Cover Page - Example

The Cordón Caulle Geothermal Area, Chile: Comparison with Other Geothermal Systems Based on Gas Geothermometry

F. Sepúlveda[1]
Department of Geology, University of Auckland, Auckland, NZ

A. Lahsen[2]
Department of Geology, University of Chile, Santiago, Chile

T. Powell[3]
Mighty River Power, Hamilton, NZ

Total No of pages (Excluding Cover Page) = 6 (maximum)

[1]Department of Geology, University of Auckland, Private Bag 92019, Auckland, NZ
Ph (64-9) 373-7599 ext 88685; Fax (64-9) 373-7435

[2]University of Chile, Department of Geology, PO Box 13518 (21), Santiago, Chile

[3]Mighty River Power, PO Box 445, Hamilton, NZ

Proceedings 28th NZ Geothermal Workshop 2006

THE CORDÓN CAULLE GEOTHERMAL AREA, CHILE: COMPARISON WITH OTHER GEOTHERMAL SYSTEMS BASED ON GAS GEOTHERMOMETRY

F. SEPÚLVEDA[1], A. LAHSEN[2], T. POWELL[3]

[1]Department of Geology, University of Auckland, Private Bag 92019, Auckland, NZ
[2]University of Chile, Department of Geology, PO Box 13518 (21), Santiago, Chile
[3]Mighty River Power, PO Box 445, Hamilton, NZ

SUMMARY –The Cordón Caulle geothermal area, Southern Chile, hosts an active geothermal system expressed at surface in multiple fumaroles and boiling hot springs. The latter correspond essentially to dilute (TDS < 600 ppm), low chloride (< 50 ppm)-bicarbonate thermal waters, where solute geothermometers yield subsurface temperatures in the range of 150°-170°C. Using $CO_2/Ar-H_2/Ar$, $CO/CO_2-CH_4/CO_2$ and $CO/CO_2-H_2/H_2O$ gas ratio plots, subsurface temperatures greater than 300°C are estimated for fumaroles and on the order of 160°C for hot spring gases. Fumaroles also match the expected compositions of vapours separated at low temperature (< 200ºC), supporting a model of a deep boiling liquid-dominated geothermal reservoir overlain by shallow steam-heated layers. In order to test these findings, gas chemistry data from selected liquid-dominated and vapour-dominated systems are also incorporated for comparison.

1. INTRODUCTION

Cordón Caulle (40.5ºS) is one of the largest active geothermal systems of the Southern Andes of Chile. Based on chemical and isotopic data from hot springs and fumarole condensates, Sepúlveda et al. (2004) hypothesized the existence of a steam-heated aquifer overlying a deep vapour-dominated system at Cordón Caulle. Estimated equilibration temperatures of the steam-heated aquifer range from 150ºC to 170ºC. No exploratory wells have been drilled at Cordón Caulle to confirm this model.

Gas chemistry data from fumaroles and hot springs of Cordón Caulle are used here to have a better understanding of the thermal and physical structure of the geothermal system. Comparison with gas data from selected liquid-dominated and vapour-dominated systems is performed by use of gas ratio plots (Giggenbach and Goguel, 1989; Chiodini and Marini, 1998).

2. GEOLOGICAL BACKGROUND

The Cordón Caulle geothermal area consists of a 15 km long, 5 km wide, flat-topped volcano-tectonic depression, bounded to the northwest by the 8.5 km wide Caldera of Cordillera Nevada (active between ca. 0.4 Ma–0.12 Ma; Sepúlveda et al., 2005a; Lara et al., 2006), and to the southeast by the 2240 m high Puyehue Volcano (active between 0.25 Ma–2.7 Ka; Harper et al. 2004).

Silicic volcanism started at ca. 40 Ka in Puyehue Volcano (Harper et al., 2004) and at ca. 70 ka in Cordón Caulle. The latest expression of silicic volcanism of Cordón Caulle corresponded to fissure eruptions of rhyodacite composition (1921-1922 and 1960; Lara et al., 2004). According to gravimetric modeling, about 500 m of felsic lavas and tephra are nested within the upper part of the depression of Cordón Caulle (Sepúlveda et al., 2005). Underlying this package are mafic-dominated lavas and crystalline rocks. The latter are inferred from geological outcrops as well as from the lithic content of Quaternary strombolian deposits in the surrounding areas (Sepúlveda et al., 2004).

