Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

STATE OF THE GEOTHERMAL RESOURCES IN BOLIVIA

LAGUNA COLORADA PROJECT

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SUMMARY

This article summarizes the geothermal research activity in Bolivia in the last few years (1995 - 1999). Among these researches, the Studies of Certification of Potential of the Field Sol de Mañana of Laguna Colorada, carried out between 1996 and 1997, stands out. This work was done to reevaluate and to certify the existence of the geothermal potential, in order to propose its commercial development. With this purpose, and with the objectives of raising the technical dependability to the international level and encouraging private investment in the Project, ENDE contracted the engineering services of the Federal Commission of Electricity (CFE) of Mexico.

The Studies of Certification of the Potential, comprised the following works:

- Geological control
- Sampling of springs
- Testing and measuring in the wells
- Numeric simulation of the field
- Economic and financial evaluation
- Environmental analysis

The results of the Study of Certification indicate that the field possesses excellent thermal and hydraulic conditions and is considered a very important energy resource with a capacity on the order of 280 to 370 MW.

According to the production of the wells of Sol de Mañana, the registrations and tests made of the numeric simulation of the reservoir certified that it is possible to generate at least 120 MW for a duration of 25 years by installing 2 condensation power generating stations of 60 MW each (2 x 60 MW). To assess the behavior of the reservoir during a low level of exploitation, and to take advantage of the existent geothermal vapor in the wells, as well as to have reliable design parameters for the power station of 120 MW and aspects for the handling of the resource, it is initially recommended to install a Pilot Plant of 5 MW, to the well. The generated energy will be available for distribution in the local market: mining, factories, processors of minerals, rural population, etc.

1.- INTRODUCTION

The first activities that allowed the formulation of the Geothermal Project Laguna Colorada go back to the decade of the nineteen-seventies, a period in which the geothermal explorations of Bolivia began. These early works were able to establish the existence of geothermal resources of high enthalpy, favorable for their energy use and other uses. The areas of geothermal interest in Bolivia are located mainly along the Cordillera Occidental of the Andes. In this mountain range, active volcanos still exist (in the fumarolic state), such as the Ollague, Putana, Irupuncu, etc.

Geothermal resources are important in the territory of Bolivia because of the relative absence of other important alternative forms of primary energy, capable of transformation into electric power, and even scarce primary energy resources for direct use. In 1976, with the cooperation of the Program of the United Nations for the Development (PNUD), and within the framewoek of the Evaluation of Energy Resources of Bolivia, the first global evaluation of geothermal resources was carried out in the country.

Later, from 1978 to 1980, with the cooperation of the Corporación Andina de Fomento (CAF) and the Government of Italy, studies of pre-feasibility of the fields of Empexa and Laguna Colorada were carried out, which included works of surface prospecting. These studies identified an area of greater potential in the field of Sol de Mañana of Laguna Colorada. From 1985 to 1990, the Studies of Feasibility of Laguna Colorada were made. These studies along with the previous ones and the perforation of the deep geothermal wells allowed the quantification and evaluation of the geothermal reservoir. This evaluation was carried out based on four (4) existing wells and the definition of a strategy of exploitation of the resources that should proceed with the installation of an Experimental Powerhouse station of 4 - 10 MW (ENEL 1991).

With the purpose of implementing the Experimental Powerhouse between 1991 and 1992, new drilling on 2 wells was done with much success. This work consisted of the deepening of well SM-4 for injection and the perforation of a new reservation well (SM-5) to a depth of 1705 m (ENDE 1994). This situation raised the necessity of another evaluation and the certification of the potential of the field based on the new results. In order to ensure technical dependability at the international level, and to encourage the private investment for commercial development of the Project Geothermal of Laguna Colorada, ENDE hired the engineering services of Mexico´s Comision Federal de Electricidad "C.F.E". They completed the Studies of Evaluation and Certification of the Potential of the project "Sol de Mañana".

