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The Cachiyacu Geothermal Prospect, Chacana Caldera, Ecuador

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ABSTRACT

Cachiyacu is located at about 65 km ESE of the capital city of Quito, in the high ranges of the Eastern Cordillera at 4000 masl, on ragged topography in a wet and cold climate. Paved accesss road and high voltage transmission line cross along its northern border; the main load center is Quito. The heat source is the southern part of the resurgent silicic Chacana caldera, which has been persistently active since late Pliocene, producing numerous rhyolitic domes, andesitic to dacitic lava flows and ignimbrites of high-K calc-alkaline affinity; latest volcanic activity comprises two large Si-andesite lava flows as recent as 240 yr BP. The 35 by 15 km diameter caldera structure is hosted in the Paleozoic-Mesozoic metamorphic basement and is likely controlled by regional NNE-striking strike-slip faults. A hot water–dominated geothermal system, with deep temperatures in excess of 200 °C is assumed to be hosted in the late Tertiary to Quaternary volcanic pile filling the caldera and in its lower wall rocks. 30 to 65 °C, highly saline hot springs are common inside the area and its waters belong to the Cl-SO4-alkaline type. Hot spring water along a NE-oriented outflow at 5 to 10 km distance, is used mainly for bathing purposes and less for space heating. Older hydrothermal alteration is widespread in the area. A preliminary geothermal model is proposed in the Cachiyacu area with a self-sealed reservoir and permeability sustained by active faults. A comprehensive magnetotelluric survey is recommended to locate the geothermal reservoir and to site the first deep drilling targets in Cachiyacu.

1. INTRODUCTION

The Ecuadorean government has priorized the development of renewable sources of energy with the aim to reduce and eventually replace the use of fossil fuels for power generation. This study was funded by Electroguayas, a state owned power generation entity, with the objective to assess the geothermal potential of the Cachiyacu area and prepare a preliminary geothermal model, based on reconnaissance geological and geochemical surveys. Geological work included field mapping and sampling, as well as geochemical assays by ACME Labs, Vancouver-Canada of the most representative rock samples. Geochemical work consisted of sampling water from 19 warm and hot springs as well as bubbling gas and surface waters; geochemical analysis of the fluids were done at the Istituto Nazionale de Geofisica e Vulcanologia at Palermo, Italy.

The Cachiyacu geothermal prospect is located in the southern end of the silicic Chacana caldera, on the crest of the Eastern Cordillera (CR), about 65 km ESE from the capital city of Quito. Elevation range from 3200 up to 4100 masl on ragged topography covered with high-altitude grassland and few cloud-forest patches. Climate is cold and wet for most of the year. There are no people living in Cachiyacu area and there is no road access to it, although the villages of El Tambo and Papallacta are 5km and 12 km away in NE direction, respectively. A paved highway connects these villages with Quito and the Amazon basin.

Earlier work on the assessment of geothermal resources by INECEL-OLADE (1980) and by Almeida (1990) and Almeida et al., 1992, didn't consider Chacana as a high temperature geothermal resource, although it is taken into account by Beate & Salgado, 2005, and Beate, 2008, which prompted the interest of Electroguayas in the area. The actual knowledge is mostly regional geology; recent vulcanological studies by IG/EPN by Hall & Mothes (2008) have outlined the evolution of Chacana Caldera and its roll as part of the Ecuadorean Rhyolitic Province (ERP). Just recently, the geochemical base line for the Ecuadorian arc has been established, including the Chacana area (IG/EPN/INGV 2009)

In the following sections we present an outline of the regional geological setting of the Chacana Caldera, a brief sketch of the geology and evolution of the Chacana Caldera with emphasis on its southern part and Cachiyacu in particular; than we outline the main results of the geochemical survey on hot spring waters and discuss the mayor issues of a preliminary geothermal model for Cachiyacu.

2. GEOLOGICAL SETTING

Continental mainland Ecuador consists of three distinct geomorphologic and geographic regions: the coastal plains or COSTA, the Andes mountain chain or SIERRA and the Amazon basin or ORIENTE; a fourth region comprises the Galapagos Islands located about 800 km to the W of the coastline in the Pacific Ocean (see fig. 1).

The Andes constitute the very backbone of the country. Its formation is due to multiple accretion since Jurassic times (Aspden and Litherland, 1992; Eguez and Aspden, 1993). It consists of two parallel NNE-striking mountain chains: a) the Eastern Cordillera or Cordillera Real (CR) which are sublinear belts of Pz-Mz metamorphic rocks intruded by both, I- and S-type granitoids of early Mesozoic age; and b) the Western Cordillera or Cordillera Occidental (CO), which consists of late Mesozoic to early Cenozoic basalts and vulcaniclastics, representing accreted oceanic terrains (Hughes and Pilatassic, 2002). These rocks are intruded by Tertiary granitoids. Both cordilleras have been folded and uplifted and are covered by late Tertiary volcanics.