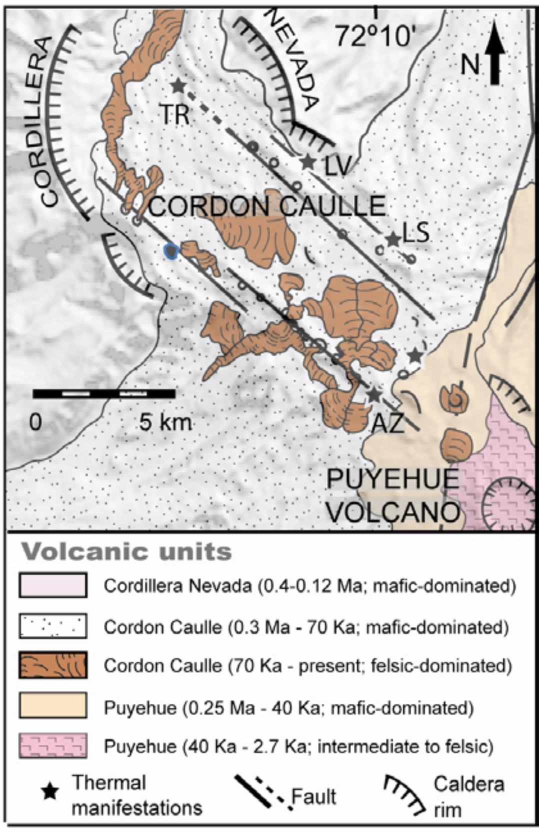

Figure 1 – Simplified geological map of the Cordon Caulle geothermal area. TR = Trahuilco; AZ = El Azufral; LS = Las Sopas; LV = Los Venados.

4. THERMAL MANIFESTATIONS

Fumaroles of Cordón Caulle occur at the top of the system (> 1400 m) spatially associated with the edges of the volcano-tectonic depression in three main discharge zones: Las Sopas (LS), Los Venados (LV) and El Azufral (AZ), the latter being emplaced in the pumice cone of the same name (1960 eruption; Fig. 1). In all these fumarolic areas steam is discharged at near-boiling temperature (93ºC) forming acid-sulfate alteration and solfataras.

Inside the Caldera of Cordillera Nevada, specifically in the locality of Trahuilco (TR; 1000 m; Fig. 1), ca. 100 l/s of boiling springs are discharged in association with silica sinter deposits (made up of Opal-A; Sepúlveda et al. 2004). In terms of these surface deposits, TR springs resemble high-enthalpy liquid-dominated system-related hot springs, but differ from these in low TDS (< 600 mg/l), low chloride (< 50 ppm) and high bicarbonate (Sepúlveda et al. 2004).

3. METHODS

Gas samples were collected into "Giggenbach-type" glass bottles (Giggenbach and Goguel, 1989) containing 100 ml 4 to 6 N NaOH and 15 ml 1 N $CdCl_2$ for the absorption of CO_2-NH_3 and H_2S, respectively. Gas samples for CO determination were taken without NaOH to avoid partial transformation of CO into formate (Giggenbach and Matsuo, 1991). Gas concentrations were determined in Thermochem Laboratories, USA, using wet analytical techniques for CO_2, H_2S and NH_3, and gas chromatography for all insoluble gases.

4. GAS GEOTHERMOMETRY

We propose a revised version of the CO_2/Ar-H_2/Ar grid (Giggenbach and Goguel, 1989) where the main modifications are:

(1) Gas samples are assumed to be boiling derivatives of a reservoir liquid, present in both liquid and vapour-dominated systems (e.g. Grant, 1979). An equilibrium vapour is calculated accordingly as $\mathrm{Log}r_{Ar,V} = \mathrm{Log}B_{Ar} + \mathrm{Log}r_{Ar,L}$. This differs from the relationship $r_{Ar,V} = r_{Ar,L}$ adopted by Giggenbach and Goguel (1989), which appears to be inconsistent with Henry's Law.

