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Micro-seismicity at the Miravalles Geothermal Field, Costa Rica (1994-2009): A Tool to Confirm the Real Extent of the Reservoir

Paul Moya and Waldo Taylor

Instituto Costarricense de Electricidad, P. O. Box 10032-1000, San José, Costa Rica

PMoya@ice.go.cr, WTaylor@ice.go.cr

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ABSTRACT

The micro-seismicity at the Miravalles geothermal field has been analyzed for the period from 1994 to the present. The study period is divided into four phases that coincide with the phases of development of the geothermal field: 1) January 1994 to May 1998; 2) June 1998 to February 2000; 3) March 2000 to December 2003; and 4) January 2004 to April 2009.

Before the commissioning of Unit 1, the micro-seismicity did not have a defined pattern related to geological structures or the extent of the geothermal reservoir. Micro-seismicity was low during the first stage of field operation, while in the second stage, after a seismic swarm in October 1997, there was a 16-month period of seismic quiescence. Since the year 2000 (third phase) the micro-seismicity has been increasing again, and its main characteristic is that it appears in groups of tens of events with short recurrence intervals (less than one hour), at depths of 2 km, with a coda magnitude (M_c) lower than 2.0; this happens especially when the total mass production rate is less than 4 X 10^6 ton per month.

During the last four years, the micro-seismicity has increased and is more closely related to the N-S and NE-SW-trending fault systems. This has allowed the reservoir extent and shape to be identified clearly. The production-injection relationship is not that clear yet.

Seismic monitoring is being employed at the Las Pailas geothermal field, where new geothermal development is taking place, in order to develop an idea of the possible boundaries of that reservoir. This new field is different from the Miravalles geothermal field, and there is a closer relationship between fluid injection and micro-seismicity.

This methodology can help to better understand the extent of the reservoir once production begins. The analysis of the micro-seismicity and its use in defining reservoir boundaries is described in the following sections.

1. INTRODUCTION

Costa Rica is located in the southern part of the Central American isthmus, between Nicaragua and Panama. The country extends over an area of approximately 51,000 km^2 and has a population of about 4.5 million.

1.1 Miravalles Geothermal Field

The most important Costa Rican geothermal area is located on the southwestern slope of the Miravalles volcano. The present field extends over an area of more than 21 km^2, of which about 16 km^2 are dedicated to production and 5 km^2 to injection. The temperature of the water-dominated geothermal reservoir is about 240^{0}C. Fifty-three geothermal wells have been drilled to date. They include observation, production and injection wells, with depths ranging from 900 to 3,000 meters. Individual wells produce enough steam to generate between 3 and 12 MW; injection wells accept between 70 and 450 kg/s of separated geothermal fluids each (Moya, 2006).

Commercial production of electricity using geothermal steam began at Miravalles in early 1994, when Unit 1, a 55 MW single-flash plant, was commissioned. The following year, the Costa Rican Institute of Electricity (ICE) completed the installation of a 5 MW wellhead unit. This unit was located in the middle of the field for almost 12 years (1995-2006), but in early 2007 it was moved to a new location at the southeastern part of the field.

Two temporary 5 MW wellhead plants came on line as part of an agreement between ICE and the Federal Commission of Electricity of Mexico (CFE) during 1996 and 1997. These two temporary units were disassembled in April 1998 and 1999 (Table 1) and returned to CFE. Unit 2, the second 55 MW plant, started production in August 1998 and in March 2000 Unit 3, a 29 MW single-flash private plant, started delivering electricity to the national grid. Finally, Unit 5, a 19 MW binary plant, increased the total installed capacity at Miravalles to 163 MW (Table 1; Moya and Yock, 2007). The history of growth of capacity at the field is shown in Figure 1, and the increase in energy production at the geothermal field is shown in Figure 2.

Table 1: Power units at the Miravalles geothermal field Abbreviations stand for: ICE-Instituto Costarricense de Electricidad; CFE-Comisión Federal de Electricidad (Mexico); WHU-Wellhead Unit; and BOT-build-operate-transfer.

Plant Name	Power (MW)	Owner	Start-up Date	Shut-down Date
Unit 1	55	ICE	3/1994	
WHU-1	5	ICE	1/1995	
WHU-2	5	CFE	9/1996	4/1999
WHU-3	5	CFE	2/1997	4/1998
Unit 2	55	ICE	8/1998	
Unit 3	29	ICE (BOT)	3/2000	
Unit 5	19	ICE	1/2004	

Figure 3 shows the location of the geothermal wells at the Miravalles geothermal field.