2.- THE GEOTHERMAL FIELD SOL DE MAÑANA

The field, Sol de Mañana of Laguna Colorada, is located in the far Southwest of Bolivia, in the Cordillera Occidental of the Andes, next to the frontier with the republic of Chile. The field is located at an elevation of approximately 4.900 m a.s.l. and 340 km to the South of the city of Uyuni (Fig. 1). This area consists of high plains, constituted by deposits of lava and glacier material, dominated by the presence of volcanic structures. Among those that stand out are: the hill Michina, Apacheta, hills Aguita Brava, Negra Muerta, and Pabellón, Putana volcano (conical peaks of 5,000 to 6,000 m a.s.l.).

Presently, we have installed 6 geothermal wells (Fig. 2), complete with production pipes, lining, and valve tree suitable for their use in electric power production. The average well depth is 1,500 m. Well depths range from 1,180 to 1,726 m, totalling 9,104 m. of lineal drilling, with highly positive and satisfactory results, being all productive wells (Delgadillo T. 1994).

3. DEVELOPEMENT OF THE STUDIES OF CERTIFICATION

In the technical cooperation agreement of 1995 between ENDE and CFE, the contract was signed for the realization of the Studies of Evaluation and Certification of the Geothermal Potential of the field Sol de Mañana in the area of Laguna Colorada. These studies were initiated at the end of 1996 and concluded in 1997.

The studies were initialized with an investigation of the geologic characteristics of the area, with the object of verifying the main physiographic and structural features of the field, next to the summary and analysis of the available technical information. Simultaneously chemical studies were undertaken, with the sampling of the main thermal springs and other manifestations near the field, in order to determining the characteristic geochemistry of the discharged fluids.

The wells selected, SM-2 and SM-5, were opened up to production for 4 months, from May until August of 1997. This program of tests allowed for measurements and observations of well behavior under conditions of flow. In the same way, samples were taken to obtain the chemical characterization of the well fluids and the determination of the quantity of incondensables gases.

4.- CONCEPTUAL MODEL OF THE FIELD

The Studies of Feasibility (1985-1990) and those of Certification of Potential (1996-1997) have characterized the different rocks that constitute the lithological column in three (3) main units for the general understanding in the conceptual pattern (Fig. 3) in the following way (Delgadillo and Puente 1998):

Unit I : Dacitic Ignimbrites
Unit II : Andesitic lavas
Unit III : Dacitic Ingnimbrites,
with intercalations of andesitic lavas

The ignimbrites (I) cover the andesitic lavas (II) in the whole area. Lithological Unit (III) comprises volcanic rocks formed in the Miocene. Their thickness is unknown because the bottom of the unit is below the deepest of the well perforations. Unit (III) is the high-permeability and high-temperature reservoir of the field.

According to the geovolcanological and photogeological analysis and the geophysical prospecting, as well as of the perforated wells, the structural panorama of the field can be pictured as having two orthogonal tectonic systems, notably clear in the NW-SE and NE-SW directions (Fig. 2). The first system is the most marked in that it affects the most recent formations and determines the position of small horsts and grabens (ENEL 1991). It is considered that this main structural system (NW-SE) has caused a fracture to depth, and that this fracture generally serves as a pipe or tube for the hot fluids that migrate toward more shallow areas. In general the permeability of the reservoir is associated with faults and fractures, and is a product of the tectonic activity, and not only the lithology. However, high permeability could also be due to the ignimbrites of Unit III.

The resistivity studies show a good correlation with the geothermal resource, as indicated by the temperatures of the wells and the thermal activity at the surface. The interpretation shows the limits of the contour of the area of Sol de Mañana clearly where the wells of Sol de Mañana and Apacheta are located. The geothermal activity possibly extends toward the west of these areas. In these areas, the geothermal fluids would be contained in the volcanic rocks of Unit (III), in which high permeability was observed during the perforations.

However, the possibility exists that the low resistivity to the west of Apacheta and northeast of Sol de Mañana indicate the presence of a sealing layer, in which the permeability of the volcanic rocks has decreased with the deposit of the loamy minerals. This conclusion is concordant with the results of the perforation test, in which the first 600 m did not register partial losses of circulation. The upward flow can be related with resistances from 30 to 50 ohm that are observed in the area of the wells starting from the 700 m depth, where the perforation operations had circulation losses.