(2) $CO_2(g)$ is assumed to follow the empirically-derived formulation of Arnórsson (1985) instead of that of Giggenbach (1984).

(3) rCO_2 is corrected for steam compressibility following Powell (2000).

In the modified CO_2/Ar-H_2/Ar grid presented at conventional redox conditions (i.e. R_H = -2.8; Giggenbach, 1987), subsurface temperatures > 300ºC are obtained for fumarolic gases (higher temperatures in LS relative to LV) and >150ºC for hot spring gases of Cordón Caulle (Fig. 2). Unlike in the conventional CO_2/Ar-H_2/Ar grid, in the modified version CO_2/Ar temperatures of sample TR are in good agreement with temperatures derived from aqueous geothermometers (Sepúlveda et al., 2004).

The modified CO_2/Ar-H_2/Ar grid also works well with other geothermal systems. Samples from Kamojang (vapour-dominated; Grant, 1979; Giggenbach et al., 2001), Philippines (Cagua and Alto Peak; T_R > 300ºC; Giggenbach, 1993) and to a lesser extent Wairakei (T_R ~ 260ºC; Mannington et al., 2004; Giggenbach and Goguel, 1989; Giggenbach, 1995) show good agreement with documented reservoir temperatures (T_R) at near conventional redox conditions. In Broadlands, where the original CO_2/Ar-H_2/Ar grid successfully predicts T_R ~ 300ºC (Hedenquist, 1990), the modified grid fails to predict reservoir temperatures with the CO_2/Ar system, but this is thought to reflect the CO_2-rich condition of Broadlands (Fig. 2).

Other liquid-dominated geothermal systems like Miravalles (T_R = 230-255ºC; Gherardi et al., 2002), Valles Caldera (T_R up to 295ºC; Goff and Janik, 2002) and to some extent Wairakei and Philippines (Mt Apo; T_R = 260ºC), show good match with reservoir temperatures at redox conditions slightly more oxidizing than conventional.

Some liquid-dominated geothermal systems, including El Tatio-Chile (T_R = 263ºC; e.g. Lahsen, 1988) and Mambucal-Philippines (T_R = 200ºC; Giggenbach, 1993), require particularly oxidizing conditions (near R_H = -4.0) to match the expected equilibration conditions. In El Tatio, high CO_2/Ar ratios have been attributed to secondary processes (Tassi et al., 2005). In The Geysers (Truesdell et al., 1991; Lowestern et al., 1999), abnormally reducing conditions (R_H = -1.7; Fig. 10) are required to reproduce measured temperatures and vapour-dominated equilibrium conditions (Fig. 2).

The CO/CO_2-CH_4/CO_2 (Giggenbach and Goguel, 1989; Fig. 3) and CO/CO_2-H_2/H_2O grids (Chiodini and Marini, 1998; Fig. 4) are used for independent assessment of reservoir temperatures, redox conditions and vapor-dominated conditions, assuming that vapours from a vapour-dominated field are most likely to form through single-step boiling at high temperature, that is, between T_R and T_R-2, and vapours from liquid-dominated systems are most likely to form through single-step boiling at low temperature, that is, between T_R-2 and 100ºC.