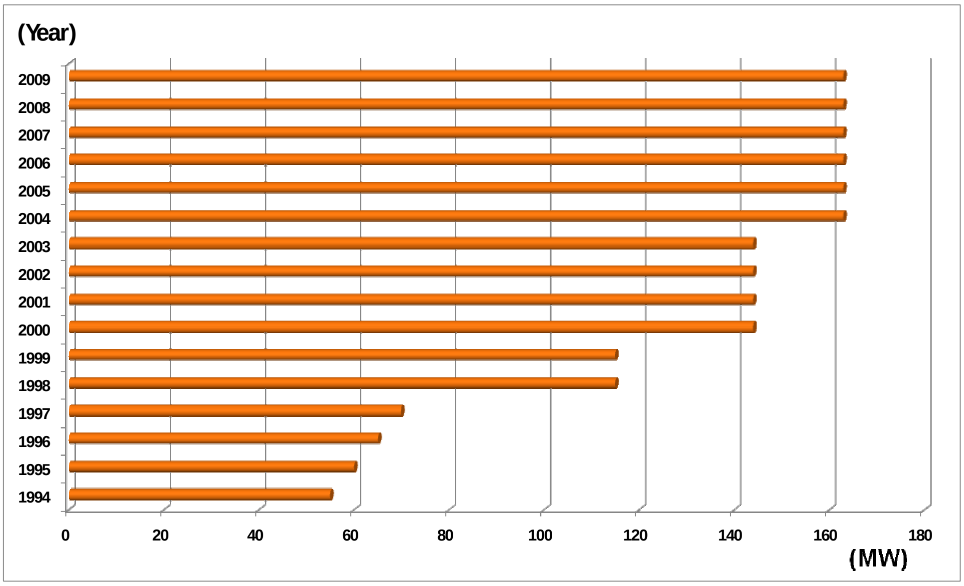

Figure 1: Geothermal installed capacity (1994 – 2009).

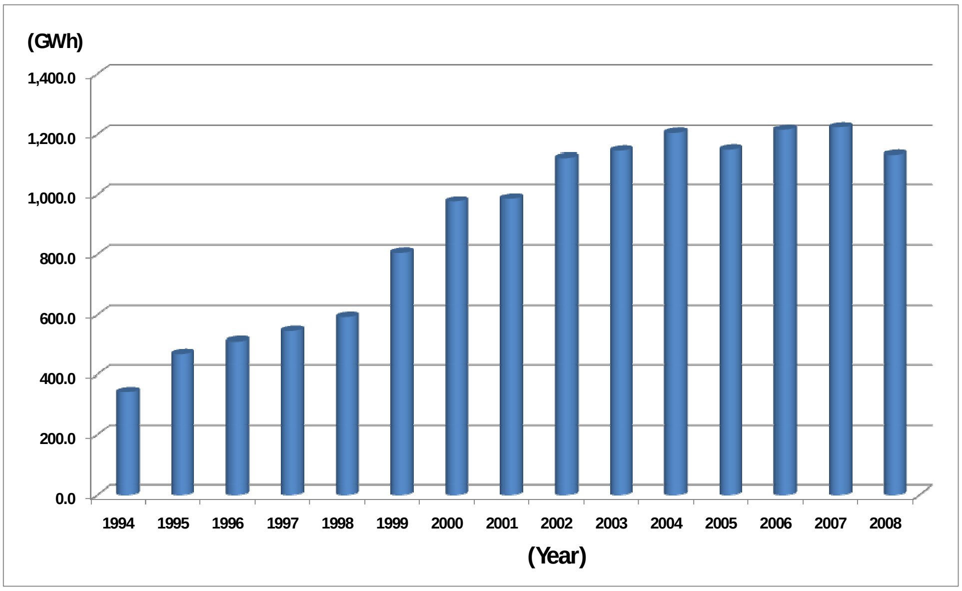

Figure 2: Energy production (1994 – 2008).

Unit 5 extracts additional energy from the separated geothermal brine before it is injected back into the geothermal reservoir.

Currently, the total steam delivered to the power plants is about 330 kg/s. Around 1,235 kg/s of residual (separated) geothermal water is sent to injection wells, which are distributed in four areas of the field (the northern, southern, eastern and southwestern sectors). A total of about 150 MW is generated from these quantities of steam and brine.

1.2 Las Pailas Geothermal Field

Due to the excellent results in the production of geothermal energy at the Miravalles geothermal field, ICE is now in the process of developing a new geothermal field on the south-southwestern slope of the Rincón de la Vieja volcano. So far, ICE has drilled 9 vertical geothermal wells looking for production and injections areas. The parameters of these wells are shown in Table 2 (see also Figure 4). Two new deviated wells (PGP-12 and PGP-24) are being drilled at present.

These wells have allowed ICE to define only the southern boundary of the reservoir. The eastern boundary is practically established since ICE is not planning to drill more production wells to the east of well PGP-02. New deviated wells are being drilled to delineate the northern and western boundaries of the field, and to achieve the production and injection capacity required for the planned 35 MW plant. The geothermal area at Las Pailas is adjacent to the Rincón de la Vieja volcano National Park; the boundary defines the northern limit of the exploitable geothermal area at Las Pailas.

Because industrial or commercial activities are prohibited inside national parks in Costa Rica, it is not yet possible to obtain permission to extract energy inside the national park. The western boundary of the field is set by a Non-Governmental Organization (NGO) called Guanacaste Dry

Forest. This NGO has signed a contractual agreement in which some geothermal development may be allowed, provided the two parties are in agreement.

ICE still needs to drill more wells to reach the level of steam and brine production required to supply the 35 MW plant. To date (July 2009) there is between 16 and 19 MW of production capacity (Table 2); the remaining capacity will be sought towards the northern and western zones of the current production area (Moya and Pérez, 2010).

