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

HEAT FLOW OF COPAHUE GEOTHERMAL FIELD, ITS RELATION WITH TECTONIC SCHEME

Luis Mas[1], Graciela Mas[2] and Leandro Bengochea[2]
[1]Dirección Provincial de Hidrocarburos y Combustibles, Belgrano 398, floor 11, 8300 Neuquén, Argentina
[2]Universidad Nacional del Sur, san Juan 670, 8000 Bahía Blanca, Argentina

Key Words : Heat Flow, Tectonics, Reservoir, Copahue Field

ABSTRACT

The Copahue geothermal field is located in a volcanic complex that has suffered a strong influence of tectonic movements from the beginning of its evolution.
Regionally, it is possible to recognize two predominant fracture systems, the main system has a N55W direction and the other one has a N15W direction. According to these fracture systems, it is possible to define the strength direction that affected the Neuquén basin since pre-Jurassic times.
The tectonics of the studied area is characterized by a fracture system associated to the evolution of the volcanic complex. Circular faults that constitute the borders of a big caldera were formed in the first stage of the volcanic evolution, developing a radial fault system, observable in the external part of the caldera.
The second stage of the Copahue volcanic complex is represented by a group of several effusive centres: Las Mellizas, Trolon, Bayo and Copahue.
Las Mellizas Centre has the largest area. It covers the bottom of the great caldera (15 x 20 km). Trolon, Bayo and Copahue effusive centres are located on the border of this caldera.
There is a fault system that affected this volcanic complex, which main direction is N55W and their associated directions are N55E, EW and N40W.
The geothermal reservoir is located predominantly in zones of secondary permeability, in calc-alkaline lavas and pyroclastic rocks of Las Mellizas Formation, and contains overheated steam.
This work was performed with the data obtained from 12 wells drilled for this purpose, with depths that ranged from 50 to 200 meters.
A Heat Flow Map was prepared, that shows the distribution of this parameter in an area of about 100 Km^2, with values above the world average of 60 mW m^{-2}. These data indicate that the thermal anomaly is significant, with peak values six times the world rate.
The comparative analysis of the heat flow distribution with the tectonic scheme of this area, shows the correlation that exists between the axe of the elongated area with the highest heat flow values, with the main structural lineament of this zone, recognized by geology and remote sensing evaluation.

INTRODUCTION

The Copahue volcano is located on the west border of Argentina, in the Neuquén Province, on the Andes Range, nearby the boundary with Chile. It is about 37º latitude S, 71º longitude W, and the altitude is from 1,600 to 3,000 meters.
The studied area is located in a semi elliptical valley of about 15 km NS and 20 km EW.
The bottom of the valley shows a dip to the ENE, with an altitude from 1,700 – 1,800 m.a.s.l. on the west side and about 1.500 m.a.s.l. on the northeast. The border of the valley is over 2.000 m.a.s.l. and is constituted by a flat peak mountains chain, except Copahue volcano, located at the west, and with an altitude of 2.977 m.a.s.l., it is the highest peak of the area.
The hydrographic net presents rivers and streams with a centrifugal radial shape, and a circular component in relation with the volcano. There is also a permanent snow covering on Copahue and some lakes and lagoons, as the lake Agrio (the most important of the region) and Tolope; and the lagoons Las Mellizas, with a very important relation with the geothermal field.
The weather in the region is typical of mountains. The rainfall is over 2.000 mm/year, and is mainly snow, covering about 200 days/year (from April to October).
The temperatures are about 25ºC on summer and -14ºC on winter, with an annual rate of about 7ºC. Predominant winds blow from the west, with mean velocity of 21 m/s; however, values of 35 m/s have been measured. On this region a “white wind” is frequent during winter that consists of snow precipitation with strong winds.
The Copahue geothermal area is known since historic times; their water and vapour springs were used for baths or spa. In the last two decades a permanent population was developed in Caviahue, near the Lake Agrio; this town and Copahue village are the only two settlements in this area. Due to the weather conditions, there is no population in Copahue village during wintertime, from May to October.
A systematic development of Copahue geothermal area began in the middle of the seventies, with the exploration of the geothermal resources for energy purposes. On 1986-87 a pilot power plant of 670 kW was installed, and on 1998-99 a pipe system on some streets of the Copahue village was installed for melting of the snow.

