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SEISMICITY AT THE MIRAVALLES GEOTHERMAL FIELD, COSTA RICA (1994-2009): A TOOL TO CONFIRM THE REAL EXTENSION OF THE RESERVOIR*

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ABSTRACT

The seismicity at the Miravalles geothermal field has been analyzed since 1994. This study is divided into four phases, depending on the development of the geothermal field. The periods are the following: a) from January 1994 to May 1998, b) from June 1998 to February 2000, c) from March 2000 to December 2003 and d) from January 2004 to March 2009. Before the commissioning of Unit 1, the seismicity did not have a defined pattern related to fault systems, geological structures or reservoir extensions. Once production began in 1994, the first stage shows low seismicity while the second stage shows that seismicity decreased almost completely after a seismic swarm in October 1997, and the geothermal system declined to a seismic quiescence for 16 months. Since the year 2000 (third phase) the seismicity has been increasing again and its main characteristic is that it appears in groups of tens of events with short time intervals (less than one hour), at depths of 2 km, with a coda magnitude (Mc) lower than 2.0, and this especially happens when the total mass produced is lower than 4 X 10^6 ton per month. During the last four years, the seismicity distribution increased and has a better relationship with the fault systems (N-S and NE-SW faults). This has allowed us to clearly identify the reservoir extension and its boundaries. The production-injection relationship is not that clear yet.

This methodology is being used at the Las Pailas geothermal field (new geothermal development) in order to give an idea of the possible boundaries of that reservoir. This new field is different from the Miravalles geothermal field and there is a better relationship between fluid injection and its corresponding seismicity. This methodology can help to better understand the extension of the reservoir, once the geothermal field begins production. The analysis of the seismicity and its contribution to better define the reservoir boundaries is described in the following sections.

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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.

1.2 Miravalles geothermal field

The most important Costa Rican geothermal area is located on the south-western slope of the Miravalles volcano. The present field extends over an area of more than 21 km^2; and about 16 km^2 are dedicated to production while 5 km^2 to injection. The temperature of the water-dominated geothermal reservoir is about 240°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, e.g. 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 south-eastern 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), e.g. 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. Figure 3 shows the location of the geothermal wells at the Miravalles geothermal field.

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	

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, i.e., the northern, southern, eastern and south-western sectors. A total of about 150 MW is generated from these quantities of steam and brine.

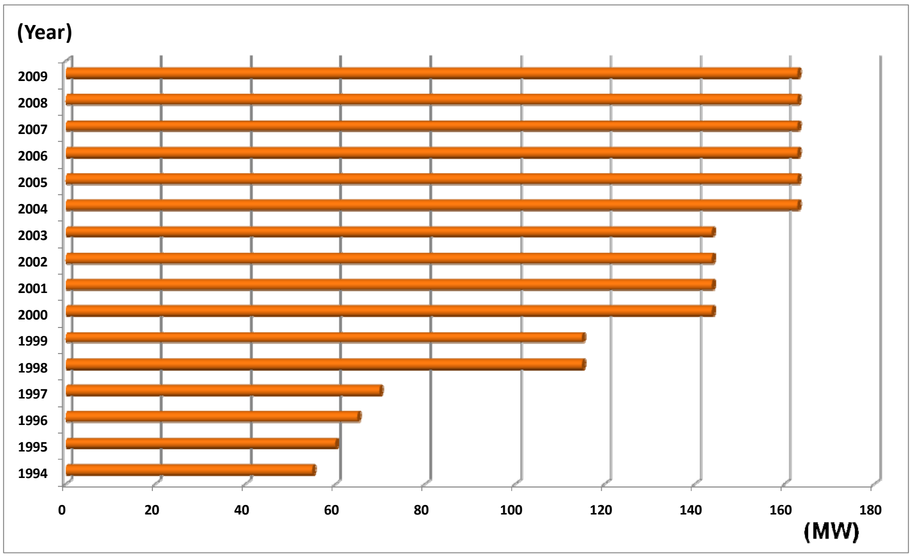

FIGURE 1: Geothermal installed capacity (1994 – 2009)

