Presented at "Short Course V on Conceptual Modelling of Geothermal Systems",
organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, February 24 - March 2, 2013.

UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

THE MIRAVALLES GEOTHERMAL SYSTEM, COSTA RICA

Osvaldo Vallejos Ruiz
Instituto Costarricense de Electricidad
C.S. Recursos Geotérmicos, Campo Geotérmico Miravalles, Guayabo, Guanacaste
COSTA RICA
ovallejos@ice.go.cr

ABSTRACT

The Miravalles Geothermal Field is a high-temperature liquid-dominated reservoir with temperatures reaching 230-255ºC, and is the first of two exploited geothermal fields in Costa Rica. The geothermal energy is an important part of the electrical supply in the country and has been producing since 1994, accounting for about 8% of Costa Rica's total electrical production to date and is an important part of it. The installed capacity of Miravalles has reached 163 MW. Since exploitation began, the reservoir's chemical, hydraulic and thermal parameters have been carefully monitored to assess the changes produced by commercial exploitation. The reservoir response over almost twenty years exploitation period has evolved notably due to massive production and injection in some sectors of the field, and different actions and strategies have been successfully implemented for sustaining the steam supply to the power plants and for reservoir management.

1. INTRODUCTION

The Miravalles Geothermal Field was the first geothermal reservoir under exploitation in Costa Rica (Figure 1). A mission of Experts of the United Nations who visit the country in 1963-64 agreed on the interest in studying the slopes of Miravalles and Rincón de la Vieja volcanoes, both of them located in the north part of the country and which showed high possibilities for the geothermal resource exploitation. In 1974 the Instituto Costarricense de Electricidad (ICE) began a general study of the mentioned area. Deep drilling started in 1978, when a high-temperature reservoir was discovered and more exploratory studies continue until 1985 (Corrales, 1985). A feasibility study for the first unit recommended the installation of a 55 MW power plant (CE and ELC, 1986), but later studies increased the possible installed capacity. Subsequent drilling stages completed the steam necessary to feed three flash plants commissioned in 1994, 1998 and 2000, and one binary plant in 2004, totalling an installed capacity of 163 MW. Three 5 MWe wellhead units have also produced for different periods, and one of them is still in use.

2. GEOLOGICAL SETTING

The Miravalles Geothermal Field is a typical high-temperature liquid-dominated reservoir, located in the northwest part of Costa Rica (Figure 2). Drilling of the first deep exploratory wells dated from 1978-1980, but it is not until 1992 that was begun the extensive drilling with exploitation purposes.

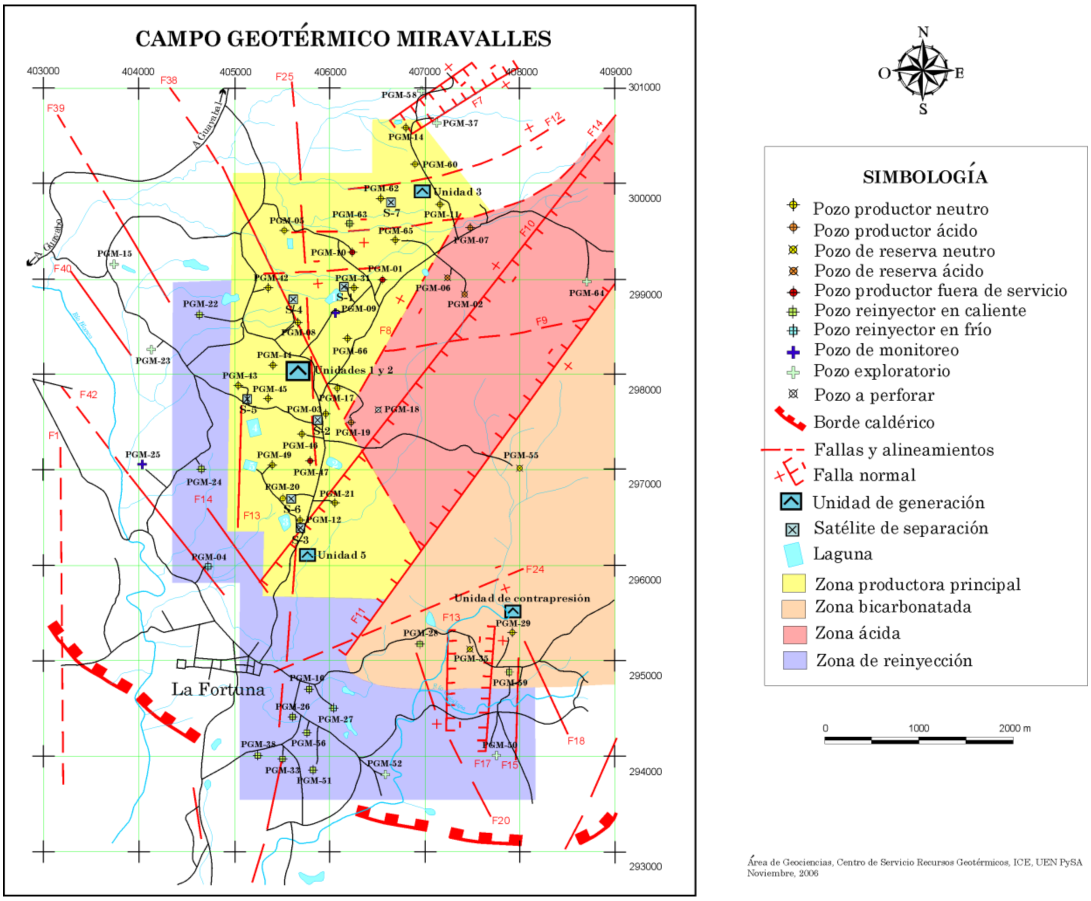

FIGURE 1: The Miravalles Geothermal Field

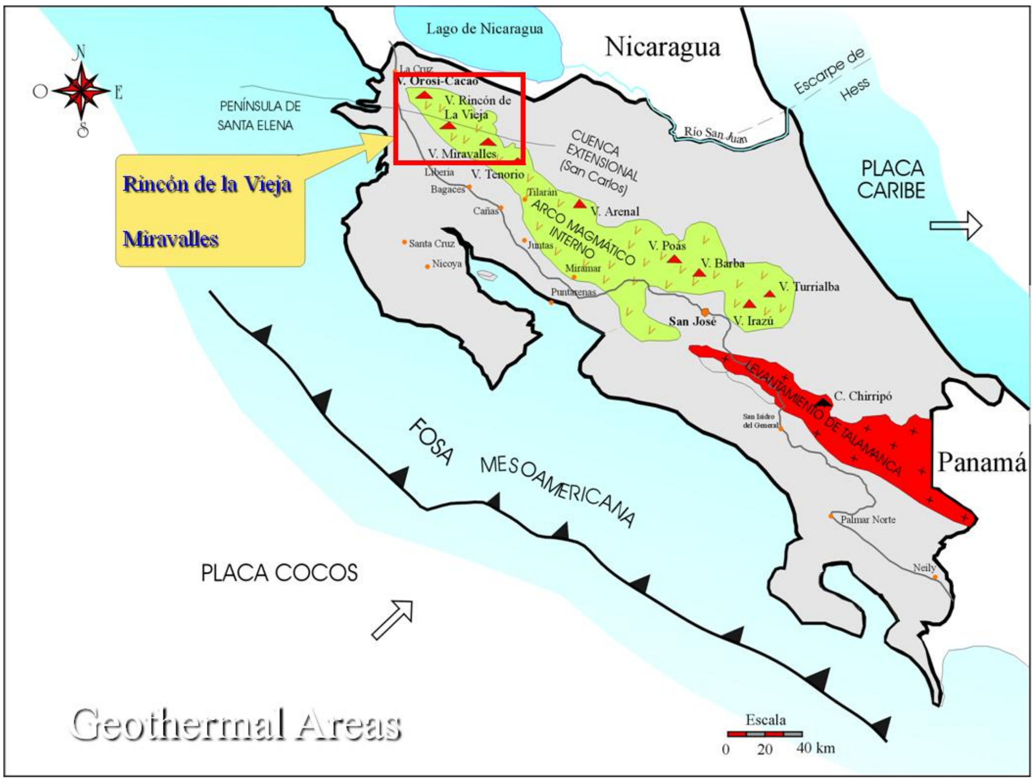

FIGURE 2: Costa Rica and the Miravalles Geothermal Field Location

The field is confined to a caldera-type collapse structure of 15 km diameter. It was formed about 600 000 years ago with the eruption and deposition of pyroclastic flows. A caldera collapse of over 1000 m has been estimated (ICE and ELC, 1986).

Associated with, or soon after, the caldera formation was a subvertical fracture striking in a NS, to NWW-SSE direction toward the east of the caldera, giving rise to a graben which extends southward beyond the caldera margin (graben La Fortuna).

In a second cycle, volcanic activity was concentrated in the east-giving rise to the andesitic complex of Cabro Muco-la Giganta, followed by the emissions of the Paleo Miravalles. Both are located on a system of faults and fractures trending SW-NE.

In the last 50 000 years, the Miravalles andesitic stratovolcano (2028 m.a.s.l.) was formed. This third cycle culminates with an explosive-effusive activity associated with lava flows and thin pumice deposits which occurred in the Santa Rosa area about 7 000 year ago. During this period, the N-S tectonic regime was reactivated producing a system with an E-W trending fault (ICE and ELC, 1986).

2.1 Stratigraphic sequence

The rock sequence within and around the Guayabo Caldera, as well as that described in the deep wells includes a series of stratigraphic units related to processes that occurred before, during and after the formation of the aforementioned structure (Figure 3). In the wells drilled, the majority of these rocks show strong hydrothermal alteration, which makes it difficult, in some cases, to recognize the original textures (this section as described in Vega et al., 2005).

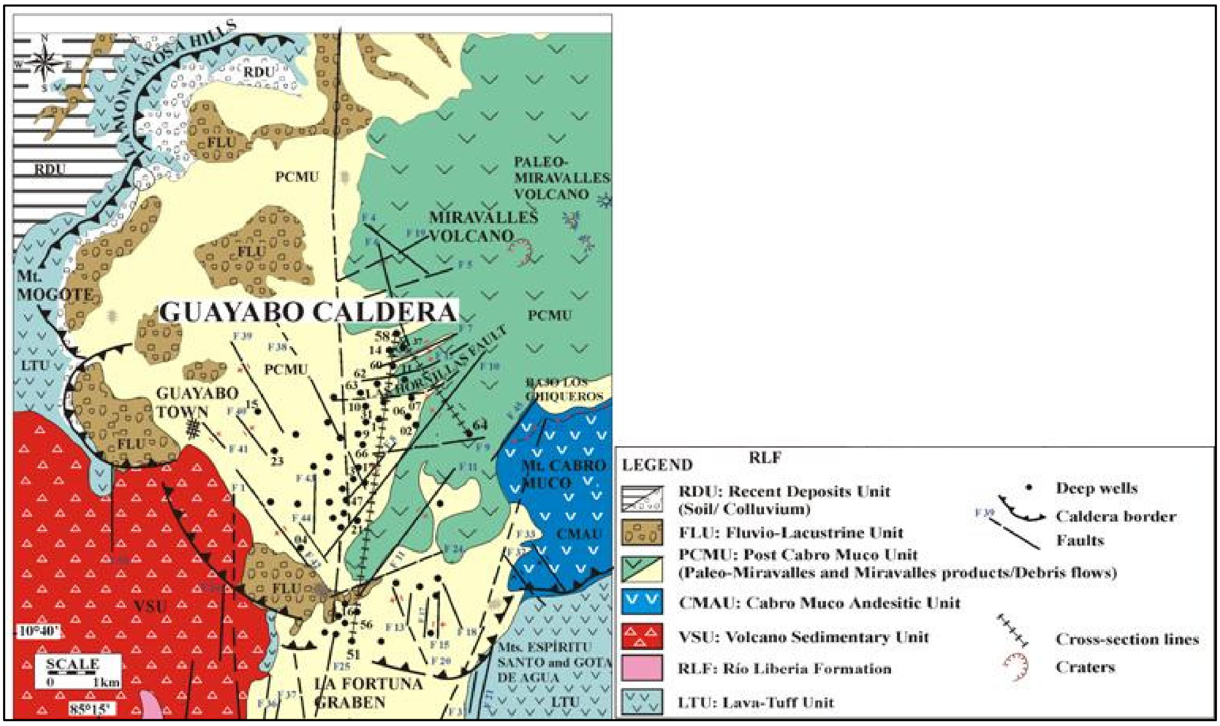

FIGURE 3: Geologic Map of the Guayabo Caldera

2.1.1 Deep lava unit (DLU)

It is composed of a lava flow sequence originated from emission centres possibly related to a paleo-volcanic arc. These rocks are predominantly andesitic and are observed only in the bottom section of well PGM-15, between 2500 and 3022 meters depth. It is interpreted as the local basement rock, and could be associated with Tertiary rocks.

2.1.2 Ignimbrite unit (IU)

It is composed of pyroclastic deposits and sporadic lava flows associated with paleo-volcanic calderas. The pyroclasts consist of tuff and ignimbrite sequences, with scarce andesitic lava intercalations. This Formation has been drilled in the wells of the northern and central sectors, reaching a maximum thickness of 1087 m, in well PGM-15. These materials could be correlated with pyroclastic sequences of the Bagaces Formation, which crop out various km south of the caldera border. It has been dated from 8 to 1.6 Ma (Gillot et al, 1994), indicating a wide period of deposition.

2.1.3 Lava -tuff unit (LTU)

This unit is composed of lavas and sporadic pyroclastic deposits. It is inferred that these materials correspond with the activity of a paleo-volcanic complex, known as Guayabo Volcano (ICE and ELC, 1983), which was emplaced over the products of the Ignimbrite Unit. The lavas are predominantly andesitic, with occasional intercalations of tuff, ignimbrite and epiclastic levels.

