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Apacheta, a New Geothermal Prospect in Northern Chile

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ABSTRACT
The discovery of two high-temperature fumaroles, with gas geochemistry compatible with an economic geothermal system, established Apacheta as one of the most attractive geothermal exploration prospects in northern Chile. These remote fumaroles at 5,150 m elevation were first sampled in 1999 by ENAP and its partners, following up on the reports of a CODELCO water exploration well that flowed small amounts of dry steam at 4,540 m elevation in the valley 4.5 km east of the fumaroles. The prospect is associated with a Plio-Pleistocene volcanic complex located within a NW-trending graben along the axis of the high Andes. The regional water table is ~4,200 masl. There are no hot springs, just the 88°C steam well and the 109° and 118°C fumaroles with gas compositions that indicate reservoir temperatures of ≥250°C, using a variety of gas geothermometers. An MT-TDEM survey was completed in 2001-2002 by Geotérmica del Norte (SDN), an ENAP-CODELCO partnership, to explore the Apacheta geothermal concession. The survey results indicated that base of the low resistivity clay cap has a structural apex just west of the fumaroles, a pattern typically associated with shallow permeability within a high temperature geothermal resource. SGN plans to drill at least one exploration well in 2002-03 to characterize a possible economic resource at Apacheta.

INTRODUCTION
The Apacheta prospect is located in northern Chile, 120 km east of the city of Calama and 60 km NNW of El Tatio (Figure 1). The prospect is centered within a NW-SE trending graben hosting a series of eroded volcanoes and young lava domes (Figure 2). Surface thermal features are associated with Cerro Aguilucho and Cerro Apacheta, two overlapping Plio-Pleistocene andesitic to dacitic composite volcanoes. The most recent volcanic activity consists of a series of dacite domes that erupted along the NE graben fault. Cerro Aguilucho exhibits fossil hydrothermal alteration related to a sulfur deposit on its west flank.

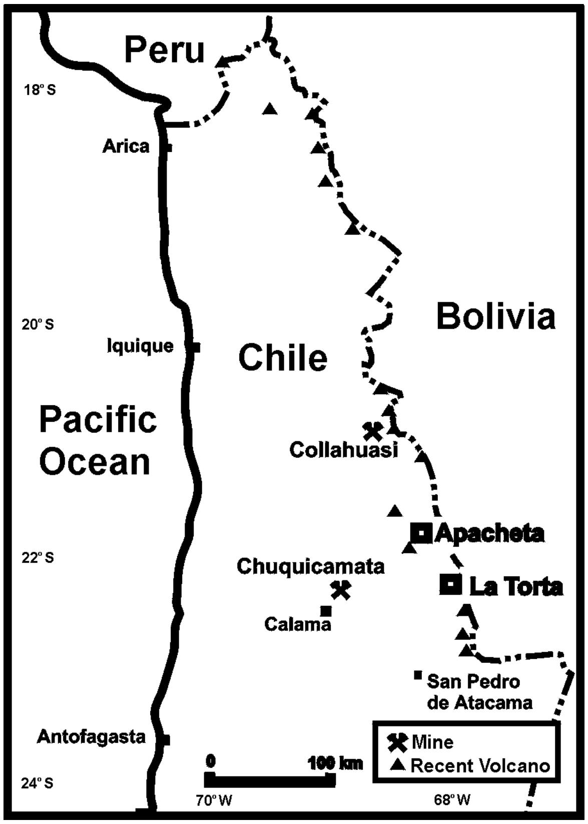

Figure 1. Location map of the Apacheta prospect

The Apacheta geothermal prospect was serendipitously discovered by CODELCO, the Chilean national mining company, which encountered steam while drilling a shallow water well (PAE-1; Figure 2) in Pampa Apacheta, a flat-floored valley within the graben. In 1999, a team of geologists from ENAP and Unocal Corporation visited and sampled both the well and two vigorous superheated fumaroles located near the summit of Cerro Apacheta, 4.5 km west of the well. Subsequent visits to the area have focused on obtaining additional geological, geochemical, and geophysical data to help characterize this resource and identify drilling targets.