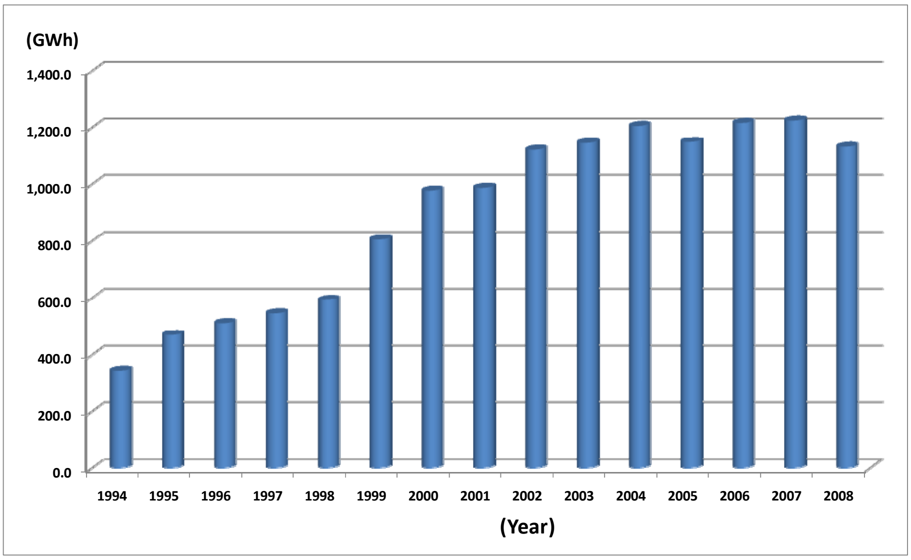

FIGURE 2: Energy production (1994 – 2008)

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-south-western slope of the Rincón de la Vieja volcano. At present there are 9 vertical geothermal wells drilled altogether. The parameters of these wells are shown in Table 7 (See also Figure 4). Two new deviated wells are being drilled at present (PGP-12 and PGP-24).

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 east of well PGP-02. New deviated wells are being drilled to find the northern and western boundaries of the field as well as the production and injection required for the 35 MW plant. The geothermal area at Las Pailas is next to the Rincón de la Vieja volcano National Park. The boundary of this park sets the northern boundary of the exploitable geothermal area at Las Pailas.