The characterization of the conceptual pattern of the field was carried out according to the results of reinterpretation of the geological and geophysical data and with the proper information obtained with the perforation of the wells in the field (CFE 1997).

For the areas of Sol de Mañana and Apacheta, according to the data of wells and to the resistivity studies, a surface of 36.1 km^2 of geothermal interest would have to be represented (CFE 1997). This area was the one used to determine the energy potential. The thickness of the productive area, or the reservoir of commercial interest, has been defined by the beginning of the area of hydrothermal alteration that starts from 800 m. depth, and extending down to 1700 m. Taking into account that 1700 m is the greatest depth registered in the perforations, the production interval could be bigger.

This alteration zone was identical in Lithological Unit (III) during the perforation of the wells, and it registers a mineralogical zone of clorite-epidote-illite-quartz, an assemblge characteristic of areas of geothermal interest. The mineralogical data and the interpretation of the geoelectrical data allow us to consider the First Lithologic Unit like a sealing layer, presenting a high occurrence of clayey minerals characterized by their low permeability. On average the thickness of this unit is 500 m. from the topographical surface.

The construction of the concentual pattern of the field (Fig. 3) has been carried out in order for the correlation of the data of the permeable areas determined in the wells and the configuration of temperatures observed in a traverse cut. The information used to constrain the conceptual pattern includes: the depths of important losses of circulation, depths of hydrothermal alteration, the depths of the 260ºC isotherm, and the depths where the pressure measured on the average in the wells was 55 bar (CFE 1997).

5.- TESTING AND MEASURING DONE IN THE WELLS

In the development of the studies, a series of tests and programmed measuring was carried out, from May to August of 1997, in the wells of the field Sol de Mañana (location shown in Fig. .2). These tests provided the following:

- Profiles of pressure and temperature, with the objective of determining the thermo-hydraulic conditions under static and dynamic conditions, before well opening and during the period of production.

- Tests of production were carried out to determine the physical and thermodynamic parameters, with the object of evaluating the power of the field, through the wells selected, SM-2 and SM-5

Results

From the analysis and evaluation of the data, we have the following results:

- The static conditions of the field, identified at the average depth of the permeable area, show a pressure of 55 bar. Temperatures in the bottom of the wells are 250-260ºC.

- The interpretation of the profiles of pressure-temperature (P-T) show that the reservoir fluids are liquid, below the piezometric half level. The change of phase of the fluid happens in the pipe at a depth of approximately 1000 m; that is to say that above this level, there is a column of gas.

- The temperature of the reservoir, by means of geothermometry of liquid phase is 265ºC. The chemical analysis of the water point to a total average content of solids of 10,000 ppm.

- The average production of the wells (to atmospheric conditions) is 350 t/h with an enthalpy of 1070 kJ/kg. The average power of each well is approximately 6 MW, and with a condensation turbine, it is possible to obtain between 8 and 9 MW.

- The content of gases in the wells is small, ~1% by weight, and the temperature of the reservoir calculated by gases is 263ºC. This temperature is very consistent with those estimated from geothermometry of the liquid phase and with those registered directly in the wells.
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6.- GEOTHERMAL POTENTIAL AVAILABLE

a) Volume Evaluation:

An evaluation of the usable power of the field, Sol de Mañana, was carried out based on 2 methods: stored total energy in the rock-fluid system and the maximum power available allowing for the pressure decrease of the system. The reservoir area was defined by means of using a minimum of resistance, ending up in a total surface of 36.1 km^2. The thickness of the productive area was determined as 1.1 km. on average, according to the interpretation of the registrations of temperature of the wells, the circulation losses observed during the perforation, the occurrence of the chorite-epidote-illite-quartz assemblage, and the geoelectrical results.

