RESERVOIR ENGINEERING STUDIES IN THE LAS PAILAS GEOTHERMAL FIELD, COSTA RICA

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ABSTRACT

The Instituto Costarricense de Electricidad (ICE) has, as part of its exploration strategy, carried out deep drilling in the Las Pailas geothermal field, located on the south flank of the Rincón de la Vieja volcano. This report includes an analysis of data related to reservoir engineering studies, obtained in the four wells drilled during 2001 and 2002. The data include downhole temperature and pressure profiles, injection, fall-off and discharge tests. The temperature and pressure logs permit estimation of reservoir temperatures and initial pressures, and simulation of dynamic conditions in two productive wells. Well parameters estimated a permeability range of 0.1-16.5 mD, the injectivity index varies from 1.5 to 13 l/s/bar and the productivity index range is 1.4-4.2 × 10^{-12} m^3, indicating good characteristics for commercial exploitation.

The Las Pailas is a liquid dominated two-phase reservoir, with temperatures of 220-245°C and a drilled thickness of 600 m. The distribution of reservoir temperatures and pressures suggests that the heat source is located in the west part of the area studied and fluid flows are from west to northeast. The dominant mechanism for heat and fluid transport is fracturing, mainly toward the central part of the reservoir.

Future exploration to quantify production conditions in Las Pailas, should focus on an area within a radius of 1 km of well PGP-01, mainly in a NW-SW direction.

1. INTRODUCTION

1.1 Background

Geothermal investigations started in Costa Rica in 1963 when a group of United Nations' scientists made an initial evaluation of the energy potential in the country (GeothermEx, 2001). Later in the mid 70`s, due to the international oil crisis and need for new energy alternatives, the Costa Rica Electricity Institute (ICE) began geological, geophysical and geochemical studies in the Guanacaste province in the northwest part of the country. Finally, due to factors like a convenient location and accessibility, the Miravalles

Volcano was selected as a primary site for further development. Since 1979 ICE has drilled 55 deep wells in Miravalles and on March 20, 1994 started the production of the first geothermal unit (55 MWe). To date, three condensing units and a back pressure unit (5 MWe) have been installed in Miravalles with a total capacity of 142 MWe. This value represents 12-15% of the total energy consumption of the country. Due to the economic and technical success of the Miravalles project, ICE is presently looking for new geothermal fields to develop; one of the fields actually under investigation is the Las Pailas geothermal field.

1.2 General information

Costa Rica is located in the south part of Central America (Figure 1). Intense volcanic activity in Costa Rica gave rise to three mountain belts in the central part of the country, oriented NW-SE (volcanic arc). The Rincón de la Vieja volcano is located in the Guanacaste volcanic range, in the northwest part of the country, approximately 250 km away from the capital San José, and 25 km northwest of the Miravalles Volcano. Widespread geothermal activity is found in the vicinity of the Rincón de la Vieja Volcano; the actual studies are concentrated on its southern part.
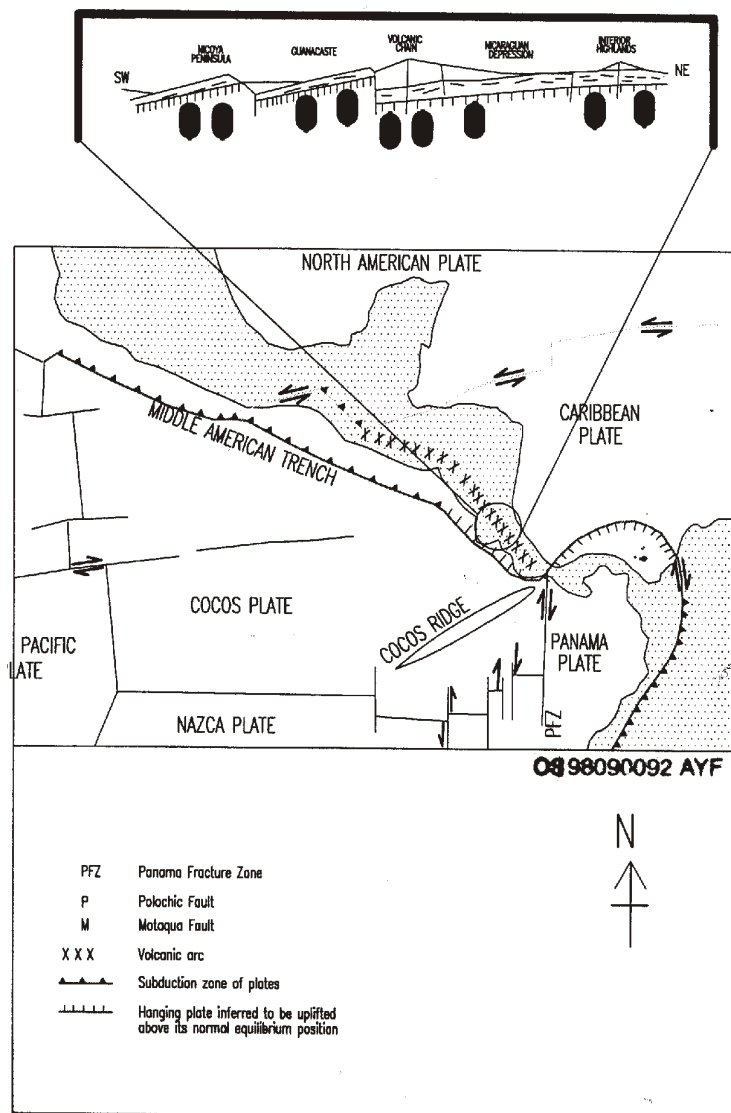

FIGURE 1: Tectonic setting of Central America (Yock, 1998)

As part of the energy strategy of ICE, the drilling of six deep wells at Las Pailas began in January 2001 to verify favourable conditions suggested by a pre-feasibility study (GeothermEx, 2001). Figure 2 shows the location of the Las Pailas wells. Two of the four wells completed at present have shown good temperatures and permeability and are also able to produce fluids of geothermal origin. Table 1 presents the general characteristics of these four wells.

TABLE 1: General characteristics of Las Pailas wells.

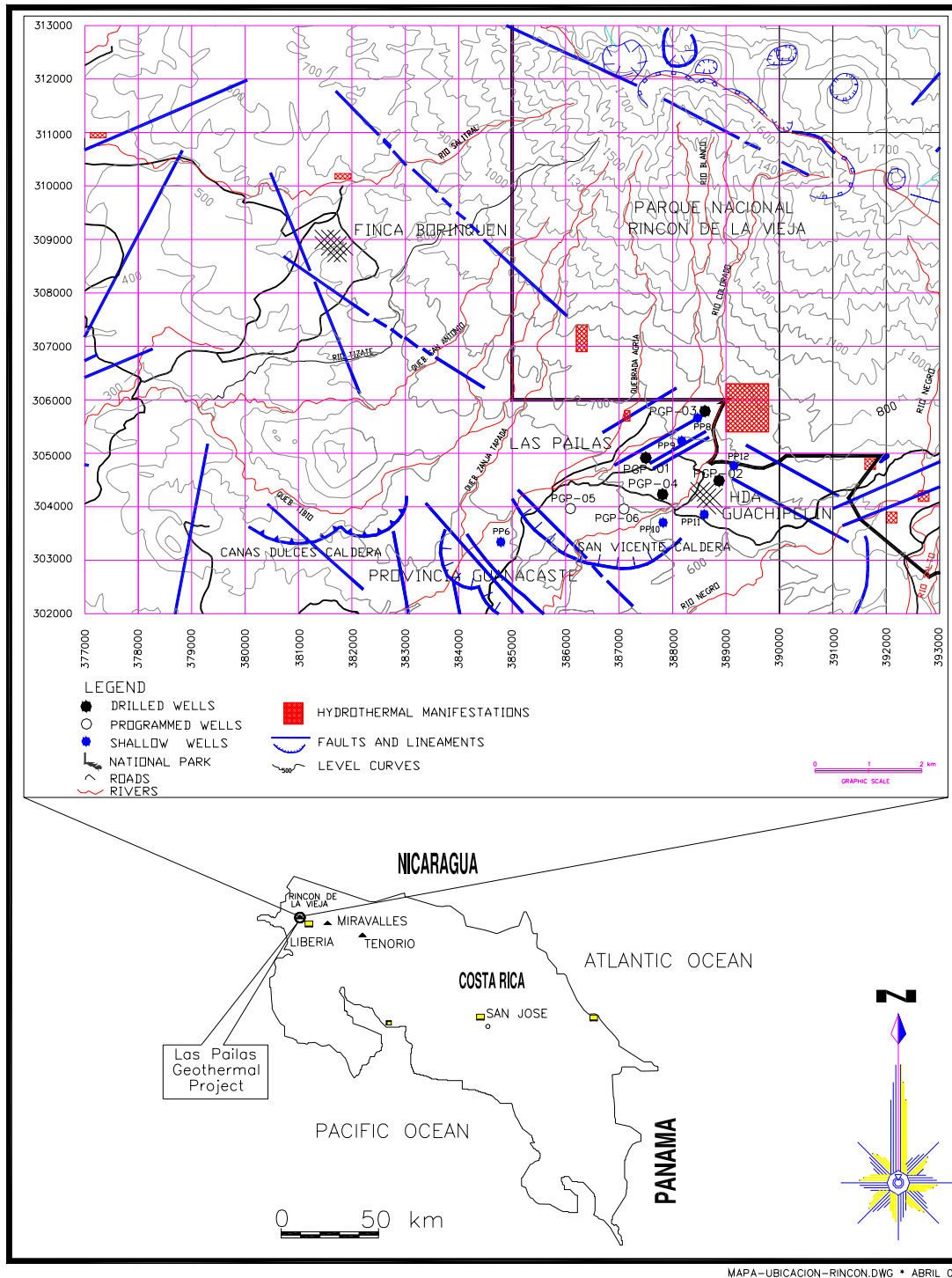| Well no.	Elevation (m a.s.l.)	Eastings (m)	Northings (m)	Depth (m)	Depth of casing shoe* (m)	Top of slotted liner** (m)
PGP-01	659	387500	304915	1418	787	750
PGP-02	676	389870	304480	1764	780	No liner
PGP-03	757	388607	305788	1767	786 (9 ⅝")	763 (7 ⅝")
PGP-04	630	387820	304230	1418	915	900

* Casing shoe 13 ⅜" ** Slotted liner (hanger) 10 ¾"

FIGURE 2:   Structural features and location of wells in the Las Pailas geothermal field

A large part of the geothermal area is within the Rincón de la Vieja national park. On the south flank of the volcano there are two main geothermal prospects, Las Pailas and Borinquén. The studies carried out in this region at present include geologic mapping, structural studies, drilling of shallow wells for determination of the temperature gradient, geochemical analysis of log fluids and thermal springs and geophysical exploration that included gravimetric and geoelectric soundings (Molina, 2000; GeothermEx, 2001).

1.3 Scope of the present study

The purpose of this study is to analyse the reservoir engineering information available in Las Pailas geothermal field, as defined by the individual characteristics of the four deep wells drilled during the last two years, and also to make a collective interpretation of the data to obtain a conceptual model for the field.

2. GEOLOGICAL SETTING

2.1 Location

Central America is situated in the "Circum Pacific Ring of Fire", characterized by abundant seismic and volcanic activity. The most important tectonic characteristic of the region is the collision zone of the Caribbean and Cocos plates, located sub-parallel to the Pacific coast. As a result of this tectonic activity, Central America is rich in volcanoes and geothermal systems (Figure 1).

The Rincón de la Vieja volcano belongs to the Guanacaste volcanic range, and is located between the Miravalles and Orosí volcanoes. It is characterized as the larger volcanic system of the range. It is active. The last active period occurred in November 1995, generating ash deposits, throwing blocks and tephras, with the development of lahars and mud flows toward the Caribbean coast of Costa Rica (GeothermEx, 2001).

