Copahue Geothermal System, Argentina - Study of a Vapor-Dominated Reservoir

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ABSTRACT

This paper presents the conceptual model of the Copahue geothermal field in Neuquén province, Argentina, and the results of resource assessment performed in the collaborating study project between Japan and Argentina. The field is characterized by activities related to active volcano (Vol.Copahue) and horst structure in the basin structure formed by volcanic depression. The geothermal manifestation where superheated steam is discharging are distributed in the horst. The vapor-dominated reservoir of more than 230°C in temperature was confirmed by exploratory wells below a depth of 600-800m. The reservoir is covered with an alteration zone and lacustrine deposits as a cap rock and is surrounded by impermeable zones. Based on the available geological, geophysical, geochemical, and reservoir engineering data involving new data of a well drilled in the project, it is concluded that the Copahue field is a promising prospect for future development, with the potential of over 30MW.

1. INTRODUCTION

The Copahue geothermal field is located at some 1,170 km west-southwest of Buenos Aires, in Neuquén Province, Argentina, adjoining the border with Chile (Figure 1). An extensive geothermal survey and drilling in the field had been carried out by Comisión Nacional de Estudios Geottrmicos since 1974, and by Consejo de Planificación para el Desarrollo (COPADE) since 1979. These works involve several geological, geophysical and geochemical surveys, and drilling of thermal gradient holes and the exploratory well COP-1 (total depth;1,414m). In 1985, Centro Regional de Energia Geotérmica del Neuquén [CREGEN; an organization in Ente Provincial de Energia del Neuquén (EPEN)] was established and drilled the exploratory well COP-2 (total depth;1,241m), and carried out electrical prospecting, a fluid geochemical survey, production tests. After that, Japan International Cooperation Agency (JICA, an agency of the Japanese government) drilled the exploratory well COP-3 (total depth;1,065m) and performed the integrated analysis for the field using all the available data to evaluate the reservoir potential, as well as formulation of the optimum development plan including economic and financial evaluation, in collaboration with CREGEN.

This paper presents the conceptual model of the Copahue geothermal system and the result of the preliminary assessment of the field studied by JICA Survey Team (it mainly consist of members from Electric Power Development Co. Ltd. (EPDC)) and CREGEN. The Copahue field is characterized by activities related to active volcano (Vol. Copahue) and by horst structure in the basin structure formed by volcanic depression. The geothermal manifestations where superheated steam is discharging are distributed in the horst. Based on the many exploration data, the well log and production tests data, it appears that a prospective vapor-dominated reservoir exists in the field, covered with an alteration zone and lacustrine deposits as a cap rock. and is surrounded by impermeable zones characterized by fault systems bordering the horst.

