PRELIMINARY GEOTHERMAL ASSESSMENT OF THE MACIZO VOLCANIC0 DEL RUIZ, COLOMBIA

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ABSTRACT

The Macizo Volcanico del Ruiz is a chain of Quaternary strato-volcanoes, aligned in a NNE-SSW direction, that ispart of the Central Colombian Ridge. This is, in turn, part of the northern portion of Los Andes, and its volcanic activity can be explained by the subduction of the Nazca Plate beneath the South American Plate. Rocks **forming** *the volcanoes are mainly andesites of calc-alkaline type, with minor basaltic to dacitic variations and some pyroclastics deposits. The Quaternary andesites are underlain by Miocenic andesites, Paleozoic schists and Paleocenic-Eocenic granodioritic intrusives. All these rocks are affected by four main structural trends: NNE-SSW, NW-SE, NE-SW and N-S; althoughfaults of the NNE-SSW trend are the oldest, there is seismic activity related to some of them. The superficial hot springs, hot soils and fumaroles were grouped into 16 geothermal zones, most of them being hot springs with related gases. Liquid geothermometry results in deep temperatures, in some cases, of about 220 to 260°C. A high geothermal potential was assessed in the Macizo Volcanico del Ruiz. The most important area is named Las Nereidas-Botero Londoiio, Volcan Machin being second and Laguna del Otún third. In the latter, as in another geothermal interest zones, more studies are recommendable, while the Las Nereidas-Botero Londoiio and Volcan Machin areas can be drilled with a high probability of success.*

INTRODUCTION

Since 1968 the Macizo Volcanico del Ruiz volcanic complex, at the East-Central portion of Colombia (Figure 1), has been explored in order to define its geothermal potential and, since 1985, to predict further probable eruptive activity.

By 1968 a first regional reconnaissance was made, conducted by technical staff of ENEL (the Italian *Ente per l 'Energie Elettrica),* in several thermal Colombian zones, including the El Ruiz complex. Between 1978 and 1983 a more intensive survey was developed by Italian and Colombian specialists, focused in two areas: the Macizo del Ruiz and Espíritu Santo. This survey included geology, volcanology, hydrology, geochemistry and geophysics (gravimetry, magnetometry and vertical electric sounding). Three distinct zones were chosen to drill exploratory wells: Las Nereidas, Laguna del Otún and the Machin Volcano, all of them belonging to the Macizo del Ruiz.

No more geothermal surveys were made until 1992, but in November, 1985, the catastrophic eruption of the Nevado del Ruiz --the main volcano of the Macizo-- took place, leaving around 25,000 dead and huge economic damage. Armero town was completely buried by mud flows and lahars triggered by the volcanic eruption.

By 1992, the Colombian company CHEC *(Central Hidroelectrica de Caldas)* and the Mexican company EPN decided to up-date and to complete former studies. in order to select some sites to drill two deep exploratory wells. So, an exhaustive revision of those studies was made, and a field trip including sampling of thermal waters and rocks was performed. Chemical analysis of

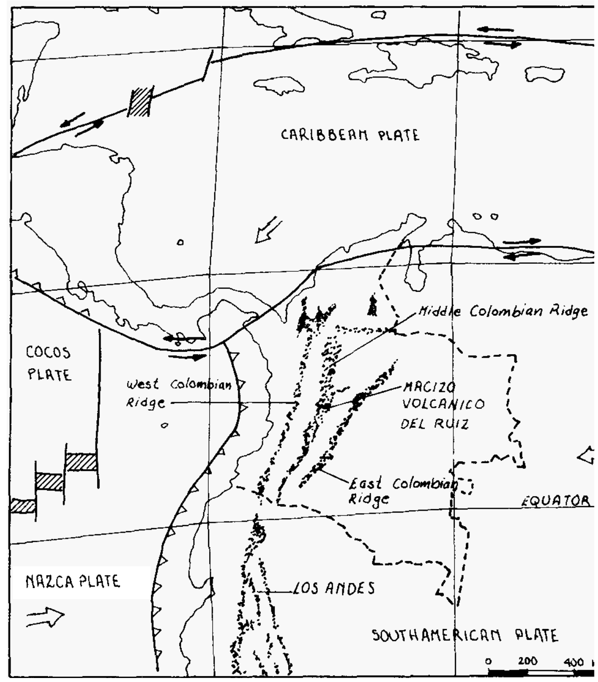

Figure 1.- Location of the Macizo Volcanico del Ruiz and tectonic setting.

sampled waters were made in the laboratories of the Universidad Nacional de Colombia, Sección Manizales, and some K-Ar dating and physical analysis of the sampled rocks were done also.

