COLOMBIA, COUNTRY UPDATE

Claudia Alfaro[1], Nelson Bernal [2],Gilma Ramírez[3], Ricardo Escovar[4]
[1,2,3,4] INGEOMINAS, (The Colombian Geological Survey). Dg. 53 No. 34-53. Santa Fe de Bogotá, Colombia

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ABSTRACT

After more than 30 years of trying to develop the geothermal potential of Colombia, a major effort is now being made to explore and assess the geothermal resources of the entire country.

Until now, the availability of conventional energy sources in Colombia prevented geothermal exploration from reaching a higher level. However, the extreme energy crisis of 1992 – 1993 alerted the authorities and the community to the necessity for exploring alternative energy sources.

In 1997, GESA (i.e. Geoenergía Andina S.A.) drilled Colombia's first geothermal well at the Las Nereidas geothermal prospect. This well allowed the scientific staff to determine some of the characteristics of the geothermal system, where permeability seems to be related to faults. Also in 1997, Ingeominas (i.e. The Colombian Geological Survey) undertook geothermal exploration of Azufral volcano, starting with geology, volcanology and geochemistry. These preliminary studies indicate the possibility of a reservoir at 200-250°C (according to empirical geothermometer calculations) in a mature strato-volcano. This project is intended to produce electrical energy for the Nariño province.

In 1999, an evaluation of the existing information collected and processed by Ingeominas on chemical characteristics of thermal springs and temperature data in oil wells showed the advantage of constructing a Geothermal Map of Colombia. This map will help determine Colombia's potential for direct and indirect utilization of geothermal resources. It will also help the government and private investors locate suitable targets for further exploration. With these projects, Colombia hopes to start exploiting its geothermal resources and decrease the serious environmental impact caused by the production of fossil combustibles and other conventional sources of energy, such as gas and coal-fired plants.

The objectives of this paper are (1) present an overview of the geothermal resources and exploration studies in Colombia, and (2) summarize the studies being developed in Colombia that focus on a new stage of exploration.

1. INTRODUCTION

As determined from the first exploration stages, the Colombian range of volcanic mountains contains a remarkable regional thermal anomaly. Evidence of this anomaly are the extended periods of magmatic activity and the existence of numerous active and recently active volcanoes. Surface manifestations (hot springs, hydrothermal eruption craters, steam vents, etc.) suggest that there is a high probably of the occurrence of hydrothermal systems related to these potential heat sources. Until now, geothermal resources have been applied in Colombia only for direct use of hot spring water for swimming and bathing in about 38 spas from 27 localities. A raw estimate of the capacity and energy use is presented in Table 1.

[Table 1]

Since the second quarter of the Nineteen Century, hot springs occurring in Colombia have attracted the interest of scientists. In 1829, Boussingault (in Forero, 1958), described the hot springs from Paipa (Cundinamarca Province) at the Academy of Sciences in Paris. A century later, Navia and Barriga (1929) studied the chemistry of those hot spring waters (23-74°C). They also studied gases, muds, flaky deposits, the geology of the area, and the therapeutic utilisation of the waters. Their more remarkable findings were an unusually high salinity of the waters (around 40 g/l) due mainly to sodium sulphate, and the occurrence of salt strata (banks). The salt strata, which are presumably related to the salinity of the waters, consist of sodium sulphate, chloride, and bicarbonate that originate from Cretaceous sea deposits. The volcanic activity of the Pliocene and its sulphur contribution (H_2S) are responsible for the sulphate formation. For these waters, an important volcanic component was postulated based on the contents of boron, phosphorous, arsenic, bromide and iodine. The meteoric component was presumably due to infiltration from a lake named Laguna de Tota, located 25 km away and 300 m above the level of the springs from Paipa.

Systematic geothermal exploration began about thirty years ago. The chronology of the main exploration studies can be summarised as follows. See location of the study areas in Fig.1.

1.1. 1968. Geothermal regional reconnaissance study at the Ruiz Volcanic Complex. This study represents the starting point of geothermal research in Colombia. It was commended by the Central Hidroelectrica de Caldas to the Ente Nazionale per L'Energia Elettrica in order to assess the geological situation of the region, to determine if there are favourable conditions for deep fluids that can be used for electrical energy production, to determine preferential areas, and to formulate a plan for the exploration.

From the geology, an extensive thermal anomaly on a regional scale was indicated along with local anomalies on

SW-NE and NW-SE orthogonals; these were recommended as priorities areas. A few hot springs were sampled and analysed. A meteoric origin was established for the thermal waters, which have isotopic compositions that change as a function of elevation. Oxygen-18 enrichment was determined for hot springs in the Botero Londoño Zone (West flank at Nevado del Ruiz), suggesting deeper circulation. Two separate circulation systems were proposed, matching the two types of waters, sulphate above 3000-3500 m and chloride and bicarbonate at lower elevations.