GEOLOGY

The morphology has been modelled by volcanic and tectonic processes, and glacial and fluvial valley erosion.
Those valleys were the place for the location of lakes and lagoons, as lake Agrio and Trolope, and the lagoons Achacosa, Rincón and Escorial.
The lagoons Las Mellizas, on the northwest side of the caldera, are not related with glacial processes, but with fault structures.
Another geomorphologic feature is the presence of basins, as a product of erosion of hydrothermally altered rocks. These zones are represented by the hot springs of Copahue village, Las Maquinas, Las Maquinitas, El Anfiteatro, and an area in the vicinity to the west side of an exploration well COP-2.
The stratigraphic evolution of the Copahue volcanic complex was related with one of the main orogenic processes of the Andes range. This process, on the upper Miocene, is the

Quechua Orogenic phase, during which the Range region adopted its present configuration, and Vicente (1972, in Yrigoyen, 1979) denominated it as "orographic phase".
Our volcanic complex began its evolution with rocks of the calc-alkaline series, with lavas of andesitic to potassic basaltic-andesitic composition of the Hualcupén Formation (Pesce, 1987). It is intercalated with volcanic conglomerates. In Chile, its equivalent is Cola de Zorro Formation (González and Vergara, 1962, in Niermeyer and Muñoz, 1983, and in Pesce, op. cit). This deposition unconformably lies on the folded pre-Pliocene rocks. Niermeyer and Muñoz (1983, op. cit) indicate that the Cola de Zorro Formation has about 1,900 m of thickness on the chilean side of Copahue. On Argentina about 1,000 m of this formation are exposed. According to the last authors, Copahue volcano presents higher values of potassium enrichment in the upper part of the sequence in comparison with other volcanic complexes, similarly to the Callaqui volcano in Chile.
The rock volume erupted from this first eruption centre, located in the vicinity of the present volcano, was estimated to be very large, because it covered tens of kilometres with important thickness.
At the end of the Pliocene, there was another orogenic phase, characterized by extension and not compression. Yrigoyen (1979) called it the "geographic phase", because the gravity faults of this phase affected the Pliocene rocks of the Central Andes, forming the present blocks structures.
During this phase, a change in the dynamics of the eruption centre was produced, and formed a large caldera with a extent of 15 km from north to south, and 20 km from west to east.
Another eruption centre, Las Mellizas, is located in the west side of the caldera (Pesce, 1987). It has calc-alkaline composition, and is constituted by andesites and basaltic-andesites of similar characteristics than those of Hualcupen Formation.
These upper Pliocene lavas (Linares et al., 1999) are intercalated with volcanic conglomerates and fluvial and lake sediments, represented by conglomerates, sandstones and shales, with a thickness of 50 meters. The pyroclastites of the Riscos Bayos Formation are associated to this centre (JICA, 1988); pumice and scoria tuff, that appear at the southeast of the field, outside of the caldera.
During the post-caldera phase, eruption centres were developed on the external border of the caldera; Cerro Bayo and Trolon are located on the northern border. The first one corresponds with which González Díaz (1978) defines as meso-silicic Pleistocene vulcanites that concentrate also in other important volcanic centres and Groeber (in González Díaz, op. cit) named Tilhué Formation. Other authors described them as trachytes and liparitic, dacitic and rhyodacitic facies. Pesce (1987) defined them as Shoshonitic series.
Groeber connected thermal hot springs of Domuyo with this type of rocks; this was later confirmed by Pesce (1983) and JICA (1984).
Trolon, the second centre, has calc-alkaline composition, with andesitic lavas, similar to those of Hualcupen and Las Mellizas Formation.
On the west border of the caldera, there is an important structure, a directional fault, with a N55W direction parallel to the regional lineaments. This structure has had influence on the formation process of a crater on this volcanic centre, of about 8 kilometres of diameter, at the end of Pleistocene. At the same time, radial faults of the eruption centre of Las Mellizas Formation were reactivated, like in the southeast sector of the crater, located on Paso Pucón Mahuida.
Contemporaneously, the Arroyo Trolope volcanic flow was produced on the northern side of the caldera. It is constituted by potassic andesite lavas that spread from a fracture related with the caldera origin.
In the crater of the Las Mellizas Formation, the present eruption centre of Copahue was formed. It reached a size notably smaller than previous volcanoes of the complex. This eruption began during the upper Pleistocene, about 1 million of years before present (Linares, op. cit.)
Copahue volcano is slightly elongated on north south direction, with a diameter of about 8 km. It has a maximum altitude of 2,977 m.a.s.l. and the base level is about of 2,100 m.a.s.l.
Lithologically it is composed by a series of lavas and pyroclastics, potassium andesites and basaltic-andesites, dark brown to grey in colour, lapilli and coarse volcanic breccia. The total thickness is less than 900 meters.
At the southeast of the volcano, a little white dome appears on the base, with a composition similar to Cerro Bayo. Niermeyer and Muñoz (op.cit.) defined it as of rhyolitic composition, and Pesce (op. cit.) as Shoshonitic series.
At the top of Copahue volcano, there are some craters aligned approximately in a north - south direction, some of them are covered with glacial calottes.
One of them, located at the east and known locally as "crater del volcán", has fumarolic activity and a lagoon where water has a pH between 0,2 and 0,6 (Jurío, 1977). This crater had activity due to gas decompression on August 1992.
The eruption activity of Copahue volcano has been contemporaneous with the last glacial period; and it is possible to recognize it because the first flow deposits appear eroded by glacial processes. Others, according with Niermeyer and Muñoz (op. cit.), are "suspended", and it demonstrates that they are interglacial; and finally, the last ones do not show erosion tracks. As an example of this, there are two small flows on the northeast side of the volcano. They are constituted by vesicular basaltic-andesitic lavas AA type, dark grey to black.