2.2 Regional geology

The Rincón de la Vieja is a composite, elliptically formed stratovolcano; it comprises an area of approximately 250 km^2, aligned with nine craters in a northwest-southeast direction (Molina, 2000). The regional geology of the area includes rocks of the Late Mesozoic-Cenozoic that form the basement and includes sandstones, limestones, conglomerates, volcanic sediments, basalts, associate intrusives and peridotites. Later in the Late Pliocene - Early Pleistocene, rocks of the Aguacate group were deposited. These include lavas from basaltic to dacitic, tuffs, volcanic sediments and ignimbrites. After that, during the Early Pleistocene, thick ignimbrites series of Liberia and Bagaces formations were deposited. Finally, starting in the Late Pleistocene and until the Holocene, the actual Rincón de la Vieja volcano became active. It erupts mainly materials of basaltic-andesitic composition, which includes lavas, tuffs, pyroclastic flows, ignimbrites and lahars. On the south part of the volcano are four domes of dacitic-ryolitic composition, called Fortuna, San Roque, Góngora and, San Vicente, and the Canas Dulces and Torre hills, of andesitic composition. The ages of these domes and hills vary between 4.3 and 1 m.y. (Molina, 2000; Arias, 2002).

2.3 Tectonic aspects

The structural settings are dominated by normal faults (GeothermEx, 2001), oriented northwest-southeast, northeast-southwest and north-south (Figure 2). Also identified are several circular depressions that have been interpreted as possible borders of a caldera (GeothermEx, 2001). The main caldera structures suggested in the area are Cañas Dulces and San Vicente; the former is located in the Borinquén area and the latter in the Las Pailas sector. The Cañas Dulces caldera has a diameter of 8-10 km and was formed on the south border by the Cañas Dulces and Torre hills, while the domes San Roque, Góngora and Fortuna are located in the central part of the structure. The San Vicente caldera is clearly defined on the south part, while other borders are not defined.

Arias (2002) proposed a different structural model for this area; the model includes two major strike-slip faults (Cañas Dulces and Las Pailas) with a NW-SE orientation. These faults were probably formed 5 million years ago when the Cocos spreading ridge entered the subduction zone. Associated with these faults are several secondary faults with NE-SW orientation. Furthermore, Arias proposed that only in the area between the Cañas Dulces and Góngora hills can a segment of a collapsed caldera be defined. Finally, he suggested a probable tectonic origin of the annular faults (pull-apart system), without volcanic activity.

2.4 Shallow drillholes

Eleven slim drillholes with depths of 52-350 m have been drilled in the Las Pailas area for determination of a thermal gradient (Molina, 2000; GeothermEx, 2001). The measurements in 5 wells were either too shallow for determining the gradient or internal flow made evaluation of formation temperatures impossible. Temperature logs from 6 other wells are shown in Figure 3. It turns out that wells located in the northeast have high gradients (PP-8, 12 and 9 have values of 300-500°C/km), while wells PP-10 and 11 present an intermediate value (~ 140°C/km). Finally, well PP-6 has a low gradient (60°C/km).
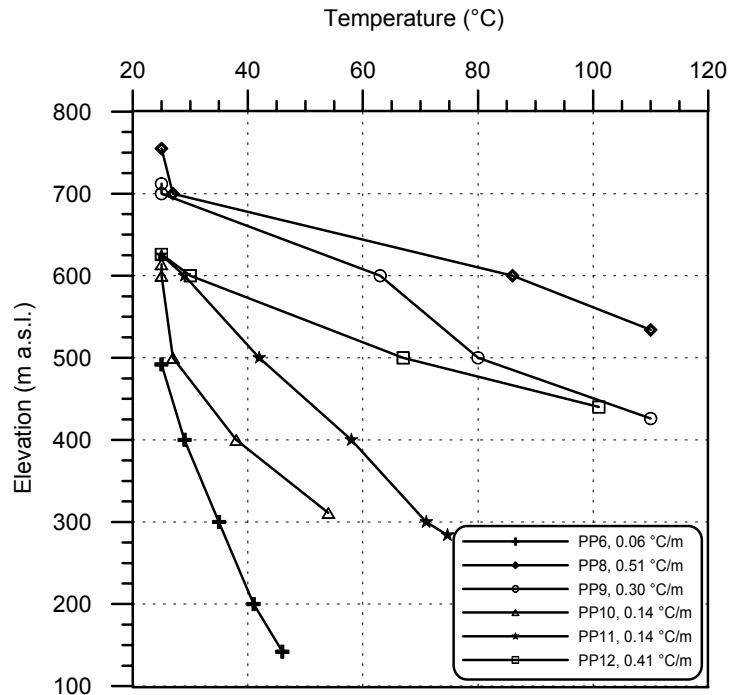

FIGURE 3: Thermal gradient in shallow wells in Las Pailas

2.5 Geochemistry

The geochemical investigations undertaken in the Las Pailas sector included sampling and isotope analysis and chemical analysis of water and gases from thermal springs, fumaroles and wells. The geothermometry of gases indicates a possible reservoir temperature of 275°C for the system, but this value should be associated with an upflow zone and not necessarily with the current zone of exploitation of the reservoir (GeothermEx, 2001).

The early data obtained during discharge tests in wells PGP-01 and PGP-03, show that reservoir fluids are of a neutral, sodium-chloride type and contain a relatively high concentration of total dissolved solids (12,600 ppm). The fluid temperature according to Na-K, Na-K-Ca and silica geothermometers varies between 245 and 275°C and the conductivity varies between 17,000 and 19,000 μS/cm (Sánchez and Torres, 2002). Considering the data obtained and assuming similar conditions in Las Pailas and Miravalles fields, Sánchez and Torres proposed that well PGP-03 is located in a peripheral reservoir zone, while well PGP-01 is located near the centre.

Based on the chemical data analysed in the Las Pailas and Borinquén prospects, GeothermEx (2001) suggested that these prospects are either associated with two different reservoirs, or are associated with a single reservoir with different recharge zones. The recharge zones are located to the north of both areas.

2.6 Geophysics

The geophysical investigations that have been carried out in the Las Pailas and Borinquén prospects include magnetotelluric (MT), DC resistivity surveys (Schlumberger), gravimetry and magnetometry.

Some data are still being analysed and conclusions are not available yet, but others, including the magnetic and gravimetry data, show a sub circular anomaly located in the south-southwest part of the Las Pailas surface manifestations. A low-resistivity anomaly appears inside the San Vicente caldera, evidenced by a top of a highly conductive layer, below 400 m (Molina, 2000; GeothermEx, 2001). These data were used for the location of the first six deep investigation wells in Las Pailas prospect (PGP-01 - PGP-06).

3. WELL TESTING AND DATA SOURCES

3.1 Types of well tests

Several kinds of well tests are generally carried out in the geothermal wells drilled in Costa Rica, with the objective of locating permeable zones, evaluating temperature and pressure in static and dynamic conditions, and for determining the permeability characteristics of the wells. To evaluate these parameters for the reservoir of Las Pailas, ICE designed a plan to evaluate the formation temperature during drilling, using the Horner plot method in the zones that show geologic evidence of medium to high temperature. In all cases the measurements were made during at least a 24 hour drilling interruption.

All downhole measurements were made with Kuster mechanical tools, and include tests for evaluating temperature, pressure transients and injectivity. Other types of geophysical logging such as neutron-neutron, natural gamma radiation and resistivity were not carried out in Las Pailas, as ICE does not posses these kind of tools. After the completion test the well is allowed to recover in temperature and pressure with regular monitoring until a reasonable equilibrium has been established. A short discharge test is then realized to obtain a preliminary output production curve, using the Russel-James method. Also, dynamic temperature and pressure profiles are carried out to obtain the temperature and pressure drawdown in the well. Depending on the well conditions observed in the previous test and the possibilities for managing the brine, further discharge tests are done, this time lasting from a week to one month.

With the four wells drilled in Las Pailas, ICE is presently carrying out a total evaluation of the production conditions of each well. The test programme consists of discharging one well for a month, while injecting the separated water into another, and reservoir pressure monitoring in the others. Due to the time needed to obtain the long-term response of the wells, the results of these tests are not available for this study.

3.2 Methodology for the different tests carried out in Las Pailas

Tests in Las Pailas were carried out using Kuster tools as mentioned earlier. The following methodology was applied for the various tests:

Temperature recovery test was conducted on-site when it was considered necessary to obtain an estimation of formation temperature. These tests are carried out at times when no water losses exist in the respective well. The temperature and pressure tools are located at the depth of interest, normally the maximum depth of the well, and both parameters are monitored for 24 hours.

Profiles for location of permeable zones. Two procedures were applied here. The first included a static profile of temperature and pressure with at least six hours of recovery; the profile included 5 minute stops in 15-30 stations at depths of interest. Later, 20 l/s of water were pumped into the well, and a new temperature and pressure profile was taken in the same stations as in the previous log.

Injection tests. After a water loss zone (> 50 l/s) was encountered in a well, and joined with geological information, a series of measurements were conducted. This included:

1. A temperature profile for location of permeable zones. The purpose of this is to identify the main permeable zone of the well. This depth is determined from the temperature and pressure profiles.
2. Pumping water into the well at three different water flowrates (flow steps), normally 20, 35 and 50 l/s, lasting 5 hours for each step.
3. Finally, the pumping is stopped and the recovery period (fall-off) is monitored for 6 hours.

Dynamics profiles were taken to obtain an estimation of the reservoir pressure, fluid inflow temperature and boiling condition in the well during discharge. The well was opened for discharge, normally at flowrates not exceeding 70 kg/s, and the temperature and pressure tools were lowered into the well and readings taken at depths of interest.

Recovery profiles. After a well was completed and circulation/injection of drilling fluid terminated, several temperature and pressure profiles were taken, normally 1, 2, 4, 8, 16, 32 and 64 days after well completion, in order to determine thermal and pressure conditions of the well and the formations near the well.

Discharge tests were carried out when the recovery profiles showed stable thermal conditions in a well. They consisted of determining a wellhead pressure range during flow and selecting three flow points within that range. At each point the wellhead pressure, lip pressure and liquid fraction (using a V-notch) were measured. Dynamic temperature and pressure profiles were measured for at least one of the wellhead/flow conditions, for estimating pressure drawdown, inflow temperature (enthalpy) and location of the boiling zone. If flashing occurred within the casing these data estimated the production capacity of each well.

4. ANALYSIS OF DOWNHOLE TEMPERATURE DATA

Temperature is one of the most important parameters in evaluating conditions in geothermal wells during drilling and after completion. To increase the accuracy of the temperature measurements, the Kuster tools are calibrated regularly. Furthermore, in the majority of the tests in Las Pailas two different elements were used to increase the reliability of the measurements.

Thermal conditions in wells are often affected by different phenomena like cooling during drilling and injection tests, internal flow in shut-in wells and discharge in flowing ones. In this chapter, all available downhole temperature data obtained in Las Pailas for estimating the undisturbed formation temperature of each well will be analysed.

4.1 Theoretical analysis of warm-up temperatures

The temperature of the rock formation is a fundamental parameter to define the properties of a geothermal reservoir. However, due to the cold fluid circulation during the drilling process and other disturbances, it can be difficult and sometimes impossible to measure the formation temperature directly (undisturbed conditions). The computer program BERGHITI was developed in Orkustofnun (Helgason, 1993) to make predictions about the formation temperature based on either temperature logs taken during drilling interruptions, or a collection of such logs during the warm-up period after completion. BERGHITI offers two methods of calculation, the Albright method and the Horner plot. These can be briefly described as follows:

The Albright method was developed by Mr. James Albright at the Los Alamos National Laboratory (Arason and Björnsson, 1994). The method applies for a direct determination of bottom-hole formation temperatures during interruptions in drilling operations. The method assumes for an arbitrary time

interval, much shorter than the total recovery time, that the rate of temperature relaxation depends only on the difference between the borehole and the formation temperatures. Assume that a thermal recovery profile consists of 100 data points. Furthermore, assume that an exponential fit can be made for every subset of 5 data points, thus suggesting a formation temperature $è_g$ and a fit parameter c, for each subset. If analysis finds a solution the result is a set of $(è_g, c)$ values which can be plotted as a straight line where the intercept at $c=0$ equals the true formation temperature.