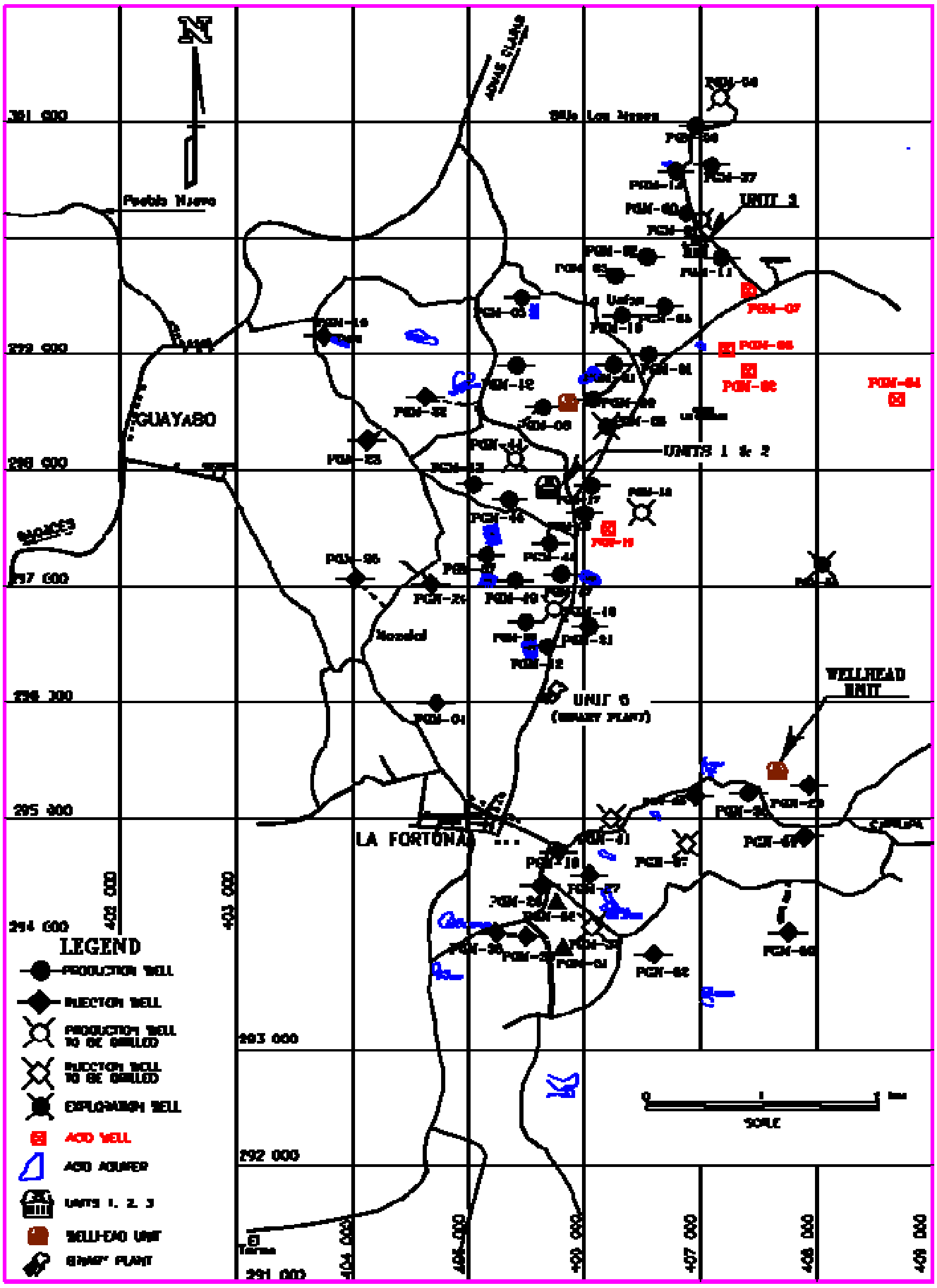

FIGURE 3: Location of the geothermal wells at the Miravalles geothermal field

Since in Costa Rica it is not possible to establish any industrial or commercial activity inside a national park, it is not possible to obtain permission to extract energy inside the national park yet. The western boundary 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 amount of fluids (steam and brine) that are required by the 35 MW plant. To date (July 2009) there are between 16 and 19 MW on reserve for production (See Table 7); the missing megawatts will be sought towards the northern and western zones of the current production area, e.g. Moya and Pérez (2010).

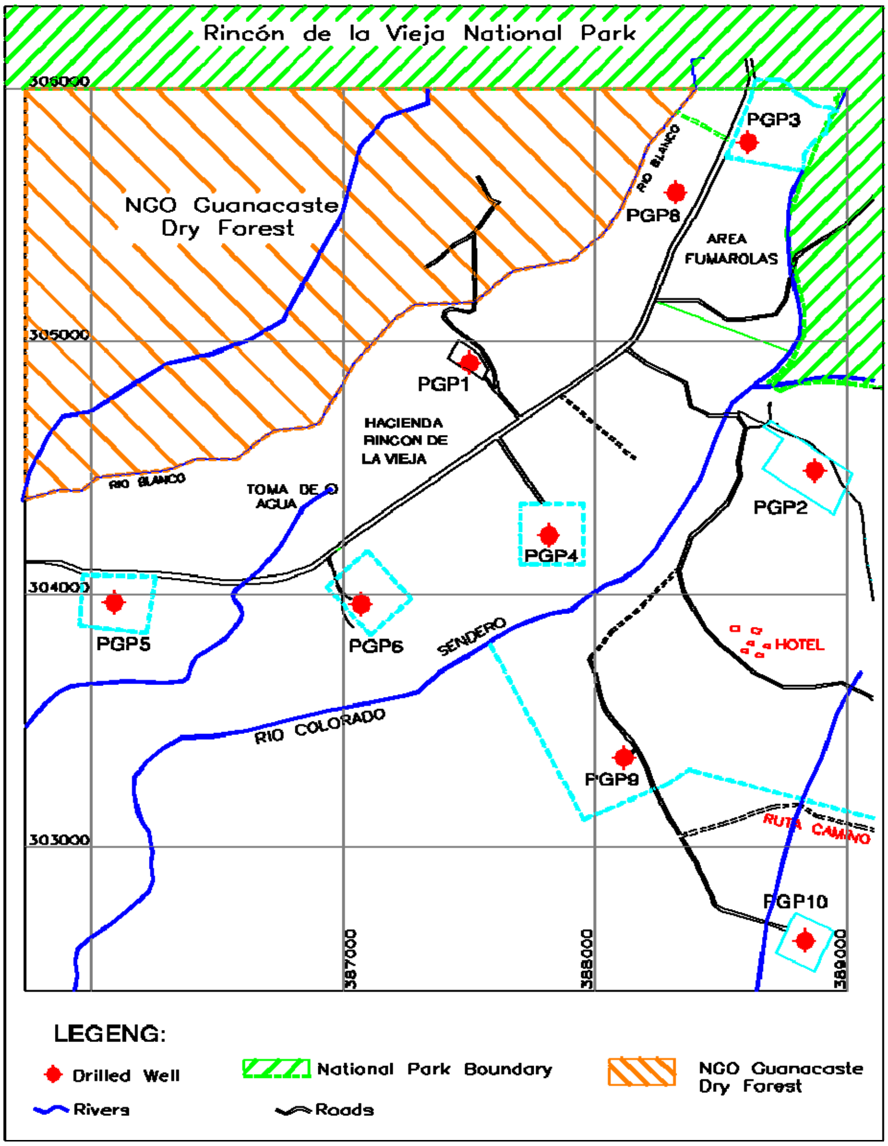

FIGURE 4: Drilled wells at the Las Pailas geothermal field

TABLE 2: Parameters of geothermal wells at Las Pailas geothermal field

Well name	Depth (m)	Temperat. (°C)	Enthalpy (kJ/kg)	Power (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	1011	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	1700	2.7
PGP-09	1,742	203	N. A.	N. A.
PGP-10	2,673	230	N. A	N. A

