSW for the induction vectors and its complementary NNE for the tipper strike. The control is much more pronounced to be very likely related to the effect of getting away from the clay cap, becoming clearly visible toward 0.1 Hz. Hence at this depth and frequency, a directional control is more developed.
Figure 5: Distribution of induction arrows and tipper strike for the E-SE area. The roses are showing a circular histogram. The greater dispersion is shown at shallower frequencies, while after one decade the distribution is much narrower. At 1 Hz typically occurs the lowest resistivity of the MT curves. Wells are in blue.
5.2 Resistivity of 2D Sections and Maps

In order to obtain profiles (Figures 6 and 7) in REC1 and REC4, the TE and TM modes, the magnetic transfer function, and the static shift were used for the 2D inversion sensu WinGLink. In REC4, five wells were used for calibration of the clay cap depth. The image of a conductor that may work as a clay cap (in red) is suggested as a continuous layer from REC4 to REC1. In both Figures 6 and 7 the signatures of geothermal activity were satisfied. Besides the wells in the vicinity yielded injectivity indices as well as temperatures, which are usable for integrating its production.

The map section (Figure 8) was taken at 1100 meters deep by looking for the depth where the clay cap has a transition to the top of the reservoir. It is shown an anomaly of 6.5 ohm-m, which suggests an extension of the conditions found toward the field center, while the sides are still showing low resistivity values (no transition to reservoir conditions). In fact around the soundings 58-67-68 the well’s permeability was one of the highest in the geothermal field with high NCG content.

Close to sounding 68 a deep well was drilled down to 1835 meters depth. This well had many mechanical problems and resulted in a low injectivity index. However its geological model does show a smooth behavior spite of the fact of been closer to the caldera rim. It is clear that some adjustments have to be made. Considering the errors and the quality of the soundings this model has to be checked (in spite of the fact of a coherent integration) with the variables analyzed. Unfortunately, some problems, such as static distortion, have been still present and need to be modeled or corrected.
Figure 6: Profile REC1 in 2D, the nearest to the E-SE deformed area. An overall error of 4.7% was obtained.

Figure 7: Profile REC4 2D, the farthest to the deformed area at E-SE. An overall error of 2% was obtained.
6. DISCUSSION

Based on the dimensionality evaluation, the 3D analysis may not be ruled out. The Swift skew suggested an environment where 3D effects were not expected in terms of a caldera, as the deformations implies.

In spite of the fact that the induction vectors (geomagnetic transfer function) could be very much influenced by galvanic effects according to Simpson and Bahr (2005), they show a remarkable dominant NE strike toward 0.1 Hz.

On the other hand the directional parameters and the apparent resistivity 1D in TE mode of the invariant showed a similar trend as the ones shown by profiles inverted in 2D, (which is a NW-SE trend).

Furthermore injection into the southern wells has provided a small amount of pressure support to the production wells. The measured chloride contents and pressure decline data have shown that the fluid injected into the southern wells has quickly moved out of the reservoir and has not come back to the production area in a significant amount. The anomaly observation then could be a response for fluids discharging outside of the modeled caldera.

Although the extension of the conductor and its core of high resistivity were unknown beyond the caldera, the anomaly is delineating a sort of a horst that goes to the S-SE, which even leads to crossing the caldera rim. Nonetheless we still have to test it carefully, most likely by adding more MT and TDM soundings toward this area, at least this should be considered for showing a plausible scenario.
Regarding the MT soundings distribution; as it is seen, there is no MT soundings in more than 4 km², which together with the low quality of some of them impose new soundings. Furthermore this area is less populated, hence there is less anthropic activity, such as power lines, motors etc, and therefore the exploration may not be as difficult as that was postulated previously.

From the well logging point of view, the volcanic stratigraphy is characterized by great lateral continuity but with a variable permeability (ranging from medium to low), which likewise changes due to the tectonic activity and mineralogical alteration. Although a trend of the structures follows a NW-SE strike, which once happened to be the most important, today they have less influence in the permeability. Perhaps the NE-SW system might have shown an important role in the channeling of deep fluids.

7. CONCLUSION

Forty three soundings were reanalyzed considering parameters, such as dimensionality, tipper strike, and induction arrows. Multiple 1D TE profiles were modeled regarding apparent resistivity patterns in order to have clear resistivity tendencies manifested in the area. None of these issues were been evaluated before. The lack of static correction with TDM soundings imposed a review were well data, Schlumberger soundings and geological knowledge of the zone, especially for modeling distortions. Finally a 2 D analysis was carried out over four profiles in spite of the irregular distribution and few data available, supported by the previous analysis. It was considered a success to lower down its ambiguity. Additionally a complex geological structure due to the proximity of the caldera rim was expected, but it was not confirmed.

The lower resistivity occurs for 1 Hz in the MT curves of apparent resistivity, and therefore it was assumed that it is correlated or that it characterizes the base of the clay cap. The dispersion seen in the Rose diagrams was related to the frequencies and thickness of it. It was manifested a deepening of the base of the conductor toward the East, implying a limit.

The reservoir condition become shallower and extends with higher resistivity values to the SE, in relation to the caldera rim or until it intersects. This rim has not been as clear as expected or is buried, although the border is modeled very near. The optimistic model could suggests that the surface morphology of the caldera almost disappears or that it is farther away, or that there is somehow a larger caldera that is not considered yet for the geothermal development.

It have been recognized that a NW-SE trend and a deeper NE-SW of tectonic faulting might be controlling any possible discharge of geothermal fluids, especially from the north, as it can be seen by the induction vectors described, by the pressure decline and by the injection results for the southern area. As this area experiment, the same decline as in the center is possible to be fed from the second up flow zone.

It is recommended to review the influence of galvanic distortions for each sounding by a suitable TDM campaign. Some of the time series are lost, and the EDI files do not preserve spectral data. Another trouble is the low traceability of some remote references for specific soundings, which should be a must for improving our records.

As we can see, there were not many soundings in REC1. If we want to weight the influence of the NNE-SSW fault system, which limits the east border, it will be hard. However, even for assessing the northern volume, it is imperative to carry out more MT soundings as far as the lava flows on surface allows it.

REFERENCES