The Horner plot method is a simple analytical technique for analysing maximum bottom-hole temperatures to determine the formation temperature. The basic criterion for the technique is the straight-line relationship between the maximum bottom-hole temperature and the natural logarithm of a relative time t, where t is defined as

$$t = \frac{\Delta t}{\Delta t + t_o} \tag{1}$$

with Δt = Time passed since circulation stopped;
t_0 = Circulating time.

The *Lim ln(t) equals zero* when $\Delta t \to \infty$. Using this mathematical condition and the fact that the system must have stabilized after infinite time, we plot the maximum bottom-hole temperature as a function of *ln (t)*. These data are used to draw a straight-line and after that extrapolate the value where *ln (t) = 0*. This is the formation temperature.

4.2 Estimation of formation temperature during drilling

The methods mentioned above were applied to the available field data in order to estimate the formation temperature in wells PGP-02 and PGP-03, during drilling interruptions. The estimation of temperature in both wells is in accordance with other formation temperature estimates. In well PGP-02, data from a test at 786 m was analysed. The best results were obtained with the Horner plot method, suggesting a formation temperature of 200°C, while formation temperature estimate from warm-up data (Table 2) at this depth is 196°C (Figure 4).
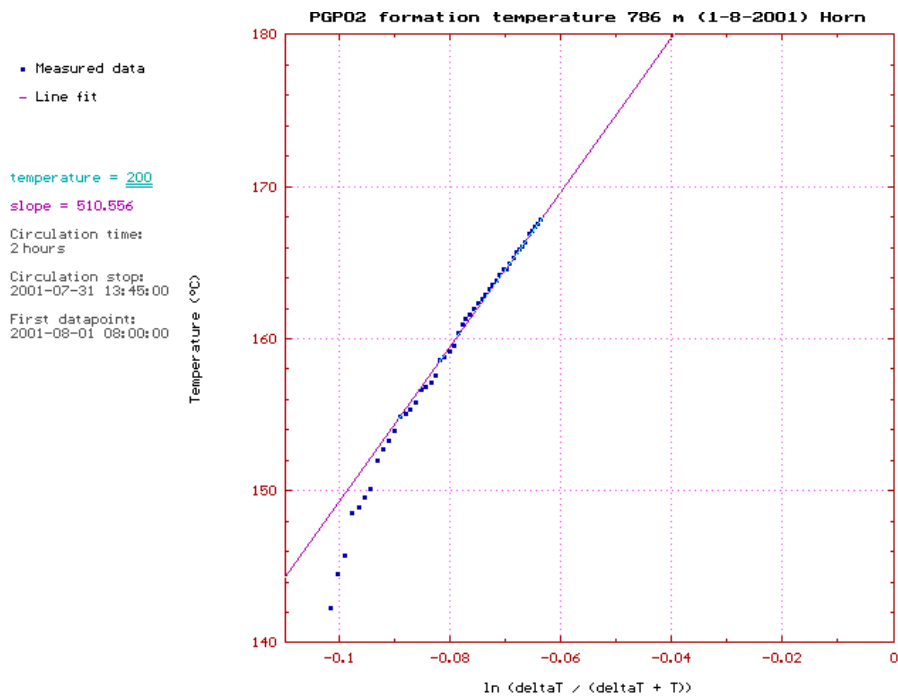

FIGURE 4: Formation temperature at 786 m depth in well PGP-02

In well PGP-03 the depth of the recovery test was 701 m. Similar to PGP-02 the best result was obtained using Horner plot; the calculated temperature was 220°C, while warm-up data (Table 2) suggested 218°C as formation temperature at this depth (Figure 5).
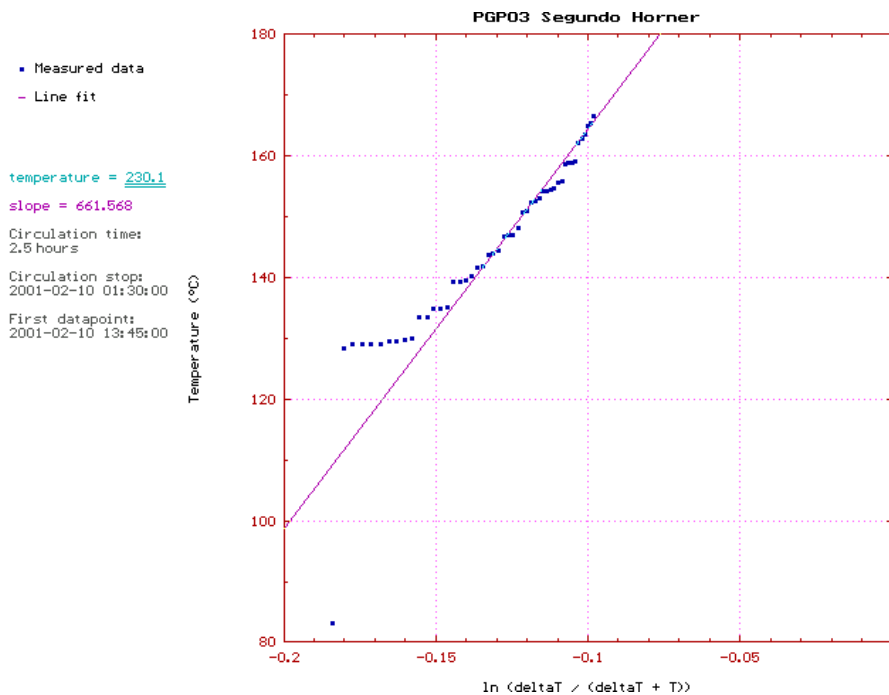
FIGURE 5:   Formation temperature at 701 m depth in well PGP-03

4.3 Downhole temperature conditions

Data obtained during the recovery period for each well was analysed in order to estimate the formation temperature profile. The analysis included the Albright and Horner methods. Numerical values of formation temperature estimates for all wells are listed in Table 2.

TABLE 2:   Estimated formation temperatures and initial pressures for Las Pailas wells

PGP-01			PGP-02			PGP-03			PGP-04		
Elevat. (m a.s.l.)	Press. (bar-a)	Temp. (°C)	Elevat. (m a.s.l.)	Press. (bar-a)	Temp. (°C)	Elevat. (m a.s.l.)	Press. (bar-a)	Temp. (°C)	Elevat. (m a.s.l.)	Press. (bar-a)	Temp. (°C)
600		40	600		50	600		74			
450		68	450		90	450		122			
300		99	300		131	300		165	300		58
150	9.74	130	150	8.91	170	150	9.28	195	150	8.47	102
0	23.31	160	0	22	186	0	21.92	215	0	22.35	140
-150	36.37	201	-150	34.88	198	-150	34.30	225	-150	35.76	174
-300	49.10	204	-300	47.61	206	-300	46.55	230	-300	48.67	208
-500	65.86	219	-450	60.25	210	-450	58.75	232	-420	58.69	220
-700	82.18	241	-600	72.83	214	-600	70.99	228	-600	73.51	228
-744	85.71	243	-750	85.28	226	-750	83.28	228	-750	85.81	228
			-900	97.48	240	-900	95.51	236			
						-1008	104.21	244			

PGP-01: Drilling of PGP-01 was carried out from November 2001 to January 2002, to a final depth of 1418 m (Mora and Herrera, 2002). Figure 6 presents a plot of the temperature profiles taken at the completion of the well (locating the feed zones), and a selection of the temperature profiles taken during 72 days after well completion (González, 2002). An estimation of the formation temperature is also
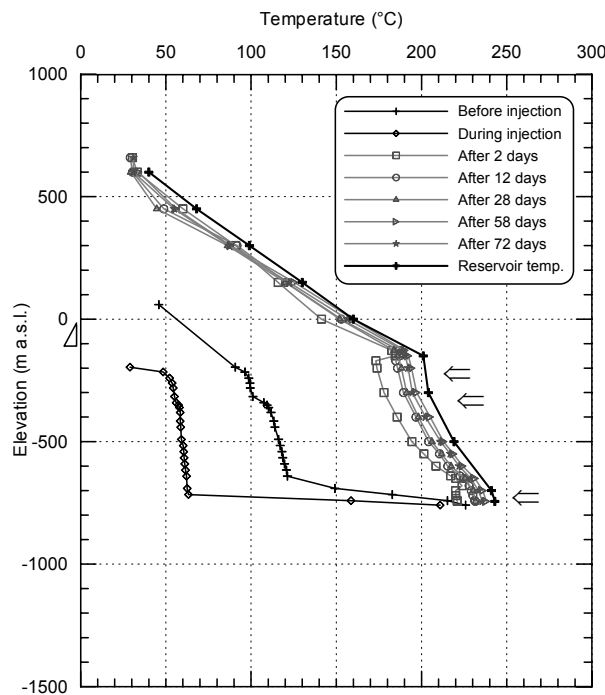
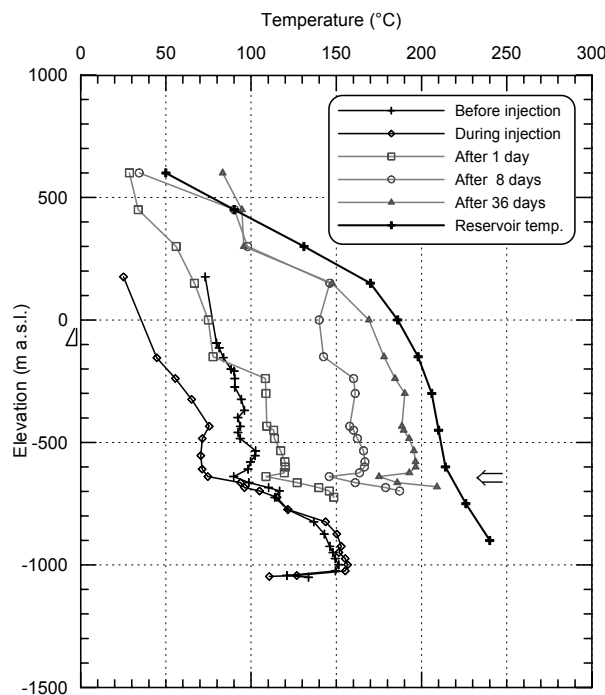FIGURE 6:   Temperature profiles in well PGP-01

included on the figure. The profiles taken during drilling show water loss into the formation at −220, −330 and −700 m a.s.l. In agreement with the drilling data, the most important permeable zones were located at −220 and −700 m a.s.l. A thermally conductive zone is located above −150 m a.s.l. (cap rock), while a convective zone, not totally developed, exists between this depth to at least −720 m a.s.l. The recovery profiles show that the maximum temperature is found at the bottom of the well (243°C).

PGP-02:   Drilling activities in PGP-02 were completed in October of 2001, after 99 days of drilling (Herrera and Mora, 2002a). The maximum depth was 1764 m. Due to numerous problems of formation stability, the drilling activity was stopped with an access depth of only 1608 m. No slotted liner was inserted into the well. The recovery period was frequently disturbed by injection of water from discharge tests of wells PGP-01 and PGP-03. The determination of formation temperature in well PGP-02 is therefore not totally accurate using the Albright and Horner methods; the estimation was also done using information obtained during several static profiles and other criteria such as geologic data and information of nearest wells. The temperature profiles are presented in Figure 7, and also included the temperature profiles for location of permeable zones in the well (Castro, 2002). Profiles taken during drilling show water loss zones at −650 and −1050 m a.s.l. The last one is, however, not accessible due to the stability problems mentioned above. A conductive zone is located above 150 m a.s.l., and a convective zone that is not fully developed, can be defined in the range 150 to at least −900 m a.s.l.