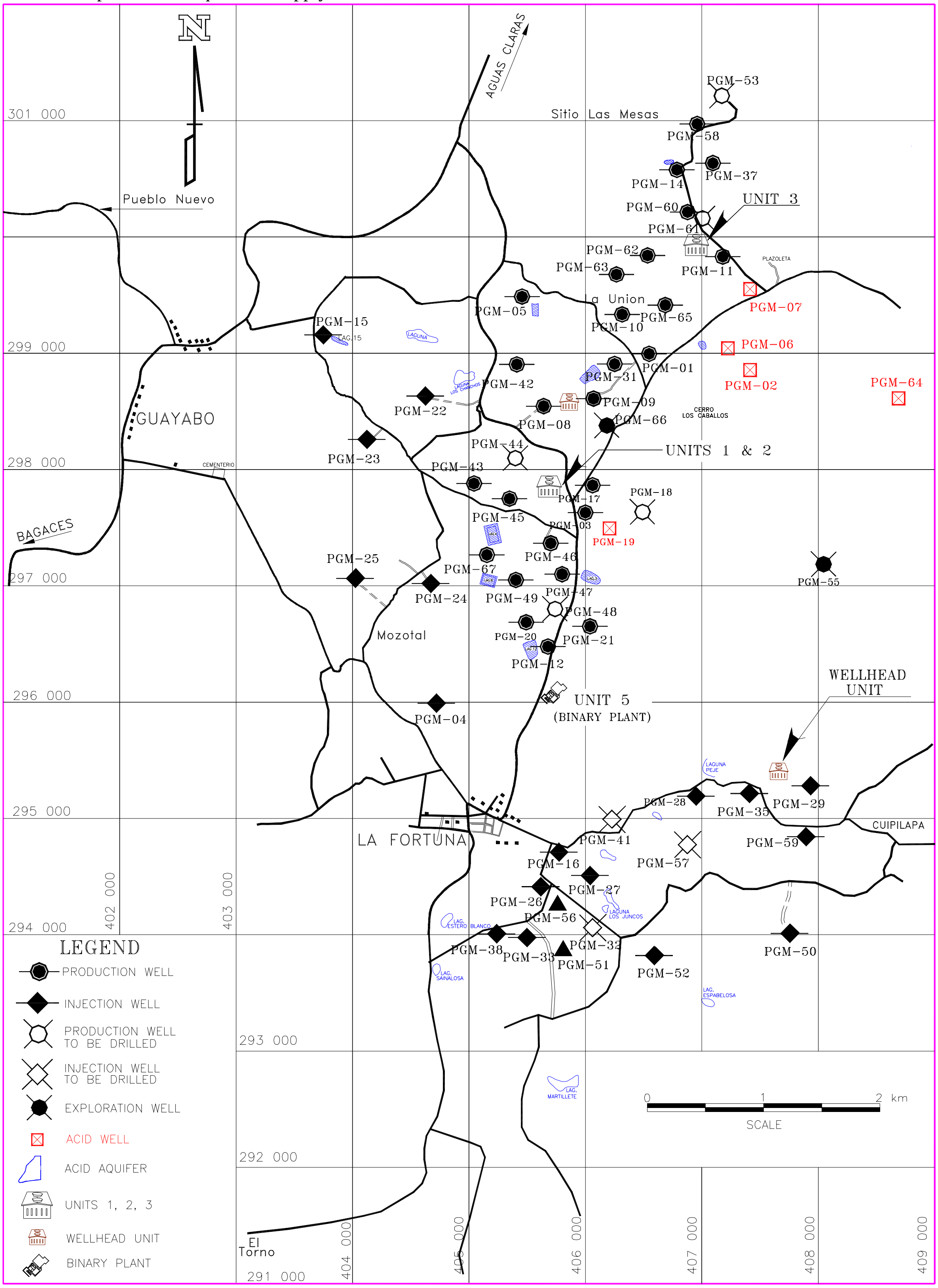

Figure 3: Location of the geothermal wells at the Miravalles geothermal field.

Table 2: Parameters of geothermal wells at Las Pailas geothermal project

Well	Depth	Temp.	Enthalpy	Power
Name	(m)	(°C)	(kJ/kg)	(MW)
PGP-01	1 418	246	1 052	8.1
PGP-02	1 764	240	N. A.	N. A.
PGP-03	1 772	243	1 128	3.7
PGP-04	1 418	232	1 011	4.5
PGP-05	1 827	160	N. A.	N. A.
PGP-06	1 327	200	N. A.	N. A.
PGP-08	1 712	240	1 700	2.7
PGP-09	1 742	203	N. A.	N. A.
PGP-10	2 673	230	N. A	N. A.

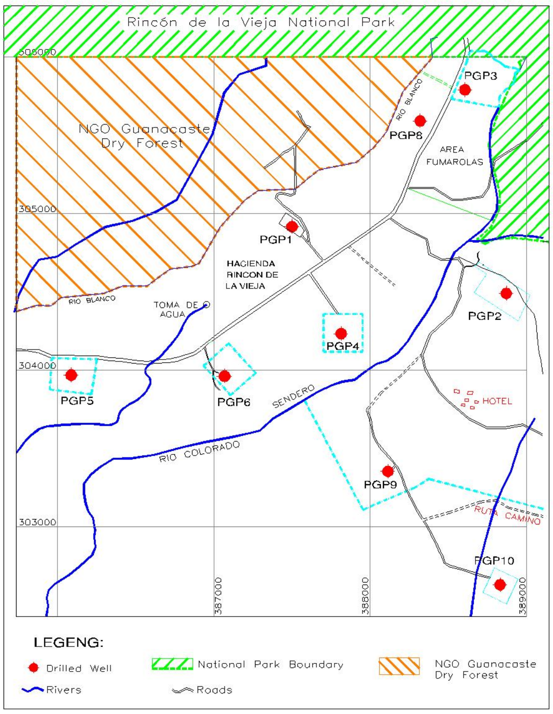

Figure 4: Drilled wells at Las Pailas geothermal field.