A plan for further studies including geology, geochemistry and geophysics was recommended

1.2. 1982. Reconnaissance study of the Geothermal Resources of Colombia. This study carried out by OLADE et al., excluded the Nevado del Ruiz Volcano Complex. Based mainly on geological and geochemical studies, nine (9) areas were identified as potential geothermal systems. They were preliminarily classified as high, middle and low priority geothermal exploration targets. The high priority systems, **Chiles-Cerro Negro** and **Azufral volcanoes**, are recent stratovolcanoes with a complete magmatic evolution (SiO_2 59-69% and 60-71.5%, respectively); their substrate consists of thick Tertiary pyroclastic deposits and both exhibit thermal manifestations such as phreatic eruption craters and hot springs with high boron that could be related to the rise of geothermal brines. Additionally, the characterisation of xenolytes from Azufral volcano showed hydrothermal zonation typical of high temperature systems. The **Paipa** and **Iza** area was classified as high-middle priority. Although this system occurs in sedimentary rocks (Cretaceous formation) where the permeability should not represent a problem, the heat source presumably corresponds to ancient volcanism (lava of 2.5 million years) with rhyolite deposits (71.5% SiO_2). Many hot springs occur in these towns with the highest temperature close to 60°C. The **Cumbal** and **Galeras** volcanoes were classified as middle priorities basically for their hydrological conditions. These are active stratovolcanoes with a moderate to limited magmatic evolution (60-64% SiO2 and 56-59% SiO2, respectively). Their substrate consists of tertiary volcanics at a depth that is probably sufficient for the existence of reservoirs. Their hot springs are quite modest with maximum temperatures of 34°C. The **Doña Juana**, **Sotará** and **Puracé** volcanoes exhibit good magmatic evolution (SiO_2 58-67%, 64-76%, 57-64%, respectively), and numerous high temperature hot springs (up to 63°C, 44°C, 74°C, respectively), and are considered low priority systems. In these volcanoes, the basement comes to the surface at high elevations, which implies unfavourable conditions for the existence of a reservoir. In addition, Puracé Volcano has a very low-permeability metamorphic basement. **Huila** volcano was also classified as a low priority potential geothermal exploration target, because of its limited magmatic evolution (SiO2 59-62.5%) and the occurrence of outcrops of basement rocks at high elevations.

1.3. 1983. Geothermal prefeasibility study at Ruiz volcanic complex. This study consisted of a topographical survey, geodesy, geology, volcanology, hydrology, geophysics (gravimetry, magnetism and vertical electrical survey), geochemistry and environmental studies, from Cerro Bravo volcano in the North to Machín volcano in the South (CHEC, et al.)

The intense volcanic activity supports a regeional thermal anomaly. A restricted area at the SW of Nevado del Ruiz was identified as the most promising area from a geothermal point of view due to the concentration of active or recent volcanoes (Cerro España, Santa Isabel, El Cisne and El Ruiz, although they do not show a complete magmatic evolution), the existence of fumaroles discharging gases at 83-85°C (Laguna del Otún and Las Nereidas) and high temperature neutral chloride hot springs (93°C) with high geochemical temperatures (>200°C). The geological formations consist of the pre-eruptive basement and tertiary and quaternary volcanics with low primary permeability. However, the substrate of the current volcanoes consists of a lava sequence with intermediate to high secondary permeability according to vertical fractures. An aquifer could be formed in the contact between the lavas and the basement rocks. The drilling targets were recently fractured areas presumably related to the rise of hot fluids. This requirement was found in the zones known as San Vicente-Botero Londoño, Laguna del Otún and Las Nereidas. The volcanic cover exhibits the greatest thickness at Laguna del Otún and Nereidas, meaning that the probability of finding deep aquifers increases in these areas where high temperature steam leaks occur.

To the South of the study area, Machín volcano stands out as a priority due to its recent age, the existence of a caldera, the relatively advanced degree of magmatic evolution (dacites) and the geochemistry of surface manifestations including 87-94°C fumaroles (steam vents) with high H_2/CH_4. This indicates high temperature gases and hot springs with evidence of geothermal steam leaks (high CO_2 discharge). Its substrate consists of the same type of rocks as the rest of the volcanic complex, and has a large number of fractures and micro-fractures that could increase the permeability, as the thermal manifestations on basement rocks suggest.

At the conclusion of this study, the areas of Nereidas, Laguna del Otún and Machín volcano were chosen as drillling targets.