Results of that last study are presented in this paper. Its objective is to show the main geologic and geothermal features of the Macizo Volcinico del Ruiz, and to present a preliminary assessment on those bases.

TECTONIC AND STRUCTURAL SETTING

El Ruiz volcanic complex is a NNE-SSW Quaternary belt, around 65 km long, which is composed by the following strato-volcanoes and domes, from North to South: Cerro Bravo (4,000 masl), a group of three domes (Alto del Plato, Alto de Santana and Alto de La Laguna, with 3,950 masl as maximum level), Nevado del Ruiz (5,311 masl), Morro Negro and Nevado del Cisne (4,700 masl), Nevado de Santa Isabel (5,100 masl), Cerro Espaiia (4,550 masl), Nevado del Quindío (5,150 masl), Nevado del Tolima (5,215 masl) and, 20 km southernly, the Machin Volcano (2,700 masl). The Paramo de Santa Rosa is also a Quaternary volcano, but older than the others and located outside the belt (Figure 2).

That volcanic belt is a part of the Central Colombian Ridge, which is, in turn, a portion of the northern section of Los Andes. It is located in a zone with active tectonics due to subduction of the

Nazca Plate beneath the South American one, which takes place at an average rate of **5.4** cm/year in this region (Figure 1).

Subduction processes have happened in the area at least since Early Jurassic --around 190 million years ago--, after a former orogenic process which folded and metamorphized the sedimentary deposits from an even .older Paleozoic geosyncline. Metamorphic basement, which is the nucleus of the Los Andes ridge and of the Macizo del Ruiz itself, was formed by that orogenic process.

Subduction, and its associated volcanism, has been constant at northern Los Andes practically since the Jurassic age to present, triggering specially intense volcanic and magmatic events by Early and Late Cretaceous, ending of Paleocene and Middle Miocene. Succesive island arcs have been integrated to the continental crust, according to western migration of the subduction zone. Volcanism has alternated with some isolated sedimentary events in the Cretaceous basins, like the Valle del Cauca and Valle del Magdalena.

Macizo del Ruiz seems to be controlled by three important structures with a NNE-SSW trend: the Romeral, Palestina and Mulato faults (Figure **2).** The Romeral fault is the border between the Valle del Cauca, to the West, and the Central Colombian Ridge, to the East. **Is** a large (around 1,000km long) right strike-slip fault, with an inverse behavior in some parts and a direction varying from NE-SW to N-S in the area of the del Ruiz complex. The Romeral fault has some active parts, according to several shallow-focus earthquakes related to it.

The Mulato fault represents the border between the Central Ridge and the Valle del Magdalena; this valley is a graben, like the Valle del Cauca, in which the Magdalena River flows. That fault is right strike-slip type with a NE-SW direction.

The Palestina fault is an important cortical weakness zone, which has allowed rising of the magma feeding the Quaternary volcanism of the Macizo del Ruiz. **This** fault is also right strike-slip, and to North, beyond the Macizo, has a **28 km** lateral displacement.

Transverse to these NNE-SSW strike-slip faults, there is a NW-SE system. This includes the Neira and Salento faults, which seem to constrain the Macizo del Ruiz, and the Rio Claro, Pereira and Villamaria-Termal faults (Figure **2).** All of these NW-SE structures seem to be more recent than those of the NNE-SSW system and contemporary to the Quaternary volcanism. Furthermore, several of the hot spring and fumaroles are related to NW-SE faults and fractures (numbers **1** through 6 in Figure **2).**

The NW-SE faults may be left strike-slip, as the Villamaría-Termal, Pereira and Salento ones, or normal type with fault planes almost vertical and southwestern down blocks, as the Rio Claro fault. The Salento fault presents also an inverse behavior in some portions.