In the wells, a thickening of this unit is observed towards the southern and western sectors of the field, reaching thicknesses between 260 and 1190 m. This sequence has been dated at 2.3± 0.1 Ma (ICE, 1976). Based on this age, it is associated with the Bagaces Formation.

2.1.4 Río Liberia formation (RLF)

It is composed of a pumitic pyroclastic sequence that includes at least four flows, which are differentiated by variations in lithic content, crystals, and the level of consolidation. All of these flows are characterized by the presence of biotite, in varying amounts. These pyroclastic flows form a regional ignimbrite mesa, with thicknesses of up to 60 m. It is considered that at the time of deposition there was a topographic high at the present-day Guayabo Caldera (possibly the Guayabo Volcano), which is why these rocks have not been found within the caldera. This Formation ranges from 1.29 ± 0.03 and 1.83 ± 0.03 Ma (Gillot et al., 1994).

2.1.5 Volcano sedimentary unit (VSU)

This unit includes pumitic pyroclastic flows, tuffs, epiclastic deposits and lacustrine deposits, as well as occasional andesite and basaltic andesite levels. It is widely distributed in the drilled wells, with thicknesses ranging from 255 to 1050 m. This unit represents the products emitted during the formation process and filling of the Guayabo Caldera.

The Volcano Sedimentary Unit is correlated by Vega et al, 2005 with the Guayabo Pyroclastic Formation (defined by Chiesa et al., 1992), which has been dated from 1.456 ± 0.036 Ma to 0.6 ± 0.011 Ma (Alvarado et al., 1992) and consists of a series of pyroclastic flows that crop out southwest of the caldera, partially covering and extending beyond its border for various kilometres.

2.1.6 Dome-flow unit (DFU)

It is series of rocks that were emplaced in the form of a dome-flow, whose distribution is limited to the northern part of the field. This unit developed during the final phases of the Volcano Sedimentary Unit, taking advantage of the distensive E-W structural system. Texturally, it is characterized by its low porphyritic index, where sparse plagioclase phenocrysts and mafic minerals, replaced by chlorite, are observed embedded in an intensely silicified matrix. Due to these characteristics, a dacitic composition is inferred for these rocks.

2.1.7 Cabro Muco andesitic unit (CMAU)

It includes mainly andesites and basaltic-andesites, as well as sporadic lithic tuff levels. These rocks are the product of activity from the Cabro Muco-La Giganta volcanic complex. This volcanic edifice rose in the south-eastern sector of the caldera, after the emplacement of the Dome-Flow Unit. It has been affected by collapses associated with volcanic explosions, erosion and tectonism. It has been reported in the majority of the wells with thicknesses between 50 and 1000 m. Radiometric dating indicates ages from 0.4±0.1 Ma (Alvarado et al., 1992).

2.1.8 Post Cabro Muco unit (PCMU)

This unit is composed of lavas and pyroclasts, from the Paleo-Miravalles and Miravalles volcanoes, as well as debris flows from these and other volcanic centres. A thickness of 25 to 156 m has been observed for this unit.

2.1.8.1 Lavas and pyroclasts from the Paleo-Miravalles and Miravalles volcanoes

These consist mainly of andesites and basaltic-andesites with sporadic pyroclastic deposits. They are volcanic products posterior to the formation of the Cabro Muco-La Giganta volcanic edifice. This complex is located in the eastern sector of the field.

Paleo-Miravalles is considered as the second-most oldest post-caldera edifice, estimated at less than 200,000 ybp (ICE and ELC, 1983); followed by the current Miravalles volcano whose activity could have initiated around 50,000 ybp (ICE, 1976). The youngest rocks are pumitic pyroclastic flows with limited extension.

2.1.8.2 Debris flow

This consists mainly of debris avalanches, lahars, and lacustrine deposits. They correspond in part with the activity of the Miravalles volcano as well as volcanic collapse events in the Bajo Los Chiqueros area and probably extending towards the Espiritu Santo Mountain.

These rocks were deposited in different stages, where dates from the lower sections indicate ages greater than 40,000 ybp (ICE, 1976) and the upper levels show ages near 9000 ybp (Alvarado et al., in press).

2.1.9 Fluvio-lacustrine unit (FLU)

This unit consists of clay, silt and fine sand intercalations that grade to andesitic alluvial deposits, which are found distributed in various localities within the caldera. These materials evidence a period of quiescence, where laminar flows and low volcanic activity dominated. The total thickness of these deposits is not known, however in outcrop they are up to 3 m.

2.1.10 Recent deposits unit (RDU)

This unit includes thick soil levels and colluvium formed by lava fragments from the border of the caldera, cropping out towards the northwest sector.

2.2 Volcano-tectonic structures

The Guayabo Caldera and the Miravalles and Paleo-Miravalles volcanic edifices comprise the most noticeable volcano-tectonic structures in the region. This caldera consists in a marked semi-circular crescent-shaped 14 km diameter depression built up in various stages of volcanism and caldera collapse. Its NE and E extremities are masked by post-calderic materials from the aforementioned volcanoes, whose craters are aligned along a NE-SW strike, associated with deep fractures. The northern and southern borders of the caldera are truncated by the N-S distensive structural system that provoked downthrowing of the caldera border in the area of the La Fortuna graben. There is not a clear panorama with respect to the tectonic forces that have affected the region, however, taking into consideration the stresses caused by interaction between the Cocos and Caribbean Plates, as well as field evidence, it is inferred that the N-S and NE-SW structural systems, identified in the Miravalles area, present recent activity.

Four structural systems have been defined. Chronologically, these systems (from oldest to youngest) correspond with the directions: NW-SE, N-S, NE-SW and E-W, all contributing significantly to the permeability of the geothermal system.

The N-S fault system, to which the La Fortuna graben is associated, existed prior to the caldera formation and was later reactivated (Chiesa et al., 1992), thus offsetting it and hence favouring the lateral discharge of reservoir fluids.

In the northern part of the field a series of horsts and grabens, associated to the E-W structural system, which is considered to be the most recent, has been defined. It has surficial expressions such as thermal anomaly and hydrothermal alteration lineations, which is why some of these faults are considered to be active (Vega et al., 2010).

2.3 Alteration mineralogy

The Miravalles Geothermal Field is comprised of a high enthalpy reservoir where the water-rock interaction has developed a pattern of hydrothermal alteration, which has been separated into the smectite (Sm), transition (I/Sm), and Illite (I) zones (Figure 4).

The smectite zone (< 165°C) corresponds to the most surficial part of the field (upper level of the cap rock) and is characterized by the presence of clays from the smectite group along with iron oxides/hydroxides and the appearance of subordinate pyrite, calcite, chlorite, zeolites, and some forms of silica (tridimite, cristobalite and quartz). Alunite and kaolinite can be present locally, particularly in areas affected by acidic fluids.

The transition zone is defined by the appearance of the mixed layered clay illite/smectite, in which the percentage of illite increases with depth. It corresponds with a range of temperatures between 140 and 220°C (Vega, 2000; Sánchez & Vallejos, 2000) and its base is localized near the top of the reservoir. In this level, there is a clear increase in the amount of calcite, quartz and chlorite minerals; as well as the first appearances of other mineral species such as adularia, leucoxene/titanite, epidote (particularly incipient type I, based on the classification given in Reyes 1990, 2000), anhydrite, pennine, zeolites, wairakite and the mixing of chlorite and smectite layers.

The illite zone is associated particularly to reservoir levels with temperatures of at least 220° C. It is characterized by the presence of illite, higher percentages of epidote (types I, II and III according to the classification given in Reyes 1990, 2000) and well-crystallized chlorite minerals. Also, quartz, wairakite, adularia, pyrite, and the mixing of chlorite and smectite layers can be observed. In some cases, prehnite, garnet, and some sulfides have been identified (Milodowski et al., 1989), in association to the highest temperatures registered at the Miravalles Geothermal Field.

Epidote is used as a high temperature indicator; illite on the other hand, due to its rapid response to temperature changes, represents current thermal conditions.

In general, the first stable appearance of these minerals corresponds well with the 220°C isotherm although this behaviour is affected by local thermal anomalies generated by fluid circulation along permeable structures (NE-SW and E-W), that disturb this condition.

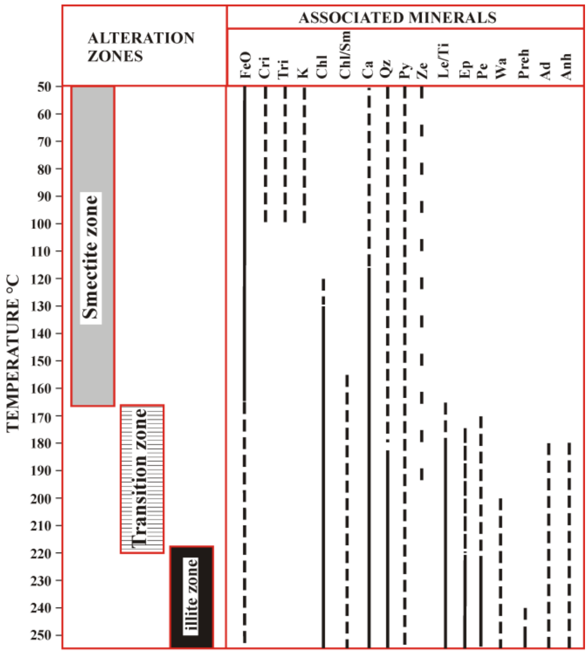

FIGURE 4: Clay alteration zones and associated mineralogy. FeO: Iron oxides/hydroxides, Cri: Cristobalite, Tri: Tridimite, K: Kaolinite, Chl: Chlorite, Chl/Sm: Mixed layered clay Chlorite Smectite, Ca: Calcite, Qz: Quartz, Py: Pyrite, Ze: Zeolites, Le/Ti: Leucoxene/Titanite, Ep: Epidote, Pe: Pennine, Wa: Wairakite, Preh: Prehnite, Ad: Adularia, Anh: Anhydrite

3. GEOCHEMISTRY

3.1 Water chemistry.

Most of the hot and cold springs on the Miravalles Geothermal Field are bicarbonate waters, with lesser sulfate waters and minor chloride waters. Most of the chloride waters discharge from the deep wells and only one chloride spring was found, located in Salitral de Bagaces in the south part of the area under study, about 19.5 km from the summit of the Miravalles Volcano and 170 m.a.s.l. It is characterized by high TDS and conductivity, with a temperature of 59.5 °C and the presence of travertine around it. The sulfate waters occur mostly in the area between Guayabal, Los Llanos and Sitio Las Mesas. The water coming from Sitio Las Mesas and Sitio Miravalles is drained by the Herrumbre Creek whose pH is close to 4. Another two zones far away from this area where this type of water emerge are: Las Azufreras, which is characterized by native sulphur deposits near the spring with H2S and stunted vegetation presence in a 50 m diameter area. The other zone is Las Hornillas, where the fumarolic activity is associated with a fracture zone and is characterized by mud pools and small steam vents, sulphur deposit etc.

The main reservoir fluids have a sodium-chloride composition with TDS of 5300 ppm, a pH of 5.7 and a silica content of 430 ppm. The main aquifer is characterized by a 230-255 ºC lateral flow (yellow zone in Figure 1). A shallow steam dominated aquifer is located in the north-eastern part of the field, and it is formed by the evaporation of fluid from the main aquifer that moves along fractures (Vallejos, 1996). Another important sector shows an acid aquifer in the north-eastern sector of the field (magenta zone in Figure 1), where a sodium-chloride acidic aquifer with pH values between 2.3 and 3.2 is present. A highly bicarbonate east-southeast zone (beige zone, not actually under exploitation excepting for well PGM-29) is also present. From the geochemical point of view this sector shows some differences relative to the main and acid reservoirs. The main differences are high bicarbonates content and the Na/K relationship, which shows a significant difference between geothermometer results and measured temperatures. Similar differences can be seen in calcium and magnesium content. The fluids in this sector have a high tendency to form calcium carbonate deposition as well as high NCG content in the steam (Sánchez et al 2010).

Over the years the chloride content in the waters have been increasing, thus indicating that reinjection waters are arriving to some sectors of the field; the most significant of these increases are related with wells to the south and western sectors of the field which are the main injection zones of the field (blue zone in Figure 1).

3.2 Calcite deposition

The Miravalles reservoir fluids have a silica content of 430 ppm and show a tendency of carbonate scaling in the wells, which ranges from strong to severe depending on the area and kind of aquifer present and causing that the wells would be obstructed in periods that range from several days to several months without a correcting inhibition process. This treatment have helped in maintaining a permanent fluid production, thus saving money in lost production and costs due to cleaning of wells by using drill rigs. The system used for the scaling inhibition has been used since the start of exploitation at Miravalles and has shown to be totally reliable.

3.3 Acidic aquifer

The Miravalles reservoir fluids typically have a neutral composition, but five of the wells drilled produce acid fluids. These wells were drilled in the north-eastern sector of the field (magenta-colored area in Figure 1), where a sodium-chloride acidic aquifer with pH values between 2.3 and 3.2 is present. This corrosive character would cause irreparable damages to the well casings and surface equipment, which would force discarding them after a few weeks of production.

Studies started in 1994, aimed to neutralized the acid fluids and commercially exploit such wells. The experience gained due to continuous experimentation allowed the commission of several acid wells. At this moment, this zone is an important supplier of fluids for production (Sanchez et al, 2005).