1.4. 1987. Geothermal prefeasibility study of the Tufiño-Chiles-Cerro Negro hydrothermal system (OLADE, et al.). Based on geological, geochemical, hydrogeological and geophysical studies, a geothermal model of this system was proposed. The heat source is related to a regional anomaly that is evidenced by a conductive intrusive. This was determined by MT surveys at 15-25 km from the surface, with local conductive bodies connected to the feed systems of recent volcanoes and to the Inter Andean Valley, located at the depth of 3-7 km. Three strata are postulated from the geophysical surveys (magnetism, gravimetry, Schlumberger electrical survey and magnetotellurics). The shallowest, about 1000 m in the thickest zone, consists of three layers; two of them resistive containing one conductive layer between them. The intermediate strata, between 1000 and 2000 m thick, is highly conductive and corresponds to an impermeable layer of volcanic rocks that is highly altered by hydrothermal activity. The deepest corresponds to the highly resistive basement. Between these strata, three aquifers were postulated, two circulating in the shallowest strata (10°C and 100°C, respectively) and a deep confined aquifer below the impermeable layer, with a temperature around 300°C. The deep water contribution to the surface hot springs is very moderated as the absence of neutral chloride water suggests (relative chloride contents are lower than 22%), while a geothermal steam leak is postulated on the basis of CO_2 (high

CO_2 pressure about 10 atmospheres), NH_3 and H_3BO_3 discharges. For the drilling stage this study recommended locating three wells in the Ecuadorian side of the hydrothermal system.

Two additional areas of potential geothermal interest were identified in this study. Theses are Cumbal volcano on the Colombian side and the Chalpatán area on the Ecuadorian side.

Due to an increasing energy demand at the present time, a new technical approach is being established between the Ecuadorian and the Colombian Governments for re-starting exploration of these systems.

2. METHODOLOGY

A compilation and review of geothermal exploration studies was carried out. As a new contribution, a summary is presented of the studies initiated by Ingeominas (The Colombian Geological Survey) since 1997, when the National Government commended this institution for geothermal exploration.

3. RESULTS

1997. Geology of well Nereidas 1. This study is part of the drilling exploration stage carried out by GEOENERGÍA ANDINA S.A. (GESA), a Colombian company that contracted the first geothermal well in Colombia, located on the west flank at Nevado del Ruiz.

According to Monsalve et al. (1998), seven geological units were identified in the well. The first, with 52 m of pyroclastic rocks, was characterised by fragments of different types of andesites, pumice, and crystals, and incipient alteration. The second unit, about 117 m thick, consists of pyroxene andesites with low alteration intensity. The third one, with a thickness of 223 m, was identified as amphibollitic andesite, where the alteration intensity is high (argillaceous unit, with veins of calcite, smectite, chlorite, kaolinite, montmorillonite and chalcedony). The unit fourth is dacite and has a thickness of about 366 m; it exhibits a moderated to high alteration intensity (Partial to total replacement of the plagioclase and matrix with calcite, argillation and silicification (chalcedony). Unit five, characterised by quartzites, is about 442 m thick and has low alteration intensity. The sixth one, 266 thick, was identified as a plagioclase and hornblende unit exhibiting moderate alteration intensity (Calc-silicate gneisses: diopside, plagioclase alterated to calcite, hornblende, epidote, garnet, sphene and accessory minerals. Biotitic gneiss: actinolite, biotite and plagioclase). The seventh unit is sericitic phyllite and is found in the bottom of the well at 1468 m (unknown thickness). It corresponds to the upper part of The Cajamarca Unit, with sericite, quartz, chlorite and plagioclase partially alterated to calcite. It also exhibits vein deposit minerals: quartz, calcite, pyrite and plagioclase.

Additionally, a clear zonation of hydrothermal alteration was identified, which is presented in Fig. 2. The deepest zone, named Thermometamorphic (1067-1469 m), contains albite, adularia, epidote, amphibole, sphene and sulfides. At least three events where recognized: (a) Plagioclase (labradorite-bytownite), diopside and hornblende association. (b) Garnet, biotite and presence of diopside in veins (c) Amphibole actinolization, albitization and epidotization of the plagioclase. At 1468 m a strong change in intensity and range of alteration was identified, with disappearance of high temperature minerals remaining: Sericite, chlorite, pyrite, sphene and calcite veins.

[Fig. 2]

The zonation of hydrothermal alteration confirmed the conclusions based on the xenolytes composition, from the reconnaissance study. This sequence suggests a high temperatures system. However the well did not reach the reservoir and new wells have to be drilled to go farther in the exploration of the reservoir.

1998-1999. Geologic setting of the Azufral Volcano and geochemical interpretation of its hydrothermal system.

The Azufral volcano (1501-09) is a stratovolcano located in the Southwest of Colombia, in the Nariño District (1°08' N – 77°73' W), along the Western Cordillera, 12 km far from Túquerres, a town of 40 thousand inhabitants in the Nariño province. Its highest elevation is 4020 masl. The geothermal system associated with this volcano was selected as a priority area for feasibility studies in the National Reconnaissance Study (OLADE et al, 1982) based on the following facts: (1) Recent age (Tertiary) and extended and persistent volcanic activity, (2) hydrothermal activity (phreatic explosion craters, fumaroles and hot springs) but not historical activity, (3) long residence period of magma with the consequent differentiation observed in the complete evolution of andesites to rhyolites and (4) hydrothermal zonation (argilic, phylic and propilitic zones) identified in xenolites .

