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Results of Geological - Geophysics Drilling of the Well H-43 the Geothermal Field in Humeros, Pue. Mexico

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ABSTRACT

The Department of Exploration and Residencia of Los Humeros, of the Management Geotermoléctricos conducted a campaign of structural-geological studies, analysis of data from existing wells, and geophysical studies and measurements to determine the best location to drill a new production well (H-43). The objective of the well is to intercept the structural zone of N-S trending fracture, located in Malpaís, Antigua and La Cuesta, which dips to the east, with a depth of interest of 1300-2200 m. In a recent multidisciplinary meeting regarding the drilling of the well, it was decided to quit in hole discovery from 1250-2200 m, at the risk of being located in an area acid. The Mexican company LATINA conducted the drilling operation, and the CFE and Schlumberger conducted data acquisition. The well H-43 was spudded on October 22th 2007 with the drill rig IDECO #2 and was drilled down to a depth of 2200 m. Well operations were concluded on January 7th 2008. Drilling reached the depth of 2200 m in 89 days. The maximum temperatures recorded in well logs was 350°C. Stabilized temperatures were calculated for 1250 m at 228°C and 383°C at 2200 m. The fluids in the region are supercritical, and are a possible indicator of corrosion phenomena. The Department of Exploration, not look that the well will reached as high temperature. In the bottom of H-43, hydrothermal and metasomatic processes are affecting the limestone and volcanic sequence. The objective structural geologic and geophysical resistivity was met satisfactorily. One tool was the benefit of passive seismic monitoring and implementation of focal mechanisms. The well was evaluated to 5 days of its opening with a Qv= 60 t/h; Qa= 0.4 t/h; Pc=50bars The structural system N-S: La Antigua Fault System is responsible for the production of the wells H-37D, H-35 and in the near future of the H-43. The Antigua fault is responsible for the net slip of 280 m: the appearance of the top of the limestone between wells H-43 (1740), and H-16 (2020m), whose expression and morphological today is not apparent on the surface. Well H-43, was left uncovered in the hole from the 1250-2200m. A petrographic analysis identified the well as being acidic, mostly observed in the rock formation. The preferential strike direction (FMI) for fracture and fault zones lies between N-S and NNE-SSW. These fault zones are consistent with field observations and the Antigua fault strike direction.

1. INTRODUCTION

All of Mexico is located within a tectonically active zone with volcanism and its main land being part lies on the North American Plate. The Trans-Mexican Volcanic Belt includes the main focus area of this report, the Los Humeros geothermal field. The Los Humeros geothermal field is the second developed geothermal field in the Mexican Volcanic Belt, the first is the Los Azufres geothermal field at 90 km east of Morelia (Fig. 1). The Los Humeros field has an installed capacity of 40 MWe and produces from 20 wells. Separated brine is completely injected back into the reservoir through 3 injection wells. The installed total geothermal capacity in Mexico reaches 953 MWe at present. The Los Humeros volcanic system is the eastern most of a series of silicic volcanic centres with active geothermal systems located north of the axis of the Mexican Volcanic Belt with a summit elevation of 3150 m, latitude 19.68°N and longitude 97.45° W (see Figure 1). The developments of post-caldera lava domes and eruptions of the 40 km3 Faby Tuff about 240,000 years BP were followed by eruptions that formed the Zaragoza Tuff formation about 100,000 years BP that markes the formation of the nested 10-km-wide Los Potreros caldera. A third and much smaller caldera (El Xalapazco) was formed approximately between 40,000 – 20,000 years BP. The most recent eruptions with extensive basaltic lava flows at the Los Humeros volcanic system formed the existing surface morphology of the area. The basaltic lava flows are undated, but are estimated to be younger than the 20,000 years BP dated rhyolitic lava flows and could be originated in part of the early Holocene age (Negendank et al., 1985). Hot springs and active fumaroles are still present at Los Humeros to this day.

Geologic interpretations of structural, geophysical, and drilling data suggest that:

(1) The water-dominated geothermal reservoir is hosted by the earliest andesitic volcanic formation that is bound by the ring-fracture zone of the Los Potreros caldera, and is covered by the deposits of the oldest caldera-forming eruption;

(2) Permeability within the andesitic formation is provided by faults and fractures that are related to intra-caldera uplift;

(3) The geothermal system has potential for a large influx of meteoric water through parts of the ring-fracture zones of both calderas.

2. GEOLOGICAL STUDIES

Existing and ongoing regional and field scale geological studies and data permit a good overview of the internal formations and structures of the subsurface at the Los Humeros geothermal field area. A new drill site needs to be proposed using all geological and geophysical information, which would help to supply additional steam, for the growing energy demand.

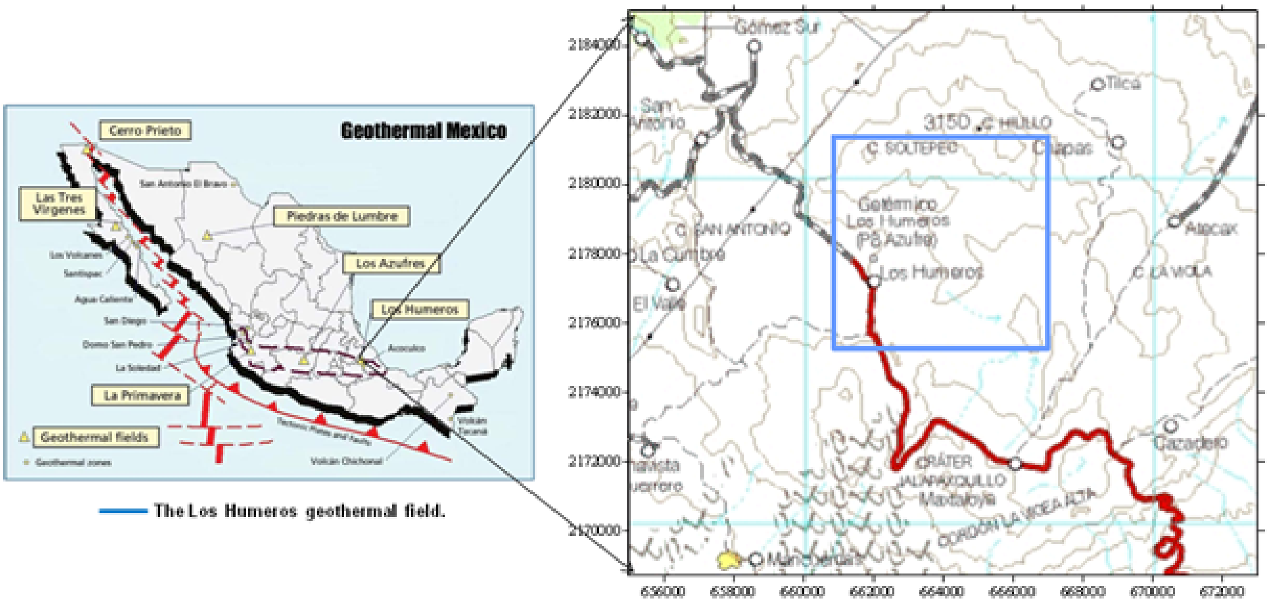


Figure 1: Geothermal zones of Mexico and the Los Humeros field location

2.1 Local Geology (Field Data)

Based on the consideration that the fractures are the major conduits for the movement of water and vapor in the most geothermal reservoirs. In addition, understand the importance of fractures, to reduce costs and increase effectiveness of exploration at the location of geothermal wells. In many reservoirs, the penetration of open fractures by a drill hole make the difference between an economic well and dry hole. Information on the depth at which fracture intersect and their strike and dip is essential to an understanding on the geometry of a fracture system.