2. METHODOLOGY

Data coming from ICE´s departments (including the Area de Amenaza y Auscultación Sísmica y Volcánica and the geothermal resources department) has been utilized to carry out this study. Micro-seismicity events were detected during the period 1994-2003 using a network of six Lennartz MARS-88 stations, which only worked with trigger systems. Later, for the period 2004-2009, the stations were replaced with continuous-recording REFTEK DAS-130 stations.

The database for the Miravalles geothermal field consists of 653 micro-earthquakes that have Root Medium Square (RMS) values of less than 0.2 and a maximum depth of 7 km. For Las Pailas geothermal field, 318 micro-earthquakes with RMS values of less than 0.2 and a maximum depth of 5 km were available. All of them were located with the HYPOCENTER program which uses a starting algorithm and tests the RMS of all the starting locations and selects the minimum RMS as the final solution. Analysis of the spatial micro-earthquake distribution is a tool that can be used to define the boundaries of the geothermal reservoir.

3. PRODUCTION PERIODS

There have been reports (e.g. Barquero, 2001a, 2001b; Taylor, 2002, 2003, 2004, and 2006) that indicate that the base micro-seismicity at the Miravalles geothermal field is low and it has increased over time in response to the exploitation of the field. The exploitation at the Miravalles geothermal field can be divided into four phases: 1) Unit 1 operation, from March 1994 to May 1998; 2) Unit 2, from June 1998 to February 2000, 3) Units 1, 2 and 3 from March 2000 to December 2003; and 4) Units 1, 2, 3 and 5, from January 2004 to April 2009.

3.1 Unit 1 (From March 1994 to May 1998)

During this first period, a total of 12 production wells (PGM-01, PGM-03, PGM-05, PGM-10, PGM-11, PGM-12, PGM-17, PGM-20, PGM-21, PGM-31, PGM-45, PGM-46) and six injectors (PGM-02, PGM-04, PGM-16, PGM-22, PGM-24, PGM-26) were utilized to supply the two phase fluid to the generation units and to inject the brine (Moya and Yock, 2001). During this period, 24 recorded micro-earthquakes indicated a low level of micro-seismicity, distributed in the center and northeast of the geothermal field. (Figure 5)

The gray dots in Figure 5 correspond to injection wells, the circles with a cross represent the producers, the back lines (continuous and dashed) are fractures, and the dashed lines with triangles represent the caldera border. The most recent lava flow is also indicated in this figure.

3.2 Units I and 2 (from June 1998 to February 2000)

In this second period, four producers were added to the exploitation of the field (PGM-08, PGM-42, PGM-43, and PGM-49) as well as three new injectors (PGM-28, PGM-51 and PGM-56). For this period, brine injection was concentrated in the southern sector of the field, around wells PGM-51, PGM-56 and PGM-28, (Moya and Castro, 2001, 2004; Moya and Yock, 2001).

In spite of the increase in the quantity of fluids extracted and injected during this second period at the Miravalles geothermal field, the micro-seismicity of the field remained very low, with only one additional micro-earthquake occurring during this period. This is probably because: a) the injection took place in the southern part of the field; and b) a seismic swarm that took place on the southeastern flank of the Miravalles volcano in 1997 (outside the boundaries of the Miravalles geothermal field) generated a quiet period that lasted 16 months, from November 1998 to April 2000.

3.3 Unit 1, 2 and 3 (from March 2000 to December 2004)

During this period, five new producers (PGM-14, PGM-60, PGM-62, PGM-63, and PGM-65) were utilized to supply the geothermal fluids to the generation units. No extra injection wells were required for this period. The injection in this period was concentrated in wells PGM-28 and PGM-56 (Moya and Castro, 2001, 2004; Moya and Yock, 2001).

The quiet period mentioned above ended in May 2000, only three months after the commissioning of Unit 3, together with full operation of Units 1 and 2. As can be seen in Figure 6, the micro-earthquakes were concentrated in the middle of the field, mainly inside the area limited by the main fractures trending N-S and NE-SO, indicating that there is a structural control due to these fractures. In total 99 shallow micro-earthquakes were registered, with an average depth of 1.8 km and with maximum local magnitudes of 3.8 during 2003 (in general they all were less than M 2.1).