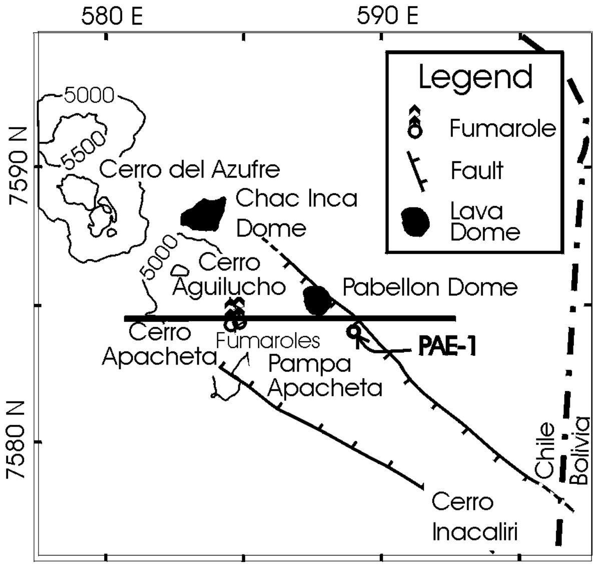

Figure 2. Map of the Apacheta prospect. Dashed line indicates location of cross section depicted in Figure 8. UTM coordinates given in kilometers.

GEOLOGY

Stratigraphy

The geology of the Apacheta area was initially mapped by Ramírez and Huete (1981). They identified two main volcanic units in the area: a sequence of moderately eroded andesitic to dacitic stratovolcanoes and a series of younger porphyritic dacite domes and flows. Cerro Aguilucho and Cerro Apacheta consist of Pliocene to Pleistocene andesitic to dacitic lavas, breccias, and tuffs that are capped by a fairly thick (~100 m) welded ash-flow tuff that forms a cliff along the upper slopes of these two massifs. A K-Ar date of 1.5 ± 0.1 Ma was reported for a dacite sample collected from the Cerro Aguilucho area (Francis and Rundle, 1976; Boric et al., 1990). The most recent volcanic activity in the region consists of a series of Pleistocene dacite lava domes (Pabellón, Chac-Inca, and Chanca) extruded along the NE graben-bounding fault (Figure 2); a biotite separate from the Cerro Pabellón dome yielded an age of 0.05 ± 0.01 Ma.

The stratigraphy of the 180 m deep well PAE-1 in Pampa Apacheta consists of an uppermost 60 m of sandstone basin fill, followed by 120 m of a volcanic sequence including lithic tuff, and dacite and andesite lavas. The probable basement rocks in the region are Eocene andesites and Oligocene to Miocene conglomerates, breccias, sandstones, limestones, and gypsum (Ramírez and Huete, 1981). Evaporitic salar deposits may also be present.

Structures

The 1:250,000 regional geologic map (Ramírez and Huete, 1981) notes the presence of a NW-trending graben extending from Cerro Inacaliri near the Bolivian border to Pampa Apacheta (Figure 2). This 3-5 km wide feature, called the Pabelloncito graben (Francis and Rundle, 1976), is clearly seen in aerial photographs and satellite images of the area, and is one of a number of extensional features in this region. A chain of volcanic centers extends 40 km to the NW from Cerro Aguilucho and Cerro del Azufre along the axis of the graben, beyond where the graben faults are clearly defined. The young dacite domes and flows are located along the projected NE margin of the graben.

Alteration

The only surficial alteration related to the active geothermal system is clay and native sulfur mineralization encountered around the fumaroles on the upper northern flank of Cerro Apacheta. There is abundant ancient argillic alteration on Cerro del Azufre and on the western flank of Cerro Aguilucho (Mina Aguilucho), an area that had previously been mined for sulfur; 1-2 cm thick silica veins were also encountered in this area. In addition, silica veins are found at the surface on the graben fault scarp SE of well PAE-1, as well as in andesites exposed along the NE flank of Cerro Apacheta. Minor amounts of clay and calcite alteration were observed in cuttings from PAE-1.

THERMAL FEATURES

Two fumaroles with high steam-discharge rates are located one kilometer north of the summit of Cerro Apacheta at 5,150 m elevation, with measured temperatures of 109° and 118°C. The boiling point at this elevation is 84°C, thus the fumaroles are superheated by 25° and 34°C, respectively.

