Surface Manifestations of Deep Fluid From Colombian Hydrothermal Systems—Review

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ABSTRACT

Based on the geochemistry of the hot spring waters, mainly located along the Colombian Andes, deep geothermal fluid reaches the surface through hot springs associated with one system developed in sedimentary rocks and five volcanoes. They were grouped according to their location in four areas, two of them towards the center of the country: (1) Cundinamarca and Boyacá Provinces and (2) Nevado del Ruiz volcano, and the others to the South: (3) Huila - Puracé – Doña Juana volcanoes and (4) Azufral volcano. The Na-K-Mg relative composition reveals these waters are highly affected by dilution. At Nevado del Ruiz and Azufral volcanoes dilution trends can be inferred. The conservative species in general, pointed out characteristic relative compositions for each system, particularly clear for those with higher number of hot springs (Nevado del Ruiz and Azufral volcanoes). The highest B/Cl ratio is found in hot springs from Nevado del Ruiz and the lowest, in the Area 1. The estimated temperatures by aqueous geothermometers, suggest the existence of intermediate to high temperature geothermal systems (160 – 260°C). This paper is based on the chemical composition of 29 hot spring waters, in which the deep contribution can be postulated, out of about 180 compiled from previous works.

Introduction

As a result of its location in an active tectonic zone, related to the subduction of the Nazca and the Caribbean plates under the South American Plate, in Colombia there are about 45 volcanoes, 12 of them active, and several geothermal systems, mainly located along the Range of Los Andes and related to volcanoes, like Chiles – Cerro Negro, Azufral, Doña Juana, Sotará, Puracé, Huila, Nevado del Ruiz, Machín and Santa Isabel, indicated in surface by different features including hot springs, fumaroles and hydrothermal eruption craters. At least 270 hot springs have been registered all over the country.

Geothermal exploration studies started in Colombia in the 80´s with a national reconnaissance study (OLADE, 1982) followed by a prefeasibility studies in the Nevado del Ruiz, which included the volcanic complex Cerro Bravo – Machín (CHEC and CONTECOL, 1983) and in the Tufiño-Chiles Cerro Negro system (OLADE-INECEL-ICEL, 1987). Other hydrothermal systems were selected as high priority exploration targets (Azufral Volcano), medium-high (Paipa), medium (Cumbal y Galeras volcanoes) and low (Nevado del Huila). Additionally, supplementary research was recommended for Doña Juana, Sotará and Puracé volcanoes (OLADE, 1982). At the present time, the most advanced stage in these studies, is the drilling of one exploration well at the west flank of the Nevado del Ruiz, in the area known as Nereidas, described geologically by Monsalve *et al.*, 1998. Other areas of geothermal interest identified in the proximity of Nevado del Ruiz, are Machín volcano and Laguna del Otún at Santa Isabel volcano (Geocónsul, S.A., 1992).

The hot springs included in this work belong to geothermal systems related to the Nevado del Ruiz, Huila, Puracé, Doña Juana and Azufral volcanoes and to the system of Paipa-Iza which occurs in sedimentary rocks. Geological aspects are discussed by OLADE (1982), CHEC and CONTECOL (1983) and, OLADE, INECEL and ICEL (1987).

The objectives of the present work are to review and release the available geochemical information on Colombian hydrothermal systems: (1) Identifying areas of surface discharge from deep hydrothermal fluid. (2) Assessing if they are suffering dilution and mixing processes, (3) Tracing their origin and (4) Estimating deep temperatures as a preliminary approach to their geothermal potential.

Methodology

Information about hot spring waters was collected from a review of geoscientific investigations required for resuming the geothermal exploration program in Colombia initiated in early 80's. From this review it was possible to identify 270, but a chemical characterisation was possible for just 180 of them. Several kinds of hot spring waters were found, about 26 were classified as acid sulphate waters, 6 of them, presumably with contribution from the volcano-magmatic system at Nevado del

Table 1. Chemical composition of hot spring waters with deep fluid contribution in Colombia