Geological studies prior to the location of the H-43 is based on the search and collection of structural data, as well as updating of the zones of hydrothermal zones and hot spring events that allows us to visualize, identify and locate more accurately the geometry of structural system present. Structural field data were projected in stereographic projection of planes. And were the subject of a statistical process: strike-dip in order to group them according to the structural systems: NS, NE-SW, WE, NW-SE.

Special emphasis was placed on determining the geometry and location of faults Malpaís, Antigua and La Cuesta, in order to subsequently determine the fault system that displaces the depth of the top of the limestone between wells H-9, H-37D, H-35 and H-16. (See Figs 2-3). A small alignment (changing slope) associated with morphological zone of hydrothermal alteration and hot springs is the structure known as La Cuesta fault with dip to the East. Well H-43 was located on the top of this block structure **(Fig. 3**)

The area of interest suggested by structural geology, was based on a system to intercept the structural fracturing-faulting of the N-S fault Malpaís Antigua and dip with the East, from 1300 m, and reach the top of the limestone in the order of 1800 m depth. The top of the limestone between wells H-9 (1720 m), H-37D (1750 m), H-43 (1740 m) are located high in the block (foot wall) and H-16 (2020m) located in low block (hanging wall) **(Fig. 3**).

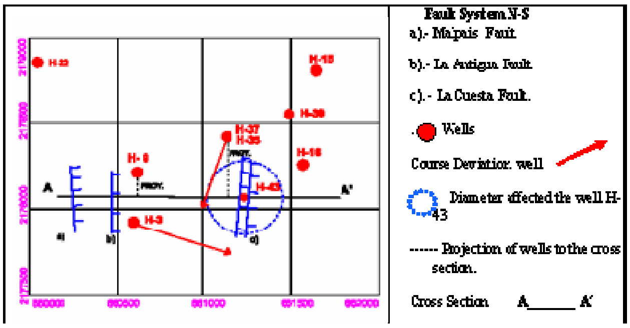


Figure 2: Location of Malpais, La Antigua and La Cuesta Faults Location of well H-43 at the Los Humeros geothermal field

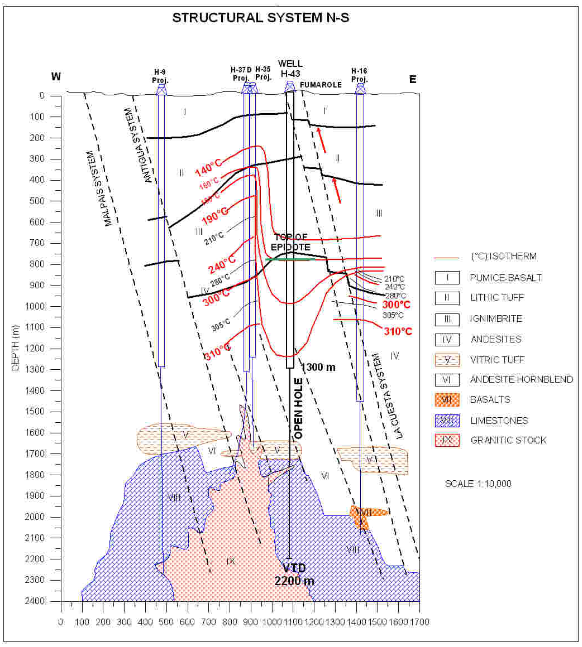


Figure: 3 Structural Systems Geological Model

Locally obtained and analyzed structural surface data in the field indicate that the main present fracture systems strike

NW-SE, NNE-SSW and also a few NE-SW. With additional field data it was also possible to detect that the hot springs are primarily following the N-S orientated fault systems. Structural Data ⇒ Stereogram (Figs 4: EE-1, EE-2, and EE-3-EE-4).

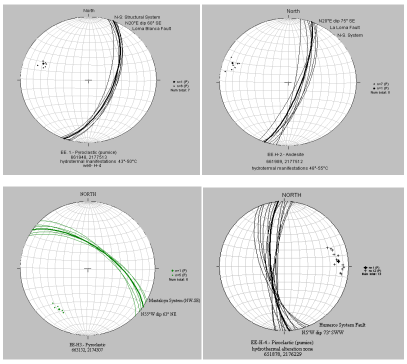
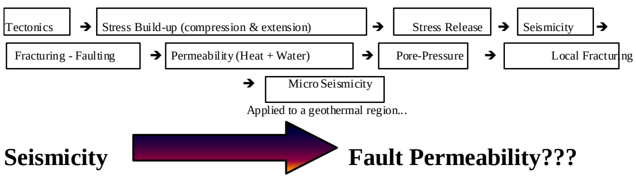


Figure 4: Stereographic representation of planes

The Los Humeros geothermal field has a complex geologic structure with a fluid flow controlled by fracturing. It has been speculated that observed narrow elongated zones of seismicity may be due to stress releases caused by fluid flow (Boyle et al., 2007), see diagram below.



2.2 Volcanology

The volcanic activities in the Los Humeros field area occurred during the Neogene period and it is possible to group these activities into three episodes in accordance to the lithologic descriptions of borehole data:

1. The volcanic activities of the Upper Miocene (10.5 Ma) are characteristic for the andesites-hornblende formation called Cuyuaco. Fractures and geological fault zones generally present the main reservoirs. These andesites have been the first overlying volcanic deposits on top of the basement, which consists of marls and limestones. These volcanic deposits are a series of tuff formations, which are mixtures between rhyolitic tuffs and Ixtacacamaxtitlan tuffs, and are associated with the intrusion of rhyolitic domes into the basement.
2. The volcanic activities of the Pliocene (1.5 Ma to 5 Ma) are represented by the andesites of augite Teziutlan formation with gross-thicknesses between 600 m to 1100 m, and with alternating deposits of tuffs and ignimbrites. These deposits can be interpreted as the stratovolcano interval of the pre-caldera structures of the Los Humeros region. The Teziutlan formation, consisting of augite rich andesites, contains the geothermal reservoirs.
3. The Plio-Quaternary volcanic activities (Pleistocene-Holocene) have been of explosive character with calderic- and post-calderic episodes of Los Humeros and of Los Potreros. The first phase had been the result of a plinian eruption with explosive deposits of approximately 15 km^3 of Xaltipan ignimbrite of rhyolitic composition (0.46 Ma ago). The collapse of the caldera was marked by a plinian eruption with associated fissures and deposits, such as lithic tuffs, rhyolitic domes, ashes, andesite domes, and olivine basalt flows and scoria that had been dated to be 0.24 Ma old and as young as 0.02 Ma old.

2.2.1 Intrusive Igneous Activity

Final stages of the Laramidic Orogeny caused the sedimentary calcareous basement to shear and break. Through zones of weakness of deep reaching fault systems the rising of intrusive bodies such as grano-dioritic intrusions, micro-granite intrusions and sienite intrusions were possible that primarily formed stock like intrusions. This is fairly well confirmed by the degree of contact-metamorphism of the sedimentary basement rock, where contacts as skarn, hornfels and marble were recorded. The dating in these intrusive rocks indicates an age between 31 Ma and 14 Ma within the Lower Oligocene to Middle Miocene.