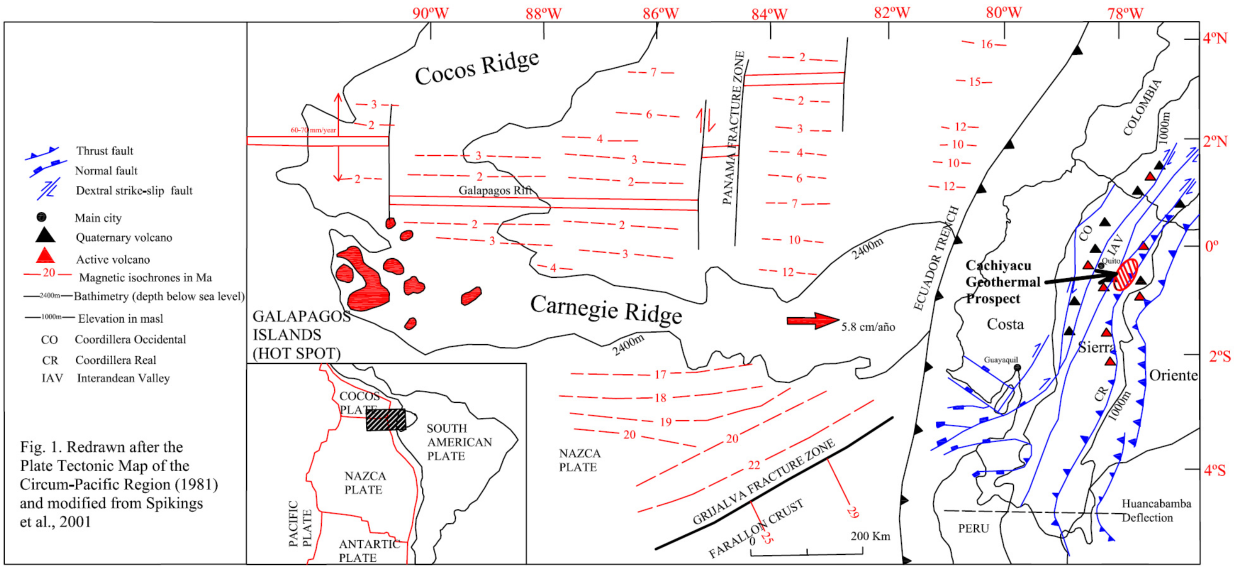

Fig. 1 Geodynamic setting of Ecuador, depicting location of Cachiyacu Geothermal Prospect

The Interandean Valley (IAV, see fig. 1) is located between the two cordilleras and comprises thick late Tertiary to Recent vulcaniclastic and epiclastic sedimentary sequences; it is bounded laterally by NS oriented terrain sutures, the Pujili – Calacali suture to W and the Peltetec suture to E, which continue into Colombia as the Cauca-Patia and Romeral sutures, respectively. Suture-paralell overprinting active faults, mostly thrust faults, mark the morphology of the actual IAV borders.

Covering both cordilleras in its northern half, a well developed, subduction-related, broad, calc-alkaline continental volcanic arc extends northwards into Colombia (Barberi et al., 1988; Hall & Beate, 1991). The arc is of Quaternary age and consists of more than 50 volcanoes, of which at least 30 are active and four are in eruption or did so in the last ten years. The southern half of the Ecuadorian Andes shows only extinct volcanic activity, the latest one being at Quimsacocha caldera at 3.6 Ma (Beate et al., 2001); the outset of volcanism is due to the flattening of the slab since late Miocene (Gutscher et al., 2000).

The Oriente is an extensive sedimentary basin, overlying cratonic basement (Baldock, 1982). Older rocks comprise Jurassic volcanics and batholiths and a Cretaceous carbonatic platform, covered by Tertiary epiclastic sediments; large NS-striking thrust faults cut the sequence toward its western limit (Tschopp, 1953). Quaternary alkalic volcanoes are located along the W margin of the basin in a back-arc setting.

The Costa is the flat region between the Andes and the Pacific Ocean. It comprises a late-Cretaceous to Cenozoic fore-arc basin underlain by mid to late Mesozoic oceanic crust (Benitez, 1995; Vallejo, 2009). There is no active volcanism in this area.

The Galapagos Islands are an active mantle hot spot and the asismic Carnegie ridge (see fig. 1) represents the trace of the hot spot over the Nazca Plate, which is actively subducting underneath continental Ecuador, producing most of its volcanism and intense seismic activity.

Geodynamic processes in Ecuador since late Oligocene are controlled by the near orthogonal convergence between Nazca and Southamerican plates, which has generated regional uplift and crustal faulting and deformation as well as extensive volcanism (Londsdale, 1978).

The compressive tectonic regime formed several intramontane basins between the two cordilleras since Miocene. The IAV has been formed as a spindle shaped basin along a restraining bend in a transpressive regime since about 6 Ma due to an increase in the coupling of the Carnegie ridge in the subduction zone (Spikings, 2001; Winkler, 2002; Villagomez, 2002).

The northern half of the country is now part of the North Andean Block (NAB), which moves at 6-10 mm/yr in NE-NNE direction along regional dextral strike-slip faults (Ego, 1993). This active regional fault system enters the gulf of Guayaquil creating extension and normal faulting (fig.1). It continues northwards along the dextral Pallatanga fault, which cuts both, the Western (CO) and the Eastern Cordillera (CR), as well as the IAV, emerging further N as the Chingual fault at the border with Colombia, where it continues along a NS strike.

This tectonic activity together with the extensive Quaternary volcanism present in the northern Ecuadorean Andes are the regional setting for the Chacana caldera and the Cachiyacu geothermal prospect.