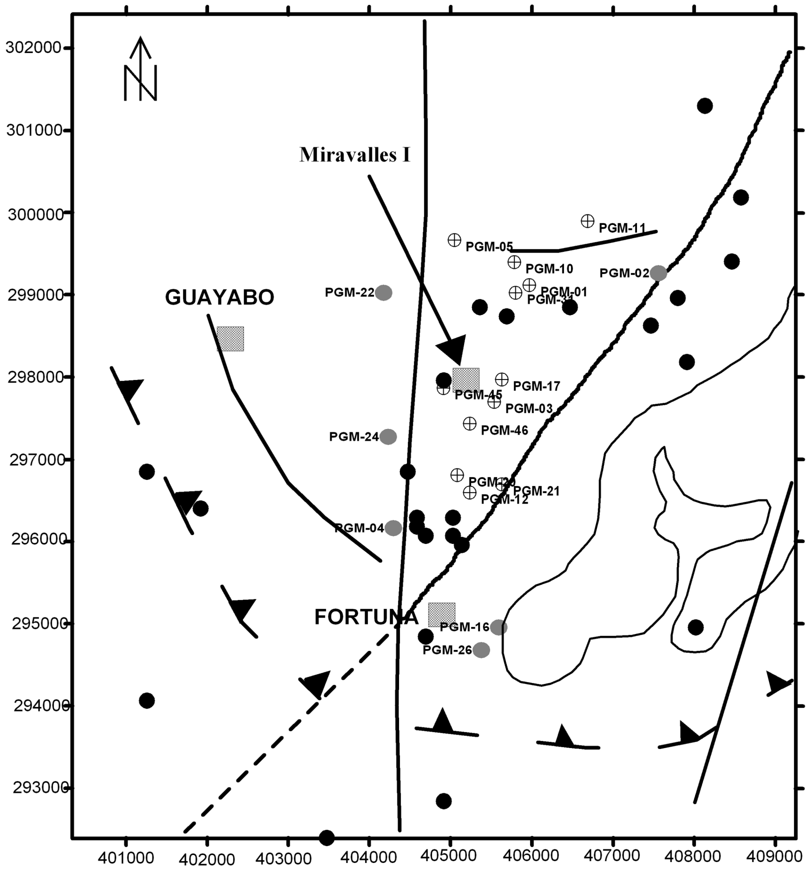

Figure 5: Location of the micro-earthquakes (black dots) during the first period (Unit 1) at the Miravalles geothermal field.

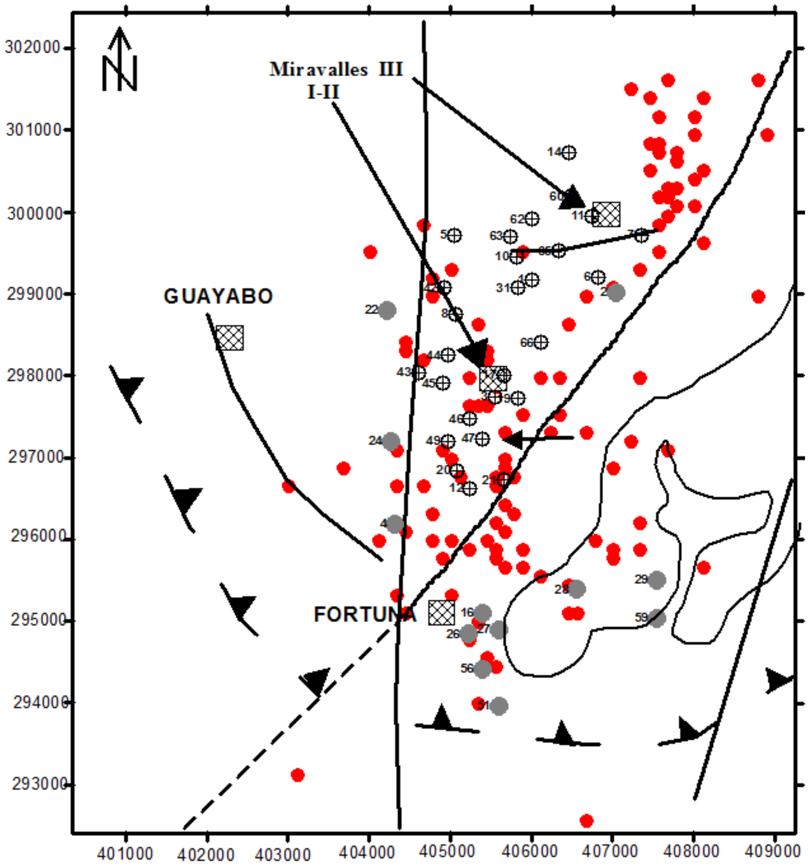

Figure 6: Location of the micro-earthquakes (red dots) during the third period (Unit 1, 2 and 3) at the Miravalles geothermal field. The symbols have the same meaning as in Figure 5.

3.4 Unit 1, 2, 3 and 5 (from January 2005 to April 2009)

This micro-seismicity inside the geothermal field has increased in recent years. Figure 7 shows the distribution of the 529 micro-earthquakes recorded during this period, the majority having local magnitudes of less than 2.

As seen in Figure 7, the micro-seismicity has increased over the entire area, and at least two important seismic zones can be identified, one in the central and southern part of the field and the other to the northeast of the Miravalles geothermal field.

4. RELATIONSHIP BETWEEN THE MICRO-SEISMICITY AND THE BOUNDARIES OF THE MIRAVALLES GEOTHERMAL FIELD.

The exploitation of a geothermal field produces changes in the stress of the geological formations, which can cause micro-earthquakes to occur. The induced micro-earthquakes will be located inside the affected region, and consequently, they represent a good (though indirect) indicator of the extent of the geothermal field. The micro-seismicity associated with the Miravalles geothermal field seems to indicate that the field has an “L” shape, with the major axis trending NNW, 2 km wide, 7 km long, with 2 km thickness, while the minor axis trends NE and is 2 km wide, 5 km long and 2 km thick (see Figures 7, 8 and 9).