2.3 Regional Structural Geology

The geological structure of the Los Humeros field has been studied on a regional scale (tectonic), from Jurassic to the present. In particular, an attempt has been made to locally explain the interrelations of lithological units and their possible geometry.

The studies indicate that the limestones of the Cretaceous lower Tamaulipas formation are located right below the volcanic belt. These limestone sequences are part of the Mexican Huayacocotla thrust belt that was created during the Late Cretaceous Laramide orogeny.

Well observations have shown that a structural high exits for the area around wells H-2 and H-5, that cut limestone of Jurassic age at 1140 m in well H-2 and 1370 m in the well H-5. The top of that or shallow structural high appears to correspond with the front folds and recumbent folds of the Huayacocotla thrust belt. On the other hand did well observations indicate structurally low areas around wells, H-4, H-7, and H-12, where the top of the lower Tamaulipas limestone formation was not reached and the deposits of volcanic rocks of the Neogeno period appear to exceed a depth of 2500 m.

The first compression episode at the end of the Cretaceous time affected the sedimentary sequences and is characterized by ductile deformation during the Laramide orogeny with its direction of maximum stress ($\sigma 1$) of N40°E. This compression resulted in the forming of anticlines, recumbent folds and created the inverse faults of the Sierra Madre Oriental the highest structural area of the region that showed strike directions between N10°W and N40°W. Not all stages of distortion that lower Tamaulipas sequence experienced thereafter have been described – but it is not possible to ignore the stage of rock distortions caused by the Lower Oligocene to Middle Miocene intrusions that introduced a trans-tensional stress regime to the rock formations. In the structurally high located areas in the region, e.g. around wells H-2 and H-5, most likely formed sets of normal faults during that time. These fault sets are striking NW-SE and N-S with a general dip direction due east and most likely reached into the uppermost crust. Examples for these fault zones are the Antigua- and possibly Malpais fault zones, where volcanic intrusion were found associated with the fault sets.

The second stage of structural deformation in the area is described as trans-tensional, which was principally caused by the three volcanic cycles of the Volcanic Mexican Belt from the Tertiary to Quaternary. To this day, no clear structural, sub-surface interpretation that could show the three-dimensional morphology of the structures and formations of the Los Humeros caldera exists. Consequently, precise fault and fracture zone locations in a three-dimensional interpretation are missing. The currently exploited Los Humeros geothermal field is located in a volcanic structure within the Los Humeros caldera (**Figure 5).**

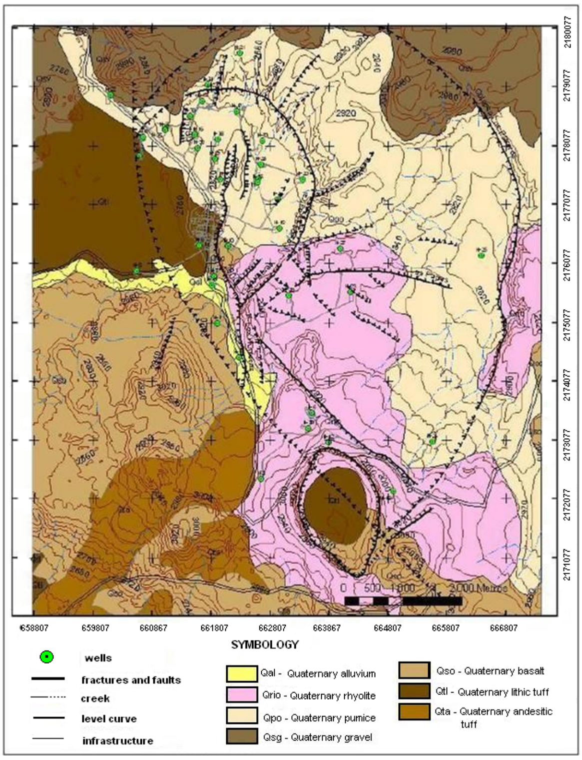


Figure 5: Local geology of the Los Humeros geothermal field

The deep andesitic formation that had been interpreted based on core and cutting samples of well H-43 suggest a possible correlation with the Cuyuaco andesite (10.5 Ma) formation of the Upper Miocene. This andesite is much fractured and presents the main geothermal reservoir. This has been interpreted to be related tectonic extension activities that began around the Pliocene (Upper Tertiary). This extension caused the forming of extensive fracture and fault systems that later coincided with emission of the lava flows. The fault and fracture systems showed at first a general strike direction between N20°W and N70°W, a later change in direction to a system striking between N0° and N20°E and a younger stage of re-activation of these structures. These youngest fault and fracture systems are associated with geothermal manifestations, such as zones of hydrothermal alteration and lineaments of volcanic centres that define them as conductive structures for heat flow (e.g. Mastaloya System, the La Cuesta fault and the Loma Blanca fault), which effected the lowermost volcanic units to the Cuyuaco andesite containing vitric tuffs, andesites of augite and possibly the Xaltipan ignimbrites.

The presence of intrusive granitic bodies and biotite rich micro-graindioritic, intrusions are part of an intrusive system that was active during the trans-tensional phase and caused metamorphism, e.g. skarns and metamorphism of the limestone sediments into marble. There has been evidence that the Cuyuaco lavas affected metamorphicaly the surrounding strata.

3. GEOPHYSICAL STUDIES

The Los Humeros geothermal field has been an object of a big number of geophysical studies. The objective of these studies was to visualize and to interpret the physical properties of the subsurface and its relation with thermally active zones.

The geophysical studies that have been conducted are:

- Electrical Vertical Soundings
- Transient Electromagnetic (TEM)
- Gravimetric surveys
- Reflection seismic surveys
- Passive seismic studies (seismic monitoring).
-

3.1 Electrical Vertical Soundings

The Electrical Vertical Soundings reveal two important anomalies of less than 80 ohm-m (Figure 6). The first anomaly defines the horizon of the andesites and secondary sequence (limestone), between 600 and 800 meters above sea level (m.a.s.l.) corresponding to the producing zone of hydrothermal alteration and the second anomaly between 1000 and 1800 m.a.s.l., at which, based on information from wells near H-43, there must exist zones contributing high temperature fluids in the igneous volcanic rocks (andesite) (Palma, 2007). The production well H-16 (elevation 2783 m) was drilled through a semi-resistivity anomaly (59 ohms-m to 85 ohms-m) that is associated with the andesites formation. The production well H-33 (elevation 2782 m) identified one small part of the La Cuesta fault at 1400 m depth.

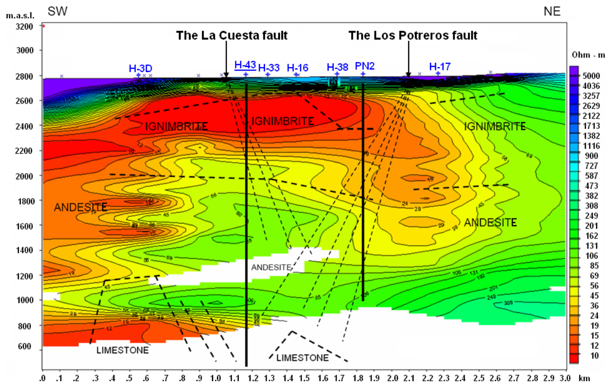


Figure 6: Electrical vertical soundings profile (by Palma, 2007). The andesite is partially white on this picture, because in this area no soundings data exist

3.2 TEM

The analysis and interpretation of the electromagnetic soundings revealed the following: A resistivity anomaly of 40 ohm-m from 500 m - 2000 m depth of vertical elongation (Figure 7). The geophysical TEM studies show a resistive geoelectric discontinuity intermediate of 80 ohm-m, associated with a volcanic body and limestone basement, localized approximately between 1750 m and 2200 m depth. This electric anomaly relates to a thermal anomaly that has been or currently is of high temperature. Furthermore, this anomaly is associated with zones of hydrothermal alteration, product the highest temperature fluids (Palma, 2007).