3. GEOLOGY OF CACHIYACU PROSPECT

The Cachiyacu prospect area is located inside the Chacana caldera, close to its southern rim and comprises about 100 km2. The area is flat caldera floor at the site of the hottest thermal springs, where it is surrounded by steep caldera walls to W, Plaza de Armas dome-flow complex to the S and Yanaurcu and San Clemente felsic domes to E and N, respectively. In contrast, topography to the E of the mentioned domes is rugged and difficult.

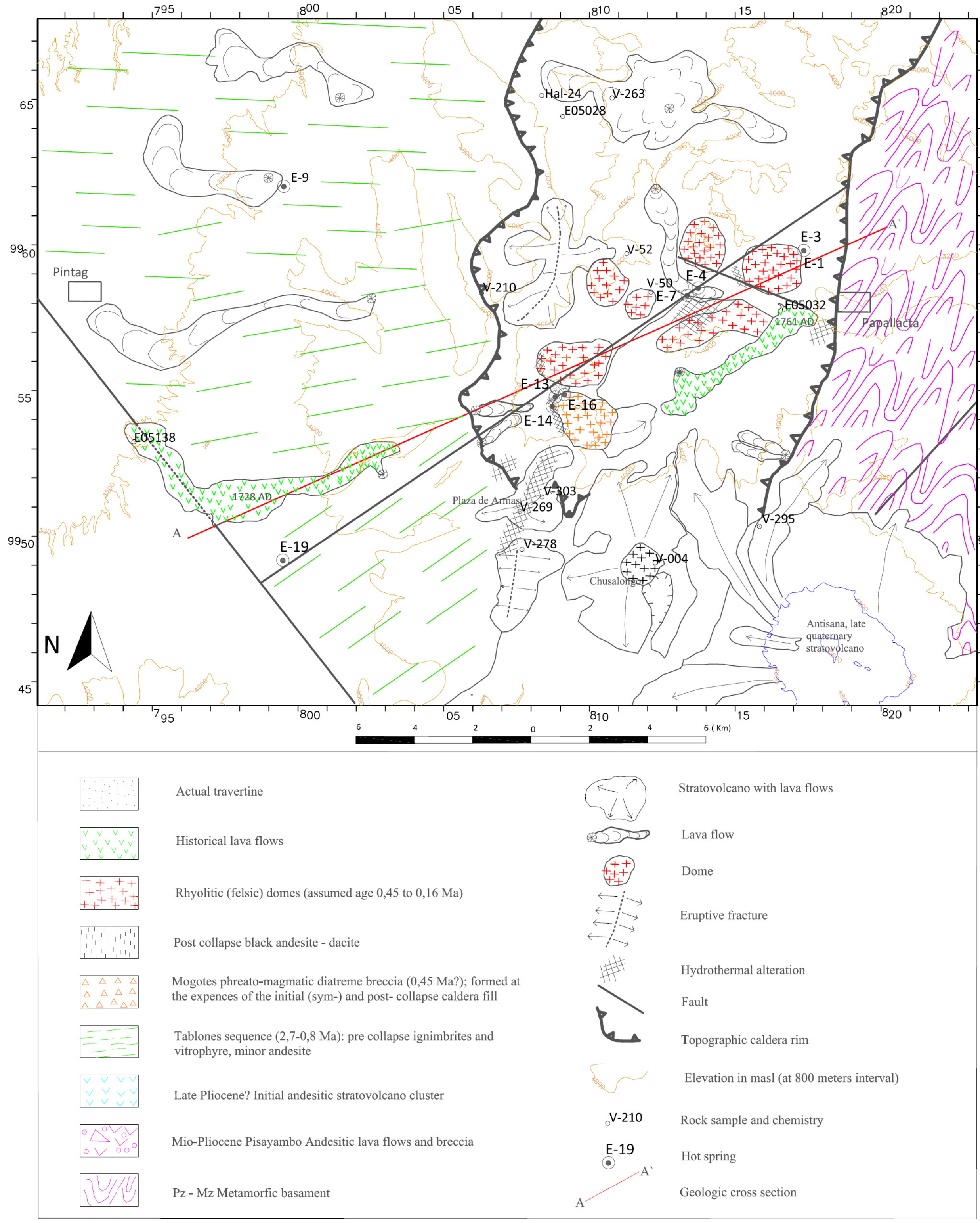

Fig. 2 Geologic map of Cachiyacu

The Chacana caldera is the largest rhyolitic eruptive center in the northern Andes (Hall & Beate, 1993; Hall and Mothes, 2001; 2008) and constitutes the northern part of the Ecuadorian Rhyolite Province (ERP), proposed by Hall & Mothes (2008). This province covers an area of about 100 x 40 km, along the crest of the Cordillera Real (CR), and consists of large silicic collapse calderas like Chacana (diameter 35 x15 km) and Chalupas (diameter 15 km, 40 km S of Chacana, INECEL 1983, Beate-1985 and Hammersley, 2003) and many rhyolitic domes and felsic intrusions; it is located on a 50 to 70 km thick continental crust, in concordance to a – 210 mgal Simple Bouguer gravity anomaly low (Feininger and Seguin, 1983).