2. METHODOLOGY

The data coming from ICE's departments such as Area de Amenaza y Auscultación Sísmica y Volcánica and the geothermal resources department was utilized to carry out this study. The seismicity was detected using a seismicity network formed by six stations (Lennartz MARS-88) used for the period 1994-2003, which only worked with trigger systems. Later, the stations were changed for stations of continuous record (REFTEK DAS-130) for the period 2004-2009.

The data utilized at the Miravalles geothermal field is formed of 653 earthquakes that have Root Medium Square (RMS) values of less than 0.2 and a maximum depth of 7 km. For the Las Pailas geothermal field, 318 earthquakes with RMS values of less than 0.2 and a maximum depth of 5 km were used. The analysis of the spatial 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 and 2001b) and Taylor (2002, 2003, 2004, and 2006) that indicate that the base micro seismicity at the Miravalles geothermal field is low and it has increased through the years as a response of the exploitation of the field. The exploitation at the Miravalles geothermal field can be divided in four phases: a) Unit 1 from March 1994 to May 1998, b) Unit 2 from June 1998 to February 2000, c) Units 1, 2 and 3 from March 2000 to December 2003 and Units 1, 2, 3 and 5 from January 2004 to March 2009.

3.1 Unit 1 (from March 1994 to May 1998)

During this first period, a total of 12 producers (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, and PGM-26) were utilized to supply the two phase fluid (to the generation units) and to inject the brine, e.g. Moya and Yock (2001). During this period, 24 earthquakes were registered, which indicated a low seismicity, distributed in the centre and northeast of the geothermal field. (Figure 5)

The gray dots correspond to injectors, the circles with a cross represent the producers, the back lines (continuous and dash lines) are fractures and the dash lines with triangles represent the caldera border. Also the last lava flow is indicated in this figure.

3.2 Units 1 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, the injection of the brine was concentrated to the southern sector of the field, around wells PGM-51, PGM-56 and PGM-28, e.g. Moya and Castro (2001 and 2004) and 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 seismicity of the field remained very low, only an additional earthquake took place during this period. This is probably due to the following: a) the injection took place in the southern part of the field and b) a seismic swarm that took place on the south-eastern flank of the Miravalles volcano in 1997 (outside from the boundaries of the Miravalles geothermal field) generated a quiet period (calmness state). This state lasted around 16 months, from November 1998 to April 2000.

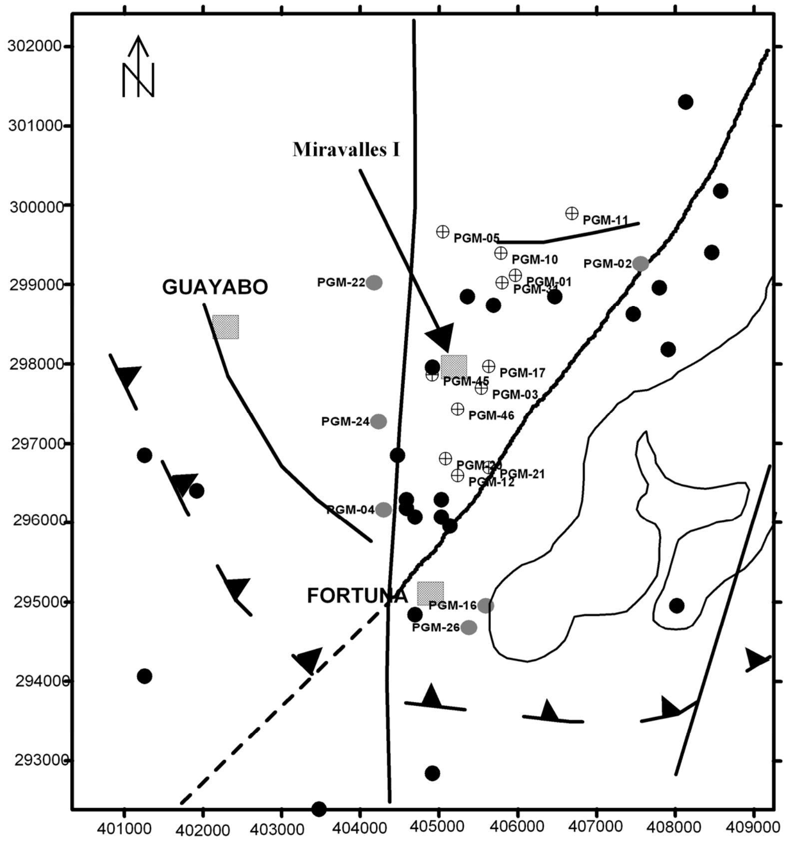

FIGURE 5: Location of the earthquakes (black dots) during the first period (Unit 1) at the Miravalles geothermal field