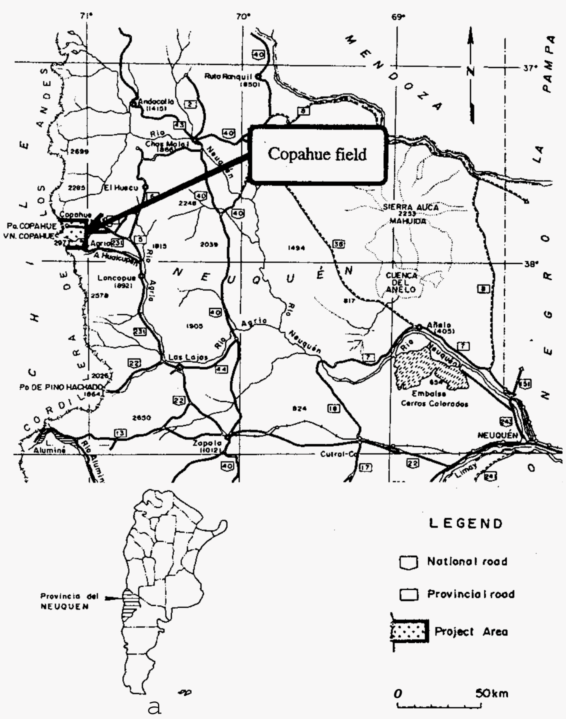

Figure 1 Location map of Copahue area

2. GEOLOGICAL SETTING

The project area is located in the east side of the Andes ranges and in the center between the Nahuever lineament and the Pino Hachado lineament (Pesce, 1987). Pre-Tertiary rocks are not distributed near this field. Tertiary and Quaternary volcanic rocks in this field are classified from bottom to top: the Hualcupen formation of Pliocene age, the Riscos Bayos pyroclastic flow deposits of the end of Pliocene age to the beginning of Pleistocene age, the Las Mellizas formation including the Caviahue conglomerate member and the A° Trolope volcanic rocks of Pleistocene age, and the Copahue volcanic rocks of late Pleistocene to Holocene ages (Figure *2).* The volcanic activities are characterized by calc-alkaline series and shoshonitic series.

After the activity of the Hualcupen formation formed a stratovolcano, the basin is formed by a volcanic depression during the period between the end of Pliocene to the beginning of the Pleistocene. The caldera basin' was filled with the Las Mellizas formation consisting of andesite, basaltic rock, agglomerate and lacustrine deposits, before the Copahue volcanic rocks unconformably overlies the Las Mellizas formation.

The distribution area of the Hualcupen formation corresponds with the area of high gravity anomaly whereas the Las Mellizas formation corresponds with the area of low gravity anomaly except for the distribution of the Copahue volcanic rocks. In the basin, the horst centering around Termas de Copahue to the west indicates the area of the high gravity anomaly. The low gravity anomaly centering around the northern part of Lago Agrio is assumed to be due to the occurrence of thick lake sediments which is observed in the thermal gradient holes. From gravity survey, the maximum depth of the caldera basement (the Hualcupen formation) is assumed to be approximately 2,000 m on the east of Lago Agrio, and the depth in the horst zone centering around the geothermal manifestations is assumed to be 1,600 m. The horst is assumed *to* have been formed by upheavals due to the the two volcanic activities of the Las Mellizas formation and Copahue volcano.

The alteration zone and lacustrine deposits are characterized as a cap rock. The following three fault systems which are closely related to the reservoirs in this area, are inferred from the geology, well data and the distribution of manifestations.

(a) The WNW-ESE fault system running from Chancho Có through Lago Agrio.
(b) The NE-SW fault system corresponding to the geothermal manifestations.
(c) The NW-SE reverse fault system on the east of Las Máquinas.

3. FLUID GEOCHEMISTRY

3.1 Fumaroles and Hot Spring Waters

Five geothermal manifestations are distributed in the horst. Chancho Co is located in the Chilean side. The other manifestations, Termas de Copahue, Las Máquinas, Las Maquinitas and Anfiteatro, are in the Argentine side. Many hot springs and fumaroles discharging superheated steam (132°C) form acidic alteration zone.