The most remarkable morphological features of the Azufral volcano are a caldera structure with a diameter of about 3 km, in which there is a green acid lake, arched shaped ("La Laguna Verde") about 1 km long and a dome complex. Surrounding the caldera to the Northwest side is an ancient caldera structure with dimensions larger than the modern caldera (Bernal, 1998).

The caldera structure and ring faults formed after the structure collapsed are the result of increasingly explosive eruptions, as the evolution from andesites to rhyolites suggests. According to the surge deposits found close the caldera, plinian, phreatic and phreatomagmatic eruptions took place during the last active stage, which according to ^{14}C ages for charcoal samples is 2800 +/- 200 years (Ramírez, 1982).

Hydrothermal alteration minerales from the argillic zone (in some breccia fragments from a shallow reservoir) and from the phillitic-propilitic transition zone (contained in surge deposit close the caldera) were identified by Ramírez (1982). The presence of epidote and adularia indicates high deep temperatures (>250°) and a good permeability reservoir at the time that the phreatomagmatic eruption took place (Bernal, 1998). Acid alteration (clays and sulfur) is present in the North area of Laguna Verde Lake where steam vents and moderated acid hot springs also occur. A time extended hydrothermal activity could be inferred from the hydrothermal paleo-alteration relicts. On the northern side of the volcano a wide altered area is found on the road to the village Potrerillos, as well as veins of quartz 10 cm thick filling andesite lava fractures, besides weathered silica sinter deposits. Also, close to the Malaveres springs, old silica sinter overlies pyroclastic deposits (Bernal, 1998).

Deposits of ignimbrites, lahars, lavas and a series of pyroclasts have been identified. Two ignimbrite outcrops were observed, one to the northwest side of the volcano and another on the west flank, extending up "El Baño" stream. This ignimbrite is covered in some places by clear, grey lava deposits, also found in the southern part of the volcanic edifice. These lava deposits were dated by Bechon and Monsalve (1991), using the K/Ar ratio, at 0.58 +/- 0.03 Ma. The second ignimbrite unit represents one of the oldest activities of Azufral and looks like a different deposit with different relationships between units. Also, outcrops of dacitic lavas are found on the western side of the volcano and along Sapuyes River.

The most explosive stage at Azufral volcano is reflected in a series of pyroclastic deposits that have been related to the emplacement of a dome complex in four different events by Fontaine and Stix (1993). They postulate a close relationship between four different events of dome emplacement inside the caldera and pyroclastic deposits of similar geochemistry and mineral composition. The first event (4050 year BP from ^{14}C in the pyroclastic deposits) was related to a felsic dome, while the second event (3600 year BP), to a more mafic emplacement explained either by new magma intrusion into the chamber or a different origin source. The third event is similar in composition and geochemistry to the second one and probably originated during the same eruptive cycle. The youngest dome, fourth event (3470 year BP), is more felsic and is presently undergoing hydrothermal alteration.

The preliminary geochemical interpretation (Alfaro, 1998) was based on secondary information of aqueous components from nine (9) hot springs (Olade, 1982 and Olade & Icel, 1987) and gas composition from the fumarolic discharge (Alfaro, 1995 and John Stix, personal communication).

The hot spring waters were classified according to the dominant anion. This classification showed the presence of the end members common in water dominated hydrothermal systems: **Neutral-chloride waters** from deep origin: El Salado de Malaver (eastern flank of the volcano), **sulphate-acid waters** (from shallower origin (steam heated): Laguna Verde (within the crater) and **neutral-bicarbonate,** peripheral steam-heated waters: La Cabaña, at the south of the volcano. Those water types mix to form the remaining types of water: Malaver dominated by similar proportions of chloride and bicarbonate (located to the SE of the crater), Quebrada Blanca (SW) dominated by chloride, and San Ramón (located to the South of the crater) dominated by bicarbonate waters.

According to the relative Na-K-Mg composition defined by Giggenbach (1988), a geoindicator varies as a function of specific environment. Mixing of the deep fluid is supported by a linear trend pointing out a reservoir temperature around 218°C. Cold shallow water contribution to the spring waters is inferred from the high magnesium contents.

High chloride, boron and lithium concentrations in the thermal areas of Malaver, Quebrada El Baño and Quebrada Blanca suggest deep fluid discharge. The relative composition of these species indicates a common origin for San Ramón, Malaver and El Baño waters, with predominance of chloride which would be explained by the absorption of low B/Cl ratio magmatic vapour or by the maturity of this hydrothermal system.

Gas compositions from very low pressure steam vents located on one of the domes of the volcanic crater indicate a hydrothermal origin rather than a volcanic-magmatic origin; that is, they are generated from a gas phase produced by boiling of the geothermal fluid. This conclusion is based on the temperature of the discharge (about the boiling point of water at that elevation), the low chloride concentration and the relative CO_2 St (total sulphur) and HCl composition.