Figure 8 and 9 shows respectively the NW and NE micro-seismicity views in 3D for the Miravalles geothermal field. These figures provide an idea of the real boundaries of the geothermal system. Also, these figures reveal the presence of two micro-seismicity nuclei, one in the central-southern sector and the other one in the northeast sector. The identification of these two sectors represents a strong indicator of the existence of a geological or structural barrier between the sectors, affected by the fractures with a NE-SW direction.

5. MICRO-SEISMICITY AT LAS PAILAS GEOTHERMAL FIELD.

As mentioned previously, the Las Pailas geothermal field is currently under development. The seismic activity in this field has been related to injection testing of the geothermal wells. During 2002 – 2009, 318 micro-earthquakes have been recorded; the majority of them with local magnitudes smaller than 1.7 and depths less than 3 km. Figure 10 and Figure 11 show the micro-earthquake distribution at the surface and at depth, respectively. The micro-earthquakes have been concentrated at the southwestern sector, where there is little or no permeability. There are no production wells in this sector (PGP-06, PGP-09 and PGP-10 do not produce), and the sector is sensitive to pressure changes, and probably related to an area of active faults. Cold water injection perturbs the in-situ stress state, leading to fracture initiation and/or activation of discontinuities such as faults and joints, which often are manifested as multiple micro-seismic events.

As mentioned before, due to the fact that the Las Pailas geothermal field is currently under development and there is no production yet, the boundaries of the reservoir are still unknown. Nevertheless, the unstable area has dimensions of 2 x 5 x 2 km and it is due to the injection tests already carried out in the region. Micro-seismic events can be monitored and analyzed to provide useful information on the stimulated zone, fracture growth, and geometry of the geological structures and in-situ stress state. The micro-seismic events have been triggered when the injection rate is greater than 50 l/s and the pressure in the well increases up to 7 bar (Taylor, 2009).

It is anticipated that future seismic monitoring will help to better define the extent and limits of Las Pailas geothermal field.

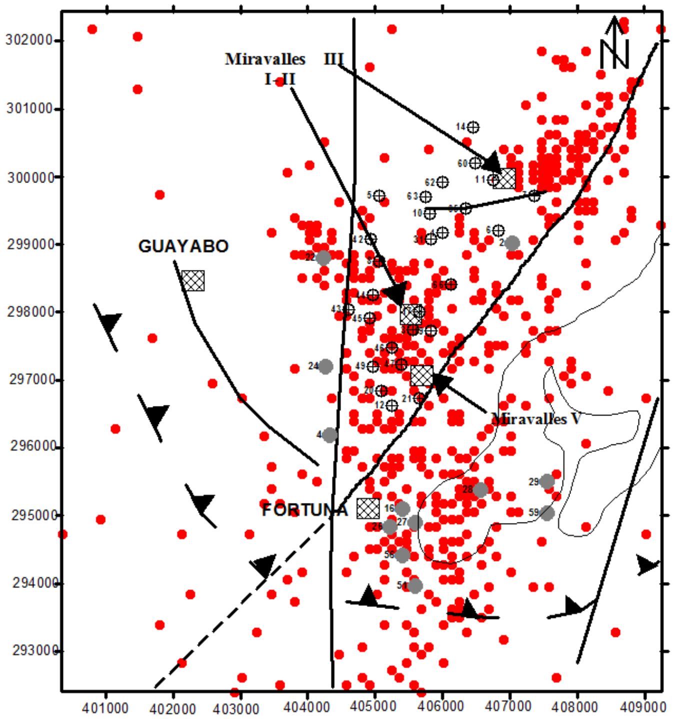

Figure 7: Location of the micro-earthquakes (red dots) during the last period (Unit 1, 2 3 and 5) at the Miravalles geothermal field. The symbols have the same meaning as in Figure 5.