The results obtained by the pattern of total energy stored in the rock-fluid system in the study of the maximum power available, considered the situation of exploitation for 20 years, and are shown in Table 1. On the other hand, the result for the pattern of maximum power consistent with the pressure decrease of the system gave a capacity of the order of 283 MW for 20 years. According to the results obtained with the two applied techniques, one can conclude that the reservoir of the field Sol de Mañana, has a very important energy capacity between 283 and 374 MW for a 20-year exploitation period (CFE 1997).

b) Numeric Simulation

The numeric pattern used for the simulation of the reservoir was the TETRAD 12, used thoroughly by CFE in the commercial evaluation of Mexican geothermal fields. For the purposes of this study, the reservoir of Sol de Mañana of Laguna Colorada was considered as a closed geothermal system with impermeable and adiabatic lateral boundaries. This is the reason that the transfer of heat and fluid through them are null. However, the pattern includes entrance of fluid in the bottom and the natural discharges in the surface.

The delimitation of the reservoir was carried out using mainly the resistivity data and supported by structural evidence that defines the faults. A total area of 60 km^2 was defined based on a mesh of 12 km for 5 km defined based on a net resistive anomaly of 12 ohm-m and determined laterally by the structural and geoeléctric elements.

The calibration of the stationary state consisted of carrying out several simulation races, assigning a value of zero to the permeabilities and porosities at different levels in the pattern.

Scenarios of exploitation

To analyze the power plant that can be installed in the geothermal field Sol de Mañana, the generating module was chosen to be exactly like an existing size found in the world market. Therefore we opted for the use of one or several modules of 60 MW condensation units. First, an analysis of the behavior from the reservoir when installing 120 MW was carried out, and secondly, a duplication of the extraction was done in order to install 240 MW in the field, although the analysis of the energy potential indicates that it could be possible to install up to 300 MW while exploiting the field for at least 20 years.

To generate 120 MW by means of 2 condensation units (2 x 60 MW), it was determined that 20 wells are required, with an average production of 50t/h of vapor to 8 bar of bolster pressure. Approximately 7 injector wells would be needed. From the results of the analysis obtained by the simulator, it is certified that the field has the capacity for commercial generation of 120 MW for 25 years, with an estimated lowering of 1.5 bar/year of reservoir pressure.

In case of generating 240 MW, using 4 condensation units (4 x 60 MW), it was determined that 33 producing wells and 11 injector wells are required. The results obtained by the simulator for this alternative, showed that the average depression of the pressure in the productive area is 2.31 bar/year. It has been observed that there are wells that would stop being productive before the considered period. Therefore we concluded that it would not be possible to certify the installation of 240 MW in the field Sol de Mañana until we have information on the evolution of the reservoir when producing 120 MW.

7.- DEVELOPMENT OF THE RESOURCES

The results of the Study of Evaluation and Certification of the Geothermal Potential, carried out by CFE, that certify a minimum potential energy in the geothermal field Sol de Mañana and the available vapor at the top of the well, allow development of the following strategy of exploitation:

a) Use of the Existent Vapor.

The available geothermal vapor in the perforated wells of the field Sol de Mañana is enough for the installation of 5 to 10 MW of of electric power generation with units of free discharge. We recommend the immediate installation of a Pilot Plant of 5MW at the well head to supply the local market. This construction could be completed in a period of one year. The Pilot Plant's installation would reveal the behavior of the geothermal reservoir at a low level of exploitation. The estimates of the geothermal potential and the geothermal pattern could then be improved. The design parameters for the construction of a power station of 120 MW could be optimized.

The recent simulation studies and those carried out previously have determined that 2 wells are suficient to guarantee a continuous production of 5 MW for 8 years.

b) Amplification of the Exploitation of the Field Sol de Mañana

According to the results of the numeric simulation of the field, it is possible to install a power station of 120 MW, with the final design based on the results obtained in the first years of exploitation of the Pilot Plant. The power station of 120 MW, would be constituted by 2 condensation units of 60 MW each. The reservoir is capable of feeding the power station for at least 25 years.

8.- CONCLUSIONS

- In the last years, from 1995 to 1999, the geothermal investigations have concentrated mainly in the area of Laguna Colorada, carrying out studies based on the potential of the field Sol de Mañana., There were two main objectives; one to update the available data set, and the other, to certify the existence of potential, favorable for commercial development.