Besides the NNE-SSW and the NW-SE systems, there are two more. One includes normal faults of NE-SW trend with northwestern down blocks; these faults seem to be even more recent than the NW-SE ones, although their superficial traces are much

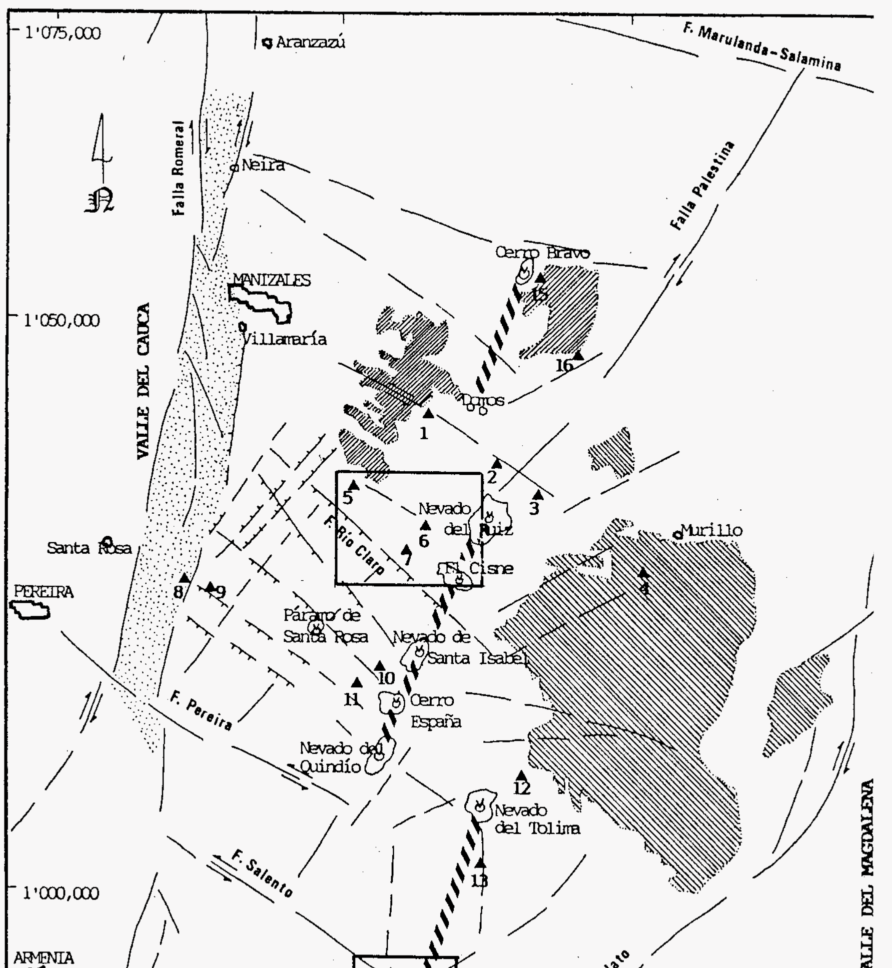

Figure 2.- Main geologic features of the Macizo Volcanico del Ruiz.

Volcanic belt.

Batolito del Bosque outcropping

Stock de Manizales outcropping.

Formación Quebrada-grande outcropping.

▲ Thermal zones are: 1. Termal del Ruiz. 2. Aguacaliente, 3. Río Azufrado, 4. Hacienda Granates. 5. Botero Londoño-Quebrada El Billar, 6. Las Nereidas, 7. El Recodo. 8. Santa Rosa, 9. San Vicente, 10. Azufrera del Otún, 11. El Edén, 12. El Cebollar, 13. El Rancho, 14. Volcán Machín-Río Toche, 15. Aguacatal, 16. San Luis.

Rectangles mark two high interest areas: Las Nereidas-Botero Londoño (up) and Volcán Machin (below).

This figure has been slightly modified from CHEC, 1983.

shorter. Some hot springs are related to those NE-SW faults (numbers 7 and 11 in Figure 2). Another system is evident just in the southern part of the Macizo del Ruiz, presenting a N-S trend; some hot springs are associated to long fractures belonging to this system (numbers 13 and 14 in Figure 2).

Trends and apparent displacements of the volcanic belt formed by the volcanoes and domes from the Macizo del Ruiz have been marked in Figure 2. Left displacements in alignment of the volcanoes are quite evident, and could be related to some NW-SE structures with a left strike-slip.