The observed difference between the applied aqueous geothermometers Na/K (~210-250°C) and K/Mg (~80-90°C) are evidence for an important dilution process. This is reflected by (1) the increase in the magnesium concentration by the meteoric waters, which is responsible for the low K/Mg temperature, and (2) in the quartz temperature (between about 140 and 180°C), based on the absolute concentration of dissolved SiO2, which naturally decreases with the dilution. The Na/K/Ca geothermometer indicates temperatures around 200°C. In summary, according to aqueous geothermometers and the hydrothermal alteration minerals, the most probable temperature of the deep fluid is between 200°C and 250°C, which indicates an intermediate to high temperature geothermal system.

Currently, the Azufral Volcano geothermal system is the highest priority for the exploration program in Colombia. A more advanced stage is being planed for a near future.

1999. Map of occurrence of hot springs. According to secondary information (Forero, 1958, CHEC and ENEL, 1968, OLADE et al., 1982, CHEC, 1983, OLADE et al., 1987, Arcila, 1985 and Garzón, 1997), Colombia has about 300 hot springs; location areas are shown in Fig. 1. The highest density of hot springs (about 100) is found in the Cerro Bravo – Machín volcanic complex, along the Central Range. The chemical characterisation is available for just around 180 hot springs (Alfaro, 1998). Their more remarkable features are presented in Table 2. About 20% of them (58 hot springs) have temperatures above 50°C. Taking into account the dominant anion (at least 50% in relative composition), 20 of the springs (11%) were classified as chloride, 109 (61%) as bicarbonate and 41 (23%) as sulphate. The remaining 5% have waters mixed in similar proportions. Half of the chloride waters are located at the Cerro Bravo – Machín volcanic complex and the others at Cundinamarca-Boyacá, Azufral, Nevado del Huila and Doña Juana volcanoes. About 24 of the sulphate springs are also acidic, indicating probable boiling processes. Between them are 6 hot springs located at Nevado del Ruiz and Puracé volcano that presumably have a magmatic contribution.

[Table 2]

The highest geochemical temperatures calculated for about 30 hot springs with presumable deep fluid contribution (Alfaro, and Bernal, 1999) indicate intermediate to high temperature geothermal systems: Nevado del Huila 160°, Doña Juana 200°C, Puracé 226°C, Azufral 230-250°C and Nevado del Ruiz (240-260°C).

1999. Map of geothermal gradients in Colombia. First version.

The first version of a map of thermal gradients was produced based on temperatures from 1711 oil wells, out of about 4400 reviewed oil well registers drilled in 13 sedimentary basins and an area named as no basin, and one geothermal well at Nevado del Ruiz. The map is shown in Fig. 3, where isotherms are represented at 3 km.

[Fig. 3]

The thermal gradient (TG) was calculated using following formula:

$$TG\ (°C/Km) = (Td - Ts) * 1.1 / d \qquad (1)$$

Where **Td** is the centigrade temperature measured at depth **d** in meters, **Ts** is the average surface centigrade temperature and 1.1 is a thermal stabilisation correction factor equivalent to a 10% increase. Temperatures corresponding to depths lower than 500 m were rejected due to their systematic high results that differ from the rest of the values calculated at greater depths. The data is summarised in Table 3.

[Table 3]

As can be observed, the highest thermal gradient is by far at the only geothermal well (127°C/km). Semi-thermal anomalies (40-70°C/km) register in most of the sedimentary basins and in the no basin area. The exceptions are Cauca-Patía, Guajira and Tumaco. Hyperthermal areas (>70°C/km) are found just in two sedimentary basins (Llanos Orientales and Upper Magdalena Valley) and in the no basin area. The temperatures at 3 km (Fig 3) show two main anomalous areas of high temperature (220-462°C) at Nevado del Ruiz and at Llanos Orientales sedimentary basin, although other sedimentary basins like Catatumbo and those from the Magdalena Valley show smaller areas with potential anomalies up to 220-245° C at 3 km.

In the next stage of this project, the information is going to be completed with the geothermal gradients calculated from the geochemical temperatures, before the calculation of the heat flow map.

4. CONCLUSIONS

4.1. Geothermal resources in Colombia seem to be extensive and related to sedimentary basins as well as magmatic heat sources.

4.2. The geothermal systems related to the Nevado del Ruiz, Chiles-Cerro Negro and Azufral volcanoes seem to be high temperature systems. They have been targeted for exploration studies; a well has already been drilled at Nevado del Ruiz. The Chiles-Cerro Negro project is currently being reactivated by the two nations (Ecuador and Colombia) and the Azufral volcano project, one of the highest priorities for the local and national government, is also being reactivated at the present time.