STRUCTURE

The structural scheme of the neuquen Province is defined by an important anisotropy. Ramos (1978) mentioned structural lines that define zones or tectonics units with particular geologic evolution
Regionally there are two dominant fracture systems; the main one is N55W and the other is N15W. From these fracture systems the stress direction of the Neuquen basin since pre-Jurassic times may be recognized. Ramos (op. cit.) indicates that the stress components are N85W, in coincidence with the subduction of the Nazca Plate below the South American Plate.
The Copahue region was formed as a result of the compressive system, described in the former paragraph.
The structural unit of Copahue Volcanic Zone is located between 37º and 38º30' of south latitude. This volcanic arc was structurally formed during intramalm diastrofism (Stipanicic and Rodrigo, 1969).
At the west of Loncopue, there is an important fault, with a direction N55W, in coincidence with the structures appointed above. It is part of a group of parallel faults, described by Bracaccini (1964 in Ramos, 1978). This fault crossed the studied area, and is observed at Cajon Chico, Lago Agrio, Lagunas Las Mellizas and Paso Copahue.

The tectonics of the studied area is characterized by a fault system associated to the evolution of the volcanic complex. In this process semicircular faults were formed, which constituted the border of the big caldera. Connected to the construction process of the caldera, there is a radial fault system, located on the external part of it.
At the internal part of the caldera, the Las Mellizas Effusive Centre was developed which radiometric age is about 2.6 ± 0.05 m.y. (Linares, E. op. cit.); this centre would be at the occidental border of the caldera.
On the tectonic evolution of this centre, was produced a crater of about 9 km of diameter. A system of radial faults on the Las Mellizas Formation appears combined with the formation of this crater.
One of the most characteristic tectonic features of the area is a system of horsts and grabens defined by Latinoconsult (1981). It is limited by the north and northwest borders of the crater and a radial fault system, located in the north side of lake Agrio. This structure coincides with the N55W regional fault system, see figure 2.
There are three fault systems; the first one is a sub parallel system with direction N55E, distributed predominantly to the north and west of Las Maquinas. Hot springs of Copahue, Anfiteatro, Las Maquinitas and partially Las Maquinas, are directly related with this structure.
Another group of faults are EW direction; and is possible to observe them in the northern part of the eastern lagoon of Las Mellizas, which is related to Las Maquinas hot springs.
A third group of faults has a direction N40W and are stepped at the northeast of Las Maquinas. They are associated with the N55E fractures.
Those fault systems are associated to the main regional structure, which has a N55W direction, as a result of the stress produced after the crater formation.
Two expansion structures were produced with directions N55E and EW, and a compressive group with N40W direction. The first two structures are directly associated with the hot springs and the presence of a steam reservoir.