PGP-03: Drilling was completed in May of 2001 at a final depth of 1767 m (Mora and Herrera, 2001). The temperature recovery profiles can be divided into two groups. The first group is the normal recovery period and contains 4 profiles taken during the first month; after that the well was open to production for 4 days. After this a new

FIGURE 7:   Temperature profiles in well PGP-02

period of recovery starts, where 3 profiles were taken during 2 months of recovery (Castro and González, 2001). Figure 8 includes also the estimation of the formation temperature. During drilling, the static and injection profiles show water loss zones at −300, −550 and −820 m a.s.l.   The zones with faster temperature recovery are located in the range −100 to −300 and −500 to −800 m a.s.l., while in the range −300 to −500 and below −850 m a.s.l. recovery is slower. This condition can be explained by considering that zones without important permeability are less affected by the drilling process. The thermally conductive zone is located above 0 m a.s.l., and the convective zone extends from 0 down to at least −1000 m a.s.l.
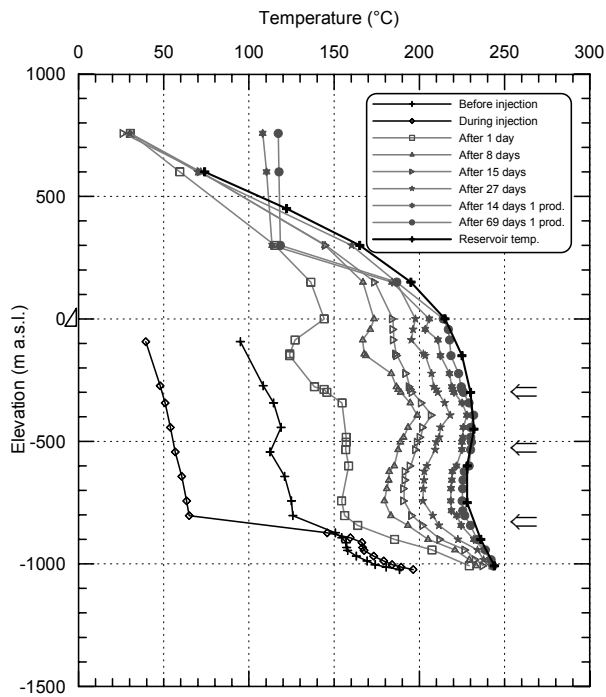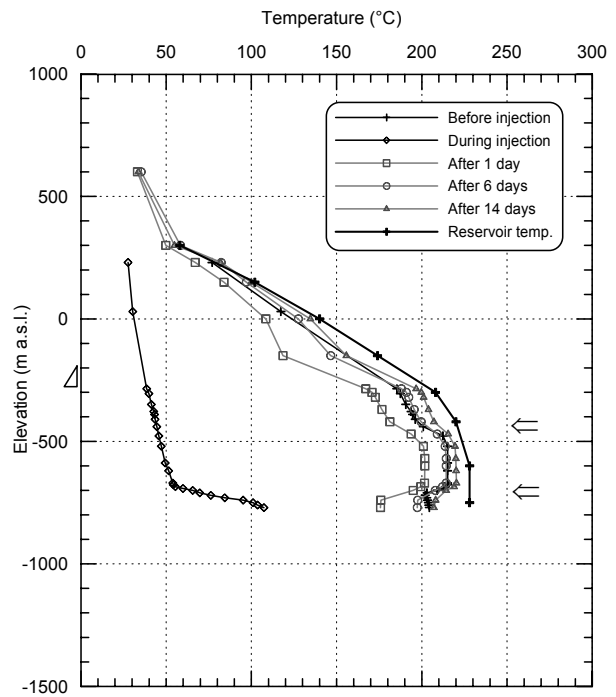
FIGURE 8: Temperature profiles in well PGP-03   FIGURE 9: Temperature profiles in well PGP-04

PGP-04: Drilling of this well was completed in June, 2002 at a depth of 1418 m (Herrera and Mora, 2002b). Figure 9 shows a plot of the three temperature recovery profiles taken before the well started to be used for monitoring reservoir pressure during comprehensive tests of the other wells at Las Pailas (González and Vallejos, 2002). For this reason the estimation of formation temperature only partially used the Albright and Horner methods; the estimation of temperatures were calculated based on geological data, information from other deep wells and on dynamic temperatures and enthalpy obtained during a short well production. Water loss zones encountered during drilling were located at –420 and –680 m a.s.l.; faster thermal recovery was located in the bottom of the well associated with the main permeable zone. The temperature profile above –300 m a.s.l. is conductive but convective in the range –400 down to at least –750 m a.s.l., in agreement with the presence of permeable zones.

5. ANALYSIS OF STATIC AND TRANSIENT PRESSURE DATA

5.1 Initial pressure conditions

Pressure logs obtained before well completion and during the recovery period after drilling in Las Pailas wells are presented in Figures 10, 11, 12, 13 and 14. Pressure profile analyses show a pivot point located between –400 and –700 m a.s.l. in all wells, confirming that the main permeability in the reservoir is within these depths. The data are in agreement with temperature profiles that show the convective zone in the four wells can be defined in the range 150 down to at least –1000 m a.s.l.

The estimated reservoir temperature discussed in Chapter 4, and the PREDYP program (Arason and Björnsson, 1994) were used to obtain the reservoir pressure. The program computes pressure in a static water column with known temperature. Also required for the calculations is the water level (or wellhead pressure), which is adjusted in calculations until the calculated profile matches the pivot point pressure, as is shown in Figure 13 (Arason and Björnsson, 1994). Table 2 presents numerical values of initial pressures for Las Pailas wells.
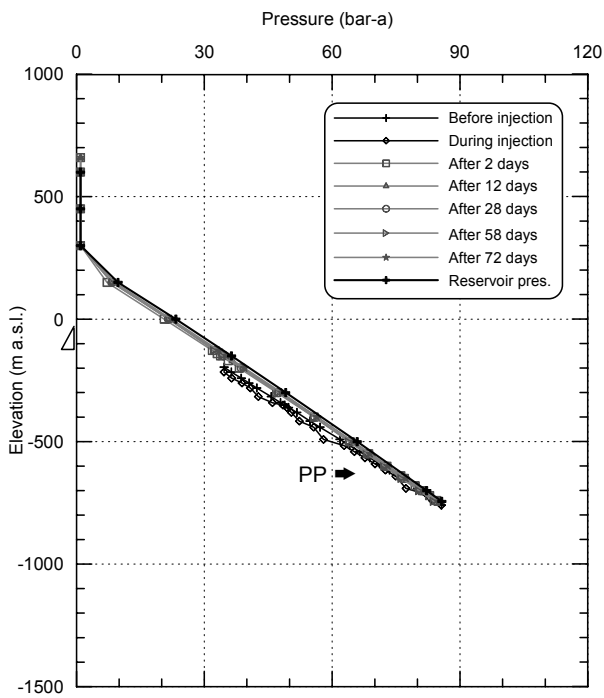
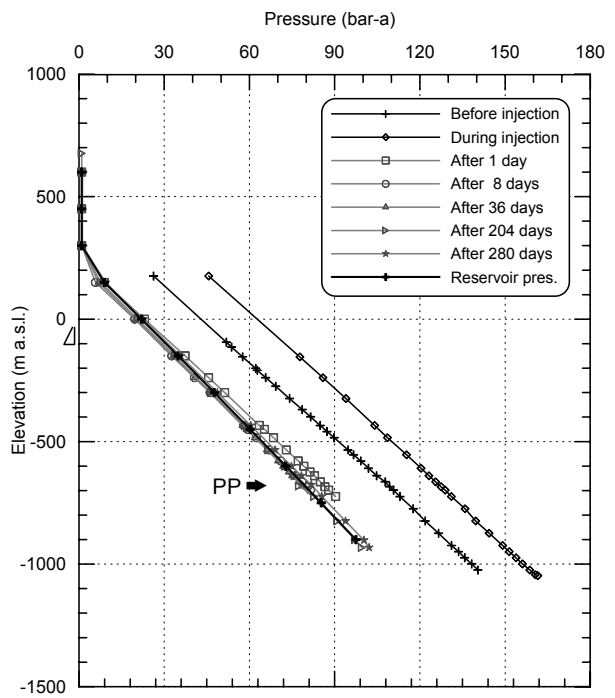FIGURE 10: Pressure profiles in well PGP-01
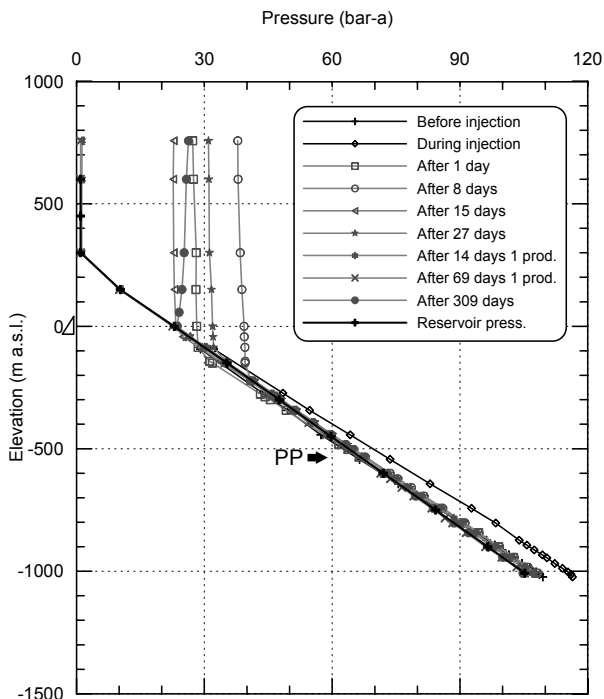
FIGURE 11: Pressure profiles in well PGP-02

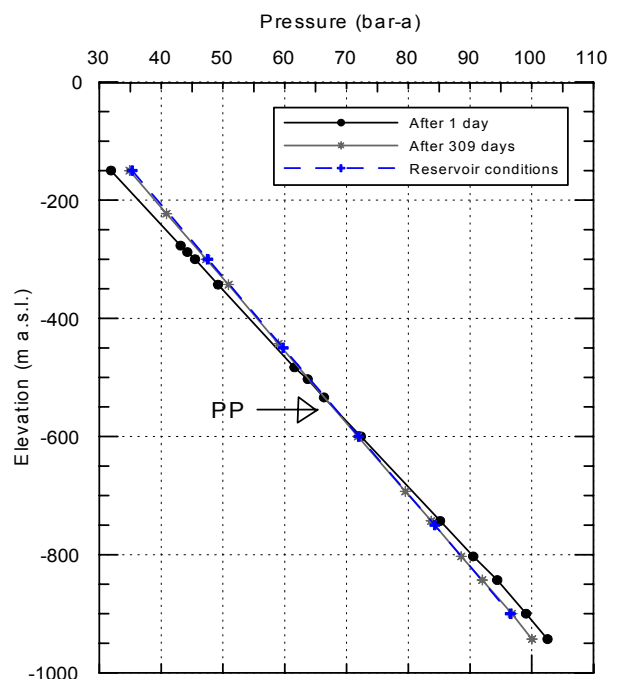FIGURE 12: Pressure profiles in well PGP-03

FIGURE 13: Pivot point determination in well PGP-03

5.2 Pressure transient analysis

Production or injection tests cause pressure disturbances that can be measured; these are provided by an impulse (usually a change in flowrate). The reservoir response is governed by parameters such as permeability, skin effect, storage coefficient, distance to boundaries, fracture properties, etc. (Horne,

1995). Well test interpretation is related using a mathematical model, based on the equation of pressure diffusion in a porous medium fully saturated by a slightly compressible fluid. The following assumptions are necessary for making the data analysis (Horne, 1995):

a) Darcy's Law is applicable;
b) Porosity, permeability, viscosity and compressibility are constant;
c) Fluid compressibility is small (this is usually not valid for gases);
d) Pressure gradients in the reservoir are small (this may not be true in high rate wells or for gases);
e) Flow is single phase;
f) Gravity and thermal effects are negligible.

The pressure diffusion equation is written for radial flow as (Sigurdsson, 1999; Horne, 1995):

FIGURE 14:   Pressure profiles in well PGP-04

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial P}{\partial r}\right] \quad = \quad \frac{\phi\mu c}{k}\frac{\partial P}{\partial t} \tag{2}$$

where P = Pressure;
            r = Radial distance from injection/production well;
            t = Time;
            ϕ = Medium porosity;
            c = Reservoir compressibility;
            k = Permeability; and
            μ = Dynamic viscosity of water.