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

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

The quiet period indicated 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 earthquakes were concentrated in the middle of the field, mainly inside the area limited by the main fractures with the directions N-S and NE-SW, indicating that there is a structural control due to these fractures. In total 99 shallow earthquakes were registered, with an average depth of 1.8 km and with maximum local magnitudes of 3.8 degrees (Richter scale) during 2003 (in general they were all less than 2.1 degrees).

3.4 Units 1, 2, 3 and 5 (from January 2005 to March 2009)

This seismicity inside the geothermal field increased during the last years. Figure 7 shows the distribution of the 529 registered earthquakes during this period, where the majority of the earthquakes had local magnitudes of less than 2 degrees. As seen in Figure 7, the seismicity was incremented in the whole area, and this has allowed the establishing of at least two important seismic areas, one in the central and southern part of the field and the other to the northeast of the Miravalles geothermal field.

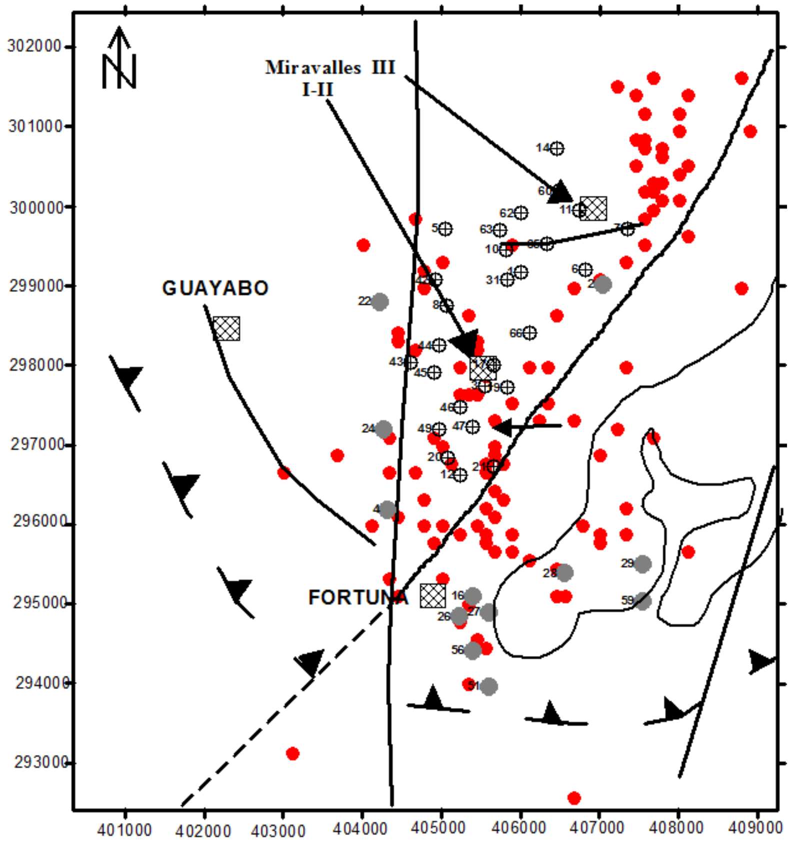

FIGURE 6: Location of the earthquakes (red dots) during the third period (Units 1, 2 and 3) at the Miravalles geothermal field; the symbols have the same meaning as in Figure 4