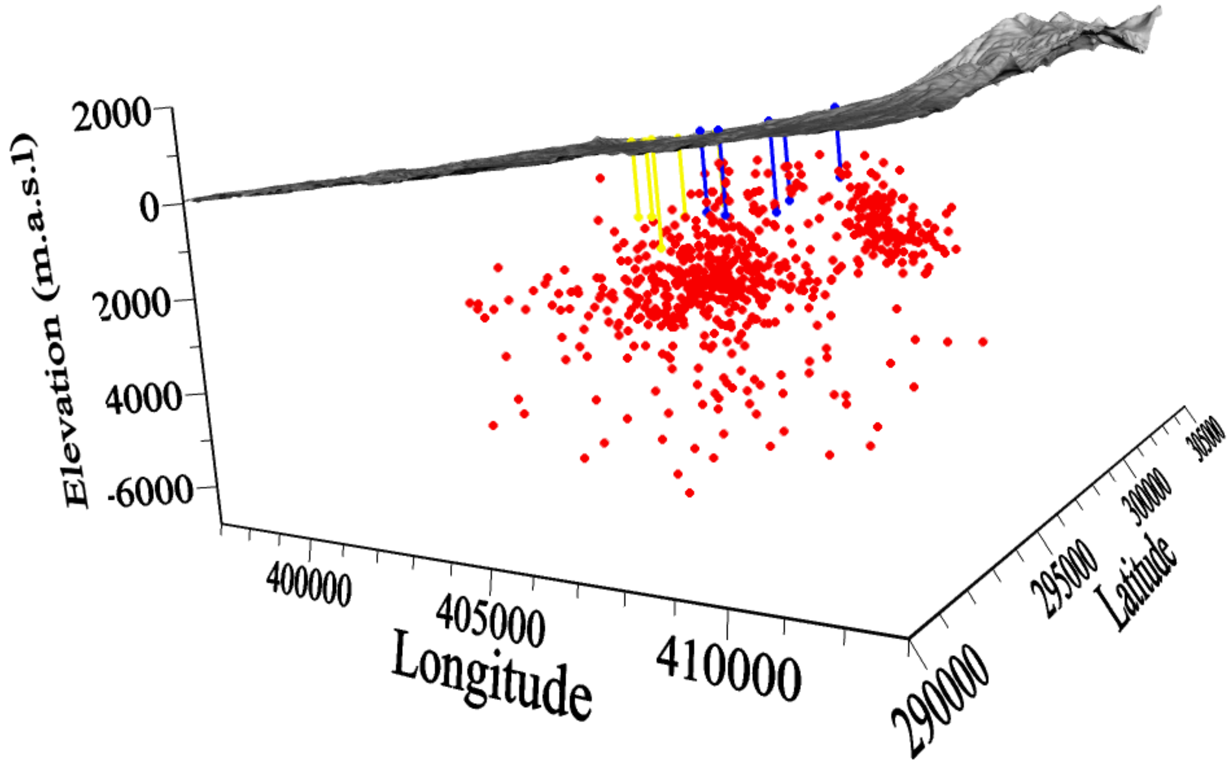

Figure 8: NW Micro-seismicity view in 3 D of the Miravalles geothermal field, where the extension of the field can be observed (red dots). The yellow lines represent the injection wells and the blue lines represent the producers.

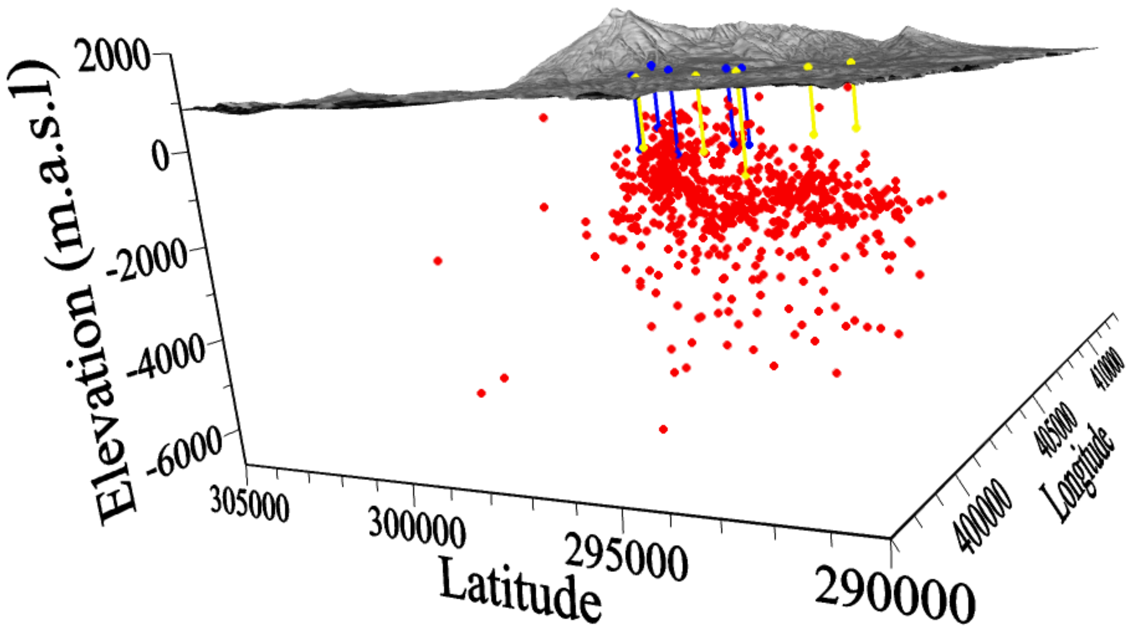

Figure 9: NE Micro-seismicity view in 3 D of the Miravalles geothermal field, where the extension of the field can be observed (red dots). The yellow lines represent the injection wells and the blue lines represent the producers.