It describes isothermal flow of fluid in porous media where a well is producing or injecting at a constant rate. After several mathematical procedures, which can be found in Sigurdsson (1999), Equation 1, often known as the Theis solution, is transformed to

$$P(r,t) \quad = \quad P_i + \frac{2.303q\mu}{4\pi kh}\left[\log\left(-\frac{\mu c_t r^2}{4kt}\right) + \frac{\gamma}{2303}\right] \tag{3}$$

where γ = Euler constant = 0.5772;
            h = Reservoir thickness;
            r = Distance;
            q = Production/injection rate.

Equation 3 is found to hold accurately for

$$t \quad \geq \quad \frac{100\mu c_t r^2}{4k}$$

It describes pressure drawdown at distance r at time t when a well is producing/injecting at a constant rate in a radial reservoir model.
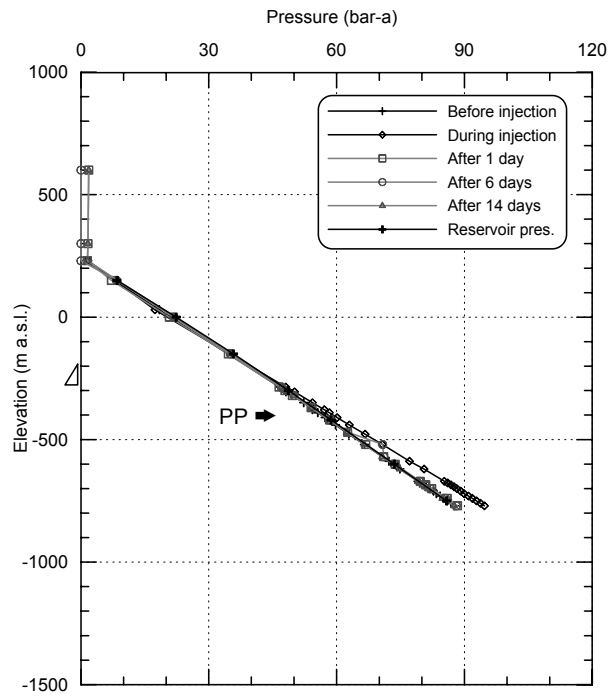
Equation 3 can be rearranged as $\Delta P = A + m \log t$. Plotting the pressure change against time on a semi-logarithmic scale yields a straight line of slope m and constant A. Re-arranging terms we obtain for reservoir transmissivity (kh/μ):

$$\frac{kh}{\mu} = \frac{2.303\,q}{4\,\pi m} \tag{4}$$

If the reservoir temperature and hence viscosity μ is known, Equation 3 can be re-arranged to give the permeability-thickness (kh). And finally, it is possible to assume an average thickness for reservoir to obtain an estimate for the intrinsic reservoir permeability (k).

With the data obtained in transient pressure tests in the field, during injection, build-up and fall-off tests, it is possible to estimate the reservoir parameters mentioned above. These parameters are important for evaluating whether well productivity is governed by wellbore effects (such as skin and storage) or by the reservoir at large. In fact, the conductivity or permeability-thickness product (kh) governs how fast fluids can flow to the well. Hence, it is a parameter that we need to know to design well spacing and the number of wells (Horne, 1995).

5.3 Injection tests and injectivity index determination

Figures 15-18 present injection tests carried out in the Las Pailas wells. In the figures it can be observed that pressure stabilization did not occur in all cases during the time allocated for the tests and also that the time used in the fall-off test, approximately 6 hours, was not enough to obtain total stabilization. Only well PGP-04 exhibits a good theoretical response in all flow steps and during the fall-off, while PGP-02 did not stabilize during the fall-off, and PGP-01 and PGP-03 shows a fast stabilization during fall-off, but some data show an irregular response that could be considered as possible induced fracturing, or indicate that it was necessary to give more time for stimulation to the wells.

The injectivity index for each well is determined by plotting for each flowrate of the injection test the difference between the stabilized pressure (after 5 hours) and the initial pressure (without injection) against the
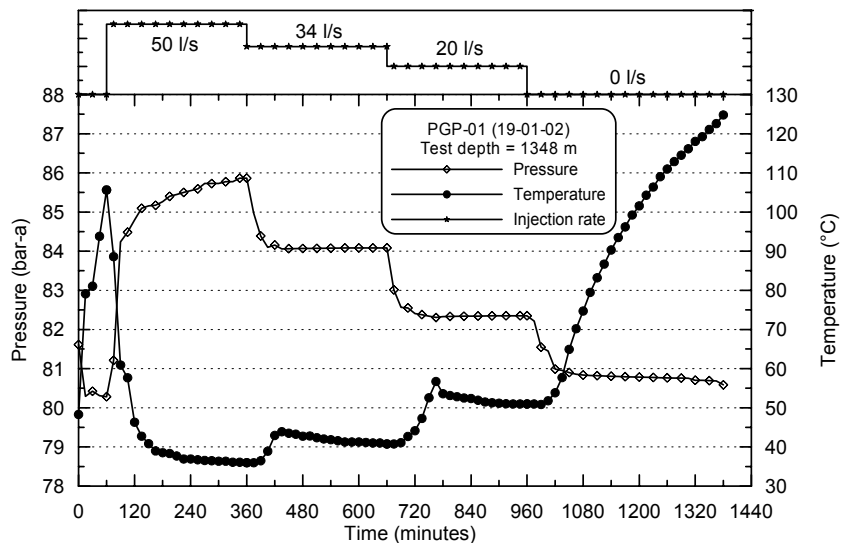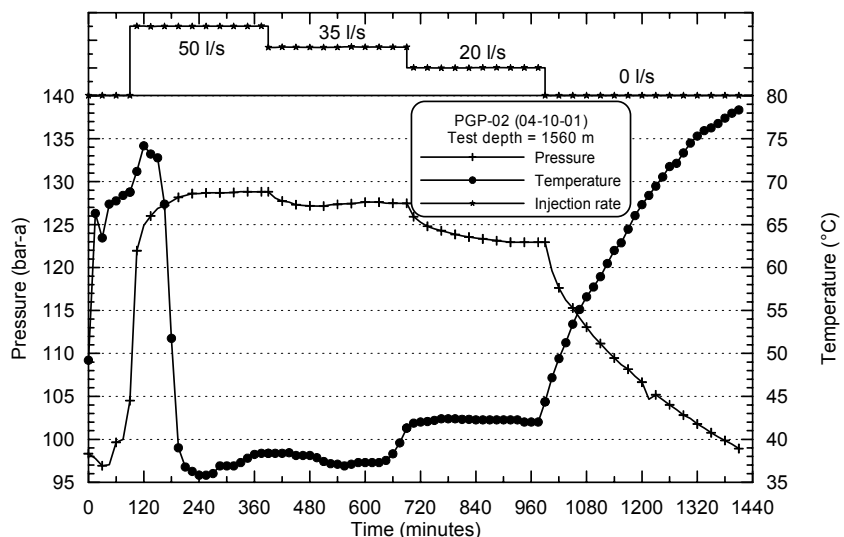

FIGURE 15: Injection test in well PGP-01

FIGURE 16: Injection test in well PGP-02

respective flow (Figure 19). For each well, 3 points exist that are united by the straight line of better adjustment; slope "m" represents the maximum value of the injectivity index of the well. If additionally a fourth point is considered (0 volume, 0 change of pressure) and a new straight line of better adjustment is traced (see data of PGP-03 in Figure 19), another value is obtained for the injectivity index, that in this case shows the minimum value of the index. The injectivity index that represents the conditions of the well varies between these two values. It is noticeable that only in wells PGP-01 and PGP-04 are both values similar. In PGP-02 and PGP-03, the determination had a wide range (Table 3).
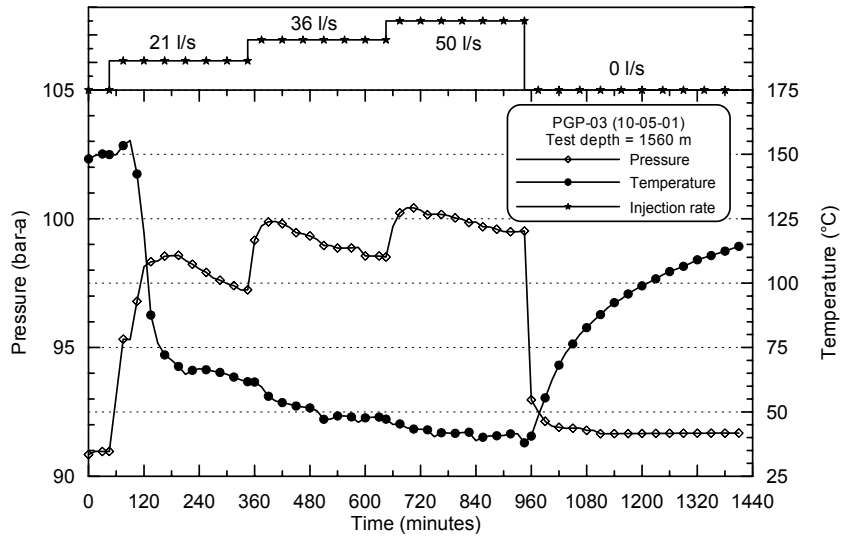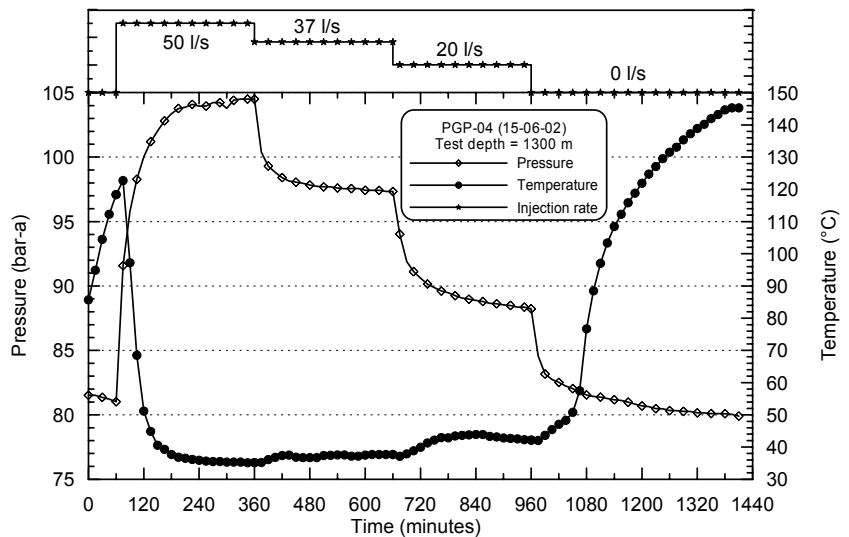

FIGURE 17: Injection test in well PGP-03

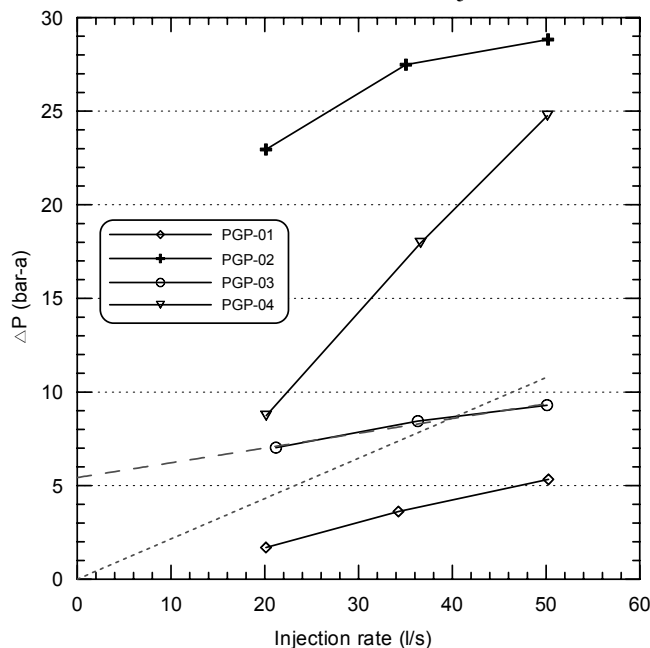FIGURE 18: Injection test in well PGP-04

FIGURE 19: Curves for determination of injectivity index in Las Pailas wells

5.4 Transmissivity determination for Las Pailas wells

Data available for analysis were obtained during injection and fall-off tests, as part of a short-term completion program. After studying the results for both cases, it was decided that fall-off data was better suited for interpretation than the data of individual flow steps. The procedure for the test analysis was as follows (Odeny, 1999):

a) The pressure change during fall-off was plotted against Horner time on a logarithmic scale;
b) Slope (*m*) of the straight portion of the graphs was calculated, considering the change in pressure over one log cycle of time;
c) Substituting for the parameters in Equation 3, to estimate transmissivity, conductivity and permeability. Presumptions are an average reservoir thickness of 600 m (according to the convective interval in the reservoir temperature profiles) and a reservoir temperature of 245°C, corresponding to a dynamic viscosity of 1.1×10^{-4} kg/m/s.