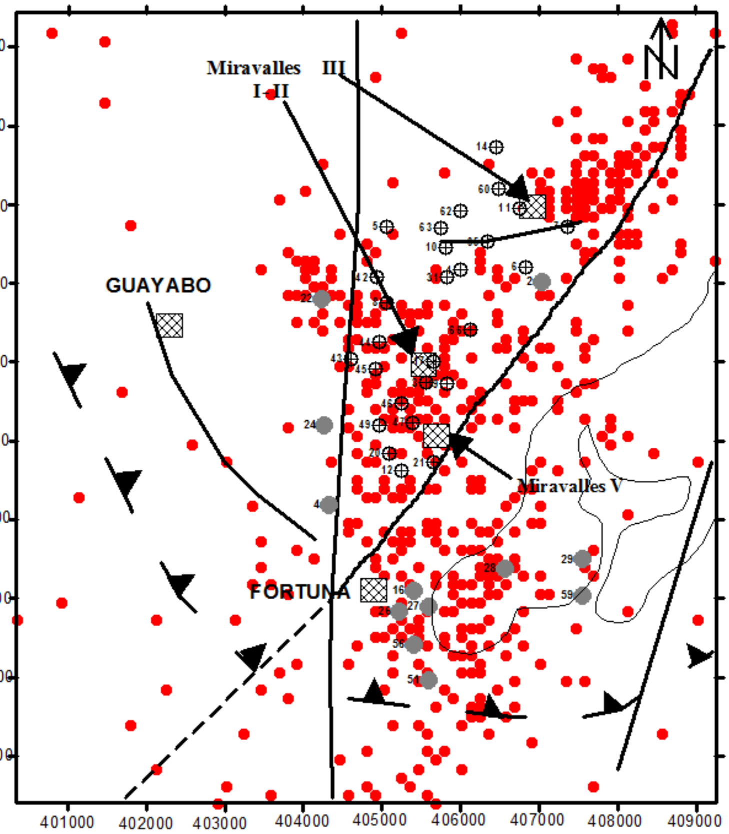

FIGURE 7: Location of the earthquakes (red dots) during the last period (Units 1, 2 3 and 5) at the Miravalles geothermal field; the symbols have the same meaning as in Figure 4

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

The exploitation of a geothermal field produces changes in the stress of the geological formations, and therefore, they produce the earthquakes associated with this process. The developed earthquakes will be located inside the affected region, and consequently, they represent an indirect and a good indicator of the extension of the geothermal field. For the Miravalles geothermal field, its associated seismicity seems to indicate that the geothermal field has an "L" shape, where the major axis has a direction of NNW, 2 km wide, 7 km long, with 2 km thickness, while the minor axis has a direction of NE, 2 km wide, 5 km long and 2 km thickness (see Figures 7, 8 and 9).

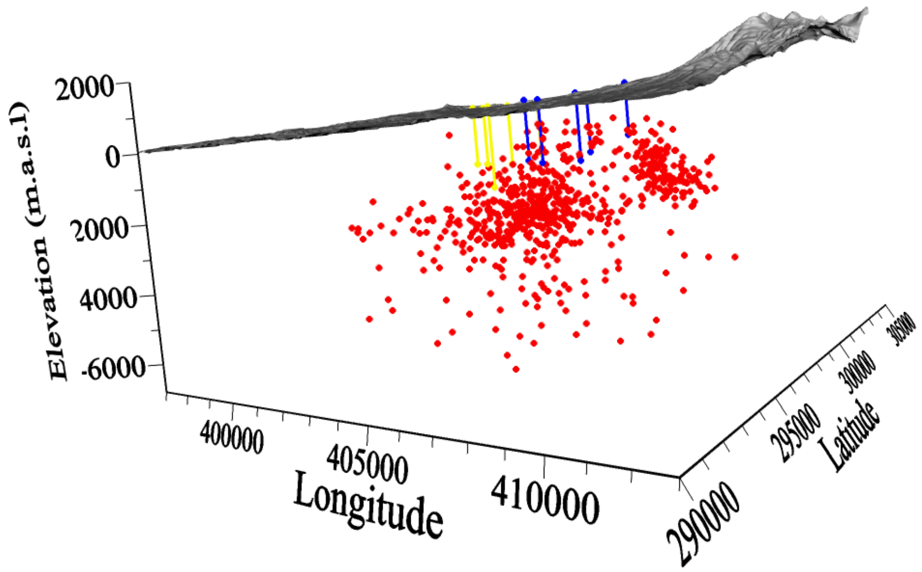

FIGURE 8: NW Seismicity view in 3D of the Miravalles geothermal field, where the extension of the field can be observed (red dots); the yellow lines represent the injection wells and the blue lines represent the producers