REGIONAL LITHOLOGY

From a regional view point, all the outcropping rocks in the area can be grouped into eight lithologic units. The oldest of them is the former Grupo Cajamarca, now named the Paleozoic Metamorphic Complex, which includes metamorphic rocks like quartz-sericitic and green schists, with minor marble, quartzites and amphibolites and local skarns and hornfels due to later intrusions. The second unit includes Late Triassic to Middle Jurassic magmatic rocks (quartz-diorites to quartz-monzonites) forming batholiths known as the Intrusivo Gnéisico del Noreste de Manizales, the lntrusivo Gnéisico de Padua, the Anfíbolita de Padua and the Batolito de Sonsón. These two units are the basement of the Macizo Volcanico del Ruiz, and their outcroppings in the zone are very restricted.

Third lithologic unit is the Formación Quebradagrande, composed by Cretaceous sedimentary rocks (black shales, sandstones, conglomerates, minor limestones) with some dynamic metamorphism, and volcanics (basalts, some pyroclastics and diabasic dykes). This unit outcrops in a narrow long belt, limited by the Romeral fault (Figure **2**).

Fourth unit is represented by two similarly composed and aged magmatic bodies, the Stock de Manizales and the Batolito del Bosque, whose outcroppings are showed in Figure 2. Both present granodioritic to quartz-dioritic composition, intruding into Paleozoic schists of the first unit. The Stock de Manizales is 57.5 +/- 1.7 My old (Late Paleocene), and the Batolito del Bosque is 49.1 +/- 1.7 My old (Early Eocene). Both would be parts of the same batholith.

Fifth unit groups Miocenic to Mio-Pliocenic andesitic rocks, with some andesitic ignimbrites and basaltic andesites, which outcrop in the central part of the Macizo, partially covered by more recent volcanics. Those rocks are products of the Tertiary Andean volcanism and represent a volcanic basement over which the Macizo del Ruiz was partially formed.

Sixth unit includes all Pleistocenic and Holocenic lava flows from the present volcanoes of the Macizo del Ruiz. They are mainly calc-alkaline andesites, but there are variations from rhyodacites and dacites (Cerro Bravo, some rocks of Nevado del Ruiz, domes, Paramo de Santa Rosa and Machin) to basaltic andesites (lava flows of nevados del Quindio y Tolima).

Seventh unit is composed by the Quaternary pyroclastic deposits from the Cerro Bravo, Nevado del Tolima and Machin volcanoes, which are the only volcanoes with presently recognizable related pyroclastic deposits (ignimbrites, ash flow and air fall tuffs, and surge deposits from Plinian events). Pyroclastics from the rest of volcanoes, if any, have been eroded, except some scarse deposits from the Nevado del Ruiz whose last eruption (1985) included ejection of some pumice ash (Calvache, 1990).

Eighth unit, at last, includes all erosion products: glaciar and lake deposits, lahar, mud flow and alluvium deposits. At the summit of highest volcanoes, up to 4,600 masl, there is a permanent ice cap which forms some glaciars.

GEOCHEMICAL FEATURES

Main thermal manifestations.were grouped in those 16 zones shown in Figure **2**. Most of them include several hot springs and/or fumaroles, except two which are isolated hot springs: number 2 (Quebrada Aguacaliente) and number 11 (El Edén). Only one of the 16 thermal zones is exclusively gaseous, without associated hot water: number 10 (Azufrera del Ohin).

The Nevado del Ruiz is the individual volcano with most apparently related thermal zones; at least zones numbers 1, 2, 3, 5 and 6, and perhaps 4 and 7, seem to be associated to this volcano.

The Cerro Bravo volcano seems to be related to zones 15 and 16, which outcrop at the border of the Stock de Manizales, while Cerro Espaiia would be the heat source for zones 10 and 11. Zones 12 and 13 are associated to the Nevado del Tolima volcano, and the Machin Volcano seems to be the source for several hot springs grouped as the zone 14.

As was mentioned before, a relationship between thermal zones and some structures is also evident. So, thermal zones 1, 2 and 3 are quite associated to the Villamaria-Termal fault, zones 5 (Botero-Londoiio hot springs) and 6 (Las Nereidas fumarole) are related to a unnamed NW-SE fracture, and zones 13 and 14 seem to be controlled by N-S and NW-SE structures (see Figure 2).