No.	Hot Spring	Probable association to volcano	T°	pH	Na	K	Ca	Mg	Li	B	Cl	SO_4	HCO_3	SiO_2	Ionic balance	TDS *	References**
				Concentration (mg/l)													
AREA 1																	
1	Tabio		55	7	506	7	54	4	0.215	0.138	780	0	220	51.6	-0.74	1623	1
2	Iza		47	6.6	460	55	40	0	1.388	0.519	638	77	342	72	-3.69	1685	1
3	Tunja			7.9	1150	98	420	38	8.328	2.544	1985	18	1220	22.2	0.21	4962	1
4	Paipa			8.5	11960	1209	142	12	22.9	5.3	5318	18720	2562	55.8	-2.01	40007	1
5	Paipa		53	7.2	12650	1560	15	16	24.29	5.83	5672	18720	2440	55.2	0.17	41158	1
5'	Paipa		53	7.2	12880	1521	112	17	24.29	5.83	5672	20160	2623	55.2	-1.38	43070	1
AREA 2																	
6	El Bosque	Nevado del Ruiz	34	6.16	345	39	44	5	2.03	9.954	496	72	226	84	-1.05	1326	2
7	Granates	Nevado del Ruiz	55	6.81	483	13	86	1	2.52	3.354	744	67	153	72	1.61	1625	2
8	El Billar	Nevado del Ruiz	92	7.42	529	70	32	4	3.29	17.31	815	40	207	234	-0.44	1957	2
9	Hacienda B. Londoño I	Nevado del Ruiz	93	7.22	552	74	44	5	3.5	18.39	851	43	256	180	-0.43	2033	2
10	La Piscina (B. Londoño)	Nevado del Ruiz	57	6.27	414	55	42	13	2.31	12.98	638	27	268	168	-0.42	1644	2
11	Hacienda B. Londoño II	Nevado del Ruiz	92	7.04	529	74	40	5	3.5	17.31	815	53	244	174	-0.93	1960	2
12	San Vicente V	Nevado del Ruiz	43	6.12	127	15	14	4	1.33	4.653	184	26	49	72	4.32	501	2
13	San Vicente VI	Nevado del Ruiz	91	6.87	552	74	46	10	5.67	22.72	886	30	275	168	-0.62	2082	2
14	San Vicente II	Nevado del Ruiz	90	6.46	483	62	40	9	4.62	18.39	744	41	256	162	-0.08	1834	2
15	San Vicente I	Nevado del Ruiz	84	6.5	437	55	38	10	4.2	17.31	674	34	244	150	-0.02	1674	2
16	San Vicente IV	Nevado del Ruiz	66	6.48	368	47	50	36	3.36	12.98	496	28	500	252	0.78	1801	2
AREA 3																	
17	Toez	Huila	40	7.9	225	8	60	1	0.569	0.606	390	62	54	55.2	-0.47	857	1
18	Toez	Huila	33	7.3	110	4	40	3	0.257	0.292	184	33	85	84	-1.11	544	1
19	A. Hirviendo	Puracé	74	8.2	2162	199	108	32	8.327	36.79	1666	2688	915	114	-4.80	7930	1
20	A. Tibias	Puracé	58	6.3	1656	59	60	8	3.886	29.21	1347	1200	915	108	-0.53	5386	1
21	Tajumbina	Doña Juana	63	8.1	1104	74	12	29	2.567	15.15	1241	178	1037	162	-2.58	3854	1
21'			62	6.4	1104	70	144	29	2.845	15.15	1241	173	1403	186	-1.82	4368	1
22	Animas	Doña Juana	52	6.5	1104	62	144	20	3.678	14.07	1312	144	1281	72	-2.09	4157	1
23	San José	Doña Juana	37	6.4	2116	113	22	102	3.47	56.26	2233	168	2440	0	-0.95	7254	1
AREA 4																	
24	El salado Malaver	Azufral	24.8	6.02	454.02	46.41	38	94.2	0.75	9.45	1204	49	736.9	113	-21.09	2746	3
25	Malaver 1	Azufral	32	6.46	1905.8	177.45	190	388.32	3.29	29.7	2853	164	2435	138	2.17	8284	3
26	Malaver 2	Azufral	32	6.55	1719	164.97	167	360	2.95	27.27	2470	134	2301	135	3.13	7495	3
27	Q. Blanca	Azufral	50	6.2	483	37.1	84	49.2	1.19	7.47	744	168	408.7	168	-1.55	2151	1
28	El Baño 1	Azufral	48	6.5	690	85.8	280	300	1.82	11.90	1383	264	1647	192	-0.21	4855	1
29	El Baño 2	Azufral	48	6.4	690	85.8	280	300	2.03	11.90	1383	269	1647	198	-0.28	4866	1