HEAT FLOW

The heat flow for the Copahue geothermal field was calculated using the geothermal gradient of 12 wells, drilled for this purpose, and the thermal conductivity values estimated from the lithology described for each well.
The thermal conductivity was estimated, based on the present knowledge of the geology of Copahue geothermal field (Perry, 1980; Kern, 1974; Mongelli, 1981). Similar studies developed at the Domuyo Geothermal Field (JICA, 1984), and a report of physical studies on core samples (Mas, 1986) were also used.
The geothermal gradient of each lithological unit was calculated from the temperature measurements of the wells.
The heat flow of each lithological unit was calculated using these values, see Table Nº 1.

$$\mathbf{Q = K \cdot G}$$

Q = Heat Flow (mW.m^{-2})
K = Thermal conductivity
G = geothermal gradient
A map of heat flow distribution was prepared with the obtained values, using interpolation by mobile rate. The results are presented in figure Nº 3, with the map of distribution of heat flow.
It is possible to find vertical variations in the values of heat flow from some wells, because of the presence of aquifers that produce a lateral heat flow. This movement is observed also in the vertical direction, due to the circulation of fluids in convective systems of permeable rocks.
We found the highest heat flow values in the west-northwest section of the studied area. The maximum value 426,36 mW.m^{-2} occurs in well Nº 9; well Nº 15 has the second to the highest value: 372,02 mW.m^{-2}, and well Nº 7, located between those two, has the third highest value, 288,42 mW.m^{-2}.

DISCUSSION

The studied area has a surface of about 100 km^2 and the heat flow shows values well above the world average of 60 mW.m^{-2},.
The evaluation of the heat flow values and its distribution indicates that the thermal anomaly is important with heat flow values six times higher than the world rate. On the other hand, the limited surface of the anomaly, of about 100 km^2 with values over 80 mW.m^{-2}, would indicate good thermal isolation of the reservoir.
Some wells show high values, like the well in Paso Copahue, that reaches 426.36 mW.m^{-2}. In this zone we can find high values following the direction from Paso Copahue to Cascada del Agrio, to the northwest of Lake Agrio, see figure 3.
Likewise, it is possible to see that the heat flow curves show a trend with an EW direction.

CONCLUSIONS

A comparative analysis of the heat flow distribution with the tectonic scheme of this area shows that there is an important correlation between the trend of the highest values of the calculated heat flow and the main structural lineaments of the zone, as we can see in figures Nº 2 and 3
The strong tectonic activity that this zone had suffered, produced secondary permeability, restricted to those areas where the hot fluids ascend to the higher levels. This fact is confirmed by the hot springs location and its relation with the lineaments.
This confirmed the high structural control of the field, since there is a direct correlation between the maximum values of heat flow with the main structures present in the field. The best example is the structure that connects the hot springs of Chinch Co (in Chile), the lagoons Las Mellizas, the hot springs of Las Maquinas, the waterfall La Escondido and the northern side of Lake Agrio.
This fact lets us conclude that the zone with a thermal anomaly is wider than the presently known reservoir, which extends to the east-southeast, in direction to the Lake Agrio.

REFERENCES:

GEOTHERMAL STUDIES COMMISSION; 1975: Copahue geothermal gradient distribution. Unedited Report. Yacimientos Petrolíferos Fiscales. Inédito.
GONZALEZ DIAZ, E.F.; 1978: Quaternary stratigraphy. In Report of Geology and Natural Resources of Neuquén Province. VII Argentine Geologic Congress. 85-98.
HOLMBERG, E.; 1978: Geomorphological Features. In Report of Geology and Natural Resources of Neuquén Province. VII Argentine Geologic Congress. 119-127.