As a part of studies made in 1978-1983, sampling and chemical analysis of waters from almost all the thermal zones were performed. Some of the main results of those analysis are presented in upper part of Figure 3, and can be compared with results of more recent analysis (lower part of the same figure). There are some differences between both series of analysis, particularly an increase in the sulfate content of some of the bicarbonate-sulfate waters. Such a change could be related to the 1985 eruption of Nevado del Ruiz, during which a huge volume of SO, was discharged (Williams *et al.*, 1986).

Analyzed waters belong to several geochemical types. Waters from zones 1 (Termal del Ruiz), 2 (Quebrada Aguacaliente) and 11 (El Edtn) are acid sulfate type (Figure 3). In zone 2 there are also some gases, which were analyzed by Giggenbach *et* al. (1990) obtaining the following results (% mol): 92.8 CO,, 2.6 H_2S, 4.78 N,, 0.178 CH,, and <0.001 H,. Zones 1 and 2 seem to be steam and gas discharges from a deep high enthalpy aquifer.

Another water geochemical group is bicarbonate-sulfate; to this group belong waters from zones 6 (Las Nereidas), 7 (El Recodo), 12 (El Cebollar) and 13 (El Rancho) (Figure 3). In Las Nereidas there are also fumaroles; one of them has this composition (Giggenbach *et al.*, 1990; in % mol): 94.9 CO,, 3.2 H_2S, 0.59 N,, 0.47 CH,, and 0.34 H,. This fumarole seems to be a discharge from a hydrothermal system of magmatic origin. The bicarbonate-sulfate type of its related water would be due to absorption of CO, and H_2S by water. Hot springs at El Rancho (zone 13) are related to a fumarole too, whose H_2S and H_2 content is lower than others (<0.1 and <0.001 % mol, respectively, after Giggenbach *et* al., 1990).

Waters from zones 4 (Hacienda Granates), **5** (Botero Londoiio and Quebrada El Billar) and 9 (San Vicente) belong to neutral sodium chloride geochemical type (Figure **3**). Geothermometers for the zone 5 were calculated as follows: $T_{K\text{-}Mg}$ 129°C, $T_{Na\text{-}K}$ 244°C, $T_{K\text{-}Na}$ 257°C, $T_{Na\text{-}K\text{-}Ca}$ 212°C, $T_{SiO_2\ (chalcedony)}$ 163°C. The more representative of them seem to be K and Na geothermometers, as long as the rest are affected by dilution with shallow groundwaters. Gases from Botero Londoiio hot springs (zone *5*) present the following composition (Giggenbach *et al.*, 1990; in % mol): 93.3 CO,, 4.0 H_2S, 2.57 N,, 0.089 CH,, and 0.06 H,. Thus hot springs of Botero Londoiio represent the discharge from a deep geothermal aquifer whose temperatures would be around 260°C. Waters from San Vicente (zone 9) would be also discharge from a