* TDS, calculating by adding ionic species in mg/l

** 1 = OLADE, 1982; 2 = CHEC + CONTECOL (1983); 3 = OLADE + INECEL + ICEL, 1987

Ruiz and Puracé volcanoes. On the other hand, according to the classification by dominant anions and the composition in conservative species (Li, B, Cl) 29 hot spring waters seem to receive contribution of deep hydrothermal fluid. These were selected to be included in this paper. Most of the remaining waters were classified as bicarbonate and a few of them as mixed bicarbonate-sulphate and bicarbonate-chloride waters. Bicarbonate waters from Chiles, Sotará and Machín volcanoes, which exhibit high concentrations of conservative species (OLADE, 1982 and CHEC-Contecol, 1983), were excluded of this work, due to their low chloride content and the impossibility of applying geothermometers.

Based on the chemical composition of the selected waters, aqueous geochemical indicators and tracers were applied (Na-K-Mg and Cl-Li-B, relative compositions, respectively). Finally, deep temperatures were calculated based on aqueous geotermometers.

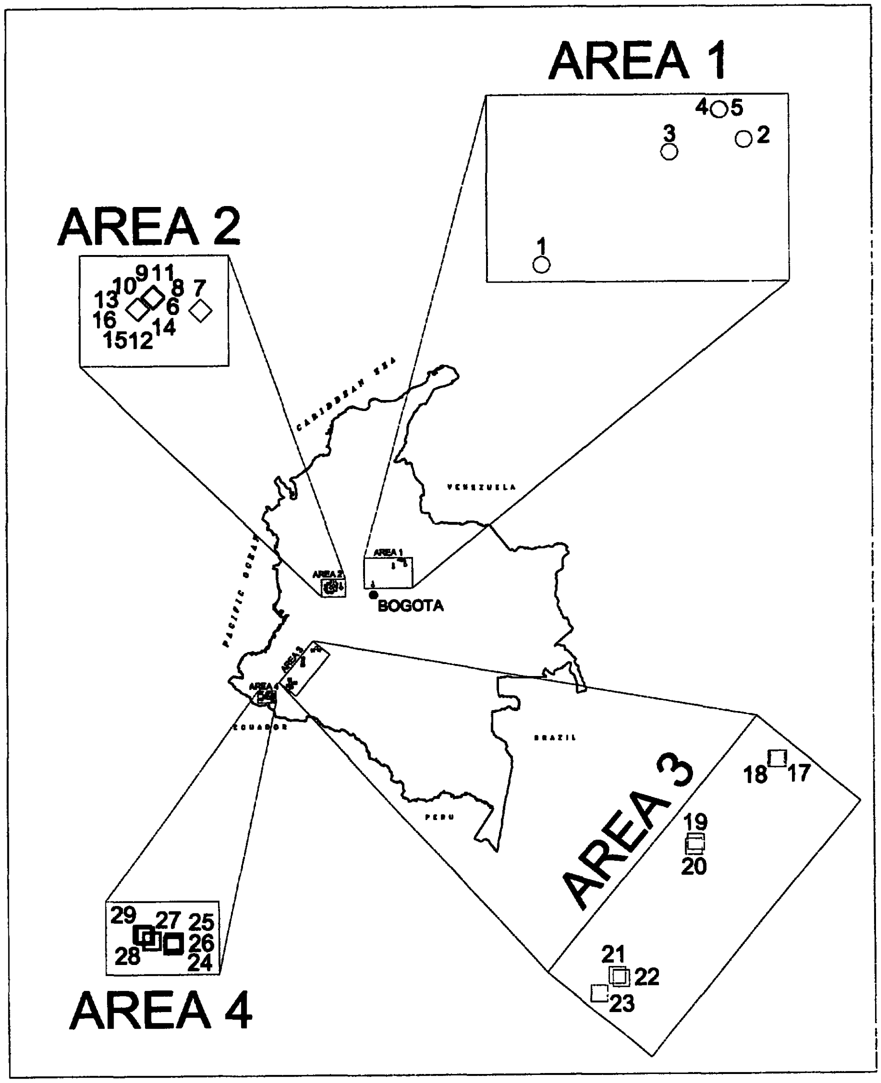

Figure 1. Location of hot springs with probable deep fluid contribution in Colombia. They occur in 4 main areas identified from 1 to 4 from North to South. Three of them related to volcanoes and one, to sedimentary rocks (Cundinamarca-Boyacá Provinces).