JICA; 1984: Argentine Republic. Final Report on the Northern Neuquén Geothermal Development Project. Japan International Cooperation Agency.
JICA; 1988: The Feasibility Study on the Northern Neuquén Geothermal Development Project. Progress Report. Japan International Cooperation Agency.
JICA; 1992: The Feasibility Study on the Northern Neuquén Geothermal Development Project. Final Report. Japan International Cooperation Agency.
JURIO,R.L.; 1977: Geochemical Characteristics of the Thermal Fluids of Copahue (Neuquen, Argentina). Main Geothermal Implication. Minning Nº 172. Buenos Aires.
KERN, D.Q.; 1974: Heat Transference Process. Continental Edition Company S.A. Mexico.
LATINOCONSULT; ELC-ELECTROCONSULT; 1981: Geothermal Feasibility Study of Copahue. Final Report. Secretaría de Estado del COPADE. Provincia del Neuquen.
LINARES, E.; OSTERA, H.A.; MAS, L.C.; 1999: Potassium-Argon Chronology of the Copahue-Caviahue Effusive Complex, Neuquen Province, Argentina. Contribution Nº 141 from Geochronology and Isotopic Geology Institute (INGEIS).
MAS, L.C.; 1986: Petrographic Studies of Alteration Minerals and Physical Parameters on Drill Rocks Samples. 16° Geothermal Exploration Course. IIRG. Unedited Report.
MONGELI, F.; 1981: Research Elements for the Geothermal Elements. Bari. Adriática Editrice.
NIERMEYER, H. y J. MUÑOZ; 1983: Laguna de La Laja Chart. Bio Region. Geologic Chart of Chile. Esc.1:250.000; N°57. National Service of Geology and Mining. Chile.
PERRY, J. ed.; 1980; Chemistry Engineer Manual. Tipographical Editorial Unión Hispano Americana. México.
PESCE, A.; 1983: Geothermal Evaluation of Co. Domuyo Area. Prefeasibility Study. Vulcanological Studies Group. National Geological Service. 35 pp.
PESCE, A.; 1987: Volcano Tectonic Evolution of the Volcanic Complex of Copahue-Caviahue and its Preliminary Geothermal Model. X° Argentine Geological Congress. Tucumán.
RAMOS, V.; 1978: Neuquén Structure; Relatorio, VIIº Argentine Geologic Congress; Neuquén, Argentina. 99-119.
STIPANICIC, P.N. y RODRIGO, F.; 1969: Diastrofism eo and mesocretacic in Argentina and Chile, with reference to the Patagonian Jurassic Movements. Proceedings IV Argentine Geological Workshop. Buenos Aires. Vol.II; 337-352.
YRIGOYEN, M.R.; 1979: Principal Cordillera. Argentine Regional Geology. National Academy of Sciences; Córdoba. 651-694.

Table 1: Gradient Wells of Copahue Geothermal Field

Well	G ($x10^{-3}$ ºC.cm^{-1})	Q (mW.m^{-2})		Calcul. Depth (m)
1	0.74	86.94	**96.98**	20 - 90
	1.43	107.43		90 - 126
3	0.76	89.45	**74.40**	10 - 100
	0.8	60.19		100 - 135
	0.63	73.57		135 - 200
4	1.61	188.1	**200.64**	20 - 60
	2.85	213.18		60 - 100
5	0.92	108.68	**108.68**	10 - 56
6	0.47	54.34	**54.34**	10 - 50
7	2.46	288.42	**288.42**	10 - 54
8	1.14	133.76	**133.76**	10 - 50
9	3.64	426.36	**426.36**	10 - 60
10	0.62	71.06	**71.06**	10 - 46
13	0.6	71.06	**45.98**	10 - 50
	0.3	20.9		50 - 60
	0.48	45.98		60 - 70
14	0.5	58.52	**73.57**	10 - 25
	0.53	87.78		25 - 51
15	2.53	372.02	**372.02**	10 - 64