3.4 Non condensable gas

At the beginning of intensive field production the non condensable gas content (NCG) was low, in the range of 0.6 to 0.9% weight/weight (w/w) of steam. The NCG is composed mainly of CO2 which is between 97 to 99% w/w, with relatively high content of nitrogen of about 1.4 to 2 % w/w, and the content of hydrogen sulfide is less than 1% w/w (ICE and ELC, 1986). However, over the years an increasing trend in the non-condensable gases present in the steam has been observed. In the present days it is 0.2 to 2.4% (w/w) in the main aquifer, from 0.9 to 1.75% w/w acid in the aquifer and approximately 3 to 18% w/w in the bicarbonate aquifer (Sánchez et al, 2010).

4. TERMOHYDRAULIC CHARACTERIZATION

4.1 Temperature and pressure

The formation temperature and the initial reservoir pressure before exploitation indicate that the geothermal fluid flow primarily follows a NE-SW direction with change to the N-S direction in the central part of the field. A fluid flow appears to come from the vicinity of wells PGM-10 and PGM-11, where the highest temperatures and pressures in the field are observed. The temperature and pressure descend gradually to the south, from a maximum of around 250 °C near well PGM-11 to around 220-230 °C in wells PGM-26 and PGM-16 The reservoir is clearly bounded to the west due to the low temperatures and pressures observed there (wells PGM-04, 15 and 22). To the east the temperature and pressure remain not completely identified due to lack of data in that part (Figure 5). There was a gradual pressure decrease of about 3-4 bar from the north to the south parts of the field (from wells PGM-11 to

PGM-26). Near wells PGM-28 and PGM-29 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; this can be considered an indication of another deep recharge zone coming from the NE or E to the field.

Temperatures and pressures around the field have changed over the years; this is a direct influence of the continuous exploitation for around 19 years.

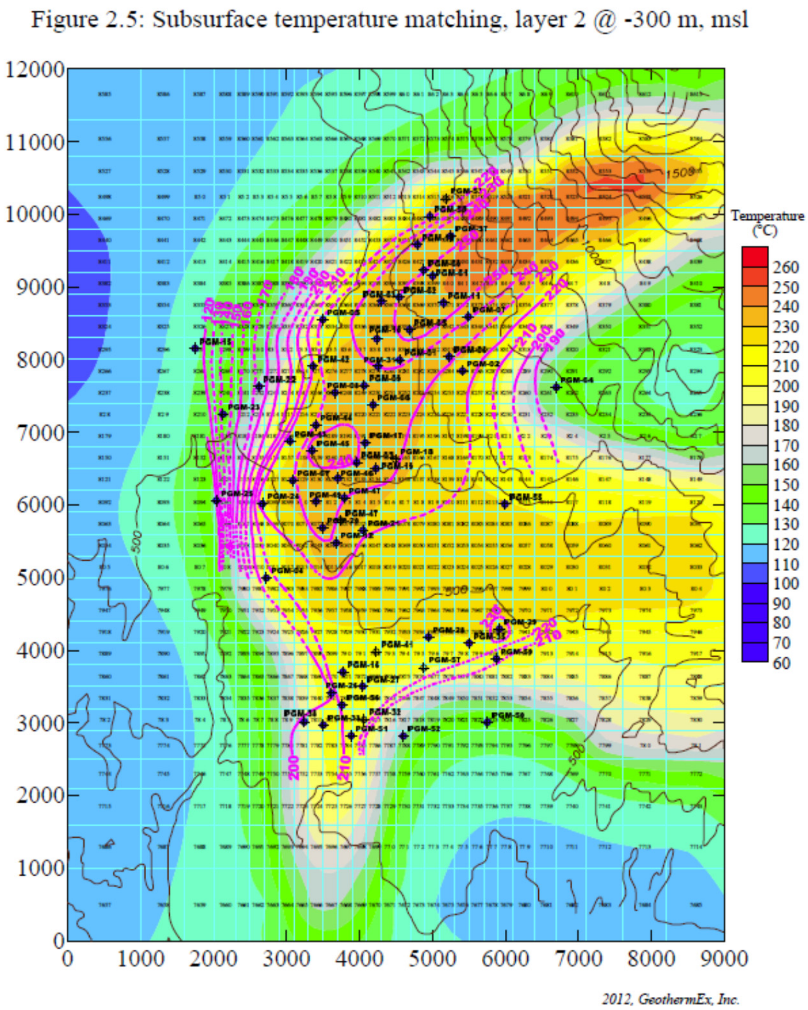

FIGURE 5: Temperature Contour Map at -300 m.a.s.l. (measured and modelled)

4.2 Permeability and porosity

The permeability in the reservoir is mainly secondary, as a result of widespread fracturing of brittle rocks due to its lithology or to hydrothermal alteration. The permeability increases from the north to the meridian part of the field, going from 60 D.m. in the north, 80 D.m. in the centre to 230 D.m. in the south. Considering a reservoir thickness of 1000-1200 m the average permeability is about 50-100 mD. The formation permeability is concentrated in very limited thick zones well defined. These zones may be highly fractured or single fractures with high permeability in a diffused less permeability medium.

More than one permeable zone is usually found in the Miravalles wells, and it is normal that spontaneous flow occurs between them. It is normally to find the first permeable zone between -100 to -300 m.a.s.l. (ICE and ELC, 1995), and the majority of the permeable zones found in the central part of the reservoir were around -198 to -1034 m a.s.l. (Castro, 1999). To characterize the productivity potential of the wells previously to production tests the injectivity index is determined, because this has been proven as a reliable way for assessing the productivity or injection performance of the wells in Miravalles (Acuña, 1994). There are a wide range of indexes, as low as 0-1 (l/s)/bar and as high as over 15 (l/s)/bar (accuracy of the measurement limits the measurement range).

During the drilling of PGM-44 a deep permeable zone was found at -1404 m a.s.l. and the well became a 4 MWe productor. After that, another deep zone was found in well PGM-46 (-1470 m a.s.l.). Prior that PGM -24 (-1314 to -1384 m a.s.l.) and PGM-25 (-1619 m a.s.l.) crossed also deep permeable zones but for different reasons there were not considered an important issue. These results showed the existence of a deep aquifer related with the main aquifer of Miravalles (yellow zone in Figure 6) in the zone around -1400 to -1600 m a.s.l.

The porosity is about 9.8%, with a standard deviation of 4.9% in the measurements. It is observed the higher values of porosity in the Volcano Sedimentary Unit, and the lower values are for the Andesite Lavas Unit and the Ignimbritic Unit (ICE and ELC, 1995). For numerical modelling purposes, the porosity is set to about 5.0 because higher values have proven not to be good for matching in recent numerical models of the field.

5. CONCEPTUAL MODEL

The conceptual model of the Miravalles Geothermal Field is shown in Figure 6. The main features of the reservoir are:

- Heat source: a magmatic body located somewhere in the NE part of the field at an unknown depth. The magmatic source is related with the extinct Miravalles Volcano.

- Caprock: its thickness is around 400-600 m and increases to the west and south. It is formed mainly by the upper part of the Volcanic-Sedimentary Unit.

- Main reservoir: volcanic units intensely fractured by neotectonic events within a graben structure. Its permeability is mainly secondary (fractures).

- Meteoric recharge: the structural conditions of the area assure an adequate recharge of the geothermal reservoir by meteoric water.

- Hydrothermal circulation: the main zone of recharge to the system is located in the NE sector of the field, near PGM-11 and possibly extending far from this well. The upflow comes through deep structures, and flows laterally through permeable formations in a SW direction showing a 250-260 °C temperature. Near well PGM-10 the flow changes direction slightly towards the south, flowing preferentially along fractures and faults related to a N-S neotectonic system. This flow continues southward and discharges to the surface at a point located 7 km from the caldera border. This flow pattern applies to the main (neutral) aquifer. The acid aquifer is located in the E-NE part of the field, and its extent is not completely defined yet (Figure 7).

A closed boundary is clearly observed in the western part of the field, as the temperature decreases rapidly in that part, as does the pressure. The reservoir is open to the north (inflow) and south (outflow). The reservoir continues to the east, but the extension cannot be estimated clearly because there are very few wells in that region.

The proven reservoir area is about 13 km2, and a similar area is classified as a sector for probable expansion. Another 15 km2 area is identified as also having some possibilities for future development (ICE and ELC, 1995). These areas may increase as the reservoir is investigated further.

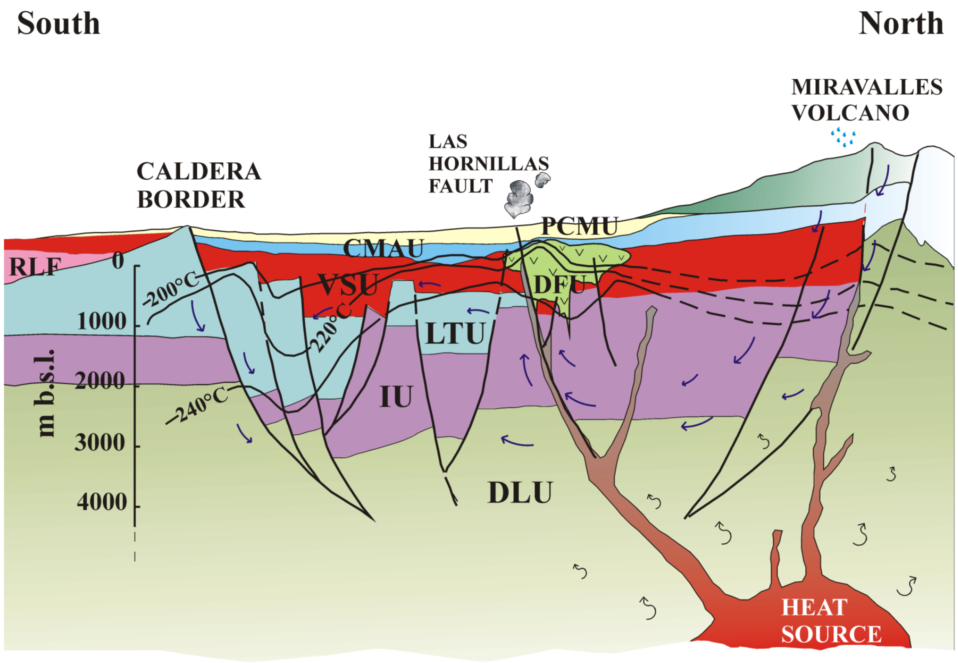

FIGURE 6: Conceptual Model of the Miravalles Geothermal Field

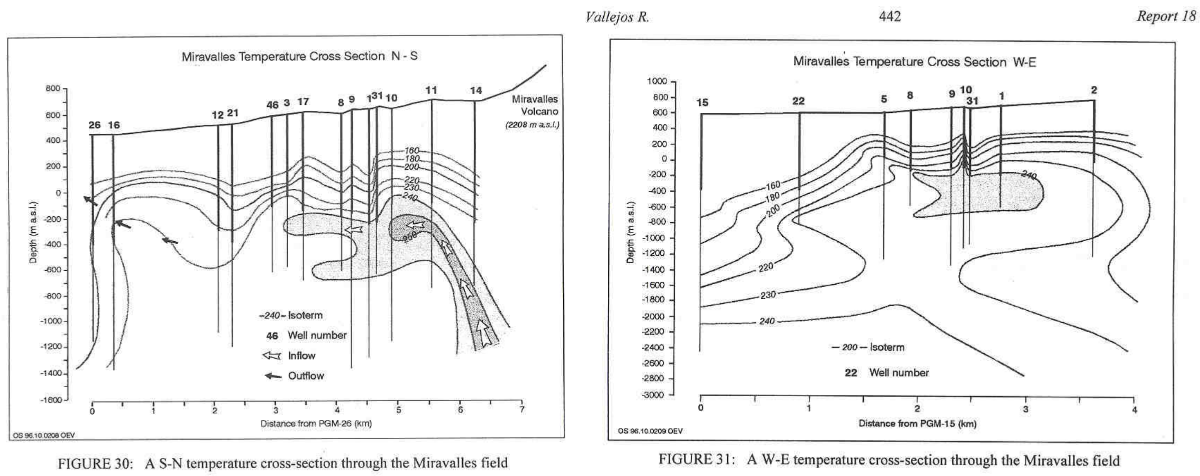

FIGURE 7: Temperature Cross Sections through the Miravalles Geothermal Field

6. NUMERICAL MODELLING

Numerical model is an important part of an assessment of a geothermal field, as a tool for helping in the decision making process during the operation of the reservoir. Two different models are used to simulate the Miravalles field data, a lumped parameter model using LUMPFIT and a three-dimensional model using TOUGH2, the latter being the most developed, accurate and used.

6.1 Lumped model

Lumped parameter modelling is a simple method where the reservoir is modelled in different parts, each of them having some distinct hydrological properties. Those properties are lumped together, simplifying the reservoir characteristics into a few dependent variables (Axelsson and Arason, 1992). The method visualizes the reservoir as a network of separate tanks and resistors, each of them representing different parts of the reservoir (tanks) and permeabilities (resistors). This network can be open or closed to a constant pressure boundary (Axelsson, 1989). An automated, least squares inversion program, LUMPFIT, is available for solving the parameters that define the lumped models that would fit the observed pressure and production history of the reservoir (Arason and Björnsson, 1994).

Lumped parameter modelling is a valuable alternative to the complex process of numerical modelling of a geothermal field. In spite of limited capacity, this modelling process can give an idea of the possible evolution of a geothermal field under different, easily envisioned production scenarios.

A development of a lumped parameter model of the Miravalles Geothermal Field was made in 2004 (Vallejos, 2005). This approach was made considering the wells PGM-09, PGM-14, PGM-29 and PGM-52. These wells had pressure monitoring units in different times of the field exploitation, being that only well PGM-09 had a pressure drawdown recorded during almost all the Miravalles Field exploitation history to that date (from October 1993 to April 2004). A second lumped parameter model was made three years later (Vallejos, 2010). Simulations were carried out in wells PGM-09, PGM-25, PGM-35 and PGM-55. Since PGM-09 has the most complete pressure drawdown history (about 14 years from October 1993 to September 2007), its corresponding model provides more confidence than the rest of the models.