Data Presentation and Discussion

Generalities

Table 1 presents a summary of the chemical composition of the selected hot spring waters for which locations are shown in the Figure 1. According to their geographic location, they were grouped in 4 areas from North to South: Area 1: Cundinamarca-Boyacá Provinces, which includes waters from Paipa, Iza, Tunja and Tabio, Area 2: Nevado del Ruiz volcano, Area 3: Huila, Puracé and Doña Juana volcanoes and, Area 4: Azufral volcano.

As can be observed, the highest surface temperatures are registered by waters from Nevado del Ruiz (92° C) and Puracé (74°C) which correspond to the areas 2 and 3, respectively. The lowest temperatures are found at hot spring waters from Malaber in Azufral volcano, probably due to shallow dilution and cooling. However these waters show high salinity and high concentrations of conservative species. All the considered waters are near neutral (pH from 6 to 8), even those from Paipa which very high sulfate contents would make suppose they are acid waters. The very high salinity (mainly due to sodium and sulfate contents) of these waters and the sedimentary rocks where they occur, possibly indicates an additional source of salts from evaporites, which was previously suggested (OLADE, 1982). This mineral contribution seems to "mask" a deep fluid of low dilution inferred from the neutral pH, low magnesium concentration and high lithium and boron levels.

Except for the waters from Toez at Nevado del Huila all of the waters can be considered brackish based on their total dissolved solids, all higher than 1000 ppm. The highest salinity corresponds to the mentioned waters from Paipa in which salinity reaches about 43000 ppm.

The conservative species (Cl, Li, B) are highest in Areas 1, 3 and 4. The highest chloride content is observed at Paipa (close to 5700 ppm) and then at Azufral (2800 ppm), the more diluted waters from Toez at Nevado del Huila, contain 180 ppm. Also the highest lithium concentration is found in waters from Paipa with values around 24 ppm. It is followed by Agua Hirviendo from Puracé volcano (about 8 ppm). The majority of the remaining waters have a lithium content ranging between 1 and 5 ppm. On the other hand the highest boron contents is 56 ppm in the San José hot spring waters at Doña Juana, also followed by Agua Hirviendo and Aguas Tibias from Puracé, with 37 and 29 ppm, and Malaber from Azufral, with 29 and 27 ppm.

Water classification

According to the anions relative composition, shown in the Figure 2, most of the selected wa-