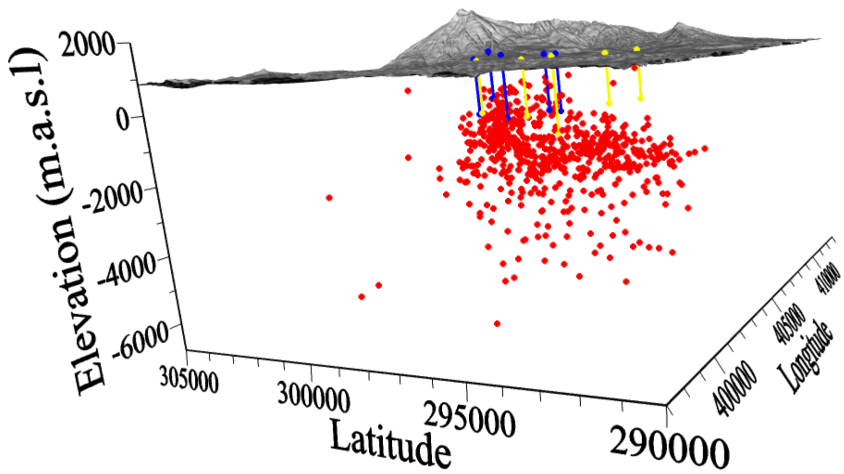

FIGURE 9: NE Seismicity view in 3D of the Miravalles geothermal field, where the extension of the field can be observed (red dots); the yellow lines represent the injection wells and the blue lines represent the producers

Figures 8 and 9 show the NW seismicity view and the NE seismicity view in 3D, respectively, for the Miravalles geothermal field. These figures give an idea of the real boundaries of the geothermal system. Also, these figures indicate two seismic 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 NW-SE direction.

5. SEISMICITY AT LAS PAILAS GEOTHERMAL FIELD.

As mentioned previously, the Las Pailas geothermal field is being developed these days. The seismic activity in this field has always been related to the injection tests at the geothermal wells. During 2002 – 2009 318 earthquakes have been registered, the majority of them with local magnitudes of less than 1.7 degrees and with depths less than 3 km. Figure 9 and Figure 10 show the earthquake distribution at the surface and at depth, respectively. The earthquakes have been concentrated in the southwest sector where there is low or no permeability, no production wells are in this sector (PGP-06, PGP-09 and PGP-10 do not produce), the sector is sensitive to the pressure changes in the rock, and this sector is 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.