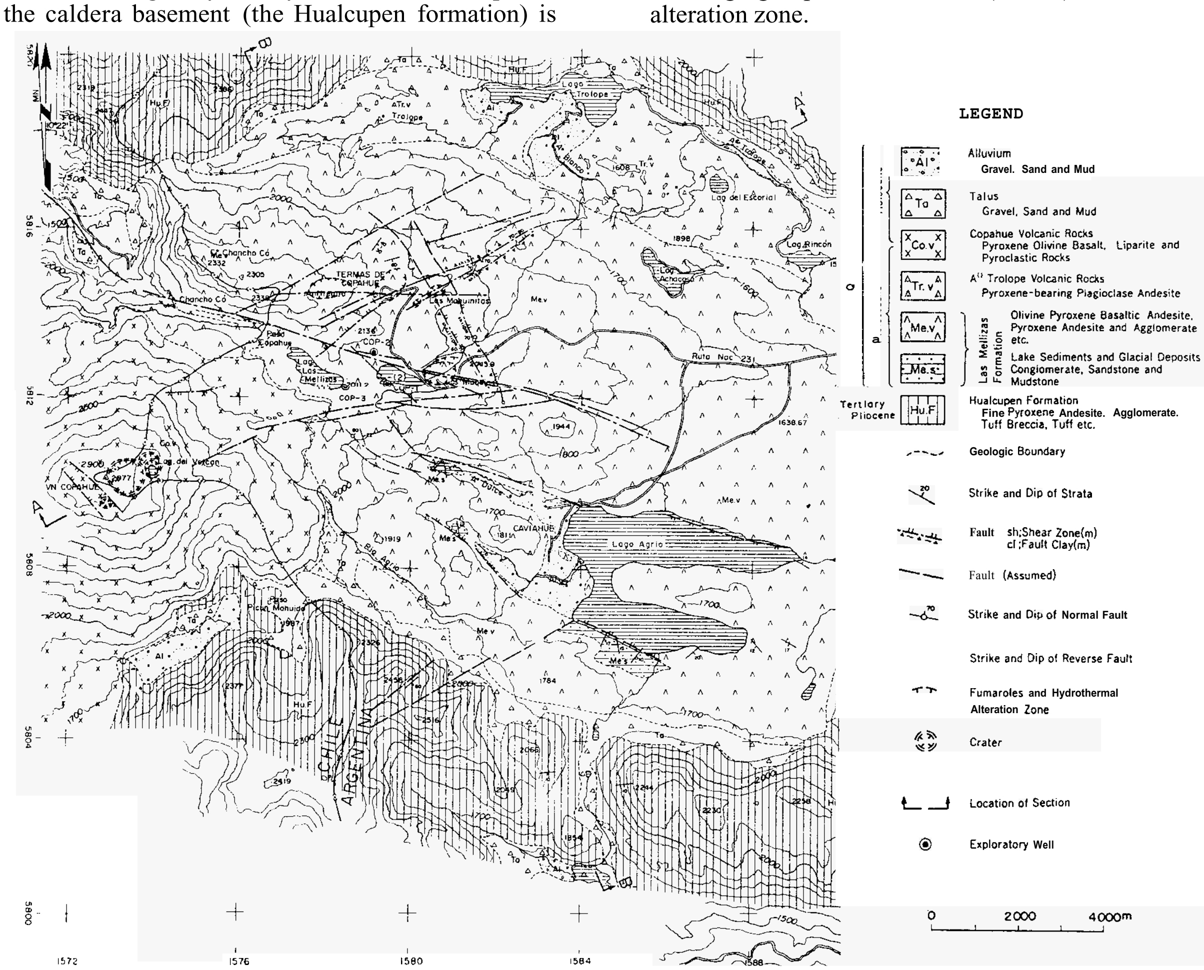

Figure *2* Geological map of the Copahue area

The waters at these manifestations are characterized by SO_4 type and HCO_3 type. SO_4 type waters are distributed at Las Máquinas, Las Maquinitas and Anfiteatro and HCO_3 type waters are at Termas de Copahue. These hot spring waters have small soluble cation concentrations, while they contain a large amount of volatile elements. Therefore, these hot springs are assumed to originate from shallow ground water which was heated by steam and gases. In addition to the geothermal manifestations mentioned above, strong acid water at the crater lake of Copahue volcano is formed by volcanic gases which may consist of H_2S, SO;?and HCl.

3.2 Well Fluid

The condition of the reservoir in the vapor-dominated system of COP-1, -2 and -3 was estimated by using the methods of D'Amore and Truesdell (1985) and D'Amore and Panichi (1980). As a result of D'Amore ***et** al.* (1988) and present study, the reservoir temperature is estimated to be 175-215°C and molar steam fraction is 1.0 at the initial productions. After that, the temperatures change to 235 - 250°C and molar steam fractions change to 0.35 - 0.45. The steam fraction equal to 1.0 at the initial production seems to be due to the gas cap as in the Geysers.