The 180 m deep PAE-1 well is located in Pampa Apacheta adjacent to the 50 Ka Cerro Pabellón dacite dome at 4,540 masl. The well produces a wispy flow of steam with a measured temperature of 88°C, around the boiling point at this elevation. The nearest warm (23°C) springs are at Ojos de San Pedro, located more than 17 km SW of the prospect. Water wells drilled in that area are warm, and some have been reported to bubble gas.

GEOCHEMISTRY

Gas analyses from the Apacheta prospect are presented in Table 1. The two superheated fumaroles from Cerro Apacheta have very similar gas chemistries, with noncondensable gas (NCG) contents of 2.5 wt. %, relatively high CO_2 contents (>98 mole % of the NCG), and other characteristics (such as elevated N_2/Ar ratios) typical of many geothermal fumarole gases. The sulfur content of the gases (0.4-0.6 mole % H_2S) is much lower than that found in volcanic summit fumaroles. The Apacheta fumarole gases do depart from most geothermal gases in that they have very low methane contents.

Sample Name	Type	Date	Wt. % gas	CO_2	H_2S	NH_3	CH_4	N_2	Ar	H_2	CO	$^3He/^4He$ (Rc/Ra)	%air contam
PA2	Well	12/9/98	10.514	97.7	<0.0106	0.0283	7.35E-04	2.22	0.0124	<0.281	6.11E-04	-	13.46
PA4	Well	3/22/99	9.5307	99.8	<0.00317	0.0137	7.16E-05	0.223	<0.00541	<0.0634	3.04E-05	1.657	4.121
F1	Fum.	3/23/99	2.5094	98.9	0.405	0.0679	5.63E-05	0.518	0.000919	0.13	1.12E-05	1.852	0.153
F2	Fum.	3/23/99	2.4954	98.5	0.612	0.107	5.88E-05	0.587	0.00125	0.163	6.55E-06	-	0.039

Values given as mole fraction of total noncondensable gas. (<) indicates below detection limit.

Table 1. Apacheta Gas Analyses

The gas and steam condensate samples from PAE-1 are considered less representative of a geothermal reservoir fluid than the fumaroles because they show high air contamination, high gas content (~10 %) and very light isotope values relative to local meteoric waters. These characteristics suggest mixing with air in the vadose zone and significant steam condensation.

Figure 3 shows a N_2-CO_2-Ar ternary diagram of the well and fumarole gas chemistry. The N_2/Ar ratios for the fumaroles are quite high (564 and 470) and thus show little atmospheric gas component, while the PAE-1 well samples have much lower values (>41 and 179), suggesting that they have a significant air component. The plotted fumarole gas samples have compositions similar to those encountered in geothermal systems located in andesitic arc environments (Giggenbach, 1992).

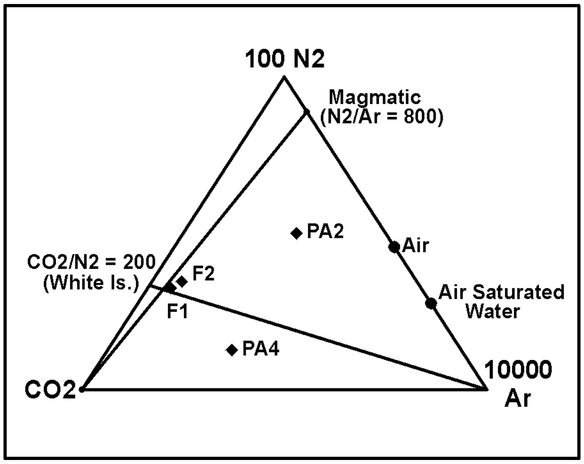

Figure 3. N_2-CO_2-Ar ternary diagram showing Apacheta gas data. Samples F1 and F2 are samples from the two Cerro Apacheta fumaroles; Samples PA2 and PA4 are from the CODELCO water well PAE-1.