The Chacana pre-caldera edifice measures 60 km NS and 28 km EW and was built initially as an andesitic stratovolcano cluster during late Pliocene. This cluster was covered by voluminous radial volcanic deposits (U1 in Table 1) of dominantly dacitic and rhyolitic ignimbrites, vitrophyres and lava flows until about 1 Ma. The whole Chacana sequence is about 1 km thick; it overlies a 1-2 km thick Mio-Pliocene pile of andesite flows, breccias and tuffs of Pisayambo Fm. The basement to the whole volcanic sequence consists of Paleozoic-Mesozoic metamorphic rocks to the center and E side, and Mesozoic oceanic basalts to the W side. The two basements were put together by accretion at 75 Ma along the NS-striking Peltetec suture (Spikings et al., 2005); this suture, now inactive, is the likely western control to ERP and to Chacana and Chalupas calderas.

A second set of active regional dextral strike-slip faults (Soulas, 1991) runs through the Chacana area along a NNE direction and is likely responsible for the caldera formation and geometry and location of subsequent volcanism. The Chacana caldera formed by structural collapse about 1 Ma ago due to the explosive and voluminous extrusion of rhyolitic ignimbrite or ash flow, now partly preserved as buried, distal, reworked tuffs in the sedimentary fill of the IAV (the Golden Tuffs of Villagomez, 2002). The topographic caldera diameter is about 35 x 15 km, elongated in a N to NNE direction, and probably corresponds to a plate collapse geometry (Lipman, 1984). The caldera depression was partly filled during and after the collapse by ignimbrite, collar-landslide breccias (as proposed by Lipman, 1997) and andesitic to dacitic lava flows (unit U2, in table 1); the top of the fill sequence consists of laminated siltstone and sandstone in the lower facies and coarser grained sandstone and blocks of caldera filling lavas towards the upper sedimentary facies.

At about 0.45 Ma, magmatic activity resumed vigorously with the intrusion of a voluminous rhyolite – dacite sill or laccolith, which caused: a) the uplift and resurgence of the central part of the caldera for about 500 m, b) the formation of an extensive 10 to 15 km diameter phreato-magmatic diatreme breccia (p-m dbx), similar in size to the Guinaoang 8.5 x 3.5 km diatreme in Philipines (Sillitoe, 1985), which partially changed the caldera floor from plate- to funnel-shaped, and c) the emplacement of late rhyolitic domes into the latter (unit U3 in table 1). Volcanic activity continued until about 0.165 Ma, with the intracaldera extrusion of andesitic, dacitic and rhyolitic lava flows and domes, obsidian flows, pyroclastic flows and extensive rhyolitic tephra fall deposits of regional extent (Hall & Mothes, 2008). The vents were located mainly along the structural collapse rim and on the caldera floor. Hydrothermal activity caused extensive alteration in the caldera filling rocks. Most of the rocks cropping out at the Cachiyacu area belong to this magmatic pulse, like the Chuzalongo andesites, Plaza de Armas rhyolites and obsidian flows and the San Clemente and Yanaurco domes (see map and cross section, fig 2 and 3, and U3 in Table 1).

In late Pleistocene and synchronous with the pleniglacial period, between 40 and 20 ka (Clapperton and Vera, 1986), several lava flows of Si-andesites poured out inside and outside of the topographic rim of the Chacana caldera (see U4 in Table 1; Hall & Mothes, 2008). The most recent eruptions in the Cachiyacu area occurred in the last thousand years (see fig. 1 and U5 in Table 1) and consist of Si-andesites; the very last lava flow occurred in 1761 AD.

The Cachiyacu area has been affected by intense glacial erosion and surface deposits consists largely of till, which is covered by a periclinal 2m thick black soil containing discrete distal tephra layers of Holocene age.