In the deuterium versus oxygen-I8 diagram (Figure 3), the slope of tie lines between the meteoric waters and vapor from COP wells indicate the boiling temperatures, which are roughly estimated to be 200 to 220°C. The change of the isotopic compositions during production suggests that (a)the reservoir for COP-I and COP-2 may not be large, or (b)a low reservoir permeability.

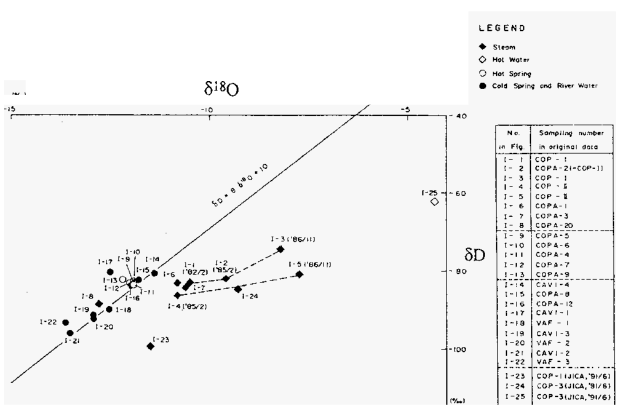

Figure 3 6D vs. $\delta^{18}O$ diagram

4. WELL LOG DATA AND WELL PRODUCTIVITY

Temperature measurements data were available from **14** shallow thermal gradient holes(PC series well) and 3 exploratory wells(COP-1, 2 and 3). Figure **4** shows the temperature logging data of these wells. Thermal gradient holes drilled on the horst indicate a fairly high temperature gradient of 25-35°C/100m. Temperature in wells COP-I, COP-2 and COP-3 also show that the steep increases in shallow depths, reaching 230°C at a depth of 800m in COP-I and COP-3 and at a 600m in COP-2 (heat flow values calculated from these temperature gradients were 0.5~0.6W/m2). The temperature below this depth shows nearly isothermal (;235~240°C), except the increase in temperature of COP-I below a depth of 1200m. On the other hand, the temperature gradient up to a depth of 50m outside horst is only 5°C/100m. The further the distance from the horst, the lower the temperature. Thus, temperatures differs extremely between the horst and elsewhere.