- The drilling of geothermal wells (6), carried out in Bolivia from 1987 to 1992, has permitted us to confirm the existence of reservoirs of high enthalpy in the field Sol de Mañana. This constituted an extraordinary experience, because of the severe conditions of labor, especially at such altitude.

- The conceptual model of the reservoir was defined based on the existing geophysical, geological, petrographic and drilling information, determined mainly by structural and lithological aspects of the field. The reservoir of commercial interest has a thickness of 900 m but could be thicker due to the fact that it has not been possible to find the lower limits of the reservoir in the already perforated wells.

- The interpretation of the profiles of pressure-temperature in static conditions shows that the reservoir is liquid-phase. During flow, a change in the phase of the fluid occurs in the casing of the well at an approximate depth of 1000 m.

- The average production of the wells is 350 t/h of geothermal fluid, with an enthalpy of 1070 KJ/kg from an approximate reservoir temperature of 260ºC. The average potential of each well is ~6 MW, and it is possible to obtain between 8 and 9 MW with a condensation turbine.

- Potential energy has been determined from the field in the following order. Total power output could be as high as 280 to 370 MW. It is possible to certify at least 120 MW for a 25-year duration, by installing 2 condensation units of 60 MW (2*60 MW).

- Future perspectives of geothermal development in Bolivia are tied to the installation of pilot units of geothermal generation in the field Sol de Mañana, this will allow the immediate use of geothermal vapor available in the wells. The installation of a 5 MW pilot plant will allow us to determine the behavior of the reservoir at a low level of exploitation.

ACKNOMLEDGMENT

The author wishes to thank the Empresa Nacional de Electricidad S.A. "ENDE" for all the support throughout the development of this project and for allowing its publication.

REFERENCE

CFE 1997 Certificación del Potencial delCampo Sol de Mañana, preparado para ENDE

Delgadillo T. Zenón 1994 Desarrollo de la Central Geotermoeléctrica Sol de Mañana

Delgadillo T. Zenón - Puente G. Hector 1988 The Laguna Colorada (Bolivia) Proyect: A Resevor Engineering Arsessment