4.3. Besides the Central Range's regional thermal anomaly, which is supported by the geothermal gradient measured at the Nereidas 1 geothermal well at Nevado del Ruiz volcano, there is an anomalous area located at the foothill of the Eastern Range (Llanos orientales basin), where extrapolated temperatures at 3 km depth reach 250°C.

4.4. Specific exploration studies must be developed in areas identified since the reconnaissance study (Paipa-Iza and Doña Juana, Puracé and Huila volcanoes) as well as in the new areas identified from the thermal gradients evaluation.

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Figure Captions.

1. Location of geothermal areas in Colombia. Most of them are found along the Central Range where the volcanic activity still persists. The location of volcanoes with related hydrohermal systems and hot spring waters, are indicated.
2. Distribution of hydrothermal alteration minerals and zones in the Nereidas 1 Geothermal Well at Nevado del Ruiz Volcano. Taken from Monsalve et al., 1997. A typical zonation of high temperature systems was established.
3. Map of geothermal gradients in Colombia. First version. Two main anomalous areas are identified at Nevado del Ruiz volcano and Llanos Orientales sedimentary basin.

TABLE 1. UTILIZATION OF GEOTHERMAL ENERGY FOR DIRECT HEAT AS OF 31 DECEMBER 1999

1) I = Industrial process heat; H = Space heating & district heating (other than heat pumps)
C = Air conditioning (cooling); B = Bathing and swimming (including balneology)
A = Agricultural drying (grain, fruit, vegetables); G = Greenhouse and soil heating
F = Fish and animal farming; O = Other (please specify by footnote)
S = Snow melting

2) Enthalpy information is given only if there is steam or two-phase flow

3) Capacity (MWt) = Max. flow rate (kg/s)[inlet temp. (^oC) - outlet temp. (^oC)] x 0.004184 (MW = 10^6 W)
or = Max. flow rate (kg/s)[inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.001

4) Energy use (TJ/yr) = Ave. flow rate (kg/s) x [inlet temp. (^oC) - outlet temp. (^oC)] x 0.1319 (TJ = 10^{12} J)
or = Ave. flow rate (kg/s) x [inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.03154

5) Capacity factor = [Annual energy use (TJ/yr) x 0.03171]/Capacity (MWt)
Note: the capacity factor must be less than or equal to 1.00 and is usually less,
since projects do not operate at 100% of capacity all year.

Locality	Type[1)]	Maximum Utilization Flow Rate (kg/s)	Temperature (^oC) Inlet	Temperature (^oC) Outlet	Enthalpy[2)] (kJ/kg) Inlet	Enthalpy[2)] (kJ/kg) Outlet	Capacity[3)] (MWt)	Annual Utilization Ave. Flow (kg/s)	Energy[4)] (TJ/yr)	Capacity Factor[5)]
Agua de Dios	B	5.23	36.0	20.0			0.35	3.32	7.00	0.63
Anapoima	B	10.5	28.0	20.0			0.35	6.63	7.00	0.63
Bochalema	B	3.8	57.0	35.0			0.35	2.41	7.00	0.63
Chinacota	B	7.60	46.0	35.0			0.35	4.82	7.00	0.63
Choachí	B	4.92	52.0	35.0			0.35	3.12	7.00	0.63
Coconuco	B	3.64	58.0	35.0			0.35	2.31	7.00	0.63
Coconuco	B	2.32	71.0	35.0			0.35	1.47	7.00	0.63
Colón	B	6.97	47.0	35.0			0.35	4.42	7.00	0.63
Cumbal	B	6.97	32.0	20.0			0.35	4.42	7.00	0.63
Cumbal	B	6.97	32.0	20.0			0.35	4.42	7.00	0.63
Cumbal	B	6.97	32.0	20.0			0.35	4.42	7.00	0.63
Gachetá	B	5.98	49.0	35.0			0.35	3.79	7.00	0.63
Gachetá	B	8.37	45.0	35.0			0.35	5.31	7.00	0.63
Girardot	B	6.43	33.0	20.0			0.35	4.08	7.00	0.63
Guicán	B	8.37	38.0	28.0			0.35	5.31	7.00	0.63
Ibagué	B	6.43	48.0	35.0			0.35	4.08	7.00	0.63
Iza	B	6.97	47.0	35.0			0.35	4.42	7.00	0.63
Iza	B	4.18	55.0	35.0			0.35	2.65	7.00	0.63
Macheta	B	3.22	61.0	35.0			0.35	2.04	7.00	0.63
Macheta	B	11.95	42.0	35.0			0.35	7.58	7.00	0.63
Macheta	B	5.58	50.0	35.0			0.35	3.54	7.00	0.63
Manizales	B	5.58	50.0	35.0			0.35	3.54	7.00	0.63
Nemocón	B	5.98	34.0	20.0			0.35	3.79	7.00	0.63
Paipa	B	4.92	52.0	35.0			0.35	3.12	7.00	0.63
Paipa	B	2.26	72.0	35.0			0.35	1.43	7.00	0.63
Pandi	B	7.60	26.0	15.0			0.35	4.82	7.00	0.63
Puracé	B	6.97	32.0	20.0			0.35	4.42	7.00	0.63
Ricaurte	B	6.97	32.0	20.0			0.35	4.42	7.00	0.63
Rivera	B	4.40	54.0	35.0			0.35	2.79	7.00	0.63
Santa Marta	B	12.0	42.0	35.0			0.35	7.58	7.00	0.63
Santa Rosa	B	1.86	80.0	35.0			0.35	1.18	7.00	0.63
Santa Rosa	B	3.64	58.0	35.0			0.35	2.31	7.00	0.63
Santa Rosa	B	3.64	58.0	35.0			0.35	2.31	7.00	0.63
Tabio	B	4.18	55.0	35.0			0.35	2.65	7.00	0.63
Tajumbina	B	3.10	62.0	35.0			0.35	1.97	7.00	0.63
Tocaima	B	6.43	33.0	20.0			0.35	4.08	7.00	0.63
Tocaima	B	6.43	33.0	20.0			0.35	4.08	7.00	0.63
Villamaría	B	2.99	63.0	35.0			0.35	1.90	7.00	0.63
TOTAL		222					13.3	141	266	