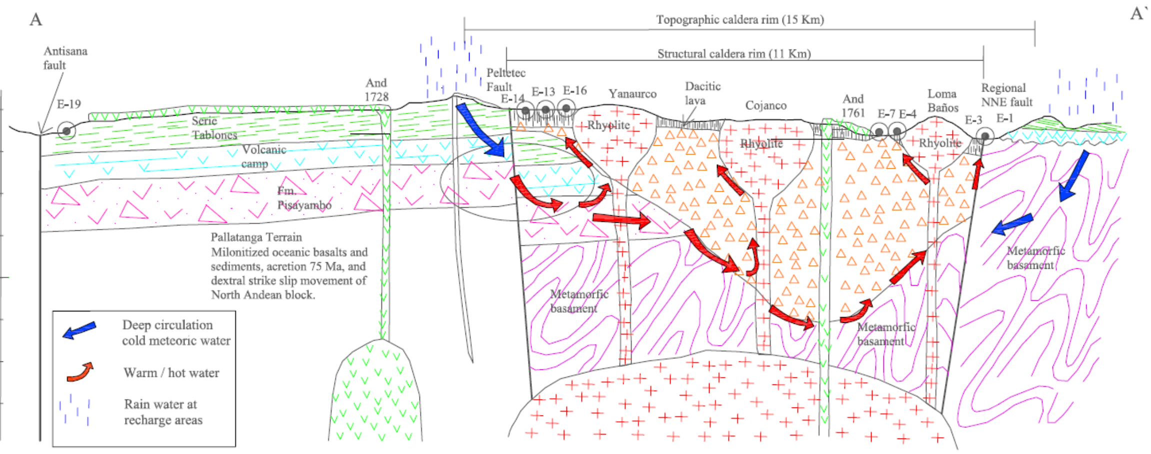

Fig. 3 A-A' geologic cross section

Table 1. Cachiyacu Rock Chemistry														
Mayor elements reported in weight %, trace elements in ppm														
Rock Type	U1		U2		U3						U4	U5		
Sample	V-210	E05020	V-52	E05028	V-50	V-263	V-269	V-303	V-004	H-1	H-2	E05032	E05138	V-295
SiO2	57,59	75,01	59,25	63,06	68,80	65,70	68,42	68,46	56,67	63,83	59,20	62,17	61,70	62,98
Al2O3	16,48	12,36	16,60	16,18	15,20	15,88	15,48	14,05	16,24	15,31	15,20	16,60	16,29	15,70
Fe2O3	7,52	0,81	6,96	5,51	3,38	4,32	3,15	1,80	7,39	5,32	5,25	5,52	5,74	5,40
MgO	4,62	0,08	3,46	2,53	0,79	1,79	0,82	0,56	4,84	1,17	4,53	2,63	2,93	2,63
CaO	6,76	0,44	5,95	4,94	2,40	3,96	2,23	1,39	7,14	3,71	5,17	5,17	5,44	4,60
Na2O	3,76	4,24	3,93	3,78	4,39	4,19	4,40	3,50	4,01	4,10	2,93	4,32	4,25	3,96
K2O	1,16	4,26	1,97	3,55	3,28	2,89	3,39	3,88	1,88	2,70	2,17	2,40	2,36	3,26
TiO2	0,73	0,14	0,85	0,69	0,42	0,55	0,49	0,31	0,90	1,00	0,93	0,76	0,78	0,72
P2O5	0,15	0,69	0,22	0,39	0,13	0,16	0,18	0,08	0,39	0,29	0,28	0,40	0,41	0,25
MnO	0,10	0,05	0,09	0,07	0,05	0,08	0,06	0,06	0,10	0,08	0,10	0,08	0,09	0,08
LOI	0,80	0,73	0,40	0,67	1,00	0,20	1,20	5,70	0,00			-0,16	-0,21	0,10
Total	99,67	98,81	99,68	101,37	99,84	99,72	99,82	99,79	99,56	97,51	95,76	99,89	99,78	99,68
Rb	25,80	141,10	57,30	82,70	106,30	86,00	108,40	141,20	53,90	79,00	61,00	61,90	64,80	131,30
Sr	529,40	37,00	645,10	541,00	336,70	505,00	365,00	274,70	1060,50	419,00	645,00	783,00	779,00	719,80
Y	11,10	17,50	14,20	14,90	13,70	10,50	14,10	11,80	13,70	23,00	19,00	10,80	11,50	14,70
Zr	91,50	102,00	143,80	164,00	156,80	123,50	169,00	176,00	123,00	225,00	188,00	173,00	148,00	193,50
Nb	4,50	13,00	8,10	8,90	10,10	8,40	11,30	11,60	9,30	10,90	10,00	9,00	8,90	11,60
UTM(E)(08)	8,12		1,12		1,21	1,07	0,75	0,90	1,21	8,08	8,12			1,56
UTM(N)(99)	6,25		5,98		5,86	6,51	5,09	5,15	4,92	6,54	6,25			5,06
U1: pre caldera lavas and ignimbrites. U2: Initial (syn-) and post- collapse caldera fill (0,8 Ma). U3: Lava flows, domes, ignimbrites post collapse (~0,45 - 0,16 Ma). U4: Lava flows (40 -20 Ka). U5: Historical lava flows.														
V-#: Fabián Villares for Electroguayas thesis in prep.; E05#: Chiaradia et, al 2009; H-#: Hall 2009, personal comunication.														

Active faults comprise the regional NNE dextral strike-slip system which marks the E limit of the NAB and likely controls the geometry of the Chacana caldera structure; it is also a most likely control on permeability for the deep fluids. Faults and dykes of nearly EW strike are common; several volcanic vents seem to follow a NS direction. The Antisana NW lineament is a dominant feature S of Cachiyacu, although is not reported as active.

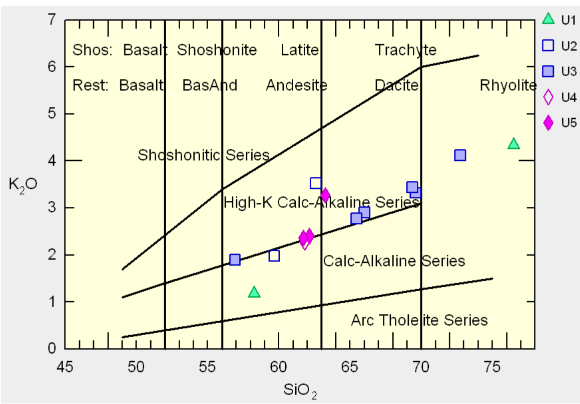

Fig. 4 SiO2 vs K2O diagram for selected rock samples of Cachiyacu

4. GEOCHEMISTRY OF CACHIYACU PROSPECT

Between one and two dozen of warm and hot springs crop out in the Cachiyacu Prospect, most of them inside the caldera topographic margin. Location of springs is depicted on the geologic map (fig. 2) and its composition and physico-chemical parameters are given in Table 2. The springs are the only surface thermal manifestation in the whole caldera; other active features such as geothermal fumaroles and steaming ground are absent. Most of the springs are distributed along a NE-striking fault (see fig. 2) on a total distance of 22 km; other springs are located on the western slope (E-9) and distant foothills (E-10;-11;-12) of the Chacana edifice.