For comparison purposes, the forecasted pressure behaviour of the previous model for well PGM-09 was compared against the corresponding new model. Also, it was tried to compare the possible evolution of the models by using the forecasted pressure behaviour of well PGM29 (made in 2004) against the forecasted pressure behaviour of well PGM-35. This was considered because these wells belong to the same area and are less than 500 m from each other.

In the case of PGM-09, the previous model was rerun with the updated mass extraction data and a new estimation for future steam production in order to compare the models under similar conditions; the results are shown in Figure 8.

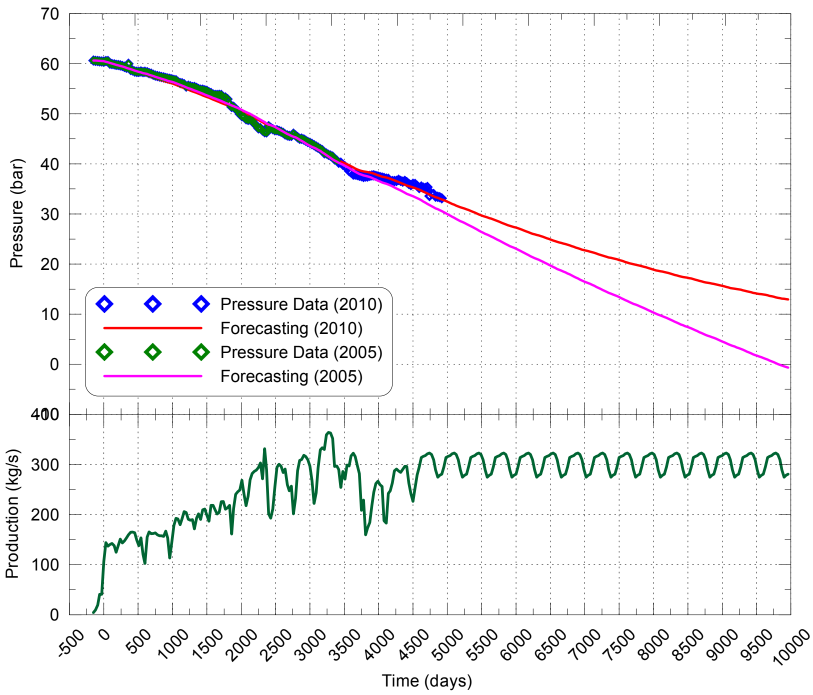

FIGURE 8: Matching and Prediction of the Future Reservoir Pressure (PGM-09) – Steamflow Rate: Comparison between Previous and Updated Lumped Parameters Model

As can be seen from Figure 10, the forecasted pressure behaviour with the newer model shows that the mass extraction is impacting the reservoir pressure less than in the previous model. This can be explained for a possible combination of reasons: 1) the reservoir has evolved and actually is developing a bigger steam cap in the northern zone of the field which appears to be extending to other zones of the reservoir; this means that more steam available allows the extraction of less mass thus reducing the pressure drop; 2) after the year 2004 the reduction in the mass extraction of the field has been reinforced, taking advantage of the annual maintenance of the different power plants at Miravalles; it has been tried to extend the time the power plants generate electricity at an amount below their installed capacity; 3) the reinjection scheme was improved, trying to divert as much water to the western zone as possible. This appears to have reduced the pressure drawdown in the wells located at the central part of the field (including PGM-09).

6.2 Three-dimension numerical model

The numerical modelling method consists of simulating the reservoir as a number of subvolumes, each of them having determined hydrological, thermodynamic and chemical properties. Those properties are set according to the measured data observed during the reservoir assessment, and change throughout the reservoir exploitation. In such a condition, simplifying the reservoir characteristics does not make sense, as the purpose of the numerical modelling is to have a reservoir model as close to reality as possible. The modelling is made using not only the data available, but also analytical and empirical equations that represent the real behaviour of the different components of the mass, rock, etc. The simulation is run in high velocity computers because of the high number of variables involved. The program TOUGH2 is one of those numerical models. The basis of TOUGH2 is the same as normally applied in geothermal reservoir simulators. The mass- and energy-balance equations are applied to the develop model and a solution for a selected period of time run is obtained (Pruess, 1991).

Different numerical models of the Miravalles reservoir have been developed over the years, for forecasting the future behaviour of the field according to the data collected.

In 1991 the Lawrence Berkeley Laboratory and ICE developed a preliminary natural-state and exploitation numerical models of Miravalles, based on the present conceptual model (Haukwa et al, 1992). The TOUGH2 code was used for the 62-block model (Figure 9).

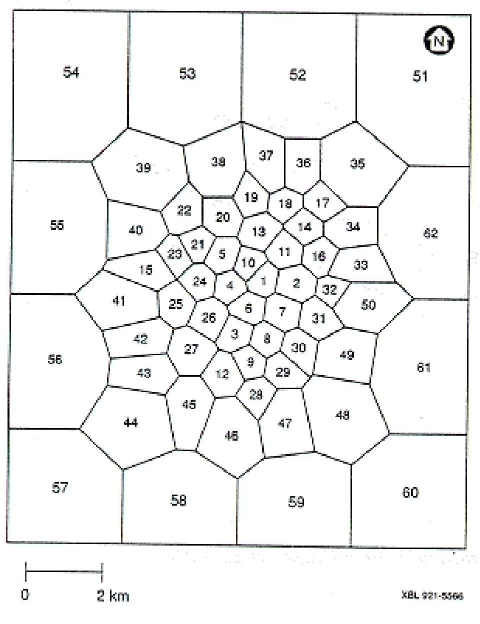

FIGURE 9: Lawrence Berkeley Laboratory/ICE Numerical Model (1991)

ELC Electroconsult and ICE developed another numerical model in 1995 (Figure 10), based in one used for the first feasibility studies done in 1985 and 1988 (made by using the GEMMA code). Natural state and exploitation models were created based on the information gathered by ICE during the exploration and the first eight months of massive reservoir exploitation. TOUGH2 was also used for this 146-block model (ICE and ELC, 1995).

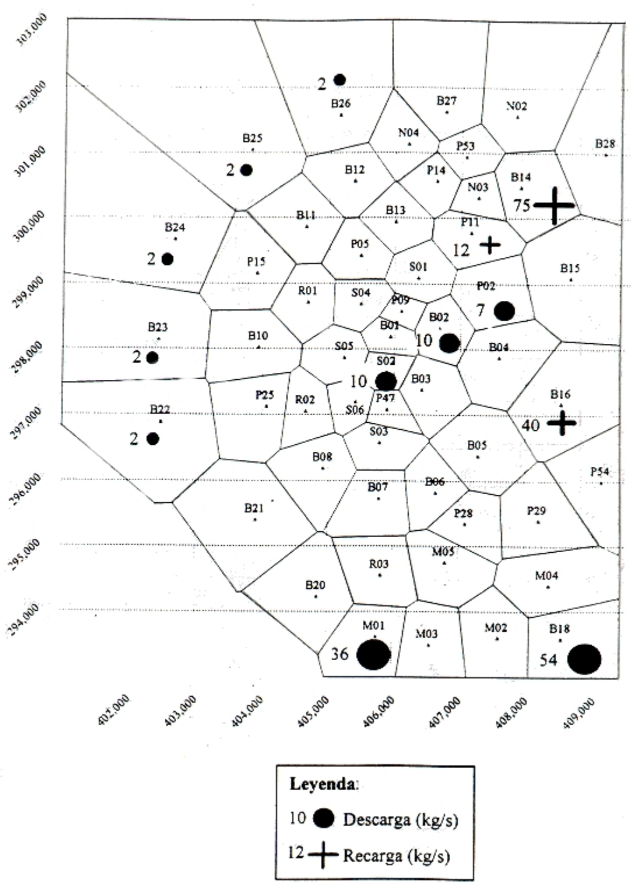

FIGURE 10: ELC Electroconsult/ICE Numerical Model (1995)

In 1998 GeothermEx, Inc. developed a TOUGH2 1953-block numerical model, this time including the data from three years of continuous field exploitation. The model comprises and area of 12 km long N-S and 9 km long E-W, extending from +100 to –1500 m m.a.s.l (1600 m total thickness) and divided into six layers of non-uniform thickness and a couple of different grid layer arrangements(layers 1, 5, 6 and layers 2, 3, 4), totalling 1953 grid blocks (Figure 11). The numerical model history matching and forecasting runs under different production and injection schemes were accomplished in that study (Pham et al, 2000). This model was updated by GeothermEx, Inc. in early 2001. The grid blocks were refined and increased to 5110 (Figure 12), and a double porosity and two-waters options were used. This code was used for matching the chloride returns observed in the fluids. Also, the model took into account the new information gathered from July 1997 to March 2001 (GeothermEx, Inc., 2002). In 2012, a third actualization of the same model was made. This time the model was extended to -1900 m.a.s.l in order to model the deep zone found in some of the deepened wells. The layers were increased from six to ten and all the layers were unified to only one design; some of them were thickened in the most permeable depths in order to get a better match in the actual enthalpy changes observed. As the layers were increased also the grid was refined; the number of base blocks were then increased to 9570 (Figure 13). After the double-porosity method is applied, this number is doubled bringing the total number of gridblocks in the model to 19,140 (GeothermEx, 2012).

Figure 3.3: Gridblocks layout in the updated model - layer 1 (from +100 m, msl to -200 m, msl)

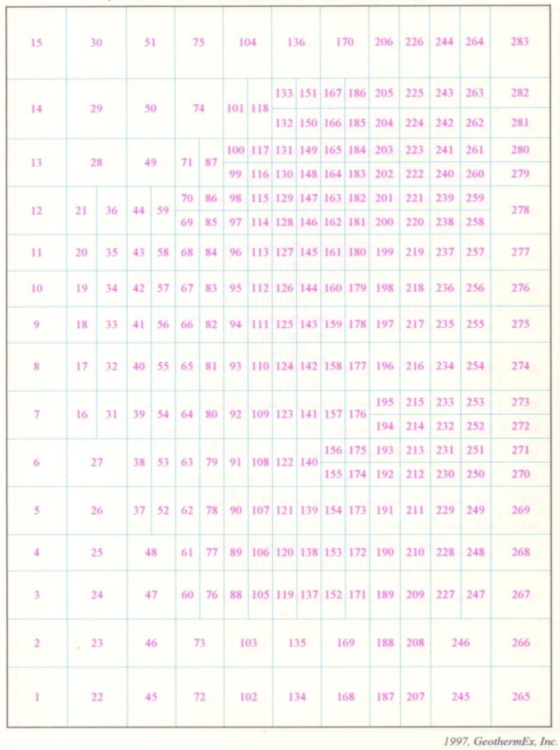

Figure 3.4: Gridblocks layout in the updated model - layer 2 (from -200 m, msl to -400 m, msl)

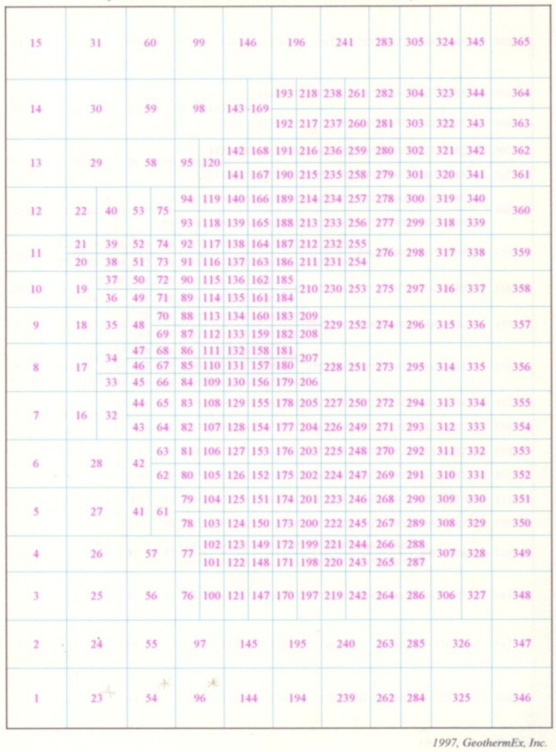

FIGURE 11: GeothermEx/ICE Numerical Model (1998)