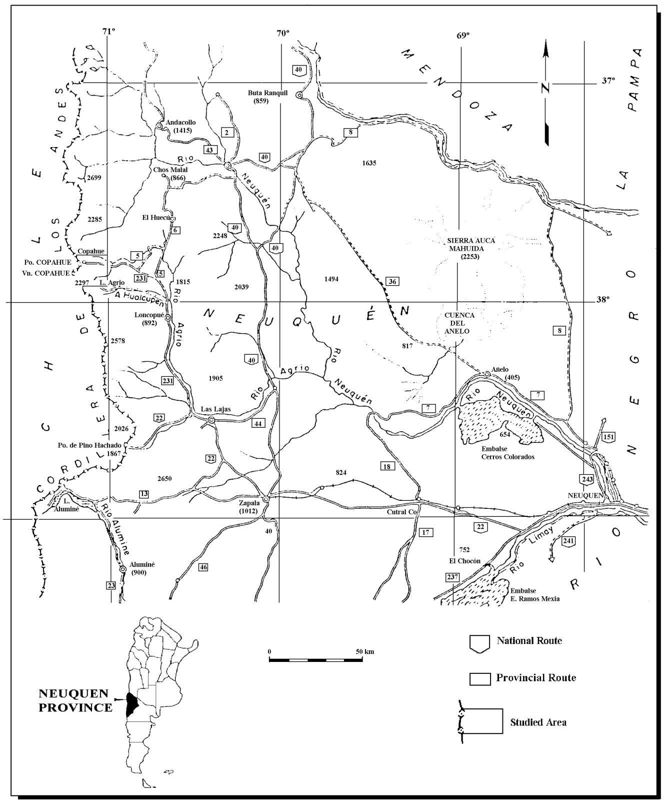

Figure 1: Location Map of the Studied Area - Based on Latinoconsults (1980) and JICA (1992).

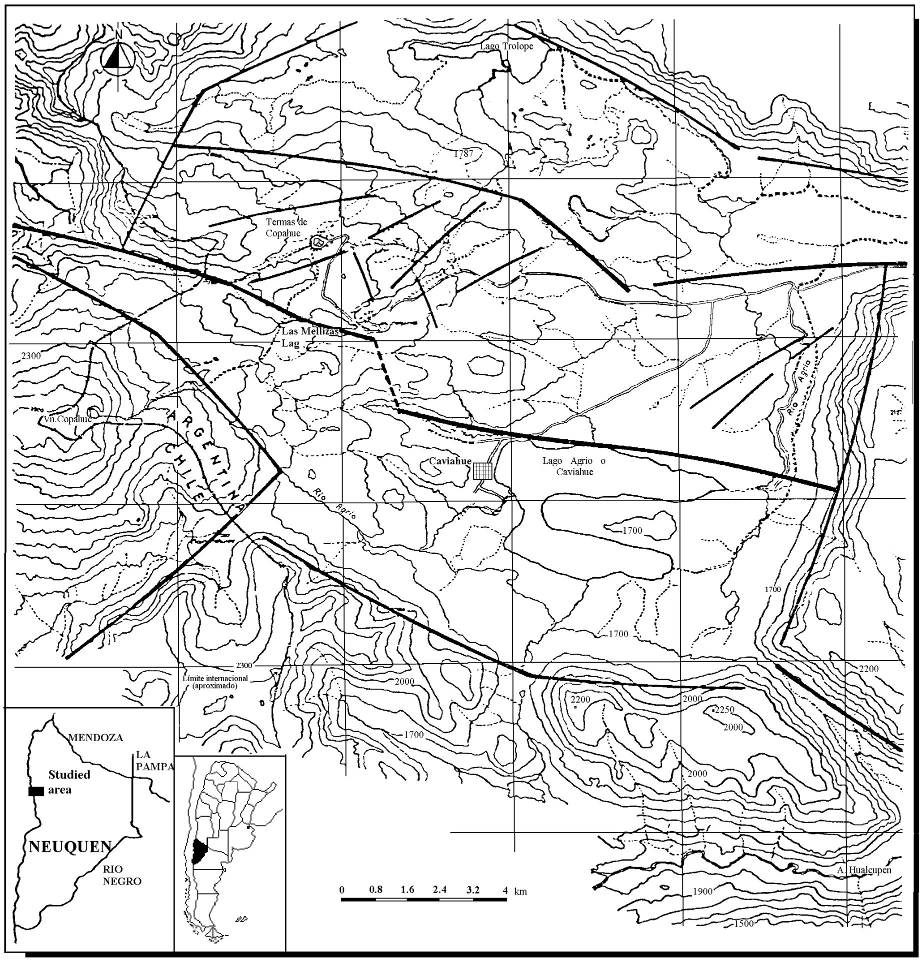

Figure 2: Main Structural Lineaments - Based on Latinoconsults (1980) and Pesce (1987), modified by Mas.