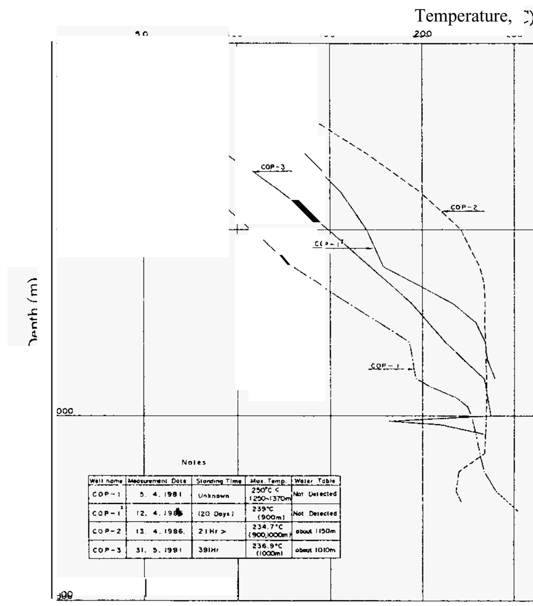

Figure **4** Temperature profiles of select wells

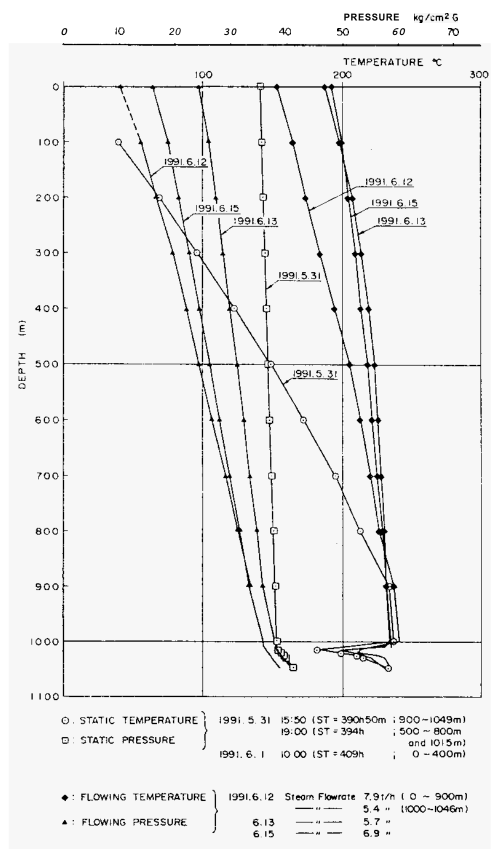

Figure *5* Pressure and temperature profiles for COP-3

Wellbore pressure and temperature profiles in both of static and flowing conditions were also available on COP-I, 2 and 3. These measurements were conducted with Amerada gauges. Figure *5* shows an example of the data on COP-3. The principal feedzone for COP-3 is located at 1,010m depth. Vapor-static pressure gradient was observed up to the depth of feedzone in the static condition. Hydrostatic pressure gradient below the feedpoint implies that no fracture exists from this depth up to bottomhole and just shows the condensed water column in the well. The feedpoint pressure of COP-3 was 38.2 bars. The nearly vapor-static pressure gradients up to the feedpoints were also observed in COP-1 and 2, and these results suggest that a vapor-dominated reservoir exists in the area.

The long term production tests were performed for each of the exploratory wells. Dry steam was discharged for all wells except initial period of production on COP-3. Figure 6 shows the production test result of COP-1. This well is produsing steam for operation of 670kw (binary cycle) pilot geothermal power plant since April 1988. Productivities of COP-I and COP-2 were not so large, and productivity indices for those wells were 0.7–0.8 (t/h)/(kg/cm²). On the other hand, productivity of COP-3 was relatively high in spite of the slim hole (;maximum discharge rate was 9 t/h), and productivity index for the well was 10.2 (t/h)/(kg/cm²) on the average. It seemed that the discharge capacity of COP-3 was limited by casing pipe (final diameter of the hole is 79 mm) rather than reservoir resistance (Figure *5).* The non-condensable gas in the discharged fluid was predominantly CO_2, and ranging from 6 to 11% by mass for all COP wells.

The results of pressure build-up tests performed after short term discharge tests indicated that permeability-thickness (kh) value inferred from COP-3 data was fairly high (–200 darcy-m), whereas those for other wells were low to moderate (3–5 d-m).

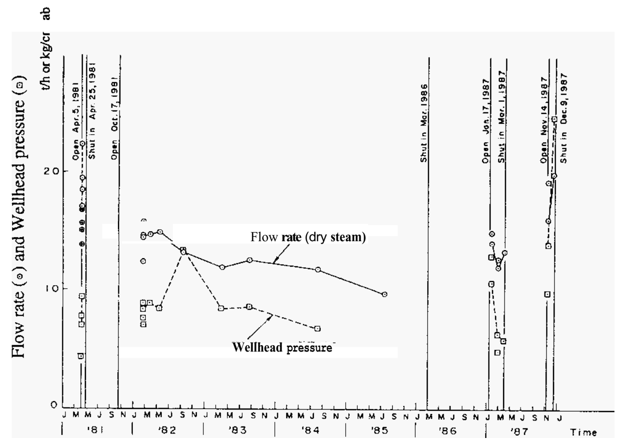

Figure 6 COP-1 production test result

5. CONCEPTUAL MODEL

The conceptual model was developed on the basis of all the available information on the field. Figure 7 illustrates a southwest-northeast cross section of the field.