The group of hottest and most abundant spring waters occur in the Cachiyacu area at 3900 m elevation on the caldera floor and associated with the Yanaurcu and San Clemente felsic domes. The total number of springs in unknown, but at least a dozen were mapped and three of them were sampled and analyzed (E-13;-14;-16). The spring water is crystalline, with a slight H2S odor, and deposits travertine in aprons and modest size terraces above river level. Temperature ranges from 40 to 64.6 °C and pH varies between 5.99 and 6.53; conductivities range between 3300 to 5700 micro siemens per cm (Fig. 5) indicating high salinities of up to 5000 mg/litre. The waters belong to the family of Cl-SO4 alkaline waters (Fig. 6).

A second group of springs (E-4 and E-7) is located in the Tambo river valley, about 5 to 6 km NE of Cachiyacu, at 3500 m elevation, and associated with glaciated, low profile rhyolitic domes. Their temperature is slightly less than the previous group (57 to 60 °C), although conductivity is up to 7250 micro S /cm. They belong to the same family of Cl-SO4-alkaline waters; these springs are used for swimming pools.

Table 2. Cachiyacu Spring Chemistry (ppm)													
	Papallacta - Jamanco springs					Cachiyacu springs			Lateral outflow to NW and SW			Meteoric recharge	
Sample	E1	E2	E3	E4	E7	E13	E14	E16	E9	E19	E11	E5	E18
Elev. (masl)	3334	3304	3278	3518	3550	3918	3926	3910	3426	3458	2571	3455	4045
UTM (E)	17,2	17,1	17,3	13,5	13,4	8,9	8,7	8,8	98,7	98,9	91,4	17,1	9,9
UTM (N)	60,0	59,9	60,0	58,5	58,4	54,8	54,6	54,8	61,8	49,0	68,1	60,9	43,3
Temp.ºC	58,9	47,2	54,2	60,8	57,8	60,1	40,5	64,6	27,2	29,9	37,7	9,0	7,5
ph	6,82	6,56	7,08	6,23	6,15	6,53	5,99	6,39	7,17	6,10	6,48	7,95	6,36
Condt. µs/cm	3980	2900	2170	6820	7250	5000	3340	5560	5720	1780	1540	105	284
Li	2,40	1,40	1,40	6,60	8,00	7,20	4,90	8,10	1,90	0,20	-	-	0,07
Na	54,02	306,60	282,40	1136,80	1306,10	825,20	553,30	916,00	1123,91	238,00	209,90	2,50	10,40
K	10,2	5,9	6,3	42,6	59,8	73,5	50,8	79,8	53,6	26,6	26,2	0,8	3,5
Ca	312,4	201,6	116,5	294,1	278,1	99,6	119,8	106,4	244,5	60,1	58,1	16,6	10,0
Mg	3,6	2,1	1,7	8,1	11,2	25,4	19,4	33,1	52,9	68,7	81,3	2,43	6,1
Si	30	24	28	50	54	75	54	80	42	68	72	9	-
B	6,90	4,10	3,70	18,16	19,80	17,40	11,20	19,00	19,80	5,10	3,30	0,01	-
Cl	973,5	492,1	401,3	1871,8	2114,2	1247,1	801,2	1302,4	493,1	234,3	107,8	1,5	2,1
F	1,90	1,50	1,90	1,80	3,00	1,00	1,00	1,00	3,80	0,80	0,60	0,01	1,10
SO4	530,4	380,2	372	300,9	236,6	117,1	86,9	115,7	1307,5	2208	73,9	2,9	10,1
HCO3	79,3	109,8	100,7	454,5	576,5	518,5	549	672,2	1576,9	762,5	902,8	62,83	73,2
As	1,03	0,66	0,96	3,2	4,22	5,71	2,7	5,4	9,15	0,2	0,41	0,001	-
TDS	2005,65	1529,96	1316,86	4188,56	4671,52	3012,71	2254,20	3339,10	4929,06	3672,52	1536,31	98,58	116,57

A third group of springs is located further 4 km to NE from the previous ones, in the Papallacta river valley at 3300 m elevation and at the structural caldera margin. Associated lithologies comprise dacite domes, flow –textured diatreme breccia and caldera wall rocks of andesitic and dacitic composition. Their temperatures vary from 47 to 59 °C and conductivities range from 2000 to 4000 micro S/cm, which is lesser than the other two groups and can be due to dilution. The waters belong to the same family of Cl-SO4-alkaline waters as the previous groups and are used intensely for bathing purposes, and at an incipient level for space heating.

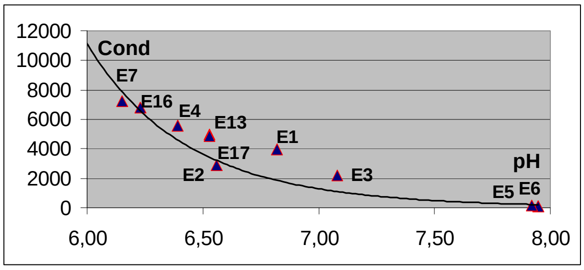

Fig. 5 Conductivity in micro Siemens/cm vs pH for Cachiyacu waters.