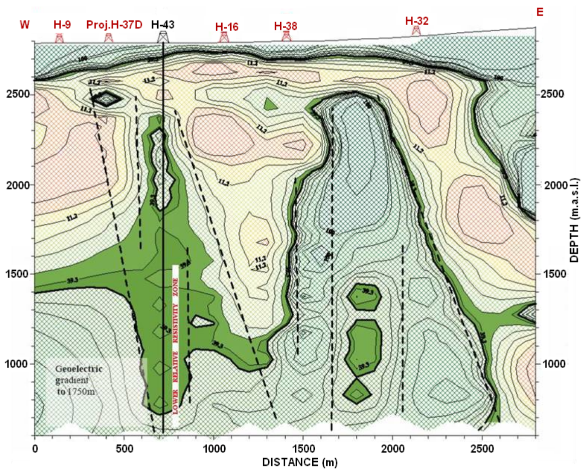


Figure 7: Gradient of lectromagnetic soundings to 1750 m.a.s.l. (from Palma, 2007)

3.3 Gravimetric and Reflection Seismic Surveys

By means of the gravimetric and reflection seismic surveys, it was interpreted that the top of sedimentary rocks would be at a depth of 2000 m. However, the well reached these at 1740 m depth, with 13 % of error in the estimation. The reflection seismic is considered to provide estimate of depths with ±10 % error (Rocha et al., 2006).

3.4 Passive Seismic Studies

Seismic information from the Los Humeros geothermal field exist since the 25th of November 1994, due to an earthquake with its hypocenter in the geothermal field at 2 km depth, a magnitude of 4.6, and its possible source related to the northern part of the Los Humeros fault (Lermo, 1999). This earthquake is the main reason that passive seismic studies are now conducted at the geothermal field, to monitor the existing seismic network. Monitoring stations were set up in December, 1997 and are continuously recording at the moment.

The M_d magnitude is based on the duration (t) measured of the recorded seismic signal after the arrival of the P wave until the amplitude of the signal is lost in noise. This magnitude is defined by the following relation:

$$M_d = a + b\log t + c\log t^2 + d\Delta$$

Where

t = the recorded seismic duration in seconds;

Δ = the epicentre distance in km; and

a, b, c and d = constants determined for every station.

Generally, the seismic activity is concentrated in the northern zone of the geothermal field, which is the production zone, and in particular in the northwest part where the well site of H-43 is located. Micro-seismic events in the north part of the Los Humeros fault and few micro-seismic events in the south zone originate from the central part of the La Antigua fault. The most important earthquakes are of duration and weight magnitude, M_d = 4.6 and M_w = 3.6, both inside the geothermal field, dating from 1994 and 2002. The error ellipses indicate the epicentre location, the red colour represents the micro-seismic activity from1994 and from 2002. The error ellipse from the first period is approximately 2 km in the maximum axis (Lermo, 1999), as presented by the regional seismic networks made available by the Seismology Service National and System of Information Seismic-telemetric of Mexico (SSN, SISMEX). The black colour ellipses representing the 95 seismic events with a minimum of 1 km in the maximum axis. (Figure 8).

The seismic hypocenter distribution is represented on the stratigraphic profile by Cedillo (1997) and Arellano et al. (2000) with a profile direction N-S (A-A'), see Figure 6. The distribution can be seen between 0.2 km and 4.0 km depth. The shallow seismic events at 0.2 km to 1.0 km are located in layers of the pomice, basalts and ignimbrites. An important grouping is observed from 2.0 km to 2.5 km depth corresponding in their locations to the andesite of hornblende strata. Another group of micro-seismicity are even more scattered from 2.5 km to 4.0 km along the same trend as those are located at the top of limestone strata. The profile also notes that the earthquake from 1994 (4.6 M_d.) is located between impermeable layers and limestone down to 2.0 km depth, whereas that of 2002 (3.6 M_w) is located in the South zone and 2.3 km depth, situated between the reservoir and intrusions (Figure 9).

The data set was recorded in the time interval from December 2005 to October 2006. Both data sets were analyzed and used to interpret all information of local seismicity in the Los Humeros field, prior to designing and drilling of well H-43. The analysis and results establish that the location of well H-43 is in a seismic zone, with 35 micro-earthquakes of magnitude of durations (M_d) between 0.9 and 1.8, and 1 km to 4 km hypocenter, with the main concentration at 2 km to 4 km. This seismic activity is associated with a system of faults oriented N-S, the La Antigua and La Cuesta faults. In the production wells H-35 and H-37D, these fault zones were encountered and the system is considered to be active (Lermo et al., 2006).

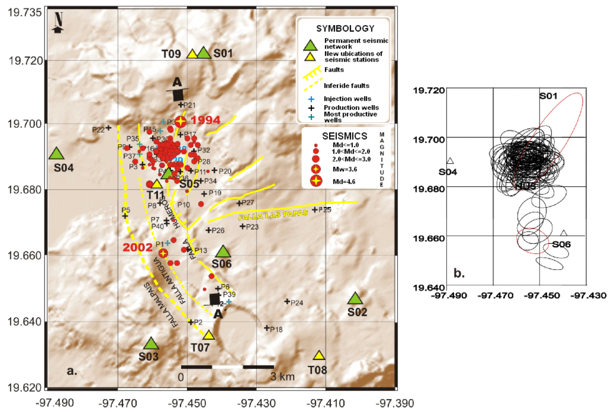


Figure 8: a) Epicentral distribution of 95 micro-seismic data events, b) Error ellipse of localization (by, Antayhua, 2007.)

The interest zone is in the depth range of 1300 to 2200 m in well H-43. In this zone, 57 % of the total micro-earthquake activity in the whole geothermal field takes place. If having known the report of the seismic activity before to the propose of drilling well H-43, the most suitable target depth would have been proposed at 2300 m, where the earthquakes were concentrated and reached 74 % of the micro-seismicity in the north zone, indicating the possibility of finding more fractures near 2300 m depth.