The temperature distribution inferred from measurements indicates higher temperatures centering around the horst, reaching over 230°C at the depth of 600~800m. The vapor-dominated reservoir extends below that depth, and nearly isothermal region of 230–240°C is indicated. Based on the comparison of the temperatures of COP-1 and 3, both located at the edge of horst, with the temperature of COP-2, located closer to the center of the horst, it seems that thermal structure is controlled by the horst structure.

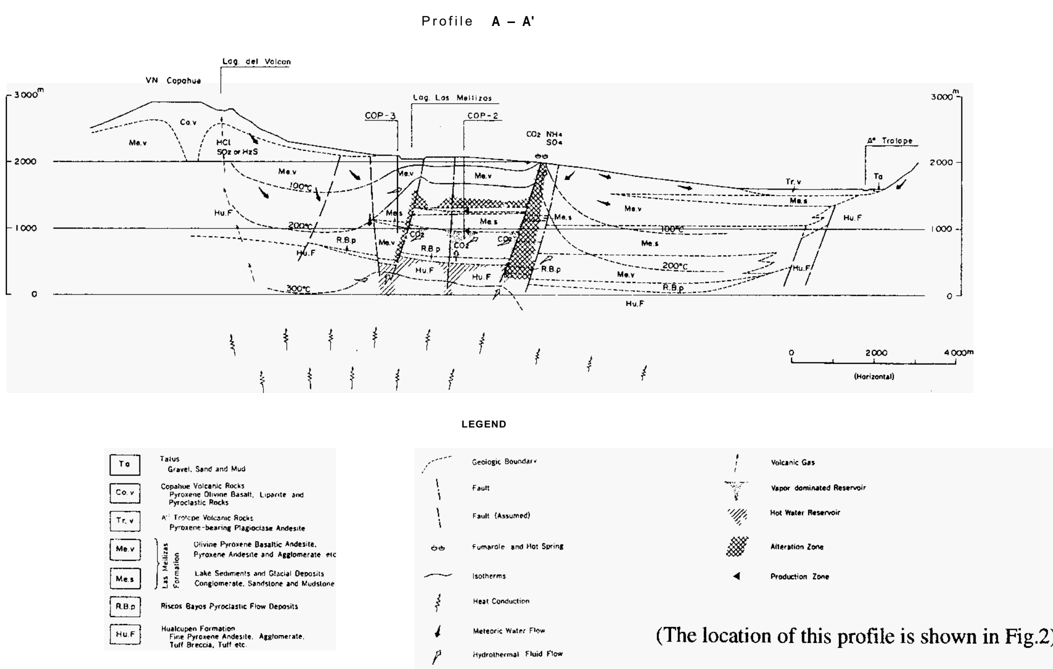

Figure 7 Hydrogeological model of the Copahue geothermal system

Above the vapor-dominated reservoir(i.e.above the top of isothermal interval in each of the wells COP-1, COP-2 and COP-3), alteration zone is distributed, and seems to function as a cap rock for the geothermal system. This zone is also inferred from the interpretation of electrical prospecting data.

Based upon feedpoints locations and temperature profiles of wells, it appears that the fractured lava in the Las Mellizas formation constitutes the principal reservoir. Furthermore, lava is predominant in the upper part of the Hualcupen formation, and based on observation of the caldera wall, it seems that the reservoir also extends in this formation along the fault zone. The bottom of the reservoir was not confirmed by drilling, and the possibility of the existence of the hot water reservoir beneath the confirmed vapor-dominated zone was suggested by (1) a deep low resistivity anomaly detected by electrical prospecting and (2) steep increase in temperature to more than 250°C at the bottom of the well COP-1.

Based on the well test data for the exploratory wells, it appears that the reservoir permeability has some variation in the horst, and fairly high permeability is expected along the inferred fault zone mentioned in the previous section.

6. PRELIMINARY RESERVOIR EVALUATION

Because of the scarcity **of** well data, preliminary resources assessment for the Copahue field was conducted in the following two steps:

Step **1** : 2-dimensional natural state modeling using steam and water two-phase numerical simulator, in order to confirm the features of the conceptual model semi-quantitatively and to refine the model.