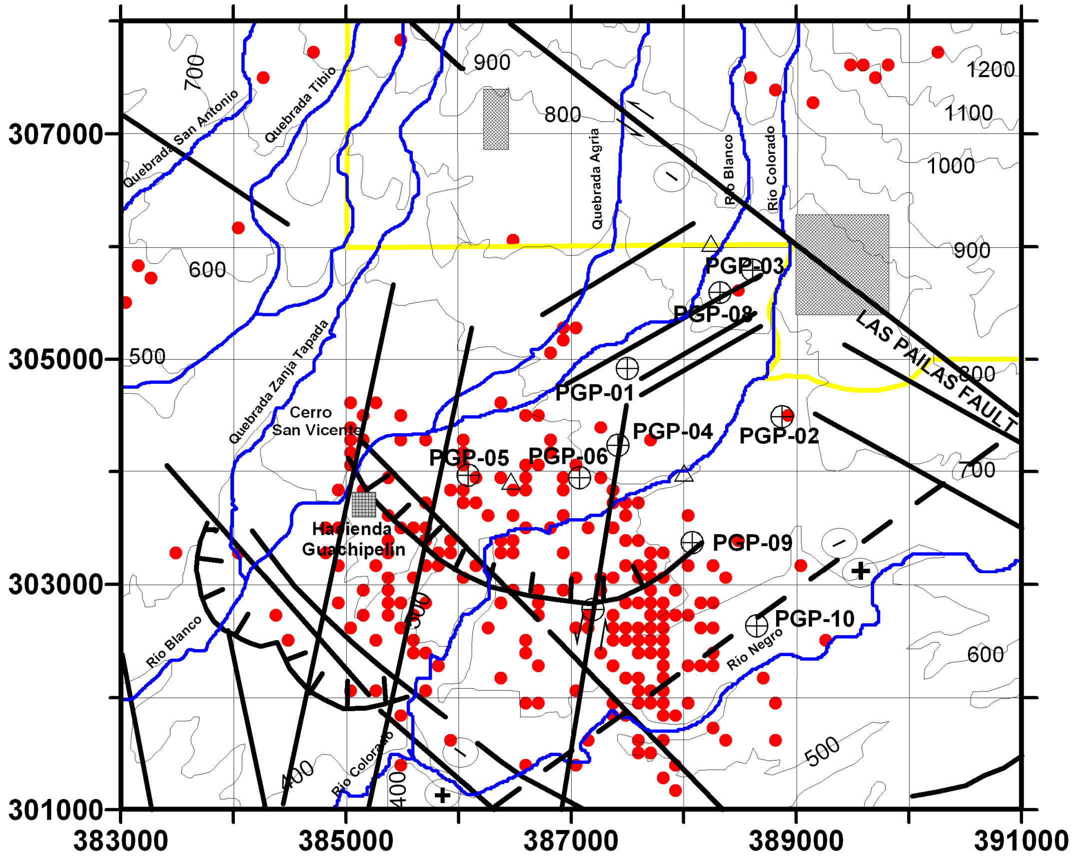

Figure 10: Top view of the Las Pailas geothermal field, where the micro-seismicity at Las Pailas can be observed (red dots). The black lines represent the possible fractures in the zone.

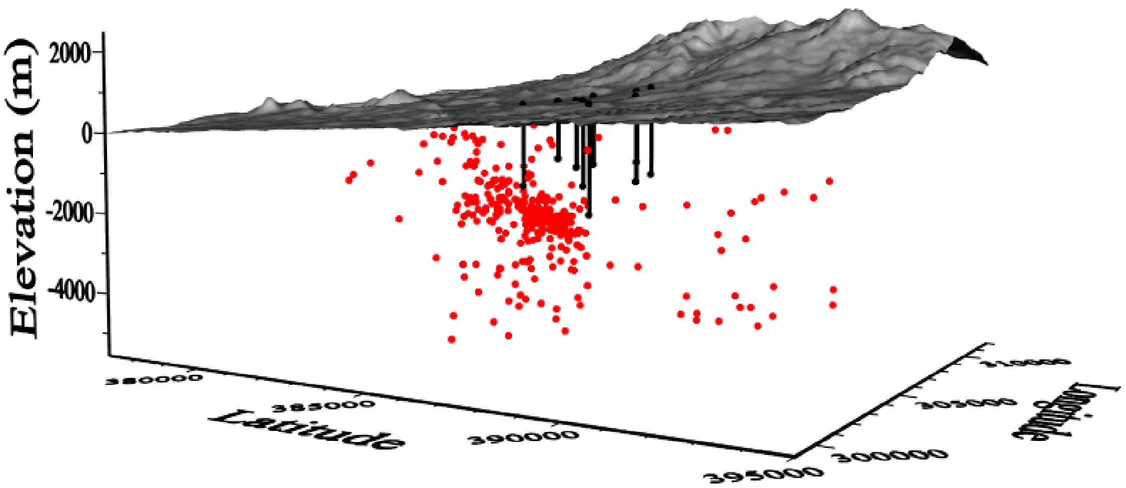

Figure 11: Micro-seismicity view in 3 D of the Las Pailas geothermal field, where the micro-seismicity at Las Pailas can be observed (red dots). The black lines represent the geothermal wells.

6. CONCLUSIONS

The micro-seismicity of a geothermal area can help to determine the real extent of the reservoir. Unfortunately, this tool is mainly applicable once the boundaries of the geothermal reservoir have been confirmed by drilling or otherwise known beforehand. Nevertheless, knowledge of the distribution of micro-earthquake at depth and at the surface helps to verify the real extent of the reservoir in a geothermal area.

Even though the level of micro-seismicity at the Miravalles geothermal field has been low, it has increased in recent years, reaching between 150 – 200 micro-earthquakes per year.

The spatial micro-earthquake distribution at the Miravalles geothermal field has permitted definition of the real extent of the field, which has an “L” shape and occupies a volume of about 20 km^3. The “L” shape coincides very well with the current pattern of pressure decline in the reservoir (Moya and Nietzen, 2010).

Because the Las Pailas geothermal field is now under development, it has not been possible to determine the extent of the geothermal reservoir. The seismic activity in this field has induced by the injection testing of the wells.

Induced micro-seismicity at Las Pailas does not provide enough information to define the overall size and limits of the geothermal reservoir. It is the micro-seismicity produced by the exploitation of the geothermal reservoir (as at the Miravalles geothermal field) that allows for determination of the reservoir`s real extent.

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