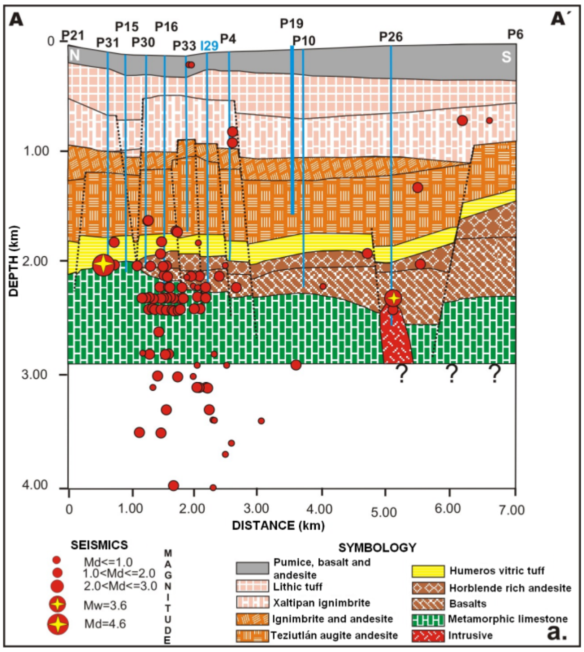


Figure 9: Stratigraphic profile of the Los Humeros geothermal field (by Cedillo, 1997 and Arellano et al., 2000), and seismic hypocenter distribution, North-South direction (A-A´), by Antayhua, 2007

4. OBJECTIVES OF WELL (TECHNICAL SUPPORT)

The official document of the drill hole H-43, "Report OGL-HM-01/06: Proposal for Support of wells in the CG. The Humeros H-41, H-42 and H-43. "

4.1 Geophysics Objectives

4.1.1 Resistivity Studies

Intercept Geoelectrical resistive discontinuity associated with the contact body and the volcanic basement limestone, the approximate range of 1500-2200 m deep. This anomaly is related to the electric thermal anomaly of high temperature.

4.1.2 Passive Seismic

In the period December 2005 to October 2006 the seismicity in the geothermal field, focuses on Fault La Antigua and Fault La Cuesta, near the major production wells, H-35 and F-37, we can conclude that Fault Antigua and the Fault La Cuesta are active. Sections and subsections should be numbered. When making reference to previous work, please follow the scientific format, e.g. Verma and Pruess (1976).

Table 1. Integration of Both Geological and Geophysical Disciplines.

PAD Well H-43	
Coordinates Source:	Target Coordinates:
X: 661240	X: 661240
Y: 2178060	Y: 2178060
Z: 2780 masl	Z: 580 masl
WELL TYPE vertical	COURSE DEVIATION: NOT APPLICABLE
HORIZONTAL DISPLACEMENT: NOT APPLICABLE	
TOTAL VERTICAL DEPTH: 2200m	
TARGET: The range of proposed and supported by geothermal structural geology, still based system to intercept the structural fracturing-faulting on north-south fault in La Antigua Malpaís and dip to the east, from 1300 m, and reach the top of the limestone in the order of 1800 m depth. As the interval defined by the electrical gradient associated with the basement limestone 1750-2200m.	
RANGE OF INTEREST. 1300-2200m.	

5. DRILLING WELL H-43

The location of well H-43 at the Los Humeros field is shown on Figure 10, in the northern zone of the geothermal field, between production wells H-35, H-33, H-9, H-3D, H-16 and south of well H-37D. The well H-43 is presently the deepest production well the in high temperature area of the Los Humeros geothermal field in Mexico.

Figure 10: Location of well H-43 at the Los Humeros geothermal field

All drilling operations of well H-43 were conducted by the drilling company LATINA from Mexico, and all the geological and geophysical data acquisition was conducted by the Residencia Los Humeros and Geothermal Projects Management the Comision Federal de Electricidad (C.F.E.). The drill hole H-43, under contract # 9400034630. Equipment used IDECO # 2. The well was drilled in 5 stages after the pre-drilling stage was concluded. An overview of all the drilling stages and casing point. The well was spudded with the pre-drilling stage for the 30" conductor casing on October 22nd 2007, and was finished on January 7th 2008. It was completed at a final depth of 2200 m on January 7th 2008. (See pictures annexe 1)

Table 2. Drilling and Casing Depths in Well H-43

Drill-Rig	Stage	Depth (m) From	Depth (m) To	Bit size (")	Casing type (")	Section depth (m) From	Section depth (m) To
IDECO 2	Pre-Drilling	1.70	5	40	30	1.70	5
IDECO 2	1. stage	5	52	26	20	5	47.13
IDECO 2	2. stage	52	505	17 ½	13 ⅜	47.13	500.97
IDECO 2	3. stage	505	1250	12 ½	9 ⅝	500.97	1244.51
IDECO 2	4. stage	1250	2200	8 ½	Open-hole	1244.51	2200

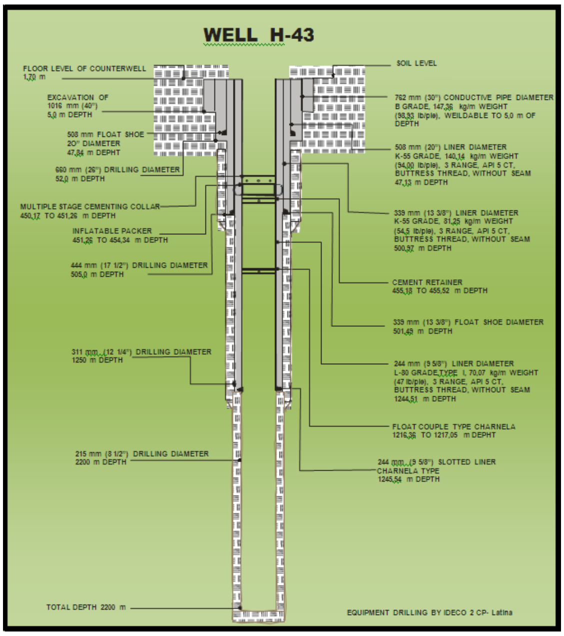


Figure 11: Well design of well H-43.

Pictures annexe 1.

5.2 Lithology Column, Alteration

The subsurface lithology and hydrothermal alteration was identified by inspection of drill cuttings every 10 m, showing in the depth range of 0-1740 m, a heterogeneous alternation of volcanic deposits, and in the depth range from 1740 m to 2200 m, a sedimentary calcareous sequence affected by dykes of andesite and by metasomatics processes and hydrothermal activity of high temperature within the marble formation. Litologhy and alteration minerals are quartz, epidote and chlorite. The main hydrothermal alteration minerals are quartz, epidote and chlorite.

5.2.1 General Lithology

The interpreted borehole lithology is based on the macros- and microscopic interpretation of drill-cutting and cores samples (see Figure 12) from the surface down to 2200 m.

That interpretation allowed determining four major lithologic units in the borehole.

UNIT 1. Volcanic deposits of the formation part of the final scoria of the Los Humeros caldera: lithic tuffs, pumice, basalts, andesites and scoria, and are interpreted as a shallow aquifer (quaternary).

UNIT 2. Pyroclastite deposits associated with the eruptive stage explosives of the caldera; they are constituted by big volumes of ignimbrites, considered by its variable gross-thickness between 400 m to 800 m and are not of geothermal interest.

UNIT 3. Volcanic pre-caldera deposits that primarily consist of augite and hornblende rich andesite deposits with in between alternating basalt and tuff sequences that have recorded most of the circulation loss zones with associated fracture and fault permeability and has been the most interesting unit for geothermal production. The unit is interpreted to be of the Tertiary time.

UNIT 4. The basement of the field is represented by Upper Cretaceous marl and limestone sequences that were affected by a re-crystallization due to contact metamorphosis caused by post-cretaceous intrusions.