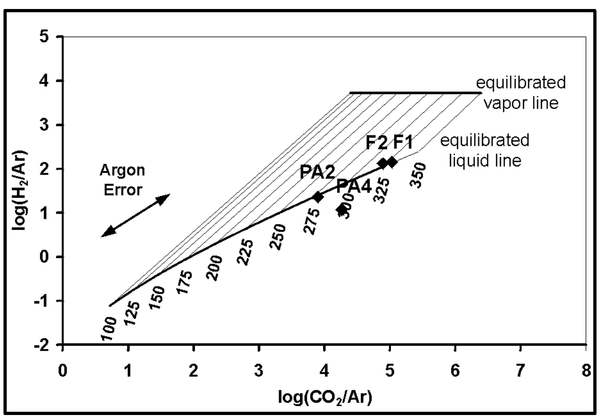

Figure 4. CO_2/Ar–H_2/Ar geothermometer grid (R_H = –2.8) with gas data from well PAE-1 (PA2 and PA4) and fumaroles (F1 and F2). All samples plot near the liquid equilibration line at 275-300°C and 325°C, respectively.

Gas Geothermometry

A variety of gas geothermometers were employed to estimate the reservoir temperature. The CO_2/Ar–H_2/Ar (CAR-HAR) gas geothermometer grid (Figure 4) with log (H_2 fugacity/H_2O fugacity) = –2.8 (the redox state, expressed as R_H; Giggenbach, 1987) shows the Apacheta fumaroles are in equilibrium with a liquid reservoir at a temperature of 325ºC. This high temperature may reflect a significant magmatic component to the geothermal system.

Other gas geothermometers suggest that the Apacheta system has more typical reservoir temperatures of around 250°C. The R_H dependence of the CO/CO_2–CH_4/CO_2 geothermometer grid (Figure 5) makes this diagram useful for assessing the redox state of the Apacheta system. From this diagram, an R_H of –4 is obtained, suggesting a slightly oxidizing reservoir environment. As this grid pairs a fast geothermometer (CO/CO_2) with a slow one (CH_4/CO_2), the predicted temperatures may be lower than actual since the temperature is mostly determined by CO/CO_2 and R_H by CH_4/CO_2 (Powell, 2000). Assuming the gases equilibrate in a liquid-dominated reservoir, the plotted gas compositions indicate a temperature between 200° and 250ºC.

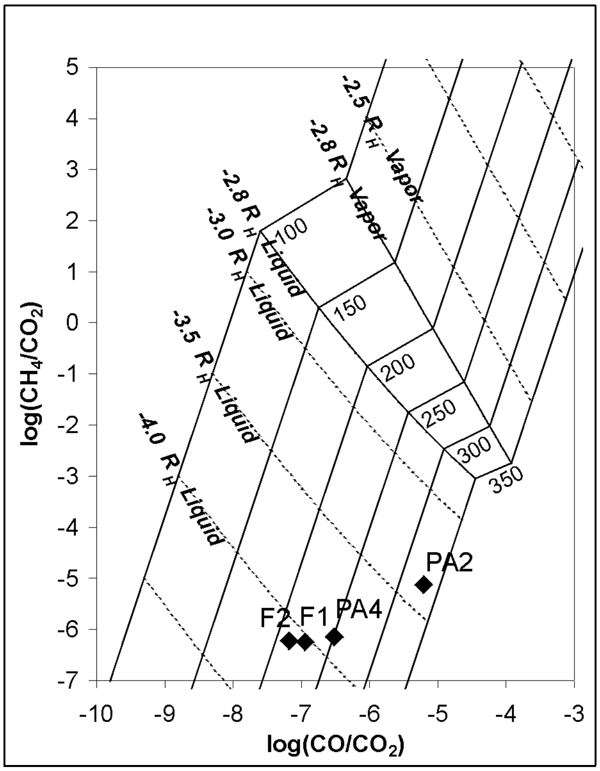

Figure 5. CO/CO_2 – CH_4/CO_2 geothermometer grid with Apacheta gas samples. Because of their low methane contents, the fumarole samples plot on the liquid equilibration line at approximately R_H –4.0.

Using the revised estimate of R_H of –4.0 suggested by Figure 5, a CAR-HAR grid with the fumarole analyses show them to have equilibrated in a two-phase region close to the vapor equilibrium line at 250°C (Figure 6). Similar temperature estimates (250–270°C) were also obtained using the Fisher-Tropsch–H_2S/H_2 (FT-HSH) geothermometer grid.