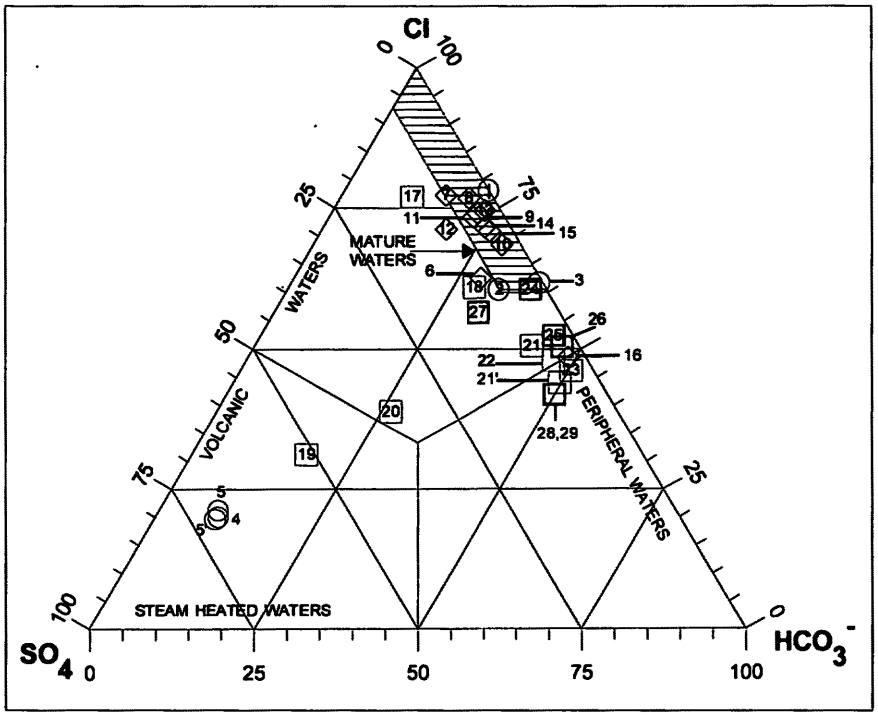

Figure 2. Relative Cl-SO_4-HCO_3 composition. Mature chloride waters are found at Iza, Nevado del Ruiz, Nevado del Huila and Azufral systems. Mixed chloride-bicarbonate waters in close proportions are found at Doña Juana, Nevado del Ruiz and Azufral. Waters from Paipa and the Puracé geothermal system seem to receive important contribution from deep water. However they are not classified as mature waters due to their high sulfate contents.

ters with presumed deep geothermal water contribution, are classified as mature chloride waters including (Tabio (1), Iza (2) and Tunja (3) from the Area 1, Nevado del Ruiz (points 6-15) from the Area 2, Toez (points 17 and 18) from the Area 3, and Salado de Malaber (24) and Quebrada Blanca (27) in the Area 4. Some areas show mixing of chloride waters with bicarbonate peripheral waters in an approximate proportion of 1 to 1. These correspond to waters from Doña Juana volcano in the Area 3, and Malaber y el Baño (25, 26, 28 and 29) in the Area 4. Finally sulfate dominated waters, likely receiving deep contribution, are found in Paipa (4 and 5) and Puracé volcano (19 and 20).

Na-K-Mg relative content

To assess the approach to equilibrium of the hydrothermal fluid with sodium, potassium and magnesium minerals from the reservoir rocks and to indicate dilution processes, triangular diagrams of Na-K-Mg relative content proposed by Giggenbach (1988) are presented in Figure 3. The waters from the Areas 1 and 3 are shown in the Figure 3(a). Most of them show a partial equilibrium with respect to feldspar. This equilibrium is not expected in waters from the Area 1, because of their sedimentary host rocks and because of the sodium "excess" coming from the supposed evaporitic mineral source. The highest extrapolated temperature on the equilibrium line corresponds to Agua Hirviendo (19) from Puracé volcano, about 225°C. The Na-K-Mg relative composition of the other hot spring from Puracé - Aguas Tibias (20) - is different from Agua Hirviendo and, these do not show any trend. Its extrapolated temperature on the equilibrium line is 160°C, which could be due to reequilibration of