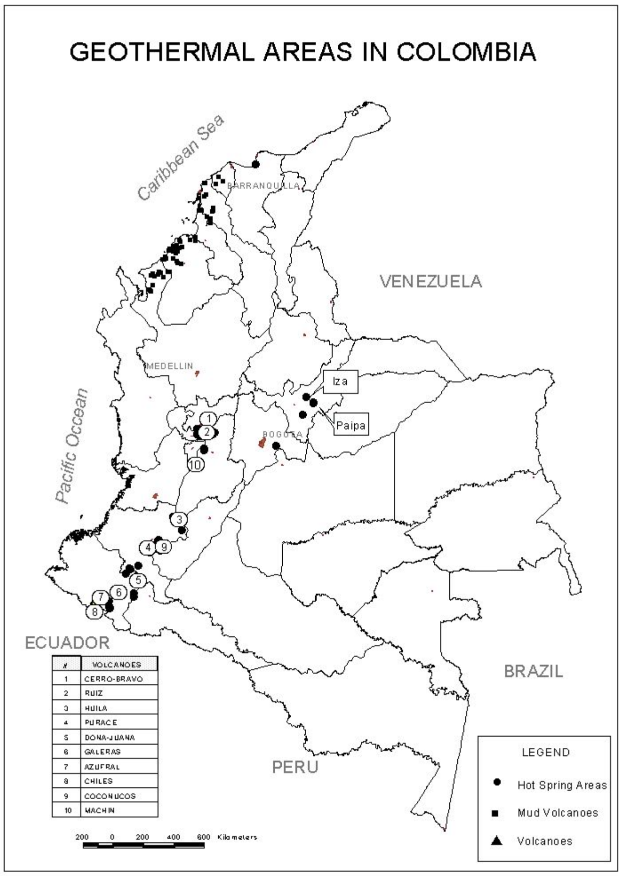
GEOTHERMAL AREAS IN COLOMBIA
Caribbean Sea
BARRANQUILLA
VENEZUELA
MEDELLIN
Pacific Occean
Iza
Paipa
BOGOTA
ECUADOR
BRAZIL
PERU
LEGEND
Hot Spring Areas
Mud Volcanoes
Volcanoes
VOLCANOES
1 CERRO-BRAVO
2 RUIZ
3 HUILA
4 PURACE
5 DONA-JUANA
6 GALERAS
7 AZUFRAL
8 CHILES
9 COCONUCOS
10 MACHIN
200 0 200 400 600 Kilometers

Fig. 1.