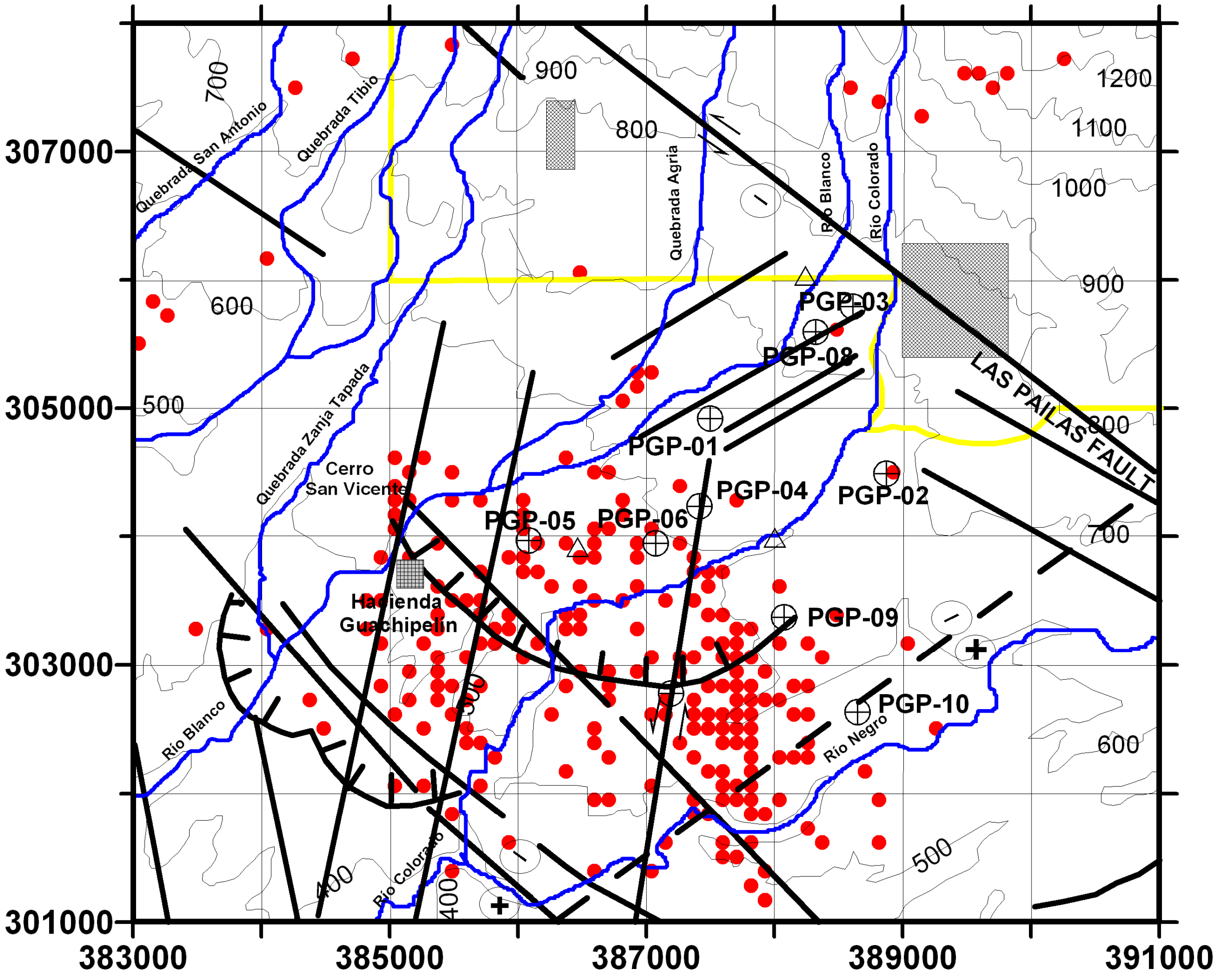

FIGURE 9: Top view of the Las Pailas geothermal field, where the earthquakes can be observed (red dots); the black lines represent the possible fractures in the zone

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 an extension of 2 x 5 x 2 km and it is due to the injection tests already carried out in the region. The detection and interpretation of 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 seismicity has been triggered when the injection discharge is greater than 50 l/s and the pressure in the well increase up to 7 bar (Taylor 2009).

Probably the future seismic registers will help to determine the current extension of the Las Pailas geothermal field.

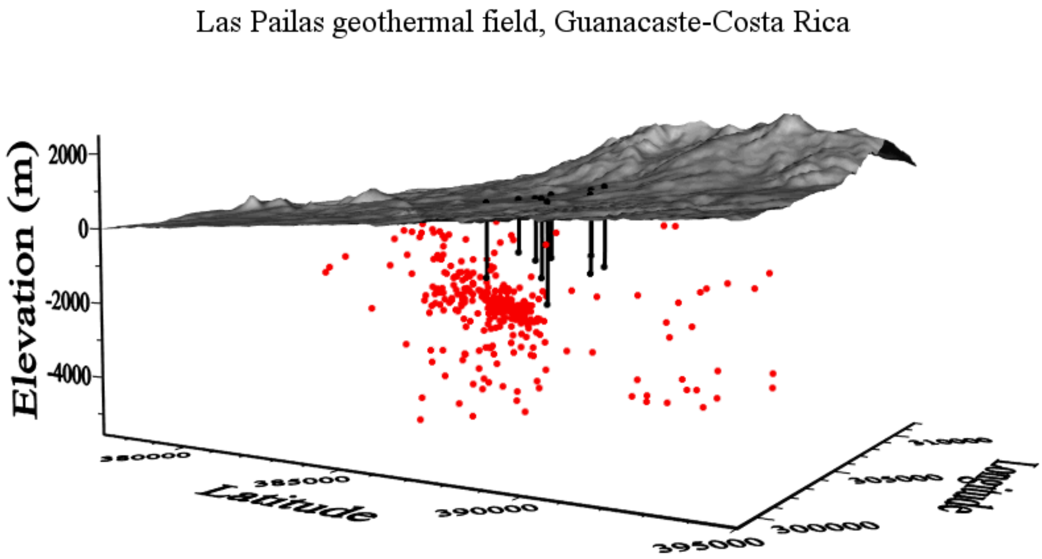

FIGURE 10: Seismicity view in 3D of the Las Pailas geothermal field, where the earthquakes can be observed (red dots); the black lines represent the geothermal wells

6. CONCLUSIONS

The seismicity in a geothermal area can help to determine the real extension of the reservoir. Unfortunately, this tool is helpful only once the boundaries of the geothermal reservoir have been confirmed by drilling or if they are known before hand. Nevertheless, this tool (the earthquake distribution at depth and at surface) helps to verify the real extension of the reservoir in a geothermal area.

Even though the seismicity at the Miravalles geothermal field has been small, it has increased during the last years, reaching between 150 – 200 earthquakes per year. The spatial earthquake distribution at the Miravalles geothermal field has allowed the defining of the real extension of the field, which has an "L" shape and embraces a volume of about 20 km^3. The "L" shape coincides very well with the current pressure decline in the reservoir, e.g. Moya and Nietzen (2010).

Due to the fact that the Las Pailas geothermal field is now under development, it has not been possible to determine the extension of the geothermal reservoir. The seismic activity in this field has been related to the induced seismicity provoked by the injection tests in the field.
Induced seismicity does not set the boundaries of the geothermal reservoir, it is the seismicity produced by the exploitation of the geothermal reservoir, the one that provides the real extension of the reservoir.

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