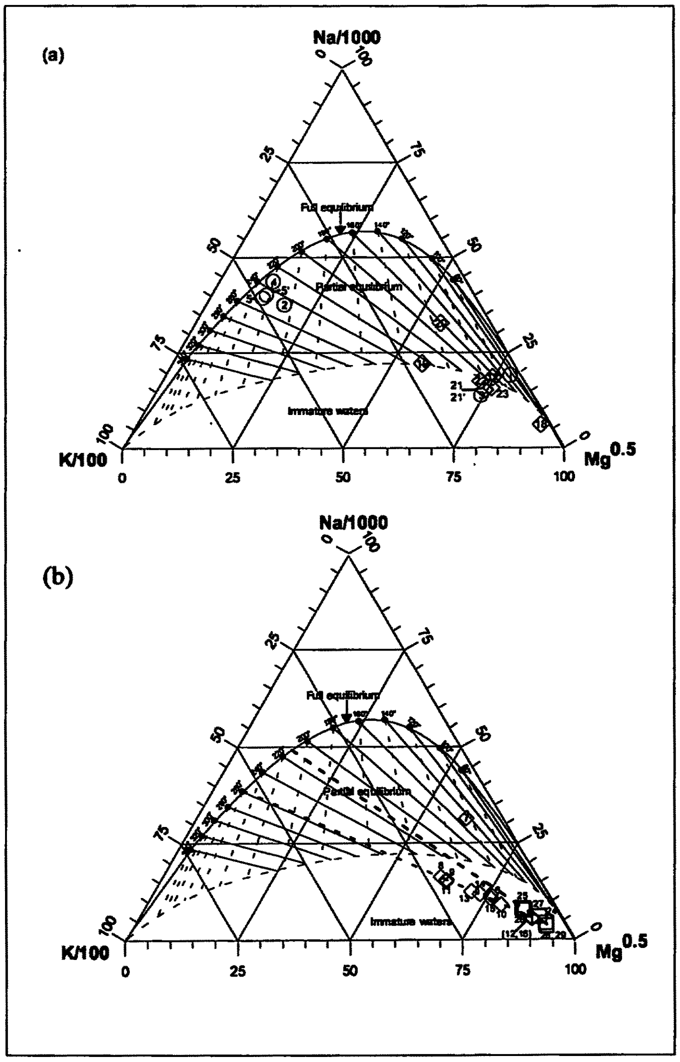

Figure 3. Relative Na-K-Mg composition. (a) Hot springs from Areas 1 (Cundinamarca and Boyacá) and 3 (Huila-Puracé-Doña Juana). Partial equilibrium between feldspars is indicated for waters from the volcanoes, pointing to a highest Na/K temperature (230° C) to Agua Hirviendo from Puracé Volcano. Taking into account, waters from the Area 1 are not related to an igneous environment and they are presumably receiving contribution of salts from different sources, the considerations about equilibrium and temperature inferred from this diagram can not be applied (OLADE, 1982). (b) Hot springs from Areas 2 (Nevado del Ruiz) and 4 (Azufral Volcano). Dilution trends are easily identified with an important meteoric water contribution as can be inferred from the high magnesium concentration. The highest Na/K temperature is observed to the waters from Nevado del Ruiz (close to 260°C).

minerals in the outflow zone. Figure 3b includes the hot spring waters related to Nevado del Ruiz and Azufral volcanoes which are the most numerous for individual systems. It is clear they are not in equilibrium, which is likely due to a mixing process with shallow waters that increases the magnesium contents. Both groups of waters describe dilution trends which extrapolation to the equilibrium line indicates temperatures of 260° and 220°C. The hot spring Granates (7) from Nevado del Ruiz, behaves differently from the rest and seems to be in partial equilibrium at a lower temperature.

Conservative species

The relative conservative species contents were calculated to compare the origin of these waters (Giggenbach, W. 1989). It is presented in the Figure 4. The waters grouped in the Area 1 exhibit the lowest relative boron content. Hot springs from Tunja (3) and Paipa (4 and 5), located about 10 km far from each other, show a similar origin while the one from Iza (2), about 5 km far from Paipa, have a significant difference in this relative composition with a lower lithium content which could means a different origin. The waters from systems with volcanic-magmatic association are dominated by chloride, which could be related either to absorption of low B/Cl magmatic vapor or to maturity of the geothermal systems, considering that volatile gases abandon the system in early stages of the heating (Giggenbach, 1989). From this, the composition of the magmatic contribution to the systems related to Azufral (Area 4) and Nevado del Huila volcanoes (Area 3), has been poorer in B/Cl ratio that the other volcanic systems considered or they has a relatively higher maturity. The relative Cl-Li-B composition of hot springs associated to Doña Juana Volcano (also from the Area 3) is not homogeneous. Waters from Tajumbina (21 and 22), with a composition close to those from Azufral and Huila, have a B/Cl ratio lower than the hot spring of San Josě, which is presumably also related to Doña Juana. The San José hot spring located 15 km far from Tajumbina and exhibiting the highest boron content of the considered waters (56 ppm) seems to receive a contribution from different sources of deep fluid than the other springs from Doña Juana. Waters from Puracé volcano, show near B/Cl ratio but the lithium content of Agua Hirviendo (19) is higher than the one from Aguas Tibias (20). Their B/Cl is similar to the one exhibit by the waters from Nevado del Ruiz.