Figure 2.3: Gridblocks arrangement at layer 1 @ -50 m, msl

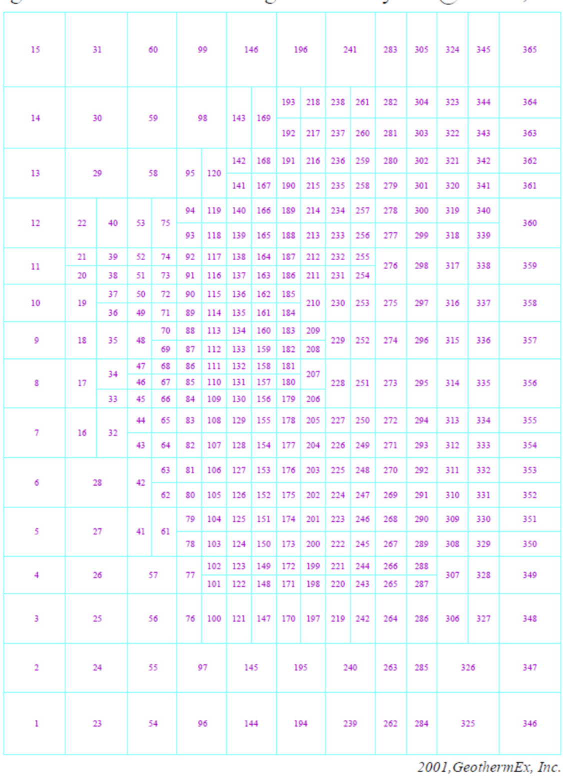

Figure 2.4: Gridblocks arrangement at layer 2 @ -300 m, msl

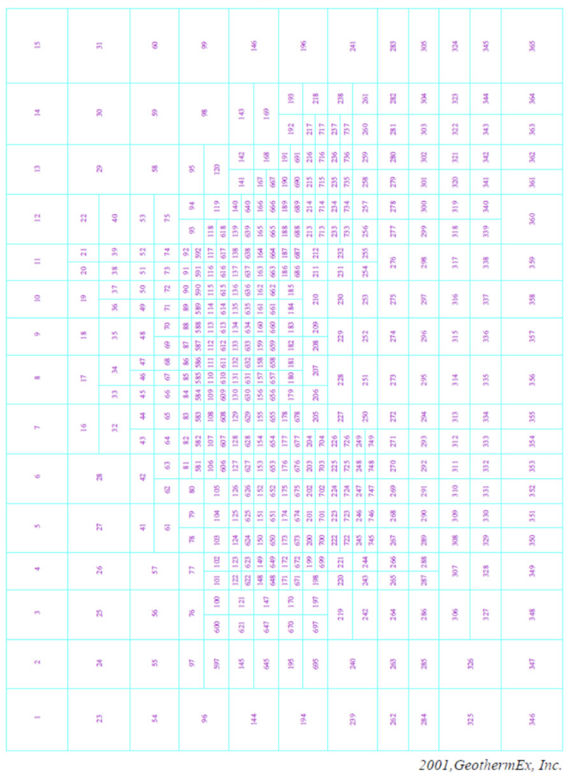

FIGURE 12: GeothermEx/ICE Numerical Model (2002)

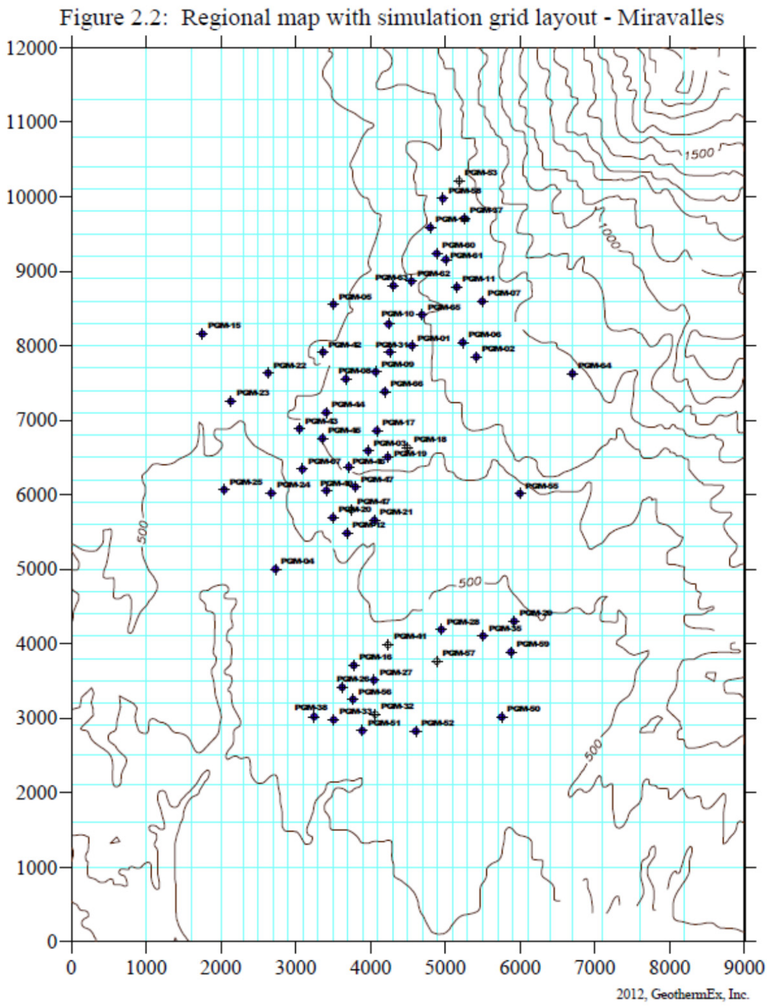

FIGURE 13: GeothermEx/ICE Numerical Model (2012)

The current model has been used for evaluating different possible exploitation scenarios which have been proposed, i.e. injecting waste brine into the north-central zone of the field, producing from the deep zone of Miravalles, etc.

The actual situation of the Miravalles reservoir is very complex and the amount of data collected over the years has become very large (geoscientific and production data). This situation joined with some technical deficiencies in the TOUGH2 program that is currently used by the ICE make it very difficult and laborious to effectively predict reservoir performance of the Miravalles field. ICE is actually taking steps to migrate the TOUGH2 simulation software to a more effective simulation program, where it can be more effectively evaluate reservoir behaviour of Miravalles and other fields in the future. The actual plans are to migrate from TOUGH2 to TETRAD platform and continue using the latter in the following years.

7. PRODUCTION HISTORY

The Miravalles Complex comprises five power units in three different power houses (Figure 14), seven separations stations, the pipeline networking, 53 wells (production, injection and observation) and a series of artificial ponds aimed for cold injection, maintenance operations and emergencies. A simple scheme of the pipeline network, wells, power plants and other facilities is shown in Figure 15.

FIGURE 14: Power Plants at Miravalles

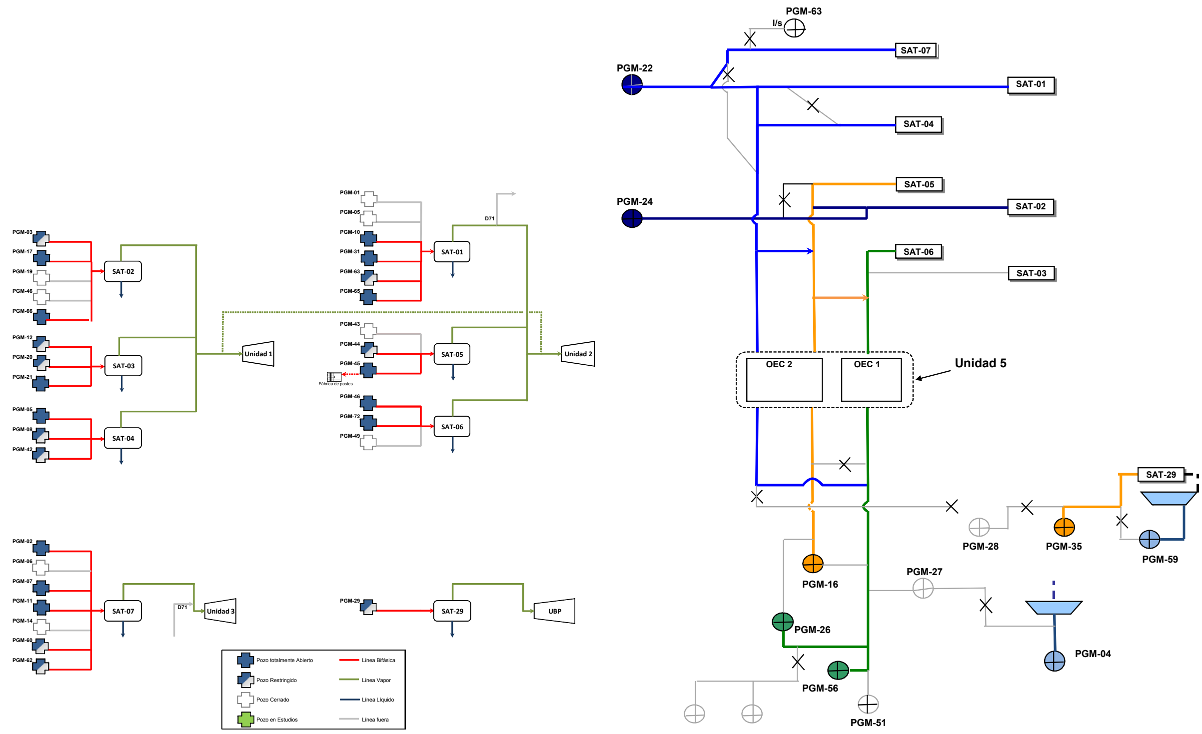

FIGURE 15: Power Plants, Wells, Separation Stations and Pipeline Networking at Miravalles

In Miravalles is also located the main facilities of the Centro de Servicios Recursos Geotérmicos (CSRG), which is the ICE´s department charge of the exploration, evaluation and exploitation of the geothermal resources in the country.

Table 1 shows the commissioning sequence of the different power plants installed in Miravalles. All the actual operative units are owned by ICE.

TABLE 1: Generation at the Miravalles Geothermal Field

Unit	*Operator*	**Power Output (MW)**	*Operation Time*	
			Start	*End*
Unit 1	ICE	55	03/1994	---
Wellhead 1	ICE	5	11/1994	---
Wellhead 2	CFE	5	09/1996	08/1998
Wellhead 3	CFE	5	04/1997	01/1999
Unit 2	ICE	55	08/1998	---
Unit 3	Geo	29	03/2000	---
Unit 5	ICE	19	12/2003	---

7.1 Mass production

The total mass extraction and injection rates in Miravalles are shown in Figure 16. Around 1500.6 kg/s of total mass are extracted from the reservoir, and 345.8 kg/s are steam used for generation (as of 13/02/2013; Nietzen, personal communication). All the waste water is injected back to the reservoir.

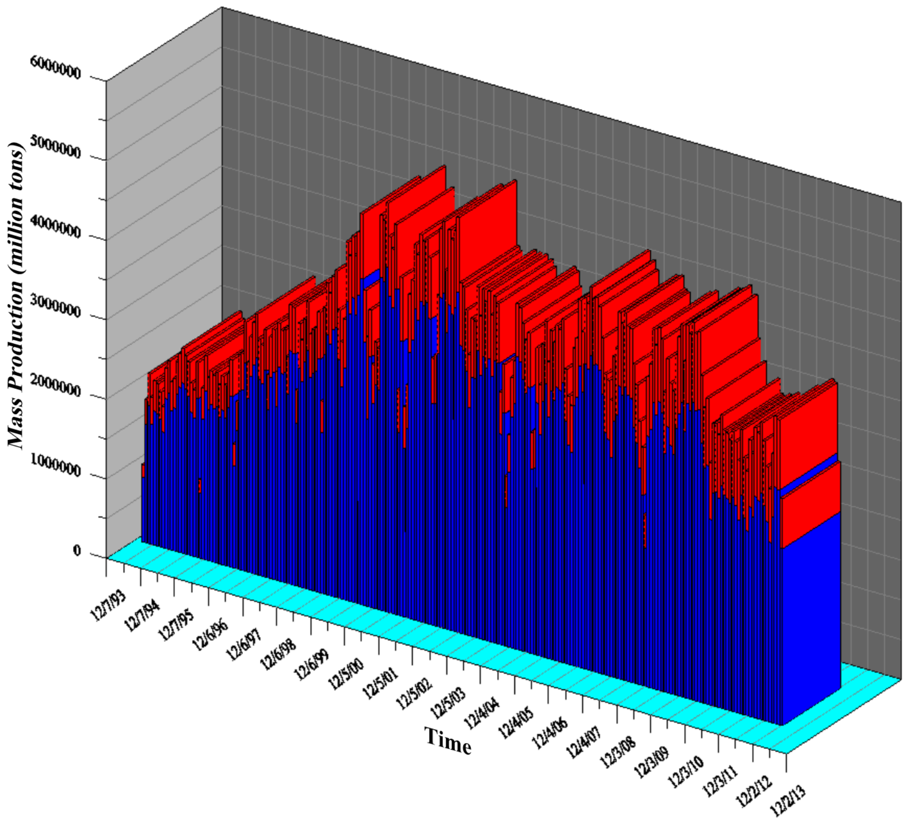

FIGURE 16: Mass Production and Injection at the Miravalles Field

The annual maintenance of the different power plants is historically scheduled during the second half of every year; this explains the observed decrease in the mass production over this period of time.

7.2 Mass injection

Injection has been an important factor of the Miravalles operation. Injection rates account for around 83% of the total mass extracted from the field. Injection into the different sectors at the Miravalles Field is shown in Table 2 as a percentage of the total injected mass into the field (Vallejos et al, 2005).

The injection of waste brine has been made in "hot" conditions that is around 165 °C, and a small proportion in "cold" conditions (less than 60 °C). "Cold" injection is located in well PGM-04, which is located to the southwest of the field. The "Hot" conditions changed when the Unit 5 came online since it recovers some of the heat of the waste brine, lowering its temperature to 136 °C. A big part of the total waste brine will pass through Unit 5 and then be injected into the southern injection zone. The western injection zone will continue receiving brine at around 165 °C.

Percentages on Table 2 are average of the injections rates over the periods considered; for example, injection in any given month can change for various reasons: a special need for producing more electricity with the binary plant, maintenance operations in one or more injector wells, etc. Sometimes the injection in a month at the southern injectors can be as high as 80% or as low as 50%, thus varying the percentages in the other wells.

TABLE 2: Injection into the Miravalles Field Zones

Start	End	South	PGM-22	PGM-24	PGM-04	PGM-63
1994	1998	30%	30%	30%	10%	---
1998	2000	65%	13%	13%	9%	---
2000	2002	73%	9%	9%	9%	---
2002	2003	63%	11%	17%	9%	---
2003	2006	65%	14%	15%	5%	small
2007	2012	65.4%	14%	13.6%	5.8%	1.2%

7.3 Electrical production

The electrical generation of the Miravalles Complex is shown in Table 3 (ARESEP, 2011) and Figure 17. The main power plants have been working at high plant load factors (90% under normal operation conditions), due to their excellent performance, maintenance and the good behaviour the reservoir has showed along these years of exploitation.