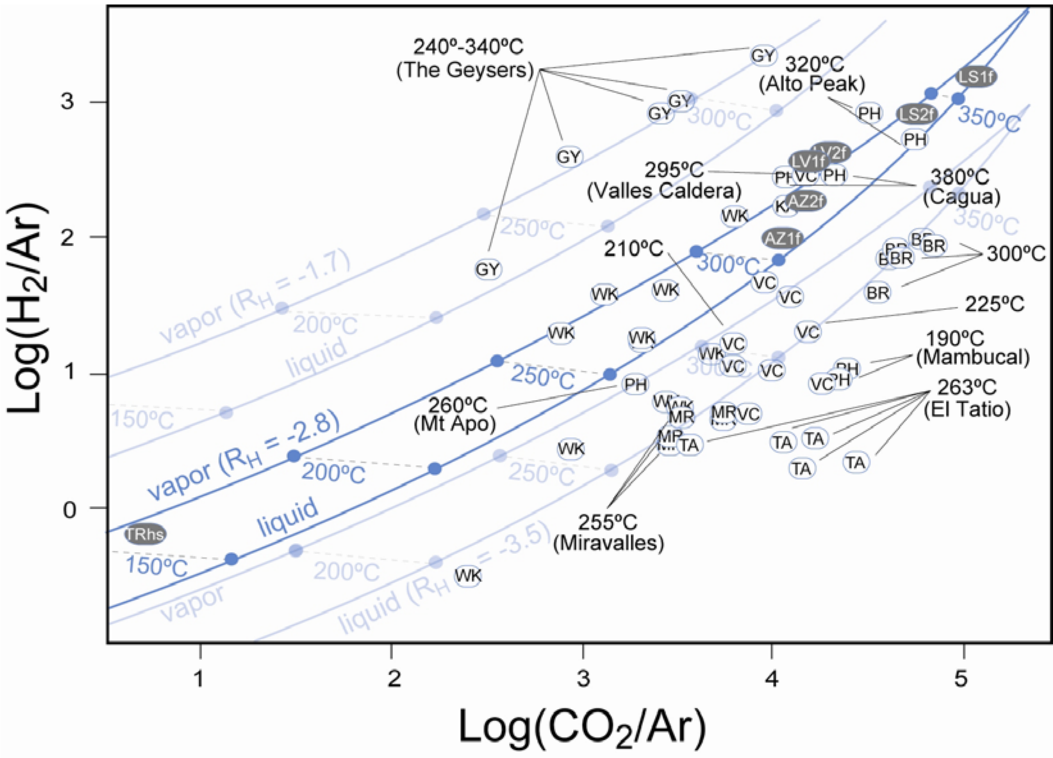

Figure 2 – The CO_2/Ar-H_2/Ar grid (after Giggenbach and Gouel, 1989) showing gas samples of Cordón Caulle (f = "fumarole", hs = "hot spring") and elsewhere at different redox states. Measured temperatures are shown for reference. VC = Valles Caldera, USA; GY = The Geysers, USA; PH = Philippines; BR = Broadlands, NZ; WK = Wairakei, NZ; TA = El Tatio, Chile; KA = Kamojang, Indonesia.

In the CO/CO_2-CH_4/CO_2 grid (Fig. 3), Larderello samples (T_R up to 270ºC; Chiodini and Marini, 1998) best match the vapor-dominated field at R_H = -2.9 (Fig. 3). Fumarolic gases of Cordón Caulle plot within the liquid-dominated field at R_H = -3.1, yielding subsurface temperatures > 300°C. Kamojang (T_R = 240ºC) shows good match with the vapor-dominated region at R_H = -3.3 (Fig. 3). At these redox conditions, liquid-dominated systems like Ahuachapán-El Salvador (T_R = 250ºC; Aunzo et al., 1991) and Cagua-Phillipines show good agreement with measured temperatures (Fig. 3). In El Tatio, only CH_4/CO_2 temperatures are in good agreement with reservoir temperatures (263ºC) at R_H = -3.3.

Presented at conventional R_H = -2.8 for TR waters, the CO/CO_2-CH_4/CO_2 grid shows CH_4/CO_2 temperatures (about 150°-160°C; Fig. 3) in good agreement with H_2/Ar temperatures, solute geothermometers and the K^2/Ca-based CO_2-barometer (Sepúlveda et al. 2004; Sepúlveda et al., 2006). However, at this redox state, the CO/CO_2 geothermometer yields temperatures > 300ºC for TR waters raising an inconsistency, not well understood yet, with respect to all the geochemical indicators listed above.