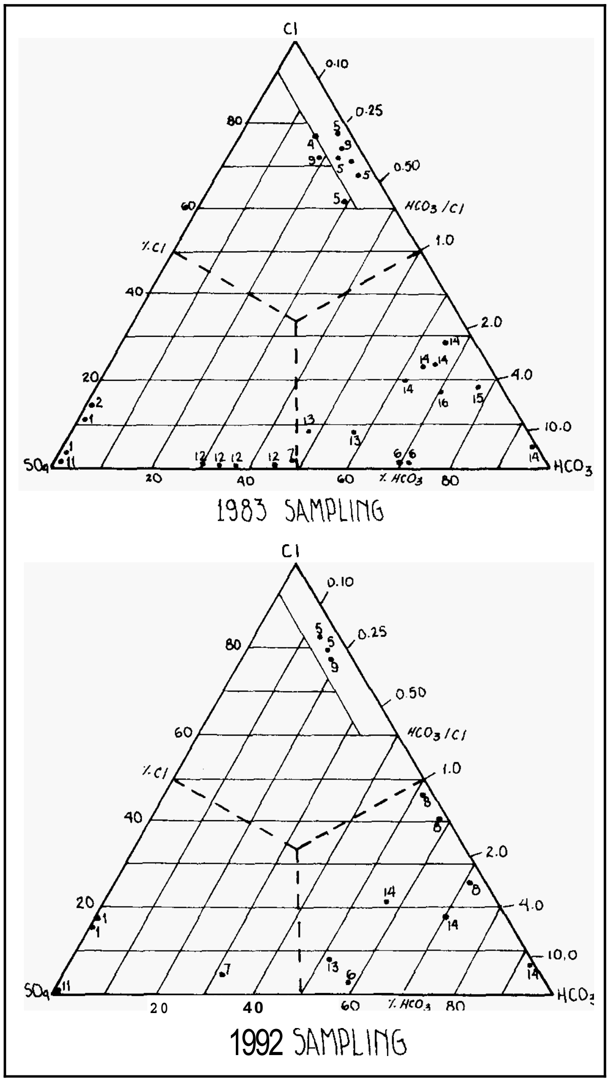

Figure* 3.-** *Geochemical* ***type *of waters.*
Sampling zones and ***maximum*** *superficial temperatures are asfollows. 1.- Termal del Ruiz* ***(63°C),*** *2.- Aguacaliente (62°C), 4.- Hacienda Granates (55°C).* ***5.-*** *Botero Londoño and Quebrada* El *Billar* (93°C). ***6.- Las*** *Nereidas (52°C;fumarole:* ***85°C),*** *7.-* ***El*** *Recodo (54°C), 8.- Santa Rosa (65°C), 9.- San* ***Vicente*** *(64°C), 11.- El* ***Eden (22°C),*** *12.-* El *Cebollar* ***(45°C),*** *13.- El Rancho* ***(53°C),*** *14.-* ***Volcán*** *Machh-Rio Toche* ***(91°C),*** *15.- Aguacatal (37°C), 16.- San Luis (45°C).*

geothermal aquifer with similar deep temperatures (250°C after Na-**K** geothermometry), but they are not evidently related to a probable heat source (see Figure 2).

A fourth geochemical type of water is the bicarbonate-chloride one. To this group belong waters from zones 8 (Santa Rosa), 14 (Volcán Machín-Río Toche), 15 (Quebrada Aguacatal) and 16 (San Luis) (Figure 3). Calculated geothermometers for the Volcan Machín-Río Toche waters are as follows: $T_{K\text{-}Mg}$ 90°C, $T_{Na\text{-}K}$ 203°C, $T_{K\text{-}Na}$ **220°C**, $T_{Na\text{-}K\text{-}Ca}$ 190°C, T_{SiO_2} **(chalcedony)** 173°C. Again, those sodium-potassium geothermometers are considered to be more representative of deep temperatures. At the top and the base of the Machin volcano there are some gas discharges; one of them has the following composition (Giggenbach *et al.*, 1990; in % mol): 90.2 CO_2, <0.1 H_2S, 6.79 N„ 0.012 CH, and 1.3 H,. According to gas and water geochemical results, the zone 14 (Volcán Machk) would be related with a deep geothermal aquifer with temperatures around 220°C. Another interesting zone is number 15, whose sodium-potassium geothermometers are around 240°C.

GEOTHERMAL AREAS FOR FURTHER EXPLORATION

The geothermal area defined in the Macizo Volcanico del Ruiz as the maximum interest prospect, has been named Las Nereidas-Botero Londoño. There are two other interesting areas: the Volcán Machin and the Laguna del Otún, but their importance seems to be lesser, specially the latter.

The Las Nereidas-Botero Londoiio area can be limited by a rectangle of 130 km^2 (13 x 10 km), located almost at the middle portion of the Macizo and related to the Nevado del Ruiz volcano (see Figure 2). This area includes zones 5, 6 and 7, with one fumarolic zone (Las Nereidas) and bicarbonate-sulfate waters (also in Las Nereidas and El Recodo) at high topographic level, and gas discharging hot springs of sodium chloride type (Botero Londoiio-Quebrada El Billar) at lower altitude. Chemical characteristics of these zones have been mentioned before, and all of them seem to be associated to a deep geothermal system, and related to structures (faults and fractures) of the NW-SE and NE-SW systems.

The heat source in that area would be the magmatic chamber beneath Nevado del Ruiz. This chamber could have some almost molten portions, but its most part should be de-gasified solid rocks. Surrounding the chamber seems to be a gaseous-fluid zone which, in turn, could be surrounded by a two-phase fluid zone, at least in some portions. This schematic model is presented in Figure 4, which has been slightly modified from Giggenbach *et al.* (1990) and Larios-López (1992).