Spring E-9, also called Tolontag or La Calera spring, is located outside the caldera structure, on the outer slopes of the caldera edifice, at an elevation of 3400 m; it is 12 km distant from Cachiyacu area in a NW direction and represents a likely outflow from Cachiyacu along a fault. Although measured temperatures are as low as 27 °C, these waters show high conductivity and elevated concentration of solutes (evaporation ?), and belong to the same family of Cl-SO4-alkaline waters as the Cachiyacu group. An associated white travertine deposit hosted in andesite lava has been recently mined out and the conduits for water ascent seem to be almost sealed up.

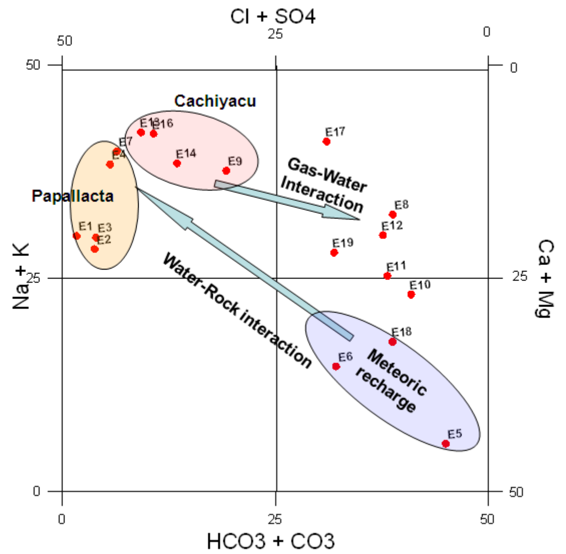

Fig. 6 Plot of Cachiyacu waters in the Langelier-Ludwig diagram.

Spring E-19, located 12 km SW of Cachiyacu and outside the caldera structure at 3400 m elevation, likely represents a lateral outflow from Cachiyacu along the NE-SW fault, which is the same structure as for the Tambo and Papallacta NE outflows. Outcrop temperature of water reaches 29.9 °C and waters show medium salinity (1780 micro S/cm conductivity); host lithology are pre-caldera rhyolitic ignimbrites. These waters belong to the family of bicarbonate-alkaline waters, according to Langelier – Ludwig diagram.

A group of low- to medium-temperature springs (E-11 in table 2; temp. 37.7 °C) is located at 22 km NW of Cachiyacu, in the IAV at 2500 m elevation. They belong to the bicarbonate-alkaline water family and it is likely that they represent a distal outflow (INE, 1985), along the same fault as E-9, from the Cachiyacu system.

A last group of water samples (E-5; -6; -18) are local surface waters at temperatures ranging from 7.5 to 10.5 °C, which represent the meteoric recharge to the deeper seated geothermal system. They belong to the family of bicarbonate earth-alkaline waters and their total dissolved salinity do not exceed 100 mg/litre.

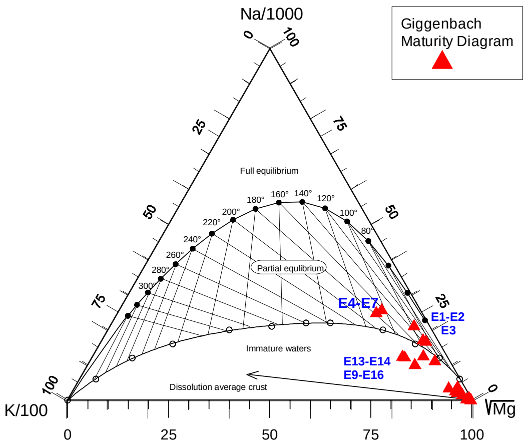

Fig. 7 Cachiyacu water samples on the Na-K-Mg Giggenbach diagram

The isotopic composition of dD and d18O in our samples (Fig. 8) highlights a meteoric origin, although only a few samples indicate a moderate oxygen shift, suggesting equilibration processes with host rocks. Samples plotted on the triangular K-Na-Mg diagram of Giggenbach (Fig. 7) indicate three different groups: a) immature waters located close to the Mg corner; b) waters at partial equilibrium (E1, E2, E3, E4 and E7, which correspond to the Papallacta and rio Tambo springs); and, c) waters plotting at the border between immature- and partial equilibrium waters (E13, E14, E16, E9, which correspond to the Cachiyacu area springs and the Tolontag spring).

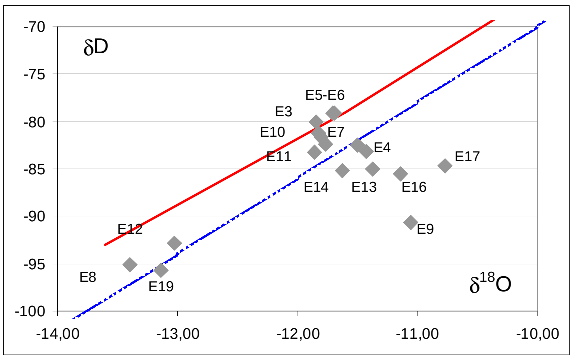

Fig. 8 Isotopic composition of Cachiyacu waters

Liquid-geothermometers, in particular Na-Li and Na-K (Ellis & Mahon, 1977), were used to estimate deep temperatures only on b) and c). The Papallacta – Rio Tambo group rendered estimated temperatures of 210 – 230 °C for the Na-Li geothermometer and 130 – 170 °C for the Na-K geothermometer. The Cachiyacu group of waters gave estimated deep temperatures of 270 and 210 °C, respectively.