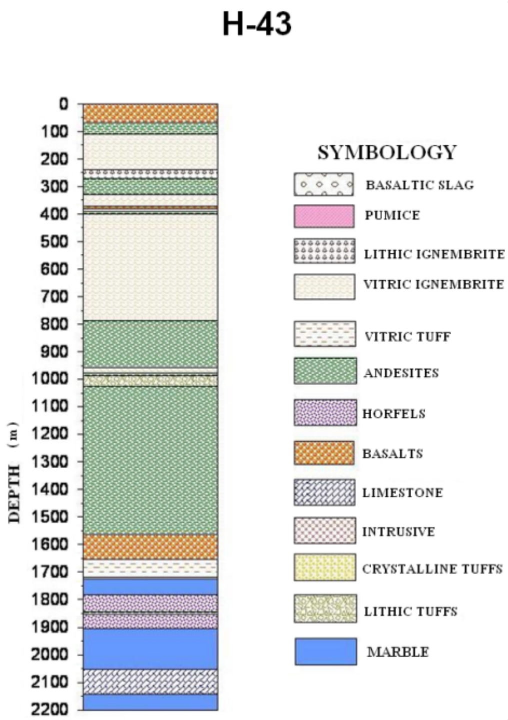


Figure 12: Lithological cuttings profile of well H-43.

5.2.2 Alteration

An overview of alteration mineral distribution and zonation is presented in Figure 13, which indicates a regular progressive hydrothermal alteration sequence with increasing depth for the well. According to the zoning proposed by Viggiano and Robles (Viggiano and Flores, 2008), para-genesis proposal suggests the existence of areas related to high temperatures (above 200° C), which is represented by the association of mineralogical Ep + Qz+ Cl sequence, which was first found at a depth of 785 m. The high total rock percentage (25% - 50%) of alteration minerals in the andesites formation, and the existence of areas of circulation losses (after cleaning and thermal breakthrough of well H-43) leads to the conclusion of movement of geothermal fluid between 785 m and 1265 m.

5.3 Intrusions

Intrusive rocks have been recorded through the macros-and microscopic interpretation of drill-cutting and cores samples, that interpretation allowed determining in the lithologic Unit 4 descriptions as a result of that the intrusive rock intensity can be described that is increasing with depth, see Table 4. In well H-43, Jimenez Salgado estimated the intrusive rock intensity for each successive 10 m depth interval in the well. The results of his review suggest that the re-crystallized limestone sequences primarily consist of light to dark grey coloured cuttings between 1735 m and 2200 m, and are very likely cut by four andesitic dykes. The re-crystallization of the limestone is due to the presence of metamorphism, documented by alteration indications of the limestone.

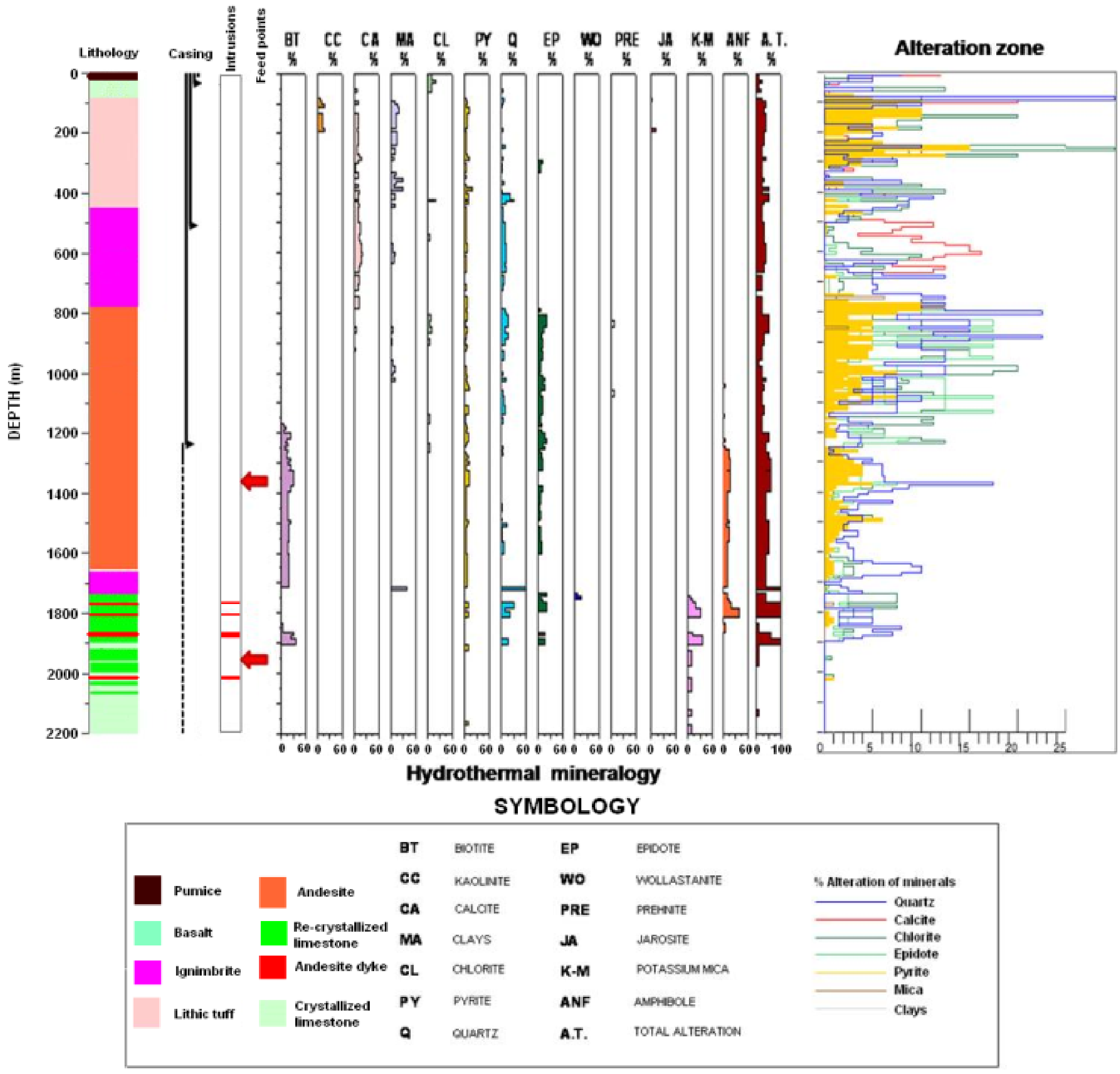


Figure 13: Hydrothermal mineralogy and alteration zone distribution of well H-43

A considerable part of the intrusive dykes are composed of andesites (intermediate), judging from the increased abundance of re-crystallized limestone into marble with increasing depth, appear to become more acid with increasing depth. The mineral calcite is also an indicator of acidity, e.g. in well H-43 calcite was observed at 60 m depth and disappears totally at 785 m depth.

6. BOREHOLE LOGGING AND ANALYSIS

6.1 Temperature and Pressure Logging

Temperature data obtained in wells serve as critical input to fields of geothermal exploration. The temperature logs can detect thermal anomalies between the well fluid and the formation fluid. Estimation of formation temperature depends on the conditions of a well. The presence of flow in a well screens the conditions in the formation and makes the determination of the formation temperature less straight-forward.

In well H-43 two temperatures and pressure surveys were performed, one to 1250 m, after drilling the 12 ¼” diameter well, and the second survey to the total depth of 2200 m, after drilling the final 8 ½” diameter well section.