A summary of the analysis for each well is presented in the next section. Figure 20 shows the curves that were used to obtain the values for parameters reported in Table 3.
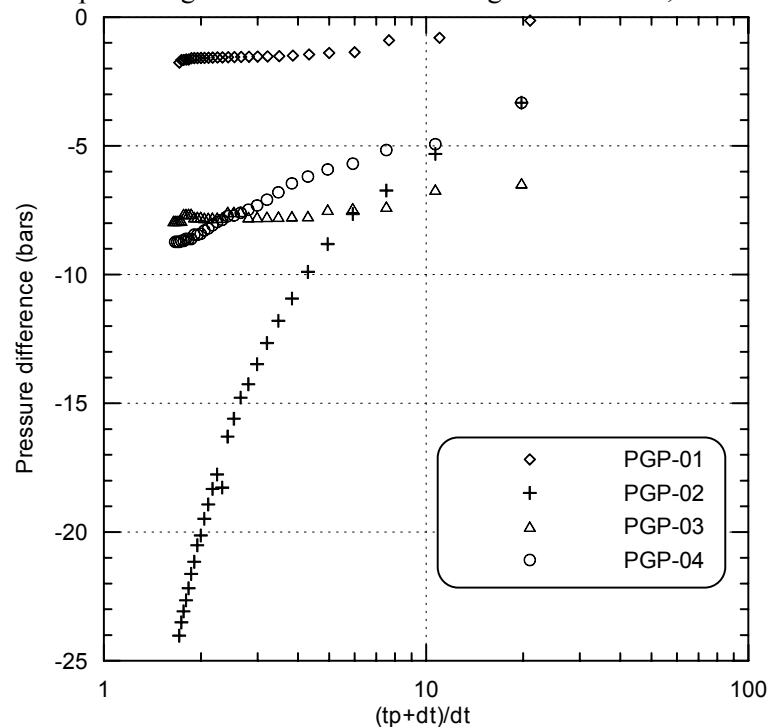

FIGURE 20: Pressure fall-off analysis for Las Pailas wells

PGP-01: In this well, the pressure data obtained show moderate stabilization during the second and third flow step and during the fall-off. The last points of the fall-off show a decrease in the pressure that can be associated to a possible increase in permeability (Figure 15). The transmissivity of PGP-01 is the second highest in the wells studied. Others parameters are defined in Table 3. These values are in agreement with the high injectivity index and the good discharge characteristics of the well (Chapter 6).

PGP-02: Well PGP-02 was in the process of stabilization during fall-off and during the last points it was not completely stabilized (Figure 16). However, it is clear that its reservoir permeability is the lowest of all the wells, possibly as a consequence of drilling problems found in the deepest part (Chapter 4.3). The low permeability is seen in the parameters reported in Table 3 and in the low injectivity index, near to 2, similar to the minimum value reported in the same table, which probably represents the real conditions of the well.

PGP-03: Pressure data obtained in tests show poor stabilization during injection, but fast stabilization during fall-off (Figure 17). The transmissivity value obtained was the highest for the four wells and also the injectivity index showed a high value (higher than 5 l/s/bar). In addition, several discharge tests have been showing an improvement in production characteristics with time (Table 3), confirming good permeability conditions of the well, and possible stimulation during the flow tests.

PGP-04: The well pressure measured during the flow steps and during the fall-off shows good stabilization, defining on the Horner plot a straight line in the last part of the measurement (Figure 18). The transmissivity and other parameters obtained are low, similar to PGP-02. The well had a low injectivity index, only around 2 l/s/bar, in agreement with the low permeability.

TABLE 3:   Summary of well test analysis

Well	PGP-01	PGP-02	PGP-03	PGP-04
Type of test	Fall-off	Fall-off	Fall-off	Fall-off
Location of Kuster tool (m)	1418	1315	1560	1300
Δq (kg/s)	0.02	0.02	0.05	0.02
$m \times 10^5$ (Pa/cycle)	1.02	58	0.65	6.25
$kh/\mu \times 10^{-8}$ (m³/s/Pa)	3.6	0.06	14.1	0.59
kh (Dm)	4	0.07	15.5	0.65
k (mD)	6.6	0.11	25.8	1.08
Injectivity index (l/s/bar)				
Max.	10.2	5.1	12.7	2.1
Min.	8.6	1.4	4.6	1.9

6. PRODUCTION CONDITIONS

6.1 Discharge testing

In Las Pailas, long-term discharge tests have been carried out in wells PGP-01 and PGP-03. The production characteristics were evaluated using the Russel-James method. It consists of measuring wellhead pressure, critical-lip pressure and water flow from a silencer. The method is based on the relationship that exists between the flowing pressure at the end of a horizontal pipe of constant diameter discharging to a silencer open to atmospheric pressure, enthalpy and the flow rate in the pipe. The separate water is measured in a V-notch weir of 90° angle (Arason and Björnsson, 1994; Amdeberham, 1998).

Due to problems, mainly associated with the disposal of silencer water, wells PGP-03 and PGP-01 have only been tested for short periods, and well PGP-04 was tested only once for a few hours. Table 4 shows characteristics in maximum flowrate conditions of the tests performed and the results obtained.

TABLE 4:   Summary of production tests in Las Pailas wells

Well no.	Date	Duration (days)	Lip pipe diam. (mm)	WHP (bar-a)	Mass (kg/s)	Enthalpy (kJ/kg)	Water (kg/s)	Power (MWe)
PGP-01	05-02-02	4	225	9.1	99	1120	79	9.2
PGP-03	14-06-01	4	185	4.4	28	970	25	1.7
PGP-03	12-09-01	14	185	5.4	32	1140	25	3.2
PGP-03	16-10-01	2	185	5.9	35	1120	28	3.2
PGP-03	10-01-02	7.5	185	6.2	35	1160	27	3.6
PGP-04	06-06-02	3 hours	225	5	47	1091	38	4.0

The electric power potential was calculated supposing a 7 bar-a separation pressure and a turbine with an efficiency of 2.22 MWe/kg/s.

PGP-01: This well is the best producer in Las Pailas. It was opened to discharge tests for four days at variable conditions of wellhead pressure. Despite the short duration, good stabilization was obtained in each flowstep. Calculated enthalpy is higher than that indicated by the dynamic downhole temperature of the well (Figure 21), suggesting a contribution of vapour phase to the fluids produced above the flashing point. Figure 22 shows the output curve of the well.
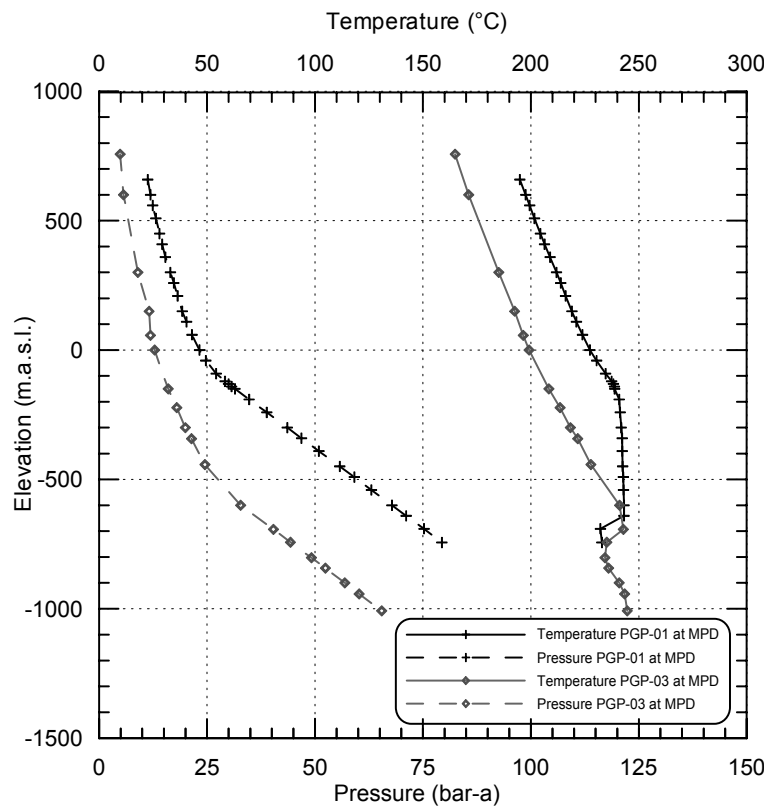
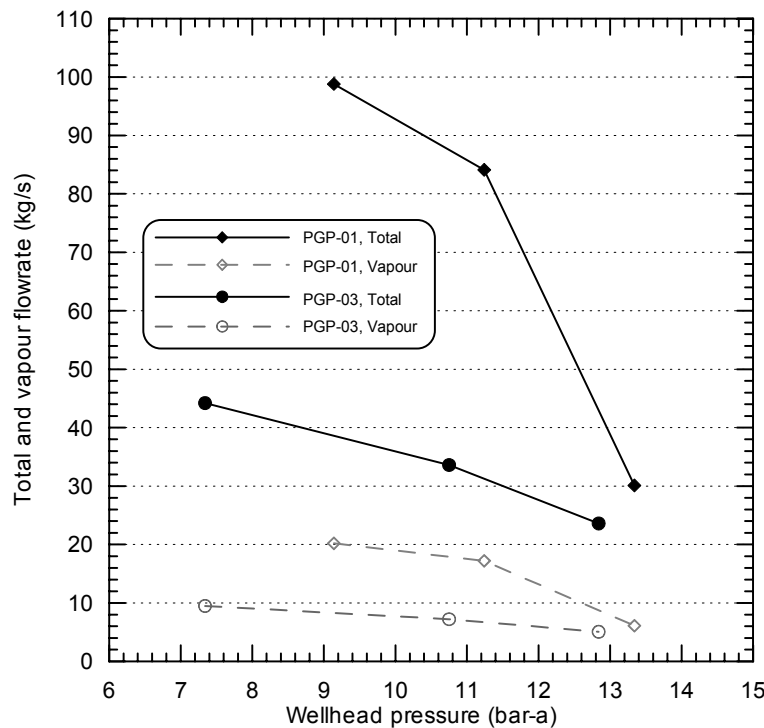FIGURE 21: Dynamic profiles in wells PGP-01 and PGP-03

FIGURE 22: Output curves in wells PGP-01 and PGP-03

PGP-02: The test duration was only 2 hours because the parameters decreased rapidly until the well stopped flowing. As the well is convenient for the injection of brines from wells PGP-03 and PGP-01 during discharge, only this single discharge test has been realized in the well.

PGP-03: Several discharge tests have been done in this well, and it has shown a positive evolution of the production parameters. The evolution could be associated with a stimulation process and thermal recovery. But in the last tests the parameters have shown little changes and can be considered stabilized. The calculated enthalpy of the fluid is higher than that calculated with the dynamic temperature measured inside the well (Figure 21) for conditions of maximum pressure discharge, suggesting a contribution of vapour phase to the fluids produced.

PGP-04: A discharge test was carried out before well completion, given 36 hours of airlift and around three hours of free discharge. The parameters were obtained without stabilization and have a high degree of uncertainty.