ENEL 1991 Estudio de Factibilidad Geotérmica en el área de Laguna Colorada

ENDE 1994. Ampliación de perforaciones Geotérmicas, Proyecto Laguna Colorada

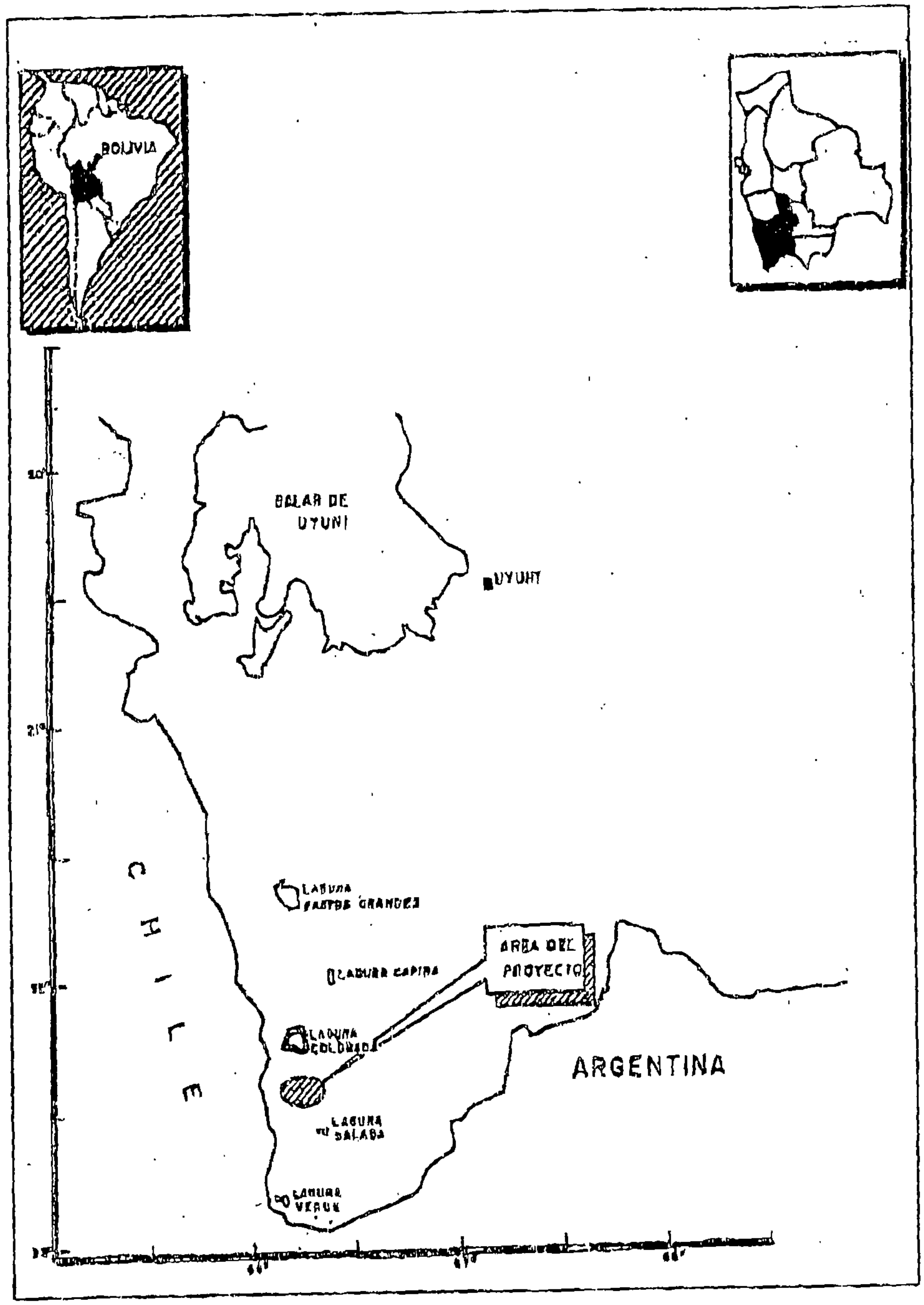

Fig. 1 Localization Map

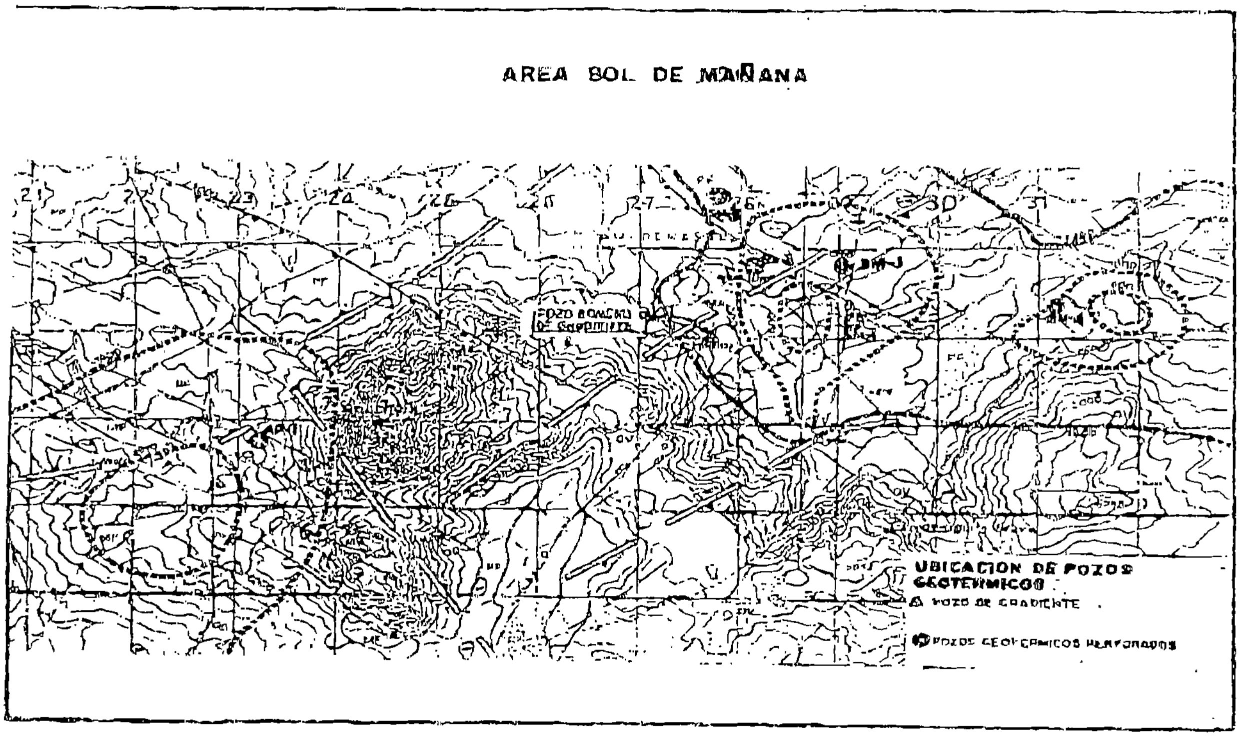

Fig. 2 Location of Wells – Structural view

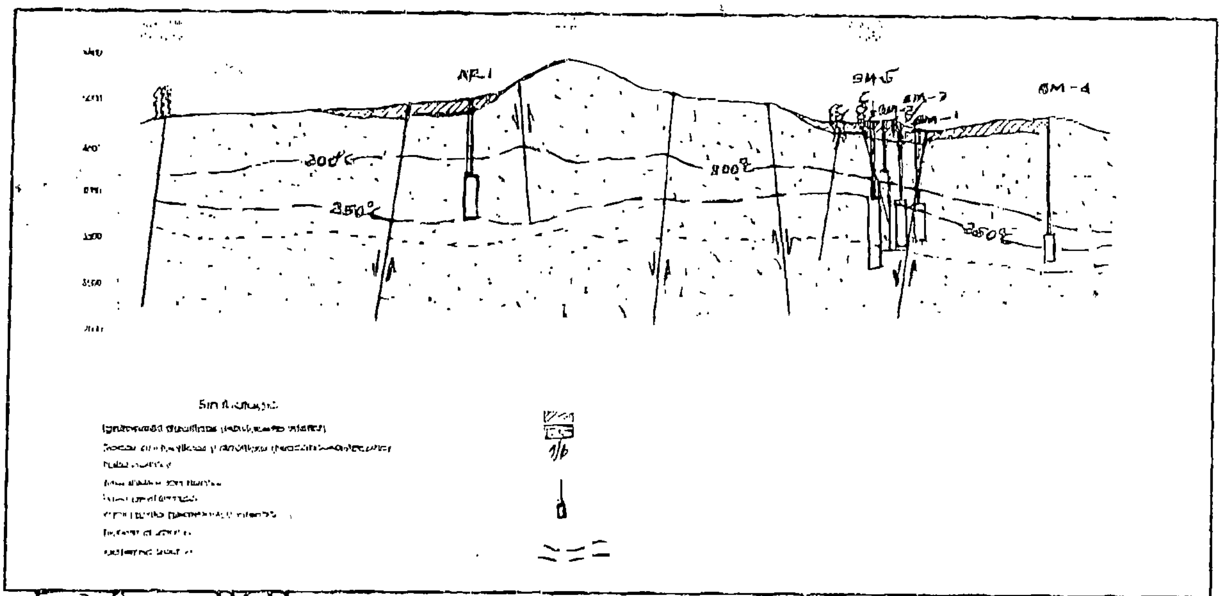

Fig. 3 Conceptual Model

Table 1 Maximum Power, Method of Total Energy Storaged in the Rock-Fluid System

SCENARY	POWER (MW)
Dominating liquid at the beginning and at the end of theexploitation	370
Dominating liquid at the beginning and vapor at the end of the exploitation	374
Dominating liquid at the beginning and end of the exploitation	324