The first temperature survey at 1250 m was performed using a mechanical instrument (Kuster), obtaining temperature logs taken 6, 12, 18 and 24 hours after end of drilling. These logs are needed for the calculation of the stabilized temperature.

The temperature logs were recorded in open-hole, and obtained four profiles of temperature and pressure taken at the times mentioned in the paragraph above. In this depth range, no circulation loss is visible (see Figure 14). The water table taken after 6 hours is located at a depth of 41 m, and after 24 hours it has decreased to 150 m depth, indicating this formation was accepting fluid. The temperature profiles show one permeable zone:

- Permeable zone, between 1000 m to 1200 m depth

The most common method used to estimate static formation temperatures is the **Horner method** or **Horner.** The temperature logs were used to calculate the stabilized formation temperature of 228°C at 1250 m depth, see Table 3 and Figure 15.

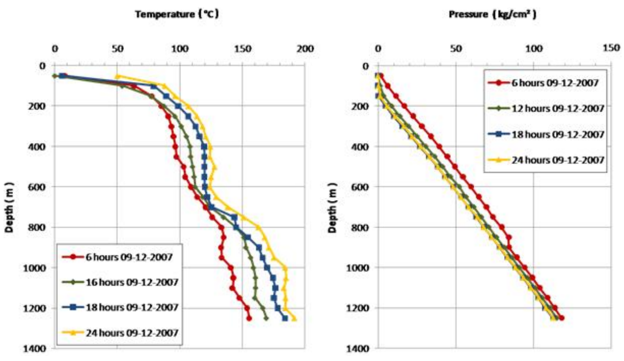


Figure 14: Temperature and pressure profiles of well H-43 to 1250 m

Table 3. Stabilized temperature calculated at 1250 m depth by Horner plot (Sánchez and Torres, 2008).

Drilling time 1247-1250 m = 0.75 h		Circulation time = 10 h	
Profile number	After time (hours)	Temperature (°C)	Horner time (no dimension)
T1	6	155.6	0.298
T2	12	169.35	0.263
T3	18	184.17	0.188
T4	24	191.74	0.151

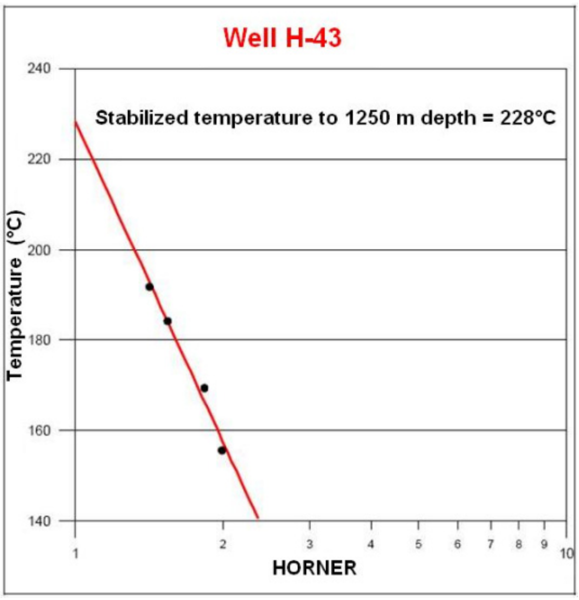


Figure 15: Semi-log graph for stabilized temperature calculation to 1250 m depth, (Sanchez and Torres, 2008)

During drilling of the 8 ½" diameter well section (prior to the second survey), no circulation loss of drilling fluid was detected. The reservoir has low permeability above the major feed zone and, as mentioned before, it is possible that the drilling fluid screens the permeable zones. Only the logs were capable of identifying the possible feed zones, and also evaluate the thermal properties in the open-hole section of the well.

The second survey recorded four pressure and temperature logs in the open-hole section that were taken 6, 12, 18 and 24 hours after the end of drilling (see Figure 16). The stabilized temperature to 2200 m depth is 383 °C which is above the critical point of water (374.15 °C).). The pressure is however not high enough to achieve the supercritical point (above 22 MPa). Note that the pressure curves do not correspond to the temperature profiles for pure water, in accordance with the existence of mud in the well.

Table 4. Stabilized temperature calculated at 2200m depth by Horner plot (Sanchez and Torres, 2008).

Drilling time 2197-2200 m = 0.75 h		Circulation time = 8.15 h	
Profile number	After time (hours)	Temperature (°C)	Horner time (no dimension)
T2	6	272.04	2.48
T3	12	287.63	1.74
T4	18	310.85	1.49
T5	24	330.33	1.37

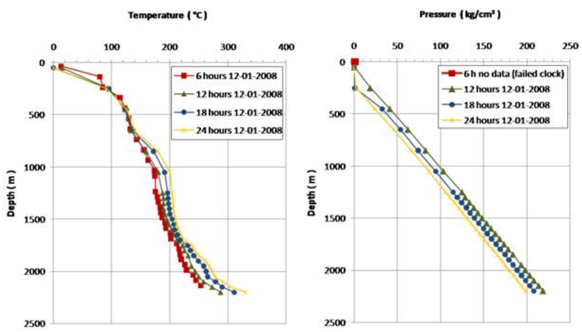


Figure 16: Temperature and pressure profiles of well H-43 to 2200 m

6.2 Fullbore Formation MicroImage (FMI) Logging

Borehole geophysical parameters were recorded and analysed using Petrophysical Analysis (1245m –1626 m); Compound Open Hole logs (1245 m –1630 m); SonFrac fractures estimation (1245 m –1620 m); Dipole Shear Sonic Imager (1626 m – 1245 m); ROXAN stability estimation (1245m –1630 m); Fullbore Formation MicroImager (FMI) fractures analysis (1250 m –1634 m); FMI fracture analysis (1711m –1813 m) and FMI Stereonet&StrucView (1711m–1811 m). The maximum temperature was recorded at 325 °C with temperature logs.

One of the objectives of the FMI log at the well H-43, was to visualize whether the limestone was fracture and possibly permeable. The recordings were made by Schlumberger, on 10th January, 2008. Due to the high temperature recorded in well H-43, it was not possible to take the FMI to the bottom of the well, as the recording instruments only support a maximum temperature of 175 °C. Two depth ranges were recorded, 1250 m- 1633m and 1711m -1813 m. The first interval did not present any problems during logging. However in the second interval one of the 4 tool pads was damaged, and did not provide complete recording.

6.2.1 Structural Analysis of Interval 1250 m - 1633.5 m

The main objective was to identify the areas of interest, where the well intercepts the geothermal system in a fracturing-faulting zone parallel to the primary strike direction N-S of the Malpais and Antigua Faults zones, which are dipping to the east. Moreover was it important to identify and measure existing fractures and faults in the well by recording the azimuths of the strike direction that is orthogonal to dip direction (fault / fracture inclination). Figure 17, shows the strike and azimuth direction of the open fractures (conductive fractures) with range from NW-SE to NE-SW. The most open fractures have strike direction NNE-SSW, with maximum dip in ESE azimuth. Figure 27, shows the strike direction of the closed fractures (resistive fractures); the most vertical main strike direction is NNW-SSE with an easterly dip azimuth. Figure 18, shows the strike and dip azimuth direction display of a fault, the main are NNE-SSW, and an ESE dip azimuth.