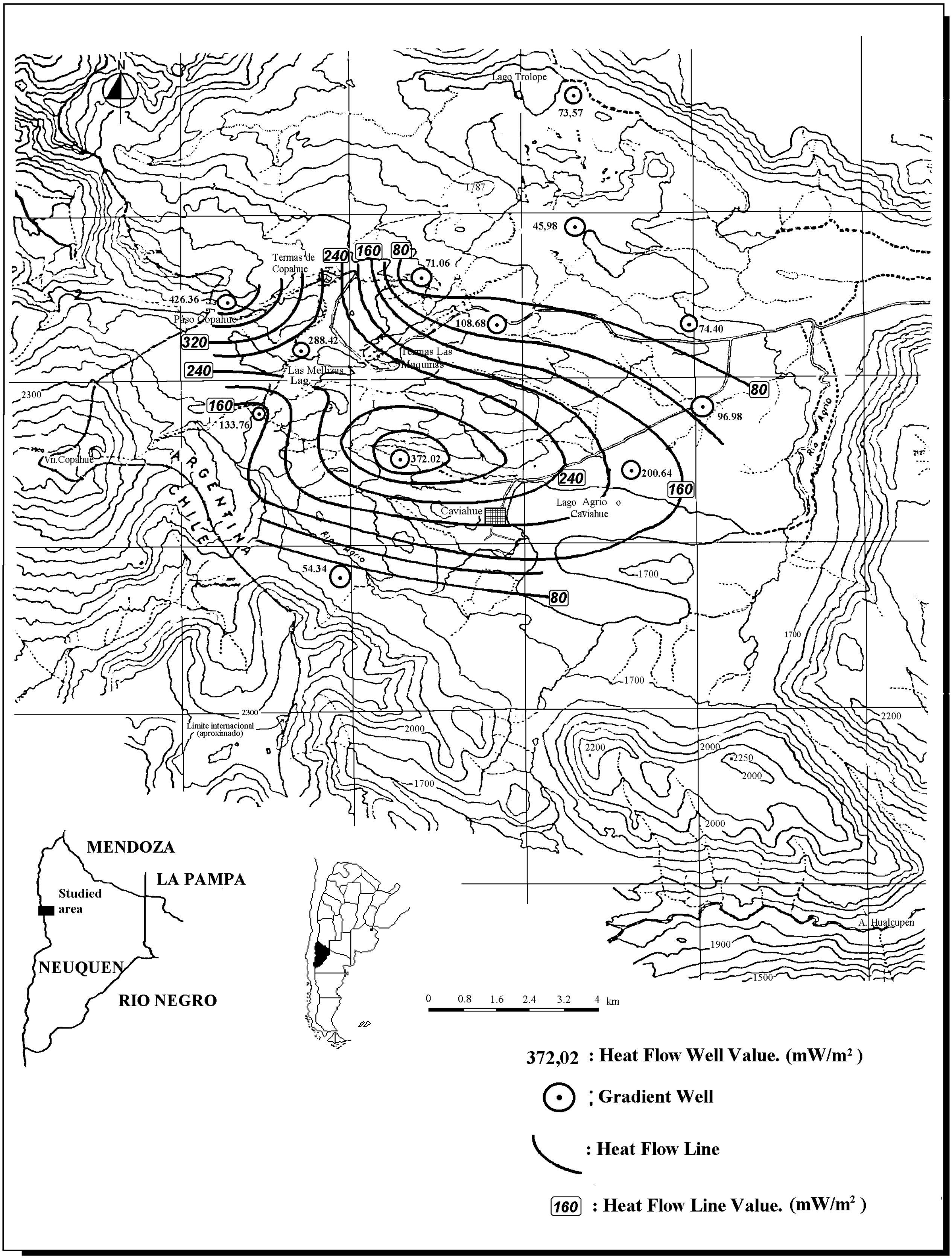

Figure 3: Heat Flow Distribution Map.