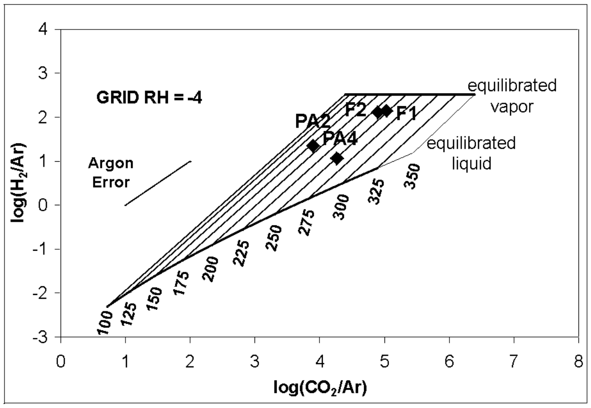

Figure 6. CAR-HAR plot at R_H –4.0. This plot shows the fumarole samples to be equilibrated at 250°C at a high vapor content.

Isotope Systematics

Figure 7 is a cross-plot of $\delta^{18}O$ and δD showing the fumarole and well steam condensate isotope compositions. The fumarole condensates plot to the right of the meteoric water line (MWL). This shift in compositions off of the MWL could result from a number of factors, including (1) a shift towards higher $\delta^{18}O$ values resulting from water-rock interaction and (2) mixing with a magmatic fluid (around a 30% magmatic component). The well condensate sample has a very depleted stable isotope composition (δD = –208‰, $\delta^{18}O$ = –29.7‰), suggestive of multiple boiling and condensation events.

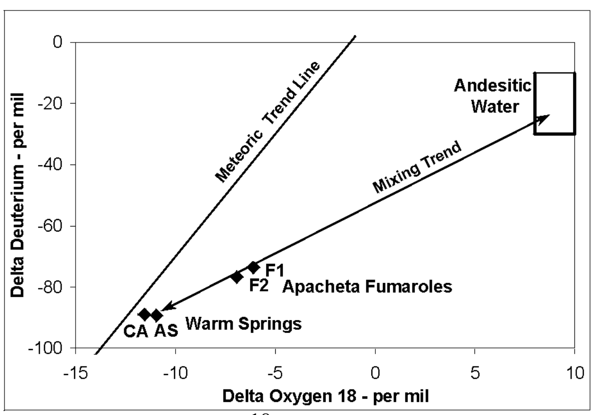

Figure 7. Plot of $\delta^{18}O$ versus δD for the Apacheta fumarole condensate (F1 and F2) and samples from warm springs at Cabana (CA) and Ascotan (AS). These springs are located 25 km SE and 20 km NW of Apacheta, respectively.

Helium isotope ratios (relative to air) for the well and highest temperature fumarole are 1.66 and 1.85, respectively. Although low for arc regions, they are similar to the values obtained at two other geothermal prospects in Northern Chile, Puchuldiza and El Tatio (1.9 and 2.7–3.0 Rc/Ra respectively; ENAP internal data). Low $^3He/^4He$ values observed in the high Cordillera of northern Chile have been attributed by Hilton et al. (1993) to loss of the primary magmatic component via degassing through the anomalously thick crust (>70km), combined with contamination by radiogenic helium through crustal assimilation.

GEOPHYSICS

As illustrated by the resistivity contours in Figure 8, the MT and TDEM surveys conducted in January 2002 resolved a <10 ohm-m low resistivity layer interpreted as a smectite clay cap overlying rocks at temperatures over 200°C as expected over geothermal reservoirs (Cumming et al. 2000). The lowest (<2 ohm-m) resistivities were detected in very shallow smectite clay zones associated with perched condensate aquifers. The upward doming of the base of the clay cap near the fumaroles and its thinning to less than 700 m just east of the Aguilucho ridgeline is characteristic of shallow high permeability zones in many geothermal fields (Anderson et al., 2000). Below the flat graben floor to the east of the fumaroles, the low resistivity layer thickness increases to >1500 m deep, probably corresponding to porous, clay-rich volcanic sediments, possibly including salar deposits. The further increase in thickness of the clay cap east of the shallow well PAE-1 suggests that either the sediments are thickening or that this marks the eastern boundary of a zone extending more than 3 km east of Cerro Aguilucho, where high heat flow results in temperatures over 200°C at drillable depths. Although this would imply a potential resource larger than 25 km^2, the initial exploration focus will be on the 7 km^2 structural high in the base of the clay cap centered between Cerro Aguilucho and the fumaroles.