7.4 Importance of the geothermal energy in Costa Rica

The installed capacity of Miravalles and Pailas fields accounts for about 8,2% of the country's total installed capacity; however, it represents around 13,2% of the country's total generation (ARESEP, 2012). Since the geothermal plants produce constantly throughout the year round, they are used as a base for the country's electrical generation, because of the variation in the hydro electrical plants production due to the seasonal variations of the Costa Rica's weather (Figure 18).

The importance of geothermal energy in Costa Rica is increasing. In 2001, geothermal represented the 8.6% of Costa Rica's total electrical production and accounted for 14.2% of the country's total generation. By 2011, the installed capacity was essentially the same (8.2%) but the generation was 13.2% of the total supplied by the National Electrical Grid or SEN (in Spanish). SEN includes all the electrical generation companies of Costa Rica (public and privates), and the total installed capacity of the country reaches 2650 MW (Table 4) and generated 9748 GWh in 2011 (ARESEP, 2012).

TABLE 3: Electrical Generation of the Miravalles Power Plants (March 1994 – December 2011)

1994-2011 (GWh)													
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Set**	**Oct**	**Nov**	**Dec**	**Total**
1994	0,0	0,0	7,0	31,9	37,1	33,6	39,2	39,7	33,8	37,2	40,5	41,7	341,8
1995	39,4	41,7	43,4	45,3	45,2	44,0	43,8	41,1	38,6	46,2	8,4	31,0	468,2
1996	47,5	42,1	45,7	45,0	43,9	40,8	45,4	43,5	45,5	48,5	26,5	35,6	510,0
1997	47,7	43,0	50,9	46,0	47,5	51,2	52,5	43,7	46,0	43,0	23,7	49,2	544,4
1998	51,1	45,5	51,8	49,3	46,4	44,6	49,3	52,6	36,8	58,9	48,0	57,7	591,9
1999	64,2	59,4	65,3	69,6	74,0	46,9	66,6	75,0	72,8	78,7	74,1	57,2	803,9
2000	66,9	72,2	82,4	94,2	94,6	93,7	100,7	102,2	79,1	59,3	67,0	64,1	976,5
2001	63,2	60,7	101,0	94,8	99,5	98,2	95,2	96,5	58,8	99,4	57,0	62,0	986,3
2002	91,4	90,7	103,3	99,8	103,6	100,0	102,2	98,9	73,4	67,7	87,5	102,5	1121,0
2003	105,2	91,7	105,8	104,3	104,9	97,0	99,8	97,9	83,3	71,8	90,1	92,4	1144,2
2004	115,7	106,6	118,7	112,2	116,2	105,3	112,4	107,6	77,7	94,4	62,9	75,9	1205,6
2005	91,0	96,2	106,5	110,2	110,0	103,9	107,2	68,5	63,1	96,5	89,2	105,3	1147,7
2006	114,8	99,1	110,8	107,5	112,1	106,7	105,1	88,6	86,5	83,1	100,7	99,9	1214,9
2007	109,2	104,0	112,2	105,9	112,3	109,6	112,2	103,8	94,4	87,3	87,9	90,3	1229,1
2008	105,6	104,8	114,3	109,9	113,3	107,9	110,0	97,2	89,0	68,3	64,1	46,4	1130,8
2009	89,0	101,8	112,5	105,8	111,7	105,3	91,5	99,0	88,7	86,8	92,8	101,1	1185,8
2010	107,7	98,8	110,0	107,6	110,1	104,9	107,9	88,9	79,1	90,7	77,3	93,2	1176,1
2011	91,2	90,0	100,8	98,8	99,9	95,2	99,5	96,2	87,0	98,0	87,4	84,9	1129,0

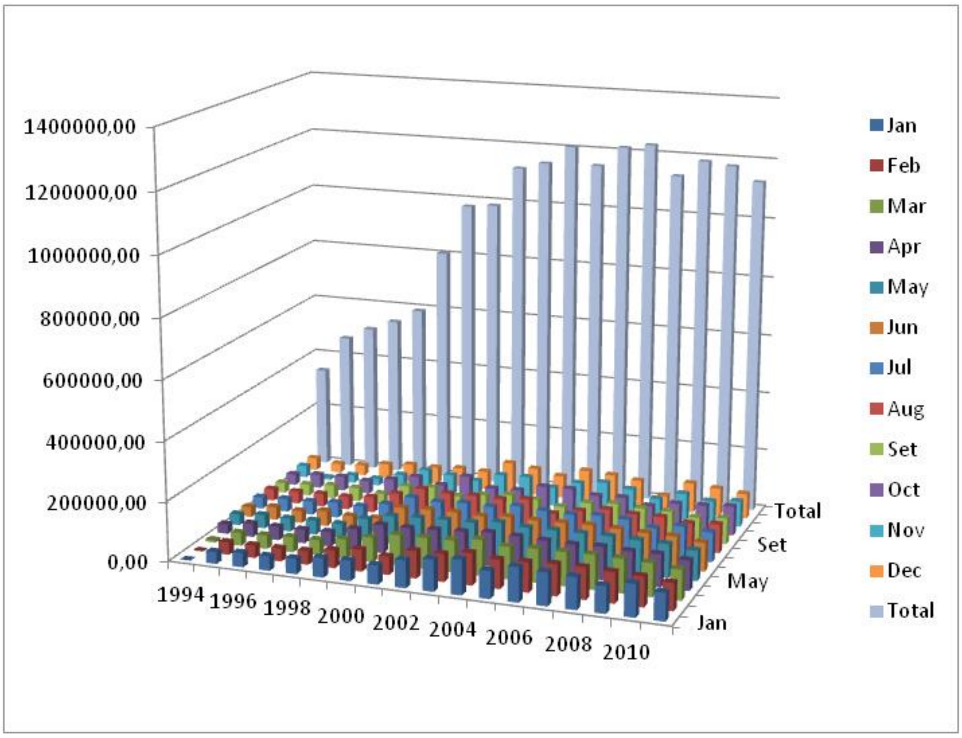

FIGURE 17: Electrical Generation of the Miravalles Power Plants (March 1994 – December 2011)

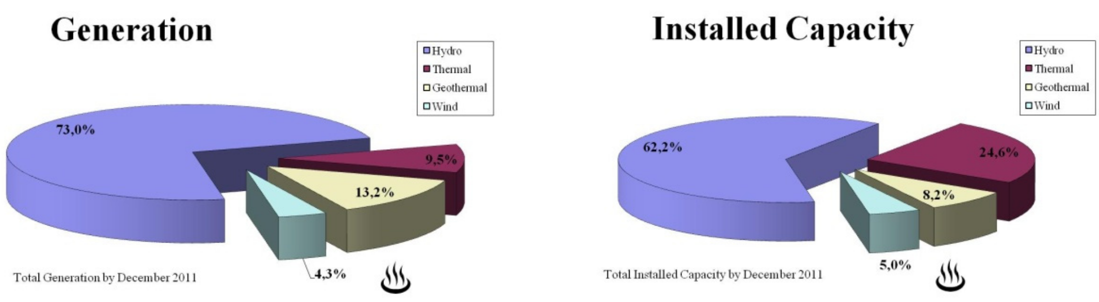

FIGURE 18: Costa Rica Installed Capacity and Generation – year 2011

TABLE 4: Costa Rica Installed Electrical Capacity and Generation

Type	**Installed Capacity (MW & %)** **Generation (%)**				
	2007	**2008**	**2009**	**2010**	**2011**
Hydro	1494.0 (69.3) (75.2)	1511.5 (63.9) (78.3)	1532.3 (63.5) (78.4)	1532.3 (58.6) (76.4)	1647.6 (62.2) (73.0)
Thermal	432.4 (20.1) (2.7)	624.4 (26.4) (3.5)	624.4 (25.9) (3.1)	826.8 (31.6) (1.0)	652.6 (24.6) (3.7)
Geothermal	163.7 (7.6) (13.8)	163.7 (6.9) (12.1)	163.7 (6.8) (12.8)	163.7 (6.3) (12.4)	217.5 (8.2) (13.2)
Wind	66.0 (3.1) (2.7)	66.0 (2.8) (2.1)	91.2 (3.8) (3.4)	91.2 (3.5) (3.8)	132.8 (5.0) (4.3)
Total	2156.0 (100.0) (100.0)	2365.5 (100.0) (100.0)	2411.6 (100.0) (100.0)	2614.0 (100.0) (100.0)	2650.4 (100.0) (100.0)

8. MIRAVALLES RESERVOIR EVOLUTION

The observed evolution of the Miravalles Field during the 19 years of production can be divided in four different stages:

a) First period: the initial condition of the field, with similar chloride concentrations over the entire field and calcium-enriched fluids in the western sector. Higher temperatures were present the northeast, and diminished naturally toward the southwest.

b) Second period: from the start of commercial exploitation of the field until April of 1999. The arrival of injection fluids coming from the west (wells PGM-22 and 24) toward the centre of the field is noticed. This injection return is mixed with more calcium-rich waters belonging to this sector. A general temperature increase along a northeast-southwest trend is observed, indicating that the established exploitation regime could be supported by the natural recharge of the field. The existing injection returns did not show any negative thermal breakthrough.

c) Third period: from May 1999 to October 2002. The increasing influence of the injection return in the southern zone of the field is noticed, as chemical breakthrough is evident. A temperature and enthalpy decline along a southwest-northeast trend is observed, indicating not only the arrival of the chemical front but also mixing with colder fluids. A production decline in some of the wells is also observed.

d) Fourth stage: starting in November 2002, a steady production decline is observed in some of the wells located in the northern sector of the field, in association with a reservoir pressure decline and a strong drop in wellhead pressures (PGM-01, 10 and 63, all of which are connected to separation station 1). PGM-01 can no longer produce and PGM-10 is seriously affected. A remarkable steam cap has formed in the northern part of the field due to the massive exploitation. This steam cap seems to be extending to the rest of the field. The effect of the relocation of reinjection toward the western part of the field in late 2002 (to mitigate the pressure drop) has been noticed chemically, and its effect on the pressure of the reservoir has proven to be effective. Even though, the effect of this action is less than expected because the quantity of reinjected water sent to the west has not been the desired.

Figures 19, 20 and 21 show the variation of some parameters in selected wells of Miravalles, specially the changes observed in some central wells of the field. Figure 22 show the generalized pressure drop observed all around the field since 1994. Most of the wells show a drop in the wellhead pressure; that condition is causing problems when the wells have to be put online. Some of them are actually operating very near to the separation station pressure, so any disturbance in the power plant can cause that the well shut off.

Figure 21 clearly shows the effect of the reinjection in some of the wells of the central part of the field; especially those located near wells PGM-22 and PGM-24. The chlorides increase and the noncondensable gas content drops in these wells. However, there are wells that increase in the noncondensable gas content; some because of the steam cap formation as mentioned earlier in this section, others because of its own nature. The overall effect over the power plants is a higher noncondensable gas content that surpasses the capacity of the actual extraction system. These are then forced to work with ejector and compressor, consuming energy and steam in the process.

Numerical modelling done in 2002 to forecast future reservoir behaviour showed that, under the then current exploitation scheme, injection returns should mostly affect the temperature of the southern production area and the nearby wells. The overall pressure in the field seemed to be seriously affected when injection was shifted to the south in 1998, and it appeared to be necessary to relocate some of the injection back to the west, in order to reduce the reservoir pressure drops to reasonable values (GeothermEx, Inc., 2002). This action were partly completed as was mention before, but changes in the production rates of wells connected to separation station 1 have made it impossible to achieve the original rate of the fluid injection into well PGM-22 (Moya and Yock, 2004).

The operation of Unit V has been possible at this point, based on forecasting results that show that the colder injection returns should not seriously affect the temperature of the field, and to date no thermal breakthrough has been seen (GeothermEx, Inc., 2002 and GeothermEx, Inc., 2012). The most recent modelling studies warn about the expected reduction in production of the binary plant due to the enthalpy rise observed under the nominal operation conditions of the field (GeothermEx, Inc., 2012). Monitoring of the field has been carried out in order to avoid future problems that might occur if lowering the temperature of the reinjection waters (from 165 to 136 ºC) impacts the reservoir more than predicted by the numerical modelling. Another possible impact of the commissioning of the binary plant is silica deposition in pipes, production casings, and fractures in the reservoir, due to an increase in silica oversaturation. This effect has not yet been detected nor quantified.

The modelling runs in 2002 clearly indicated the need to transfer the back-pressure unit from its current location to well PGM 29, in order to reduce the pressure drop observed in the centre of the field. This was achieved by the end of 2006, and since then the back pressure unit has been producing to its maximum capacity and well PGM-29 has been very stable in their productive and thermo hydraulic parameters.

The most recent numerical model, developed in March 2012, forecasts the sustainability of the exploitation of the Miravalles reservoir under the conditions described below:

UNIT I: generating up to 55 MW.
UNIT II: generating up to 55 MW.
UNIT III: generating up to 27.5 MW.
UNIT V: generating up to 14 MW (injection temperature 136 °C.)
Wellhead unit: installed in well PGM-29 (generating up to 5 MW).