6.2 Modelling of discharge conditions using program HOLA

The wellbore simulator HOLA (Björnsson et al., 1993), is a multi-feedzone geothermal simulator that reproduces the measured flowing temperature and pressure profiles in flowing wells, solving numerically the differential equations that describe the steady-state energy, mass and momentum flow in a vertical pipe. The output tests of wells PGP-01 and PGP-03 were analysed with HOLA, to predict the influence of possible future reservoir pressure and enthalpy changes, due to long-term exploitation. The data analysis assumes that the wells only have one permeable zone. The method used is briefly described as follows:

a) The simulator input data for each well includes well design, fluid enthalpy, reservoir pressure at the feedzone and the pressure measured during discharge tests at same depth. By iteration a productivity index is defined for the feedzone, which connects the well to the reservoir. This value represents a geometric property of the well connection to the reservoir.

b) For the estimated productivity index, the reservoir pressure or enthalpy of the fluid can be changed, while keeping other parameters constant. The final result is a prediction of the output curve for these different reservoir conditions.
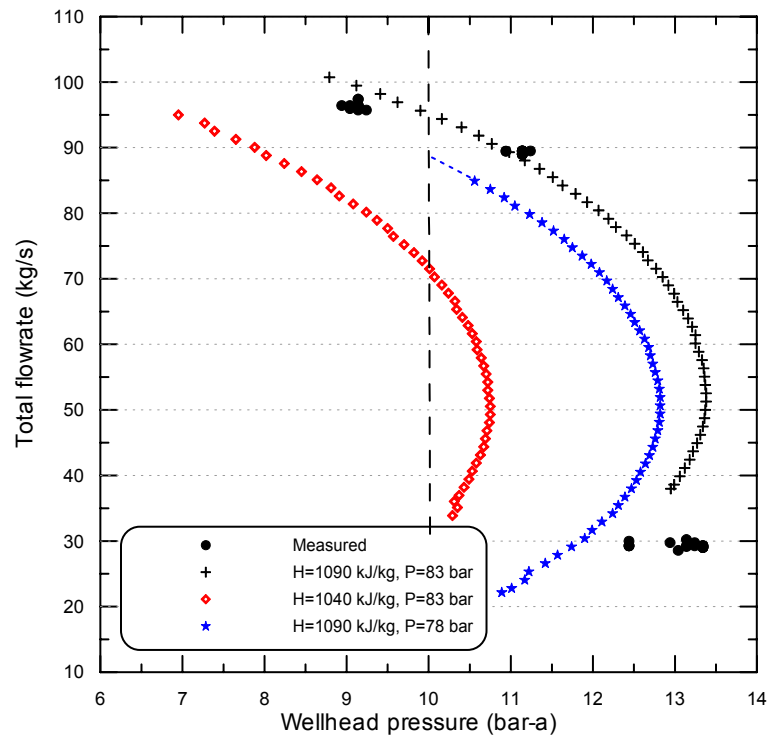
PGP-01: Figure 23 shows measured and simulated output curves of well PGP-01. The main feedzone is located at 1325 m depth, and the feedzone productivity index is estimated as 4.2×10^{-12} m^3. Two possible scenarios were considered and values obtained were compared considering a reference of 10 bar-a of wellhead pressure. Firstly, with an enthalpy decline of 50 kJ/kg. This leads to a shift in wellhead pressures of 2-3 bars and a decrease in flowrate of almost 25 kg/s. Secondly, an output curve was calculated for a reduction of the reservoir pressure by 5 bars. This also shifts the output curve to the left, but not as drastically as in the case of reduce enthalpy.
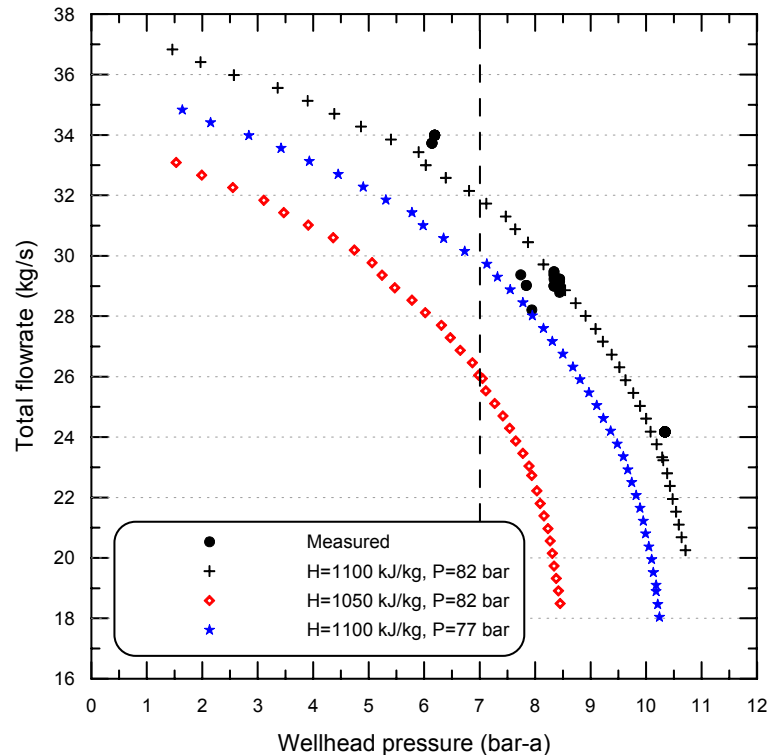
PGP-03: Figure 24 presents the measured and simulated output curves for well PGP-03. The feedzone depth is 1575 m, using HOLA results in a productivity index estimated at 1.4×10^{-12} m^3.

FIGURE 23: Simulated output curves for well PGP-01

FIGURE 24: Simulated output curves for well PGP-03

The scenarios considered were similar to the ones for PGP-01, but reference pressure is 7 bar-a. An enthalpy decrease of 50 kJ/kg, produce a reduction of 5 kg/s in total flow rate and wellhead pressure of 2 bars. Considering a reduction of 5 bars in bottom-hole pressure the total flowrate decreases by 2 kg/s and wellhead pressure decline by only 0.5 bars.

7. A CONCEPTUAL RESERVOIR MODEL

Development of a conceptual model of a geothermal reservoir is an important tool for the comprehension and management of geothermal resources. The conceptual model should consider all information available of temperature and pressure, but it is also necessary to include geologic, geochemical, geophysical information and the internal structure of the reservoir. In this section an attempt is made to set up a preliminary conceptual model for Las Pailas geothermal field. The model is based on the estimated formation temperature and the initial pressure obtained in Sections 4.3 and 5.1, for each well. It is important to remember that the reported values are estimates and some inaccuracy should be considered. This is due to calibration of the Kuster tools and uncertainty of the Albright and the Horner plot methods. The duration of the monitoring time is also important, especially in wells PGP-02 and PGP-04, which adds to the inaccuracy in estimations of temperature and pressure in those wells. However, this inaccuracy will probably not change the overall tendency in the temperature and pressure distribution for the field.

FIGURE 25:   Estimated reservoir temperatures
in the Las Pailas wells

7.1 Data analysis

Formation temperatures estimated for the Las Pailas wells are plotted in Figure 25. The graph indicates similar thermal gradients in the conductive zone (caprock) in all wells, but in wells PGP-01 and PGP-04 the base of this zone extends approximate 300 m deeper than in wells PGP-02 and PGP-03. Below −300 m a.s.l. wells PGP-03 and PGP-04 have a convective profile, and show temperatures in the range of 210- 245°C. Wells PGP-02 and PGP-01, on the other hand, have

FIGURE 26:   Estimated reservoir pressures
in the Las Pailas wells

increasing temperatures below the caprock of lower gradient, but not clearly conductive. This suggests lower permeability in the vicinity of these wells. Figure 26 presents the estimated initial pressures in the Las Pailas wells. The highest pressure is found in well PGP-01 and the lowest in well PGP-03; the difference is 2 bars.
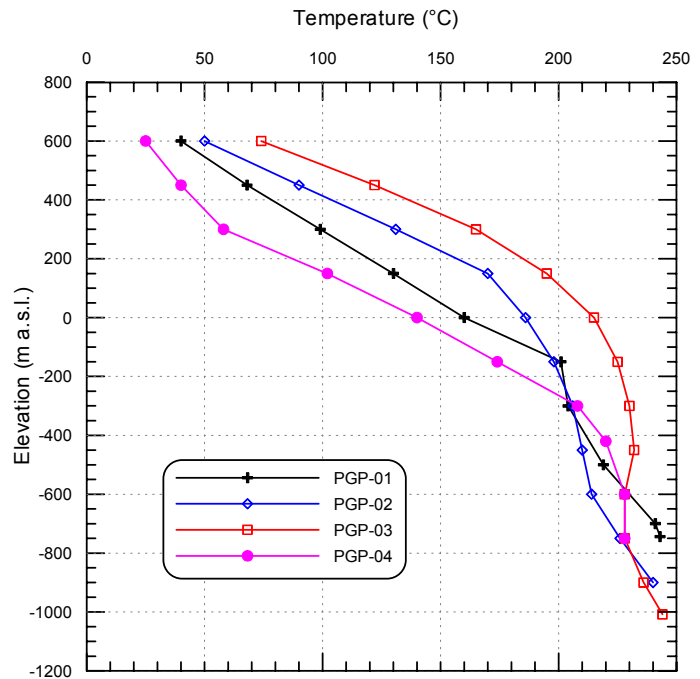
Two contour maps, at −450 and −700 m a.s.l., were made with the objective of making a spatial analysis of the pressure and temperature data obtained. Figure 27a shows isotherms and isobars at −450 m a.s.l. The map indicates that the maximum temperature is found in the northeast part, near well PGP-03. This
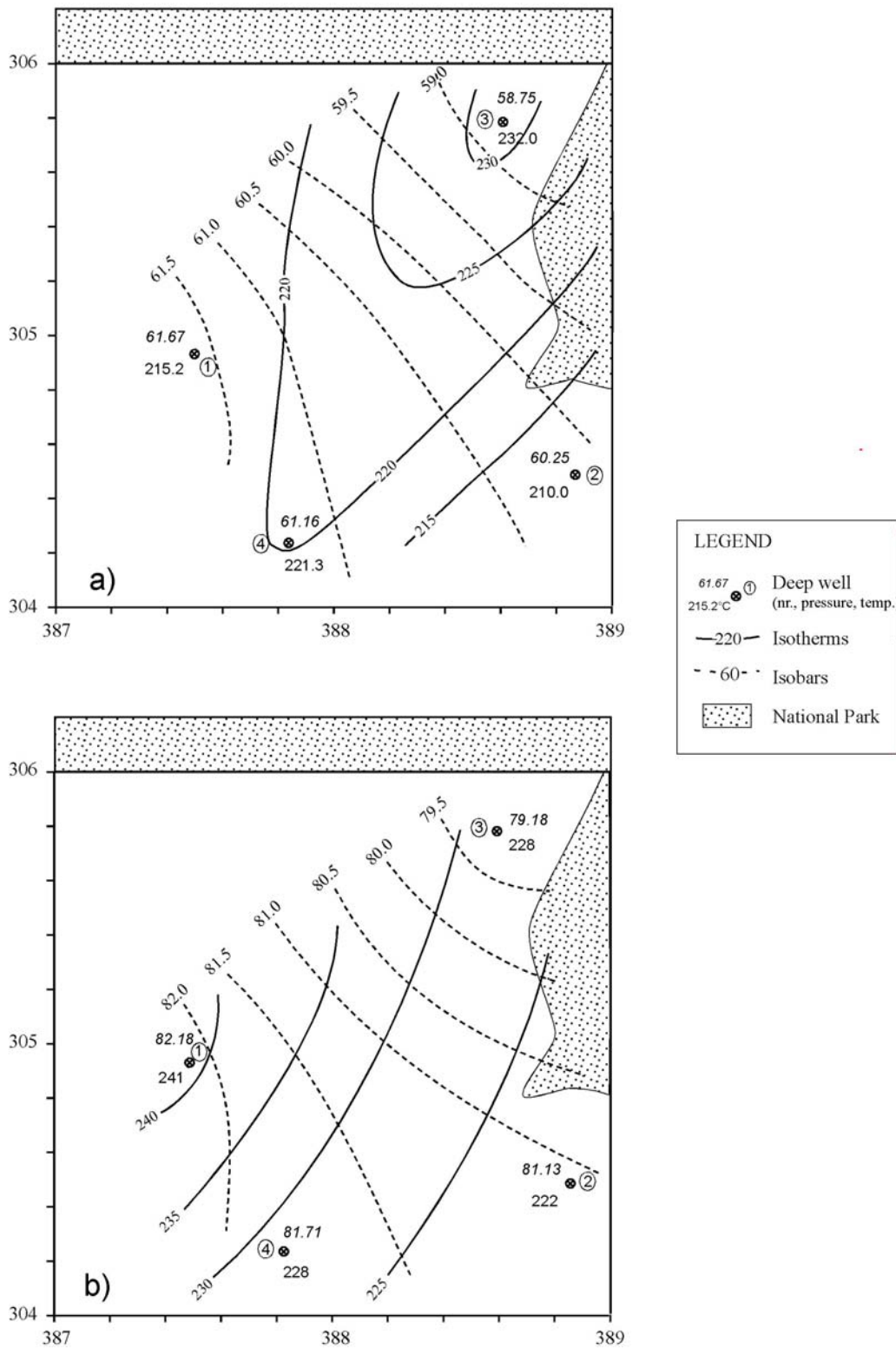
FIGURE 27: Contour maps at a) −450 m a.s.l.; and b) −700 m a.s.l.

thermal anomaly can be related to local convection as, below this depth, temperature in PGP-03 does not increase but maintains the same value. Pressure has a tendency to decrease to the northeast with the point of maximum pressure located near well PGP-01 and the minimum at well PGP-03. It is also possible to

distinguish in the south, near well PGP-04, a sector with a lower pressure gradient than that observed in the centre and north parts of the drilling area.