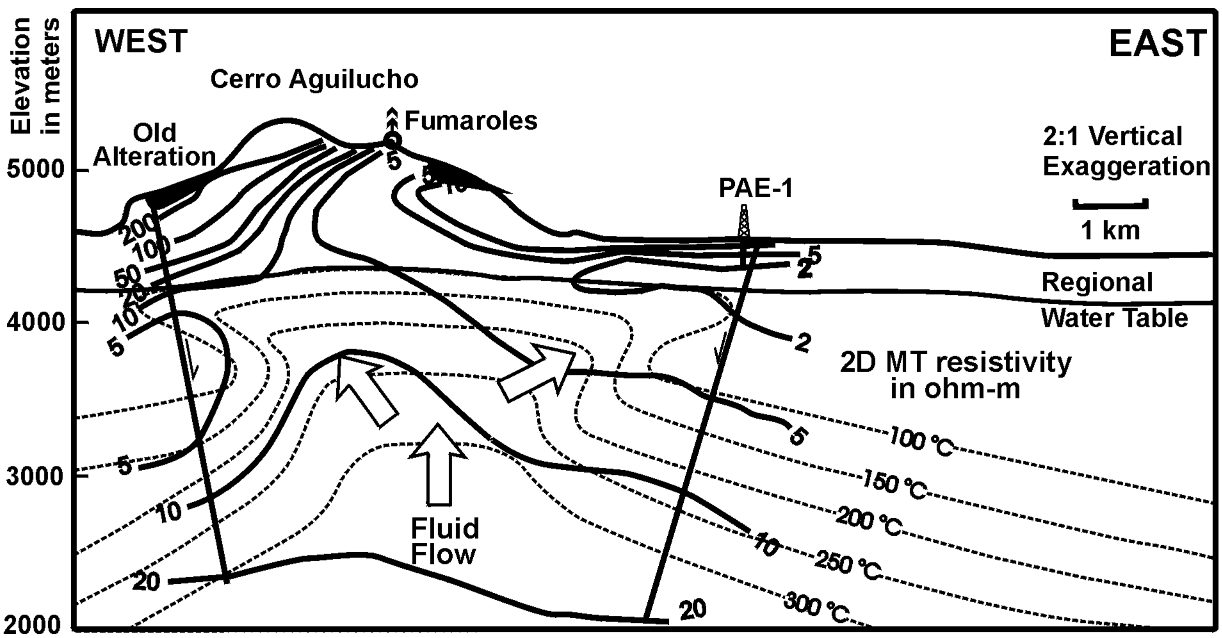

Figure 8. Conceptual cross section of temperature and MT resistivity. Cross section location is given in Figure 2.

CONCLUSIONS

The gas chemistry of the two superheated fumaroles in the Apacheta geothermal prospect suggests that they are related to a high-temperature geothermal system. The reservoir temperature given by the CAR-HAR geothermometer grid at $R_H = -4$ is 250°C, matching well with the temperatures given by FT-HSH and CO/CO_2–CH_4/CO_2 grid. All these grids show evidence of a high vapor content in the reservoir, possibly reflecting a steam cap at relatively low R_H. Higher reservoir temperatures (325°C) are estimated by using the CAR-HAR gas grid with an R_H of –2.8. The reservoir fluids may have a significant magmatic component, as suggested by their low methane contents, elevated N_2/Ar values, and stable isotope compositions. However, the low noncondensable gas and H_2S contents suggest that the Apacheta fumaroles are not volcanic summit fumaroles, but instead are derived from a geothermal reservoir fluid. The low H_2S content argues against the likelihood of acid-sulfate rich corrosive reservoir fluids. Indications of low R_H are similar to that found at the El Tatio Field, 60 km to the SSE (ENAP, internal data) and may be due to relatively oxidized reservoir and/or basement rocks.

The geophysical data indicate that the fumaroles are associated with a structural high in the base of the low resistivity smectite clay cap that is commonly associated with shallow high permeability zones in geothermal reservoirs. SGN plans to drill at least one deep exploration well targeted on this zone to find and delineate a possible high-temperature resource in 2002-03.

ACKNOWLEDGMENTS

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