Bubbling gas analysis from the same thermal waters indicate dominance of CO2. Preliminar gas-geothermometer estimates, in particular on the CH4-CO2 vs CO-CO2 diagram, indicate a good correspondence with estimated liquid geothermometers deep temperature for the two important spring-water groups, namely 250 °C for Papallacta – El Tambo and 300 °C for Cachiyacu.

5. DISCUSSION

Cachiyacu is a novel geothermal area in Ecuador, which haven't been considered in earlier geothermal assessments, mainly due to lack of data. With the newly acquired geological and geochemical data, we propose a preliminary geothermal model for Cachiyacu, which has to be tested in follow-up studies, mainly geophysics.

Mapping of the main volcanic features has led to a better understanding of the evolution of the Chacana Caldera, which hosts the Cachiyacu prospect. Persistent volcanic activity has been active in the area for at least 2 – 3 Ma. It constructed the voluminous Chacana edifice, leading to it's collapse and formation of the caldera depression, refilling this depression with pyroclastic deposits, landslide breccias and lava flows, causing resurgence, diatreme formation and emplacement of intracaldera dacitic and rhyolitic domes and dome-flows, accompanied by explosive activity of ignimbrite and plinian eruptions of regional extend, the latter dated in about 160 ka; the last volcanic activity occurred as recent as 240 years ago in the vicinity of Cachiyacu, following many long-reaching lava flows extruded in the last pleni-glacial period (40 – 20 ka). All these volcanic activity is evidence for the shallow-level emplacement of evolved, voluminous magma bodies below Chacana Caldera, which constitute the primary heat source. Cachiyacu in particular is surrounded by dacitic and rhyolitic domes and lava flows, which vary in age from about 0.45 - 0.16 Ma to recent, and represent interest as a heat source (Bloomquist, 1995); such large rhyolite intrusions are of primary interest as deeper targets for EGS systems (Duffield and Sass, 2003).

Reservoir rocks in Cachiyacu are assumed to consists of burried pre-caldera lava flows and breccias of the Mio-Pliocene Pisayambo Formation, as well as andesitic lavas of the early volcano cluster and wall rock facies, either collapsed or close to the structural caldera rim. The caldera collapse structure as well as regional NE-striking faults should assure reasonable permeability to the deep circulating fluids. The likely location of the up-flow could be close to Plaza de Armas rhyolitic dome-flow complex, some what 2 – 3 km S of Cachiyacu hotsprings. Extensive steam – heated hydrothermal alteration is widespread on Plaza de Armas N flank and indicates self-sealing of the upper parts of the system. Temperature of the deep fluids seems to be well in excess of 200 °C according to liquid- and gas-geothermometers and the system appears to be water-dominated; its location is likely to be rather deep than shallow.

The seal cap to the system is the before mentioned self-sealing at the southern part as well as the tuff and diatreme breccia dominated caldera infill towards N. The diatreme breccia is highly propylitized and clay rich, and its funnel-shape geometry towards the central part of the caldera, has rendered this central part as impermeable. That's the reason that there are not hotsprings in the whole central part, except along the NE-striking fault that connects Cachiyacu with Tambo and Papallacta, which crosses the diatreme breccia and several rhyolite domes (see fig. 3).

The recharge to the system consists of meteoric water, which is plenty available in the area. Recharge zones are crests along the topographic rim of the caldera as well as volcanic vents and domes at the rim or on the caldera floor.

The shortcoming at this stage of knowledge is the lack of absolute age determinations of rocks and waters and should be accomplished in future work, with the aim to put up a more completed geological-geochemical model to be checked with geophysics, i.e. magneto-telluric surveys. Since Cachiyacu is located in an ecological sensitive area, the Antisana Ecological Reserve, it is mandatory to comply with all the regulations imposed by law, if the permit is granted to develop Cachiyacu towards tapping geothermal energy for power generation.

6. CONCLUSIONS AND RECOMMENDATIONS

- Cachiyacu is a promising geothermal prospect hosted in the southern edge of the Quaternary silicic Chacana caldera, located at the crest of Eastern Cordillera, about 65 km ESE of the Capital city of Quito.

- Persistent and voluminous andesitic and dacitic to rhyolitic volcanic activity is the indirect evidence of the presence of big-size magma bodies, emplaced at shallow crustal levels below Chacana caldera in general and Cachiyacu area in particular.

- A geothermal reservoir is assumed to exist in the Cachiyacu area, hosted in lavas and breccia of the 1 - 2 km thick pre-caldera volcanic sequence. Permeability is inherent to fractured lavas and enhaced by active regional faults, with cross the caldera structure along a NE-strike.

- Estimated liquid and gas geothermometer temperatures of the deep fluids in Cachiyacu are estimated in the range of 210 to 300 °C, which is well in excess of 200 °C.

- Hot spring fluids at Cachiyacu are partially equilibrated Cl-SO4-alkaline waters, with a salinity of up to 5000 mg/litre.

- Follow-up studies of the Cachiyacu prospect should take into account Ar/Ar age determinations for the volcanic rocks pertinent to the area, as well as a comprehensive geophysical survey using with preference the deep-reaching magneto-telluric method, to locate the geothermal reservoir as well as shallow heat sources (cooling magma bodies).

- Cachiyacu's location in an ecological-sensitive and protected area needs the political decision of the government to proceed with development, with the challenge to be environmentally benign and economically feasible.

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