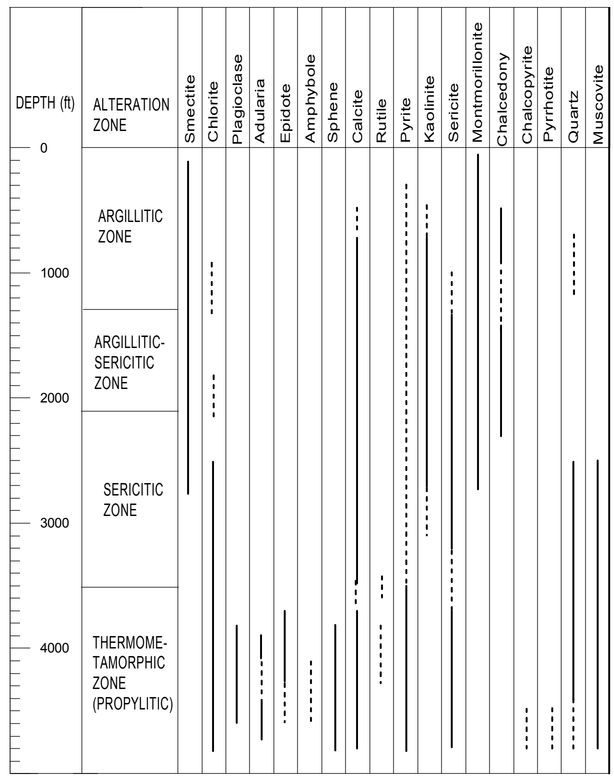
DEPTH (ft)
ALTERATION ZONE
Smectite
Chlorite
Plagioclase
Adularia
Epidote
Amphybole
Sphene
Calcite
Rutile
Pyrite
Kaolinite
Sericite
Montmorillonite
Chalcedony
Chalcopyrite
Pyrrhotite
Quartz
Muscovite
0
1000
2000
3000
4000
ARGILLITIC ZONE
ARGILLITIC-SERICITIC ZONE
SERICITIC ZONE
THERMOME-TAMORPHIC ZONE (PROPYLITIC)

Fig. 2.

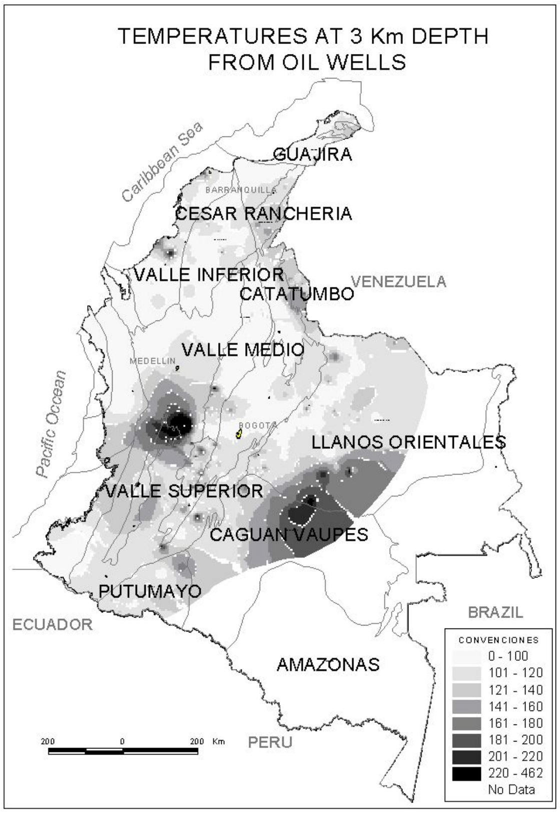

Fig. 3

Table 2. Inventory of reported Hot Springs in Colombia

Parameters	**No.**	**Highest Geochemical Temperatures (°C)**
Reported hot springs	298	
Chemical characterisation	178	
Classification (Dominant anion >50%)		
⇒ Neutral chloride waters	17	
⇒ Bicarbonate	102	
⇒ Sulphate	37	
⇒ Mixed in similar proportions	22	
Acid sulphate waters	24	
Presumably magmatic contribution	6	
Presumably deep fluid contribution	**29**	
Located at		
⇒ Cundinamarca-Boyacá		
⇒ Nevado del Ruiz volcanic complex		240-260
⇒ Huila		160
⇒ Puracé		220
⇒ Doña Juana		200
⇒ Azufral		230-250
Surface Temperature (°C)		
⇒ <30°C	112	
⇒ 30-50°C	115	
⇒ 50-70°C	43	
⇒ 70-95°C	15	

Table 3. Geothermal Gradients from Oil Wells in Colombia

Sementary Basin	Number of Wells	Gradient (°C/km)			Gradients distribution (%)		
		Average	Maximum	Minimum	<40°C/km	40-70°C/km	>70°C/km
No basin *	49	32	127	18	89.7	4.0	6.0
Caguán Vaupes	12	40	63	16	50.0	50.0	
Catatumbo	53	30	68	21	88.7	11.3	
Cauca Patía	2	23	26	19	100.0		
Cesar Ranchería	7	32	41	22	85.8	14.3	
Eastern Range	15	28	46	16	80.0	20.0	
Guajira	40	19	38	14	100.0		
Llanos Orientales	322	26	74	9	93.4	5.9	0.6
Putumayo	166	28	58	11	93.4	6.6	
Tumaco	2	21	28	13	100		
Uraba	6	17	26	11	100		
Lower Magdalena Valley	131	24	65	10	94.7	5.4	
Intermediate Magdalena Valley	615	20	66	11	98.7	1.4	
Upper Magdalena Valley	292	27	72	16	88.3	10.9	0.7
Total	1712						
Averages		26					
Maximum values			127				
Minimum values				9			

* Includes Geothermal Well Nereidas 1 at Nevado del Ruiz which gradient measured from the BHT is 127°C/km (381 °C at 3 km)