In that figure a self-sealing zone has been marked bounding the two-phase zone. A low temperature liquid zone, composed by mixing of groundwaters and deep rising geothermal fluids, has been indicated too. Such a zone could feed the Botero Londoño hot springs.

Deep geothermal fluids of that system would be contained into the basement rocks and, partially, in the volcanic rocks. Basement rocks must be Paleozoic schists and granitic rocks of the Batolito del Bosque. If this batholith and the Stock de Manizales were both portions of the same intrusive body, then the suggested geothermal fluids would be contained mainly in granitic rocks. This possibility is presented in Figure **4** by an almost horizontal projection of the top of the Batolito del Bosque to Northwest (upper dashed line); in this case, the schist portion of basement would be very restricted. On the contrary, basement would be composed mainly by schists if the mentioned intrusives are two isolated bodies. In this case, top of the batholith would dip sharply to northwest, as **is** shown in Figure 4 by the lower dashed line. According to our modeling on the results of the gravimetric survey made by CHEC (1983), this latter case seems to be the most probable. Anyway, the fact is that important portions of basement could be composed by schists.

Samples of outcropping schists were analyzed in the laboratories of the Instituto de Investigaciones Eléctricas in Mexico. Average measurements were as follows: 2.3 g/cm^3 as total density, 14.8% as effective porosity, 15.1% as total porosity, and 1.6 md as horizontal permeability. Even though the vertical permeability (i.e. transverse to schistosity) was almost zero, the rest of parameters are comparable with those from volcanic geothermal fields. This is specially true if it is taken into account that values are reported for the whole rock, without fault or fracture planes.

SOME CONCLUSIONS

The Macizo Volcanico del Ruiz has a high geothermal potential. Its 16 geothermal zones can be grouped, according to their geological and geochemical features, in some interest areas for further exploratory drilling or specific surveys. This is the case of the areas named as Las Nereidas-Botero Londoiio, related to the Nevado del Ruiz volcano, Volcán Machín-Río Toche, related to this

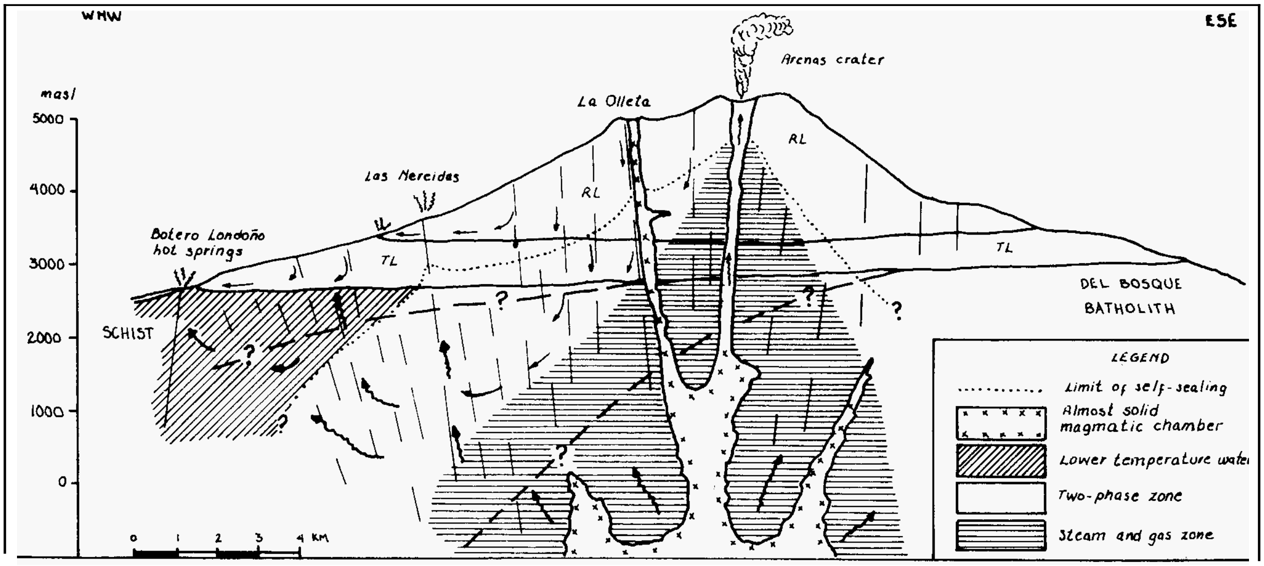

Figure 4.- *Schematic modelfor the Nevado del Ruiz geothermal system.*
TL: Tertiary andesitic lavas. RL: Quaternary andesitic lavas ojthe volcano. Dashed lines: See text.

southern volcano, and Laguna del Otún, probably associated to the Nevado de Santa Isabel volcano.