Waters from Nevado del Ruiz show the highest B/Cl ratio (about 0.02 – 0.03). Again, an important difference is observed in the Granates hot spring (7), in front of the others from Ruiz, may be due to different origin. It is comparatively poor in boron. Little differences can also be observed in the lithium content between waters from San Vicente (12-16) and waters from Nereidas area (Botero Londoño).

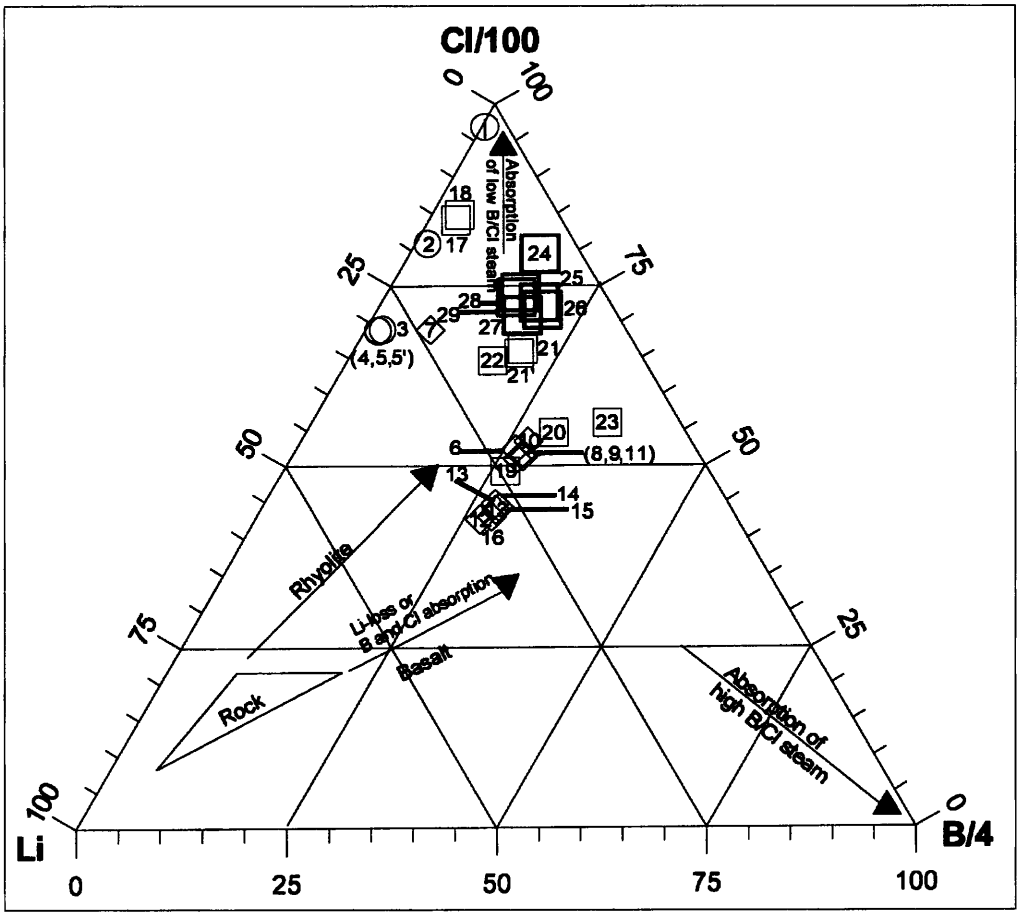

Figure 4. Relative Cl-Li-B composition. The waters from the Area 1 show the lowest relative B/Cl ratios ($2x10^{-4}$ to $1.3x10^{-3}$) and are spread out showing different origins, excepting the waters from Paipa (4 y 5) and Tunja (3) which appear to have a common origin. The Area 2, corresponding to Nevado del Ruiz, show one of the highest B/Cl ratio (0.02-0.03). A significant difference in the origin of the Granates hot spring (7) is observed, which B/Cl ratio is about 4.5 x 10^{-3}. The waters from San Vicente zone (12-16) show a higher lithium concentration than those from Nereidas zone (6-11), at Nevado del Ruiz. The waters from the Area 3, related to different volcanoes, are scattered indicating their different origin. The San José hot spring (23) from Doña Juana, exhibits the highest B content and seems to have a different origin from the others at Doña Juana (21-22). The waters from Azufral (Area 4) and Nevado del Huila (Area 3), have a relatively low B/Cl contents which could be related to a low B/Cl magmatic contribution or to a higher maturity.