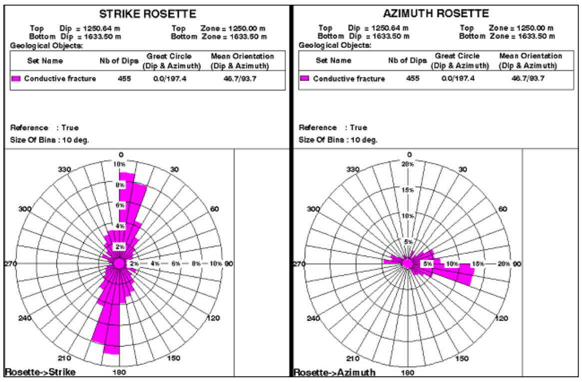


Figure 17: Strike and dip azimuth direction display of open fractures, FMI interpretation of well H-43, interval 1250 m – 1630 m

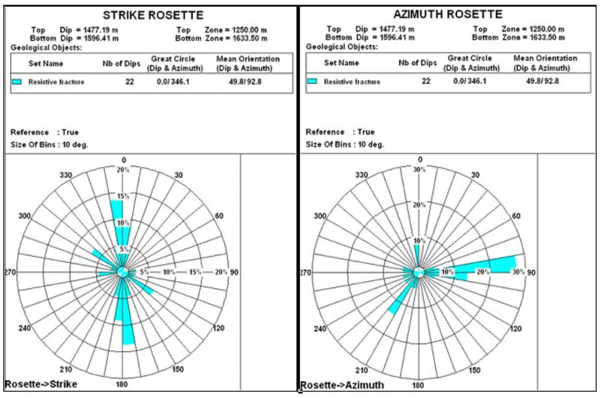


Figure 18: Strike and dip azimuth direction display of closed fractures, FMI interpretation of well H-43, interval 1250 m – 1630 m

6.2.3 Structural Analysis Interval 1711-1813 m

The FMI log for this interval was recorded and processed by Schlumberger as well and interpretations by Schlumberger were used for this report. The second interval is in the depth range of 1711 m – 1813 m.

Figure 31, shows the Stereonet of fracture orientations and the same data in a histogram. The structural analysis presents maximum conductive fractures with main orientation SSW-NNE and dip intervals between 30-40 degrees and 70-80 degrees. Nine faults with dip between 50 and 70 degrees can also be seen. Only three drilling induced faults were recorded with fault dip values between 80 - 90 degrees. The percentage of conductive faults was about 10%.

Figure 19, shows the strike and dip azimuth direction of the open fractures (conductive fractures), the main direction ranges from NW-SE to NE-SW with most open fractures striking N-S. Most conductive fractures appear to be dipping primarily due west. Figure 20, shows the strike and dip azimuth direction of the closed fractures (resistive fractures), the main strike direction here lies N-S and also W-E respectively.

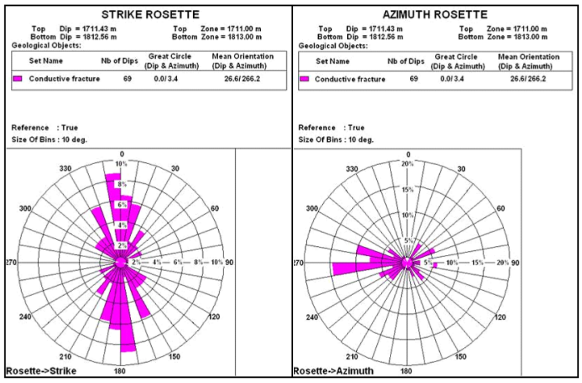


Figure 19: Strike and dip azimuth direction display of open fractures FMI interpretation of well H-43, interval 1711 m – 1813 m

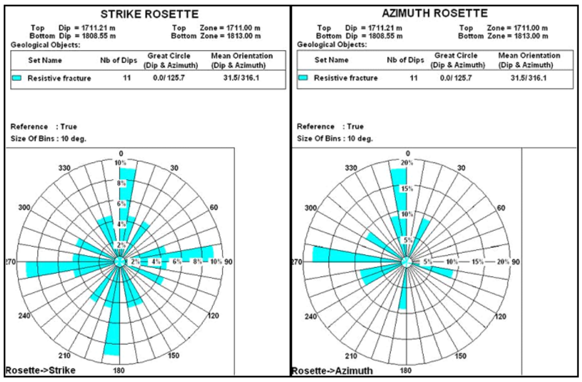


Figure 20: Strike and dip azimuth direction display of closed fractures, FMI interpretation of well H-43, interval 1711 m – 1813 m

In March 2008, temperature and pressure measurements were recorded in well H-43 *see Figure 21*. The maximum temperature that had been recorded at the bottom of the well (2200 m) was 395.4 °C at a pressure of 112.74 kg/cm^2. These conditions are already at the upper limit of conventional high temperature logging instruments and actually beyond the range of any borehole instruments other than special temperature and pressure gauges.

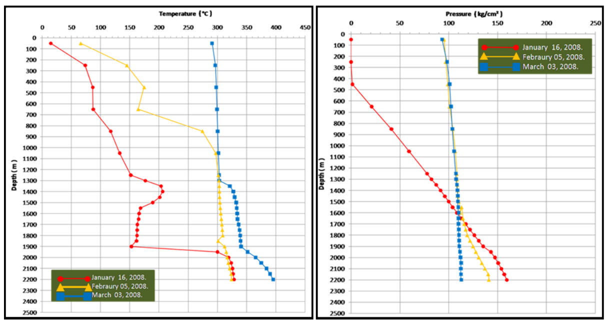


Figure 21: Temperature and pressure logs, red colour after thermal breakthrough, yellow and blue colours after heating of well H-43

The measured maximum temperature of well H-43 after heating up is similar to the calculated extrapolated Horner temperature are, which is 383 °C at 2200 m depth . The final temperature at 2200 m depth is well above the supercritical point of water 374.15 °C, but the pressure does not correspond to that water phase (above 224 kg/cm^2).

CONCLUSIONS

• In the basement of the H-43, active hydrothermal and metasomatic processes occur, which affect the limestone unit.

• The geological-structural objectives were met satisfactorily.

• The objectives of geophysical gravity and power are within the tolerance of error that is satisfactory.

Research and analysis results of well H-43 show the following conclusions:

✓ Well H-43 presents two feed zones intervals:

FEED ZONE	DEPTH INTERVAL	LITHOLOGY
Secondary zone	1250 m - 1550 m	Andesite layer (igneous rock)
Main zone	1950 m - 2200 m	Limestone (fractured)

✓ Well H-43 has the following specifications:

-Highest temperature after thermal breakthrough was 328.64 °C.
-Highest temperature after heating 395.4 °C.
-Pressure after thermal breakthrough 159.34 kg/cm^2
-Pressure after heating 112.74 kg/cm^2.
-Depth of well 2200 m

✓ The FMI analysis show: layer limit, conductive, resistive and inductive fractures and faults.

✓ The conductive fractures have main dip values between 40 and 60 degrees, the preferential strike directions are N-S to NNE-SSW.

✓ The identified faults have preferential strike directions of NNE-SSW and N-S, the dip values are between 50 and 80 degrees. Major faults recorded within the deeper data coverage between 1782 m–1813 m could be related with micro-seismicity that had been recorded as well, indicating presence of stress release but no direct indication of permeability for that logged interval.

✓ The deepest interval of the well, below 1813 m, with the main feed zone below 1950 m has not been logged due to temperature restrictions of the logging tools.

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