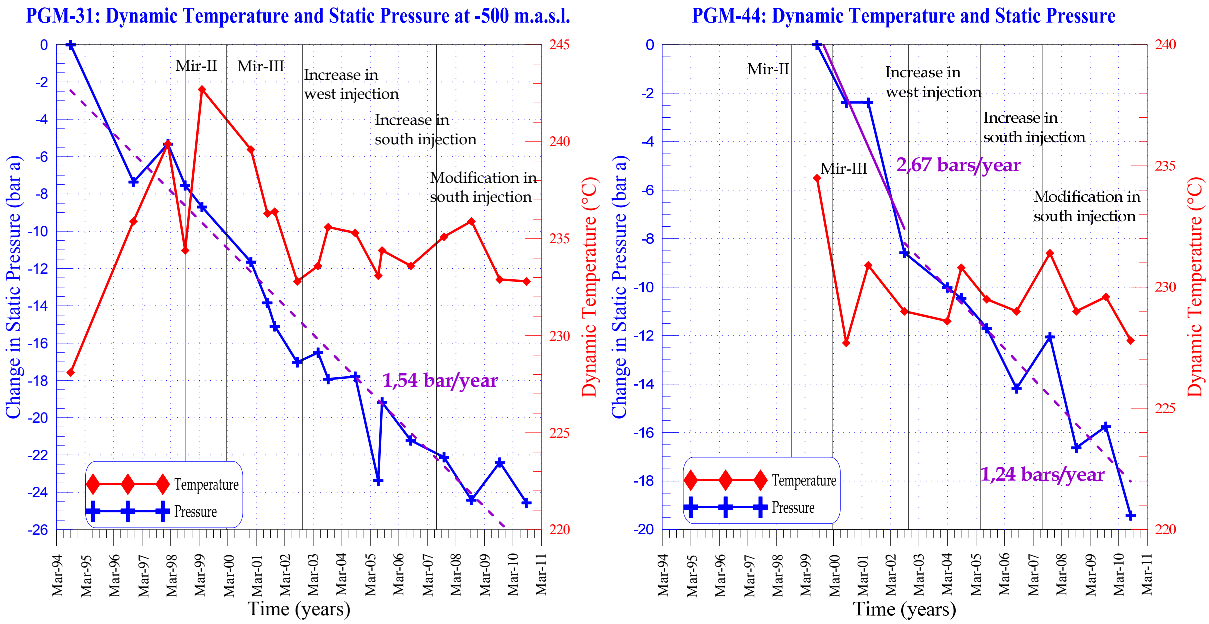

FIGURE 19: Temperature and Pressure Drop in Some Miravalles Central Zone Wells

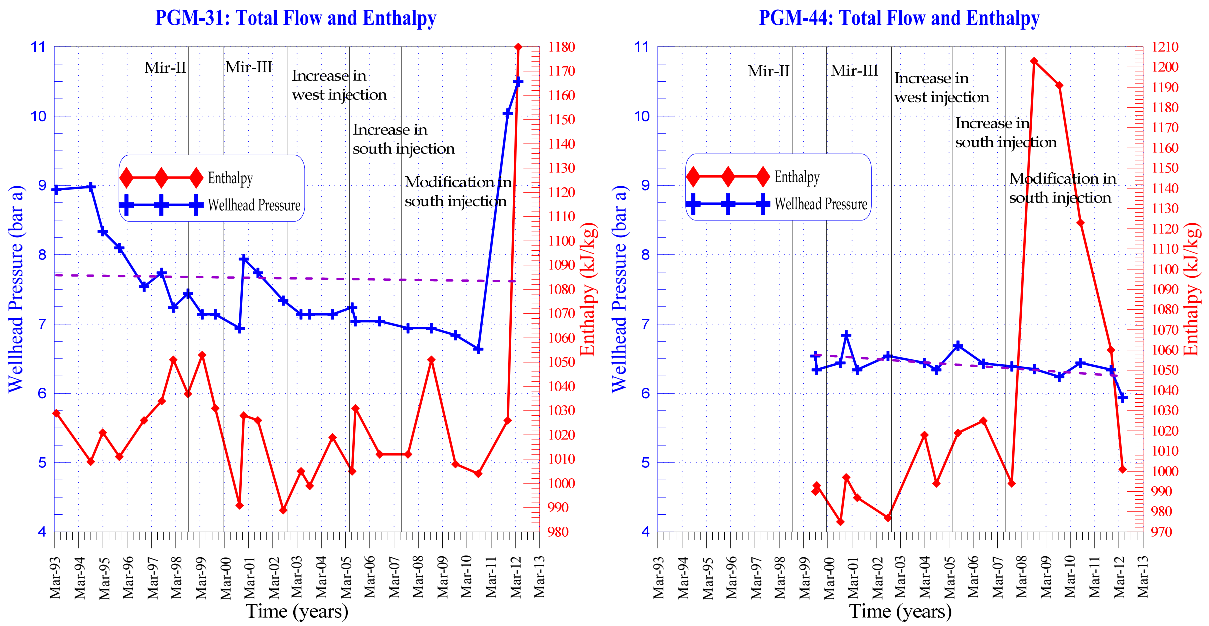

FIGURE 20: Wellhead Pressure and Enthalpy in Some Miravalles Central Zone Wells

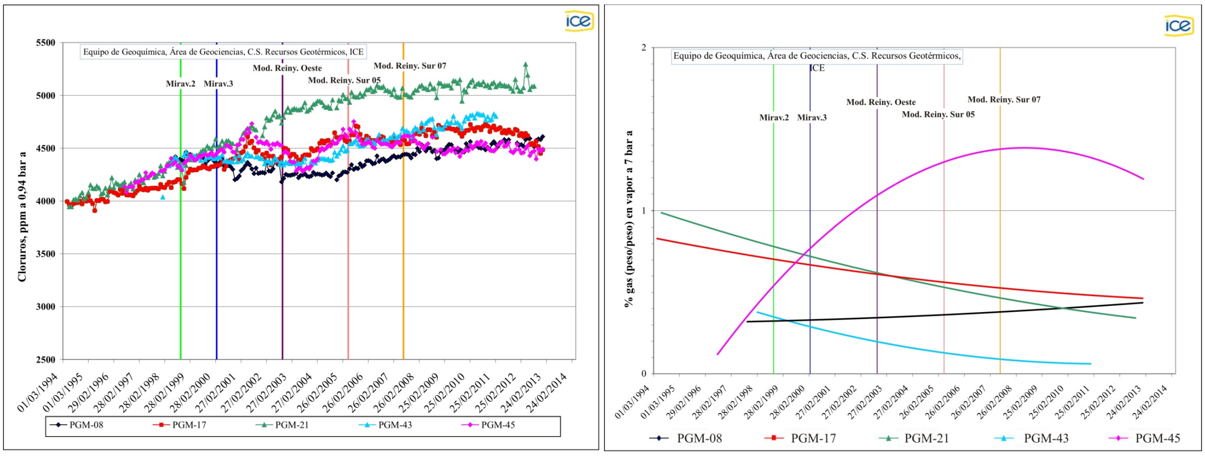

FIGURE 21: Chlorides and Non Condensable Gas Content in Some Miravalles Central Zone Wells

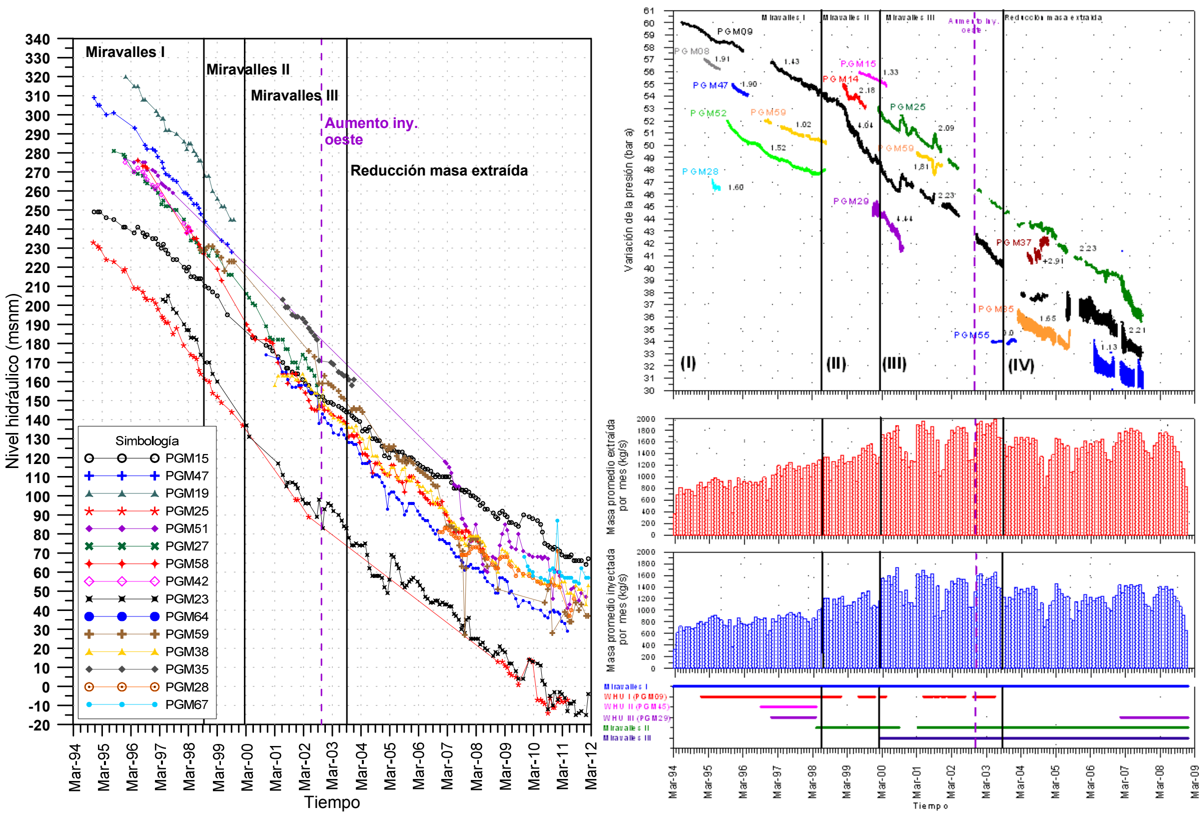

FIGURE 22: Pressure Drop at the Miravalles Field (hydraulic levels and monitoring probes)

The main conclusions of this study were the following (GeothermEx, 20120):

- Wells in the field will continue to cease producing due to high pressure drop in the reservoir under the present conditions of exploitation (Figure 22).

- Modelling results and measured data suggest the increase in the injection rate since 2003 has had a positive impact on the pressure decline rate observed in the reservoir. Pressure decline rate measured in the field has an average decline rate of 1.7-2.0 bar/yr prior to the shift of injection to the western injection wells. After the injection rate was increased in the two western injectors (PGM-22 and PGM-24), the reservoir pressure decline rate has averaged about 1.4 bar/yr (Figure 22).

- Injection into the southern wells has provided little pressure support to the production wells. Measured chloride 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 any significant amount.

- Expect reduced production from the binary unit (unit 5) as the enthalpy in the reservoir is expected to continue to increase (Figure 23).

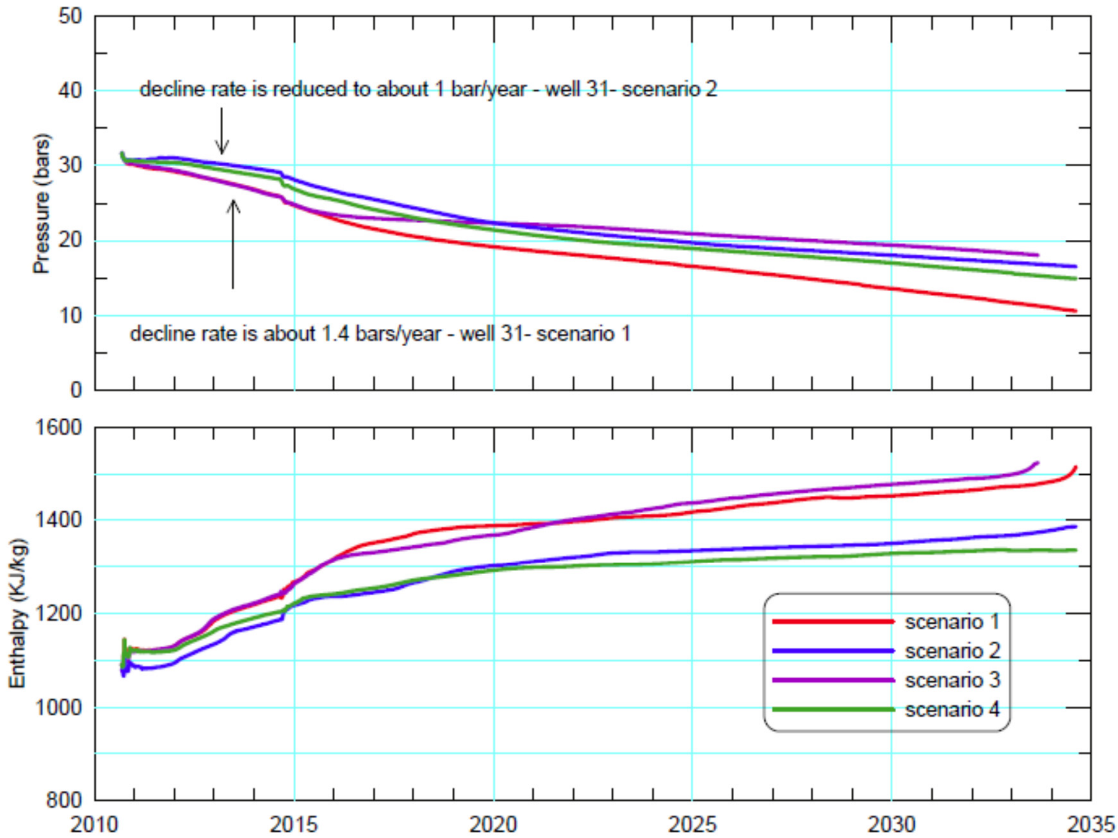

Figure 23: Forecast of Pressure an Enthalpy under different Production Scenarios at Miravalles (2012)

Currently, the northern zone of the field is the most strongly affected by the continuous exploitation of the reservoir. Specific actions are and must be implemented in this part of the field to restore some of the seriously affected wells and to avoid future problems in wells that have not been affected yet. Reduction in the extraction rates during certain periods of the year is done during the rainy season of every year, taking advantage of the peak in production of the hydro power plants. In this period of the year, the main power plants produce 45 MWe each and the binary plant produces about 12 MWe. Among the actions considered is the injection of controlled quantities of water (at 165 ºC) into the northern part of the field. Some former production wells are being prepared in order to become injectors and inject some quantities of water in the near future.