Geothermometers

Table 2 presents a summary of aqueous geothermometers. Four geothermometers were applied: Na/K, K/Mg, Na/K/Ca and SiO_2.

Large differences can be observed which are likely due to the evident dilution that all these waters have suffered. The K/Mg geothermometer is highly affected by dilution because of the increase of magnesium giving lower temperature values, as observed. The SiO_2 temperature also shows low values, which can also be attributed to dilution. Probably, the most valid geotermometers, are Na/K and Na/K/Ca as they are less affected by dilution. They show the closest values the one to the other. Na/K can be applied considering $Ca^{1/2}/Na$ is less than 1 for all the considered waters and it gives temperatures higher than 180°C, excepting for waters from Toez related to Nevado del Huila and Aguas Tibias from Puracé. A large difference (80-100°C) between the temperatures calculated through these two geothermometers are found in the waters from Toez.

Table 2. Deep temperatures calculated by aqueous geothermometers

No.	Na/K	K/Mg	Na/K/Ca	Qtz no steam loss	Qtz max steam loss
6	242	109	193	128	
7	145	103	93	120	
8	256	131	215		177
9	257	129	213	173	163
10	256	106	207	169	
11	261	129	216		161
12	248	87	188	120	
13	257	119	213		159
14	254	115	209		157
15	251	110	205		153
16	252	88	200	196	
17	160	91	76	107	
18	161	60	56	128	
19	226	131	209	145	
20	161	115	157	142	
21	203	103	198	166	
21'	199	102	172	175	
22	191	103	166	120	
23	187	98	192		
24	234	76	194	144	
25	227	92	201	156	
26	229	91	202	155	
27	212	78	172	169	
28	250	77	194	177	
29	250	77	194	179	

Na/K = (1390/(LOG(Na/K)+1.75))-273 (Giggenbach)

K/Mg = (4410/(14-LOG(K^2/Mg)))-273 (Giggenbach)

$\mathbf{Qtz_{msl}}$ = $(1309/(5.19-LOG(SiO_2)))-273$ (Fournier)

$\mathbf{Qtz_{nsl}}$ = $(1522/(5.75-LOG(SiO_2)))-273$ (Fournier)

Na/K/Mg = $(1647/((Log/Na/K)+\beta(Log(Ca^{1/2}/Na)+2.06)+2.47)))-273$. Beta ($\beta$) = 1/3 ó 4/3) (Fournier and Truesdell)

Conclusions

- At least five hydrothermal systems related to volcanic heat sources, exhibit deep water discharges on surface. The hot spring waters from Paipa–Iza system, have very high concentrations of conservative species, particularly the waters from Paipa and Tunja, that suggest a deep contribution, but also extremely high sulphate and sodium concentrations that indicates a different source of salts, possibly from evaporites as previously stated.
- The hot springs from volcanic geothermal systems in Colombia, with deep fluid contribution, are far from equilibrium with Na, K and Mg minerals. Partial equilibrium is inferred in hot spring waters from the Area 3. The higher equilibrium condition is observed in waters from Puracé Volcano.
- The geothermal systems of Nevado del Ruiz and Azufral volcanoes, have enough hot springs to identify dilution trends as is clear on the Na-K-Mg diagram. The trends indicate equilibrium close to 260°C in Nevado del Ruiz, and to 220° in Azufral.
- Deep temperatures calculated by applying aqueous geothermometers to waters from systems related to volcanoes, indicate the existence of intermediate to high temperature systems. Waters from Nevado del Huila (Toez) present the lower temperature (160°C). Waters from Doña Juana (Tajumbina) indicate temperatures about 200°C, while Agua Hirviendo from Puracé, 226°C. The highest temperatures are calculated to Azufral (230-250°C) and Nevado del Ruiz (240-260°C).

Acknowledgment

We acknowledge the support given by Ingeominas to our work and to the growing geothermal research in Colombia. Also we thank Mr. G. Suárez for his collaboration for preparing the map.

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