The most interest area is Las Nereidas-Botero Londoiio (Figure 2), in which the drilling of deep (2,000 meters) exploratory wells is recommendable, at a site between the Las Nereidas fumarole and the Botero Londoiio hot springs, in order to intersect one or more NW-SE normal faults. Prior to drilling, it would be convenient to run a magnetotelluric survey for a more accurate location of the exploratory wells.

In the Volcán Machin area (Figure 2) a deep exploratory well could be drilled inside the caldera at the volcano summit, between the caldera trace and the Western dacitic intra-calderic dome. The probable geothermal system in this area would probably be smaller than the Las Nereidas-Botero Londoiio one. Geothermal fluids must be contained, also, in Paleozoic schists.

There are another important zones, like those related to the Cerro Bravo volcano (numbers 15 and 16), those associated to the Villamaria-Termal faults (numbers 1, 2, 3), and zones 8 and 9, probably related to a low-enthalpy reservoir. In all these zones, like Laguna del Otún, it is necessary to complete more exploratory surveys in order to decide if deep drilling is recommendable.

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REFERENCES AND BIBLIOGRAPHY

Barberi, F., M. Martini, and M. Rosi (1990). Nevado del Ruiz volcano (Colombia): Pre-emption observations and the November 13, 1985 catastrophic event. *J. Volcanol. Geotherm. Res.,* 42, pp. 1-12.

Calvache V., M.L. (1990). Pyroclastics deposits of the November 13, 1985 eruption of Nevado del Ruiz volcano, Colombia. *J. Volcanol. Geotherm. Res..* **41,** pp. 67-68.

CHEC (Central Hidroelectrica de Caldas, S.A.) (1983). *Investigacidn geotérmica. Macizo Volcanico del Ruiz.* Internal unpublished report in ten volumes.

Constructora y Perforadora Latina, S.A. de C.V. (COPERLASA) (1992). *Proyecto geotermico Macizo del Ruiz, Republica de Colombia.* Internal unpublished report.

García-Parra, N., A. Londoiio-Carvajal, N. Rojas-Grisales y L.A. Rodriguez-Valencia (1987). Estudio geoquimico de los fluidos emanados del Macizo Volcanico del Ruiz. 1a. Parte. *Cuadernos de Investigación CINDEC No. 11.*

Giggenbach, W.F., N. Garcia P., A. Londoiio C., L. Rodriguez, N. Rojas G., and M.L. Calvache (1990). The chemistry of fumarolic vapor and thermal-springs discharges from the Nevado del Ruiz volcanic-magmatic-hydrothermal system, Colombia. *J. Volcanol. Geotherm. Res.,* 42, pp. 13-39.

Larios-Lopez, D.A. (1992). *The hydrothermal system d Nevado del Ruiz volcano.* Ph.D. Thesis, Lousiana State University, U.S.A. (Unpublished).

Londoiio-Carvajal, A. (1992). Written personal communication.

Thouret, J.C., N. Vatin-Perignon, J.M. Cantagrel, R. Salinas et A. Murcia (1985). Le Nevado del Ruiz (Cordillère Centralle des Andes de Colombia): stratigraphie, structures et dynamisme d'un appareil volcanique andtsitique, compost et polygtnique. *Rev. de Geol. Dyn. et de Geogr. Phys.,* Vol. 26, Fasc. 5, pp. 257-271.

Williams, S.N., R.E. Stoiber, N. Garcia P., **A.** Londoiio C., J.B. Gemmel, D.R. Lowe, and C.B. Connor (1986). Eruption of the Nevado del Ruiz volcano, Colombia, on 13 November 1985: gas flux and fluid geochemistry. *Science,* 233, pp. 964-967.

Williams, S.N., Y. Sano, and H. Wakita (1987). Helium-3 emission from Nevado del Ruiz volcano, Colombia. *Geoph. Res. Letters,* V. 14, No. 10, pp. 1035-1038.