Step 2 : Volumetric assessment of the recoverable geothermal reserves from the field, based on the conceptual model. **A** probabilistic approach to volumetric reserve estimation was used to reflect the uncertainties.

6.1 The Natural State Modeling

Based on the amount and density of data, the cross section shown in Figure 8 was chosen for the two-dimensional numerical simulation. The computational grid extends from 0 to **17 km** in the horizontal direction and -2,000mASL to +1,500mASL (3,500meters total) in the vertical direction. The model consists of 10 subdivisions in horizontal direction, and 6 subdivisions in vertical direction for a total of 60 gridblocks. The bottom boundary was treated as impermeable and constant heat flux boundary, and the heat flux distribution inferred from well temperature measurements was imposed for the central horst structure. The constant pressures and temperatures were prescribed at the top and lateral boundaries. The permeability distribution was used as the main fitting parameter in the natural state simulation.

Figure 9 shows the final result of the simulation, the quasi-steady state calculated after a simulated "geological" time of 50,000 years without any production and injection. The computed temperature distribution, the computed pressure, and the computed steam saturation distribution are shown. These figures indicate that the two-phase zone of nearly 240°C extends in a region surrounded by altered impermeable zone, and steam is upwelling and flow into the shallow aquifer at the surface recharge area (the calculated steam flow rate to the shallow aquifer was 1.6 kg/sec). The strong contrast between the permeability of caprock and nearly-impermeable side zones (0.001md in the model)and that of the vapor-dominated zone (50md) was the one of the key factors for the stabilization of vapor-dominated two-phase zone in the simulation. On the whole, the results of the simulation validated most features of the conceptual model, although the qualities of the simulation were relatively limited.