Figure 27b presents isotherms and isobars at −700 m a.s.l. In this case, the temperature has a W-E pattern with the highest temperatures in the west part at well PGP-01 and lowest temperatures in wells PGP-03 and PGP-02. Pressure has a similar pattern, as found at −450 m a.s.l, with a tendency of decreasing pressures in a SW-NE direction, with the maximum pressure to the west of PGP-01. Also, the pressures contours in Figure 27b show lower gradients near well PGP-04 as in Figure 27a.

7.2 An initial model

Figure 28 shows a conceptual model for Las Pailas. The model can be explained in the following terms:

a)   The main heat source is located to the west of well PGP-01.
b)   Wells PGP-02 and PGP-03 (primarily the latter) present a shallow thermal anomaly located between −300 m a.s.l. and −600 m a.s.l., that is responsible for the anomalous thermal gradient determined by the shallow wells in this area (Figure 3). However, the regional gradient shows highest temperatures in the west, near wells PGP-01 and PGP-04.
c)   Caprock determines the boundary between the conductive and convective zones. The boundary temperature is at 180°C. On average, the bottom of the caprock in Las Pailas is located at −100 m a.s.l.
d)   The current thickness of the drilled reservoir is around 600 m. However, in wells PGP-03 and PGP-02 a greater thickness is present as a consequence of the local anomaly mentioned in b). This is supported by the permeability distribution found at −200 to −900 m a.s.l. in these wells.
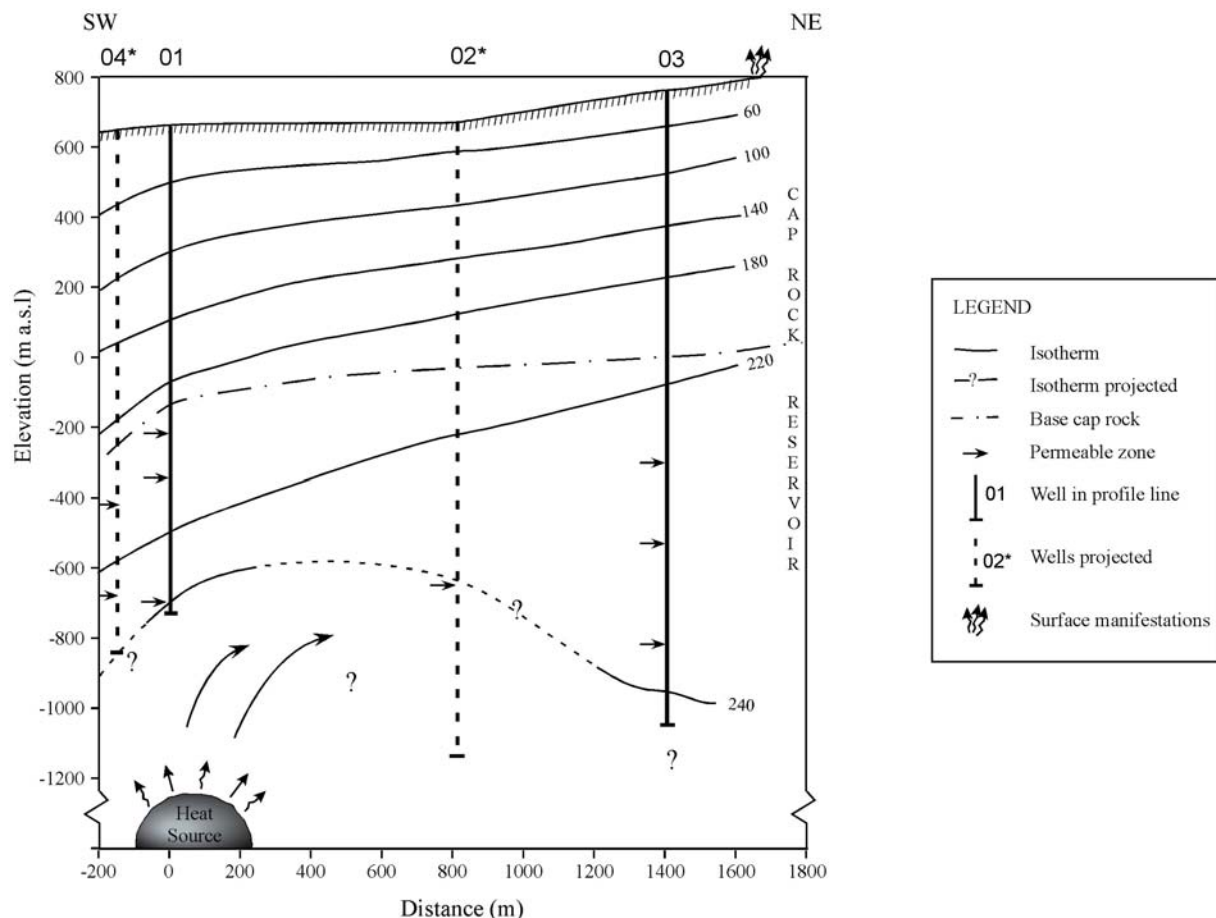

FIGURE 28:   Initial conceptual model of Las Pailas

e) Pressure gradients indicate that fluids enter the well field to the west of well PGP-01, and flow preferably to the northeast. Data are in accordance with the regional thermal gradient.

f) Data suggest that fractures are the most important factor in the permeability and heat transport in the Las Pailas wells. The fractures were the original mechanism for the local thermal anomalies of wells PGP-03 and PGP-02, and could also be the origin for the surface manifestations, which are northeast of well PGP-03.

g) Discharge tests carried out in P GP-01 and PGP-03 have shown the presence of an excess of enthalpy in fluids. This characteristic suggests boiling during discharge in the aquifer feedzone, ascending to shallow levels along fractures.

h) Transmissivity values obtained confirm that wells PGP-03 and PGP-01 have better permeability than wells PGP-04 and PGP-02, possibly because of their location in the main part of the reservoir.

The model proposed is supported by two previous studies. Molina (2000), in his conclusions, suggests model A which: "assumes a cooling magma chamber rests under the San Vicente caldera, and this model is more favourable to future exploitation as a considerable part of the geothermal reservoir would be outside the Rincón de la Vieja national park". Torres and Sánchez (2002) in an ICE internal report proposed, considering silica and calcium data analysis of discharge tests in wells PGP-01 and PGP-03, that the first well produced from a central part of the reservoir with higher temperature, while the second is located at reservoir boundaries.

7.3 Correlation of reservoir parameters with other geothermal fields

Reservoir parameters obtained in Las Pailas were compared with results of previous studies carried out in some geothermal fields. Values are presented in Table 4 and show that Las Pailas wells (excluding PGP-02) have similar values to these fields, indicating good conditions for future exploitation.

TABLE 5: Reservoir parameters in some geothermal fields
(Resources : Krafla (Bödvarsson et al., 1984); Tendaho (Amdeberham, 1998);
Olkaria Domes (Odeny, 1999); Berlín (Monterrosa, 1993))

Geothermal field	Injectivity index (l/s/bar)	Permeability-thickness [kh] (Dm)	Permeability [k] (mD)	Productivity index (m³)
Krafla (Iceland)	-	1.5-2.5	-	-
Tendaho (Ethiopia)	3-5	2.4-10.0	-	$6\text{-}60\times10^{-12}$
Domes (Kenya)	1.2-6.2	0.4-3.0	0.9-6.1	-
Berlín (El Salvador)	-	-	50-100	$5\text{-}10\times10^{-12}$
Las Pailas (Costa Rica)	2-9.4	0.65-15.5	1.1-25.8	$2\text{-}9\times10^{-12}$

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

a) Formation temperature and initial reservoir pressure in Las Pailas were defined applying the programs BERGHITI and PREDYP to the collected data obtained during the recovery period (after drilling), considering both static and dynamic profiles. Also considered were geological data from each well. In general terms, the caprock extends down to –100 m a.s.l., and the reservoir can be defined in the depth range –200 to –800 m a.s.l.

b) Pressure transient tests carried out in Las Pailas wells show a wide variation in permeability between the wells. Analyses made considering data from the fall-off indicate that wells PGP-03 and PGP-01 have good permeability (6.5-16.5 mD) but wells PGP-04 and PGP-02 have low permeability (0.11-1.08 mD). These values are in agreement with injectivity index values found for the wells.

c) Las Pailas field presents a liquid-dominated, two-phase geothermal reservoir hosted in volcanic rocks, with at least 600 m of thickness and formation temperature ranges between 220 and 245°C; the average enthalpy of fluids is 1120 kJ/kg. The main reservoir sector could be located in the west part of the actual study area. The most important factor for permeability and heat transport in Las Pailas reservoir are fractures, which probably give rise to permeable zones found in all the wells. The local thermal anomalies observed in the northeast part of the field, mainly in PGP-03 and PGP-02, between –300 and –700 m a.s.l. are associated with fractures.

d) A conceptual reservoir model proposed for Las Pailas, indicates that the heat source is located to the west of well PGP-01. Hot fluid recharge upflow from this zone, rises to about –600 m a.s.l. near PGP-01, and then flows laterally northeast and east, where well PGP-03 is located. Wells PGP-02 and PGP-04 are located on the boundaries of the reservoir. In this context surface manifestations located in the Rincón de la Vieja national park could represent the reservoir outflow. Available information did not permit description of the conditions present in the zone located west of well PGP-01.

e) Simulations of the output curves for wells PGP-01 and PGP-03 indicate a productivity index of 4.2 and 1.4×10^{-12} m^3 respectively, and an enthalpy of 1100 kJ/kg in both wells, confirming values measured during discharge tests. Simulation predicts that the production characteristics of wells will be more affected if cooling occurs (enthalpy decrease) than if a pressure reduction occurs in the reservoir.

8.2 Recommendations

a) It is necessary to drill at least two wells at distances no greater than 1000 m and in a north-northwest to southwest direction of well PGP-01, to confirm the conceptual model proposed.

b) Pressure transient analysis requires modification of the actual well testing programme, as the time allowed for stabilization was not enough in the well tests carried out in Las Pailas wells.

c) Considering the isotherm pattern found in the field, it is necessary to drill wells to a depth of at least 2000 m, with the objective of studying thermal conditions in deeper parts of the reservoir.

Finally, my deepest gratitude to my dear wife Karen and my dear son Esteban for their love and continued spiritual support during these six months and for enduring my long absence from home; this work is dedicated to them.

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