9. FINAL REMARKS

The Miravalles Geothermal Field has completed almost nineteen years of successful exploitation, and the continuous exploration and development that has increased its installed capacity from 55 to 163 MWe.

The installed capacity of geothermal energy accounts for more than 8% of the country's installed capacity, and produces more than 13% of the country's total generation. The Miravalles Complex itself supplies the 11,5% of the total generation of the country. This position must give the sustainability of the Miravalles reservoir an important subject under the energetic planning strategy of ICE.

ICE have implemented different actions focused on sustaining the steam supply to the power plants and also on reservoir management. So far, these actions have been successful in sustaining the production of the field to the actual levels when required by the National Electrical Grid but the Miravalles reservoir faces an actual evolution that has forced to reduce the production in certain times of the year. The reservoir must be carefully monitored in order to avoid a future decline in production and electrical generation.

The actual knowledge of the reservoir and the evolutions trend observed has headed to conclude that the Miravalles field has actually reached its maximum extraction rates. There are still more zones under exploration (east zone, acid aquifer) which can help (and actually does) to solve the production decline observed in the main aquifer, and in a future to evaluate an expansion of the field if it is proven that these other zones are independent and not following the same declining rates of the main aquifer.

In the near future the actions to be taken for ICE in order to stabilize the field production and reach the maximum field productive levels are the following:

- - It should be drilled a limited number of wells in the northern area to supplement the steam rate going to Unit III.

- - An infield injection testing program using wells PGM-01 and PGM-10 should be conduct. The test must be done gradually to avoid watering out nearby production wells (start injecting at a low rate and gradually increase the rate if no adverse impacts are seen). The infield injection should provide more pressure support to production wells and help stabilizing the trend of the produced non-condensable gasses. A test injecting into well PGM-63 started in July 2005, injecting 40 l/s and monitoring the nearby producer wells (water chemistry and occasional temperature and pressure surveys). Further increments in the injection regime (up to 80 kg/s) showed no impact in temperature nor thermal and hydraulic parameters, as the pressure and chlorides parameters in the nearby wells. The test lasted up to August 2006 (Vallejos, 2005(2); González and Sánchez, 2006).

- The noncondensable extraction system at the main power plants (Unit 1 and 2) is actually being upgraded. The capacity will increase in the near future from 1,0 to 2,5% in order to reduce the use of compressors and ejectors(less energy consumption and less steam consumption that can be used in the energy conversion process).

- - The injection fluid from the south should be gradually shifted to the middle and to the west (as much as it is operationally feasible). Unit 5 can continue partial production if a pipeline is built from unit 5 to injection well PGM-24.

- - Wells in the east-south-eastern area of the field should be drilled. This is an unexplored area, and if steam is successfully proven in this area, the produced steam could be sent to Units I and II. Wells could be deviated from PGM-55 or drilled from new pads. The east-southeast zone comprises the wells PGM-28, 29, 59, 55 and 35. From geochemical point of view this sector shows some differences regarding the main and acid reservoirs. The main differences are in the high bicarbonates content and their Na/K relationship, which shows an important difference between the geothermometers and the measured temperatures. Similar differences can be seen in the values of calcium and magnesium. For their characteristics, these fluids present a high tendency to form calcium carbonate deposition and a high non condensable gases content in the steam. The first point has been treated successfully with the correct inhibitor dosage, but the later presents a big restriction in the face of the current non condensable gas extraction capacities Units 1 and 2. This problem has partially been solved since the non condensable gas extraction system of these units is being improved from the actual 1% to 2.5%. Actual and future studies are now oriented to define the dimensions of this aquifer, the stable productive characteristics of their wells and the correct way to handle the high noncondensable gas content (Sánchez et al, 2005 and Cumming et al, 2005). Future drilling in this zone is not intended to increase but to give support to the current production of Miravalles (163 MW)

- - The well deepening program should be continued to investigate further the benefits of tapping fluids from the deep zone in the reservoir. Wells PGM-44, PGM -24, PGM-45and PGM-25 (-1619 m a.s.l.) crossed deep permeable zones but for different reasons there were not considered an important issue at the beginning of exploration in Miravalles. The results in those wells and further analysis showed the existence of a deep aquifer related with the main aquifer of Miravalles (yellow zone in Figure 1) in the zone around -1400 to -1600 m a.s.l. (Sánchez et al, 2010).

REFERENCES

Autoridad Reguladora de los Servicios Públicos (ARESEP). 2012. Estadísticas de generación eléctrica por tipo de fuente: años 2007 al 2011. FUENTE: Empresas del Sistema Eléctrico Nacional y Autoridad Reguladora. (In Spanish).

Acuña, Jorge. 1990. Prueba de interferencia 1990. Área de Ingeniería de Reservorios, Oficina de Desarrollo Geotérmico, Departamento de Recursos Geotérmicos. Instituto Costarricense de Electricidad. (Internal Report). (In Spanish).

Acuña C., Jorge. 1994. Measurement of Injectivity Indexes in Geothermal Wells with Two Permeable Zones. Proceedings of the 19th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, USA. January 1994. pp. 21-26.

Alvarado, G.E.; Kussmaul, S.; Chiesa, S.; Gillot, P.-Y.; Appel, H.; Wörner, G. and Rundle, C. 1992. Resumen cronoestratigráfico de las rocas ígneas de Costa Rica, basado en dataciones radiométricas. J. South Amer. Earth Sci., 6(3), (1992), pp. 151-168. (In Spanish).

Arason, P. and Björnsson, G. 1994. ICEBOX. 2nd Edition. Orkustofnun. Reykjavík, Iceland. 38 pp. (1994).

Axelsson, G. and Arason, P. 1992. LUMPFIT, Automated Simulation of Pressure Changes in Hydrological Reservoirs. Version 3.1, User's Guide. Orkustofnun. Reykjavík, Iceland. 32 pp. (1992).

Castro Zúñiga, Sergio. 1999. Comportamiento de la presión del yacimiento en el Campo Geotérmico Miravalles, Informe semestral II-98. Internal report. Instituto Costarricense de Electricidad, Centro de Servicio Recursos Geotérmicos. Costa Rica. (In Spanish). January 1999.

Corrales, Manuel F. 1985. Costa Rica: Country Update Report. 1985 International Symposium on Geothermal Energy. Geothermal Resources Council. Davis, California, USA. 1985.

Chiesa, S.; Civelli, G.; Gillot, P.; Mora, O. and Alvarado, G. 1992. Rocas piroclásticas asociadas con la formación de la caldera de Guayabo, (Cordillera de Guanacaste), Costa Rica, América Central. Rev. Geol. Amér. Central. 14, (1992), pp. 61-66. (In Spanish).

Cumming, William; Di Pippo, Ronald; Duffield, Wendell; Horne, Roland; Truesdell, Alfred. Report of the Twentieth Meeting of the Miravalles Geothermal Project Advisory Panel. Miravalles Geothermal Field 20th Advisory Consultant Panel Meeting. Costa Rica (In Spanish). March 2005.

Gillot, P.-Y.; Chiesa, S. and Alvarado, G. 1994. Chronostratigraphy of Upper Miocene-Quaternary Volcanism in Northern Costa Rica. Rev. Geol. Amér. Central, 17, (1994), pp. 45-53.

Haukwa, C.; Bodvarsson, G. S.; Lippmann, M. J.; Mainieri, A. 1992. Preliminary Reservoir Engineering Studies of the Miravalles Geothermal Field, Costa Rica. Proceedings of the 17th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, USA. January 1992. pp. 127-137.

Instituto Costarricense de Electricidad. 1976. Proyecto geotérmico de Guanacaste: Informe de preabilidad técnica anexo A: Geología. [informe interno], (1976), p. 130. (In Spanish).

Instituto Costarricense de Electricidad and ELC Electroconsult. 1983. Proyecto Geotérmico Miravalles. Informe geovulcanológico. - [informe interno], (1983), p. 58. (In Spanish).

Instituto Costarricense de Electricidad, ELC Electroconsult. 1986. Proyecto Geotérmico Miravalles: Informe de factibilidad 1a. Unidad. Instituto Costarricense de Electricidad, ELC Electroconsult. Informe GMV-2-ELC-R-12400(R01). San José, Costa Rica. 1986. (In Spanish).

Instituto Costarricense de Electricidad and ELC Electroconsult. 1995. Proyecto geotérmico Miravalles: Informe de factibilidad 3ª. y 4ª. Unidad. Instituto Costarricense de Electricidad and ELC Electroconsult. Report GMV-2-ELC-R-12400(R01). San José, Costa Rica. (In Spanish).

GeothermEx, Inc. 2002. Updated Numerical Simulation of the Miravalles Geothermal Field, Costa Rica. Internal Report. Costa Rica. May 2002.

GeothermEx, Inc. 2012. Updated Numerical Simulation of the Miravalles Geothermal Field, Costa Rica. Internal Report. Costa Rica. April 2012.

González, Carlos and Sánchez, Eddy. 2006. *Informe prueba de inyección en caliente en el pozo PGM-63*. Internal report. Instituto Costarricense de Electricidad, Centro de Servicio Recursos Geotérmicos. Costa Rica. (In Spanish). November 2006.

Milodowski, A.E.; Savage, D.; Bath, A. H.; Fortey, N.J.; Nancarrow, P.H.A. and Shepherd, T. J. 1989. Hydrothermal Mineralogy in Geothermal Assessment: Studies of Miravalles Field, Costa Rica and Experimental Simulations of Hydrothermal Alteration. British Geological Survey, Nottingham NG 12 5 GG. (1989), p. 128.

Pham, Minh; Sanyal, Subir; Granados, Eduardo; Mainieri, Alfredo and González, Carlos. 2000. Numerical Modeling of the Miravalles Geothermal Field, Costa Rica. Proceedings World Geothermal Congress 2000. Japan.

Pruess, Karsten. 1991. TOUGH 2 – A General-Purpose Numerical Simulator for Multiphase Fluid and Heat Flow. Lawrence Berkeley Laboratory, University of California. Report LBL-29400. USA.
Reyes, Agnes G. 1990. Petrology of Philippine geothermal systems and the application of alteration mineralogy to their assessment. Jour. Volc. And Geothern. Res., 43, (1990), pp. 279-309.

Reyes, Agnes G. 2000. Petrology and Mineral Alteration in Hydrothermal Systems: From Diagenesis to Volcanic Catastrophes. Reports 1998, 18, The United Nations University, (2000), p. 76.

Sánchez Rivera, Eddy. and Vallejos Ruiz, Osvaldo. 2000. Practical uses of clay minerals at the Miravalles Geothermal Field, Costa Rica. Proceedings World Geothermal Congress, Kyushu-Tohoku, Japan (2000).

Sánchez, Eddy; González, Carlos and Vega, Eduardo. Campo Geotérmico Miravalles. Aprovechamiento del recurso del sector este – sureste. Miravalles Geothermal Field 20th Advisory Consultant Panel Meeting. Costa Rica (In Spanish). March 2005.

Sánchez Rivera, Eddy; Vallejos Ruiz, Osvaldo; Rodríguez Badilla, Alejandro and Guido Sequeira, Hartman. 2005. Chemical Treatments of Fluids on the Miravalles Geothermal Field: Investigation, Application and its Relationship With Reservoir Management. Proceedings World Geothermal Congress 2005. Turkey.

Sánchez Rivera, Eddy; Vallejos Ruiz, Osvaldo and González Vargas, Carlos. 2010. Maintenance of the Production in the Miravalles Geothermal Field, Costa Rica: New Productive Zones. Proceedings World Geothermal Congress 2010. Bali, Indonesia. (2010).

Vallejos Ruiz, Osvaldo: A Conceptual Reservoir Model and Numerical Simulation Studies for the Miravalles Geothermal Field, Costa Rica. Geothermal Training in Iceland 1996. UNU G.T.P. Report 18. Iceland. pp. 418-456. (1996).

Vallejos Ruiz, Osvaldo. 2005. Lumped Parameter Model of the Miravalles Geothermal Field. Proceedings World Geothermal Congress 2005. Antalya, Turkey. (2005).

Vallejos Ruiz, Osvaldo. 2005(2). *Estudios de inyección en la zona norte del Campo Geotérmico Miravalles*. Internal report. Instituto Costarricense de Electricidad, Centro de Servicio Recursos Geotérmicos. Costa Rica. (In Spanish). January 2005.

Vallejos Ruiz, Osvaldo. 2010. Update of a Lumped Parameter Model of the Miravalles Geothermal Field. Proceedings World Geothermal Congress 2010. Bali, Indonesia. (2010).

Vega Zúñiga, Eduardo. 2000. Patrones de alteración hidrotermal en el campo Geotérmico Miravalles y su correlación con la temperatura. Tesis inédita - Universidad de Costa Rica. (2000), p. 67. (In Spanish).

Vega Zúñiga, Eduardo; Chavarría Rojas, Leyner ; Barrantes Víquez, Manuel ; Molina Zúñiga, Fernando; Hakanson, Edward C. and Mora Protti, Oscar. 2010. Geologic Model of The Miravalles Geothermal Field, Costa Rica. Proceedings World Geothermal Congress 2010. Bali, Indonesia. (2010).