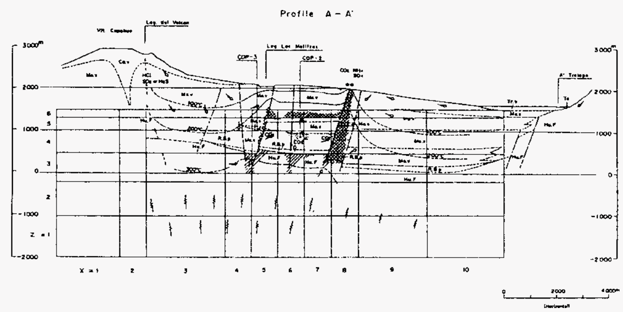

Figure 8 Simulation model grid blocks

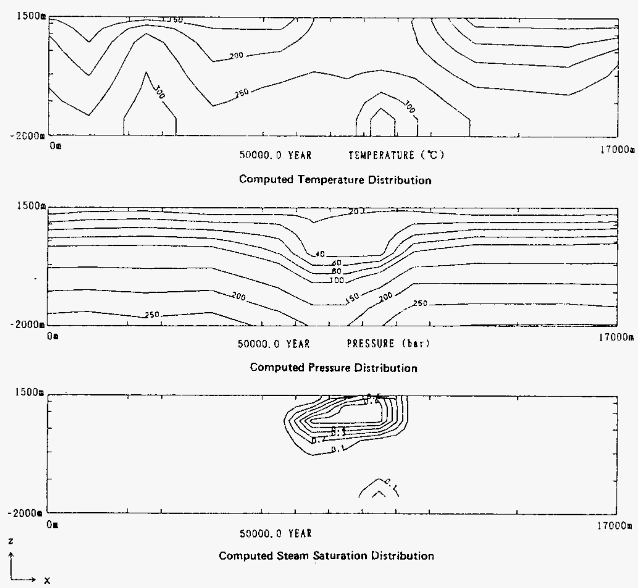

Figure 9 Computed results

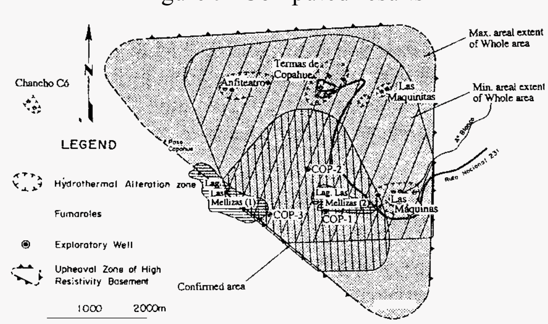

Figure 10 Map of confirmed and whole area

Table 1 Parameters in calculation of reserves for confirmed area

Parameter	Unit	Type of Probability (~~or fixed~~)	Minimum Value	Maximum Value	Most Likely Value
areal extent	km²	fixed			4
thickness	m	triangular	600	1200	900
temperature	C	triangular	230	250	240
porosity		uniform	0. 04	0. I	
water saturation		uniform	0 3	0. 5	
recovery iaclor		uniform	0 04	0 15	–
volumetric specific heal of rack	kJ/m³°C	fixed			2360
rejection temperature	°C	fixed			I0
utilization iaclor		fixed			0. 6
power plant load factor		fired			0 85
power plant life	years	fixed			30

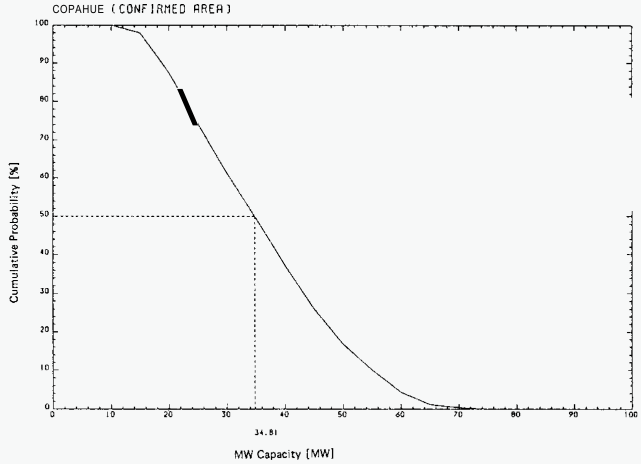

Figure 11 Cumulative probability of MW capacity

6.2 Volumetric Assessment

The recoverable geothermal reserves in MW capacity were estimated volumetrically based on the conceptual model. The volumetric reserve estimation introduced by Muffler and Cataldi (1978) and Muffler(1979) was used with some modifications. A probabilistic approach was applied to the method, to account for uncertainties in some parameters. The reserve estimations were performed for the following two specific areas (Figure 10):

a) Confirmed area ; area where reservoir is confirmed by COP-1, COP-2 and COP-3.

b) Whole area ; area in the triangle zone (i.e., the upheaval zone of high resistivity zone detected by electrical exploration) including all geothermal manifestations such as Termas de Copahue etc.

The results only for the Confirmed area are discussed below, because of attracting most interests.

For the confirmed area (about 4km²), probable limits of reservoir thickness, porosity, average temperature, water saturation and recovery factor were estimated to make a Monte Carlo simulation study of probability distribution of reserves, based on various information on the field. Table **1** shows the input data used for the Monte Carlo simulation.

The value of the uncertain parameters were sampled randomly 1,000 times, and reserves were calculated for each sampled set of parameters. Figure 11 presents the results of simulation in terms of the cumulative probability distribution for the Confirmed area. The results of these calculations are : a)the mean value of the calculated MW capacity of the area is 35MW; b) there is a 86% probability that the resource will exceed 20MW; and c) there is a ***62%*** probability that the resource will exceed 30MW.

7. CONCLUSIONS

Our present study of the Copahue field suggests that the field, characterized a vapor-dominated reservoir, is a very promising prospect for future development for electrical power generation. Additional exploration and drilling of wells to further delineate the characteristics and capacity of the reservoir are highly expected.

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