In the CO/CO_2-H_2/H_2O grid (Fig. 4), samples from Larderello fall within the vapor-dominated field at empirical redox conditions (D'Amore and Panichi, 1980). Kamojang departs only slightly from this vapor-dominated field. Other liquid-dominated fields (e.g. Ahuachapán and most Phillipine systems) plot within the liquid-dominated field at these redox conditions (Fig. 4). Fumaroles of Cordón Caulle plot within the liquid-dominated field for a range of redox conditions, including the empirical buffer shown in Figure 4, yielding subsurface temperatures greater than 300ºC. This fact does not corroborate the hypothesis of Sepúlveda et al. (2004) of a deep vapor-dominated system.

5. CONCLUSIONS

By comparison of gas data of Cordón Caulle and elsewhere, it follows that a high variability of redox conditions is present among geothermal systems and eventually within a particular geothermal system. The advocated variability is well represented by Cordón Caulle, where fumarolic gases appear to have equilibrated in a boiling liquid-dominated reservoir at temperatures greater than 300ºC under redox conditions slightly more oxidizing than conventional redox conditions. On the contrary, hot spring gases of Cordón Caulle appear to have equilibrated in a cooler (about 160ºC) and more reducing environment (near the conventional redox state), most likely related to a secondary steam-heated aquifer.

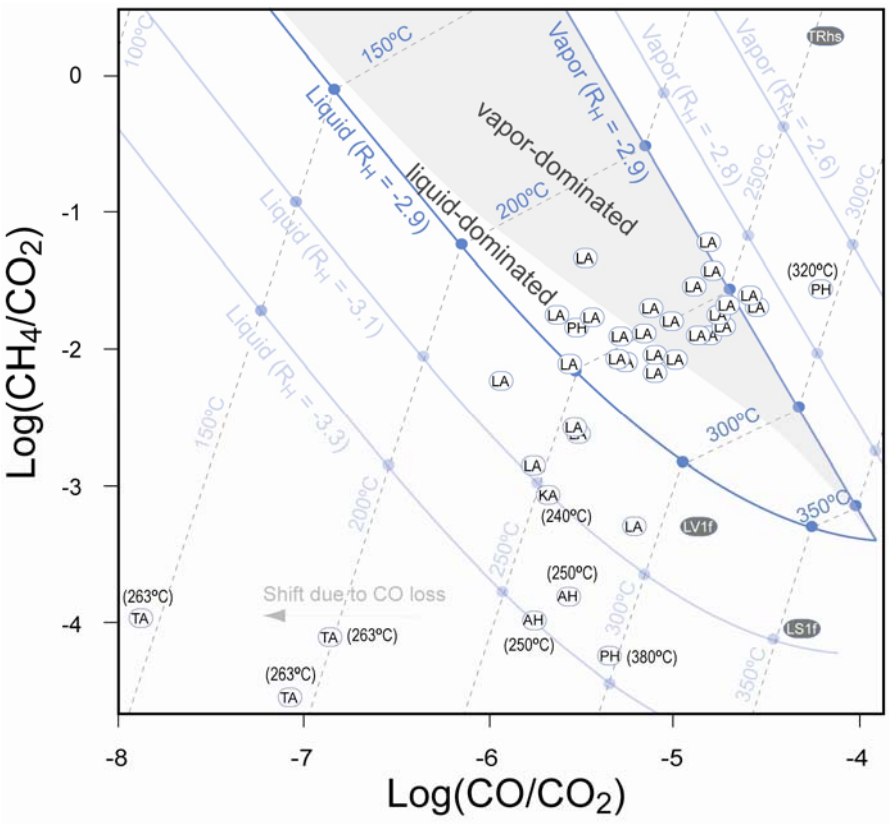

Figure 3 – The CO/CO_2-CH_4/CO_2 grid (Giggenbach and Gouel, 1989) showing gas samples of Cordón Caulle and elsewhere at different redox states. Measured temperatures (in brackets) and a hypothetical "vapour-dominated field" shown for reference. LA = Larderello, Italy; PH = Philippines; AH = Ahuachapán; TA = El Tatio, Chile; KA = Kamojang, Indonesia.

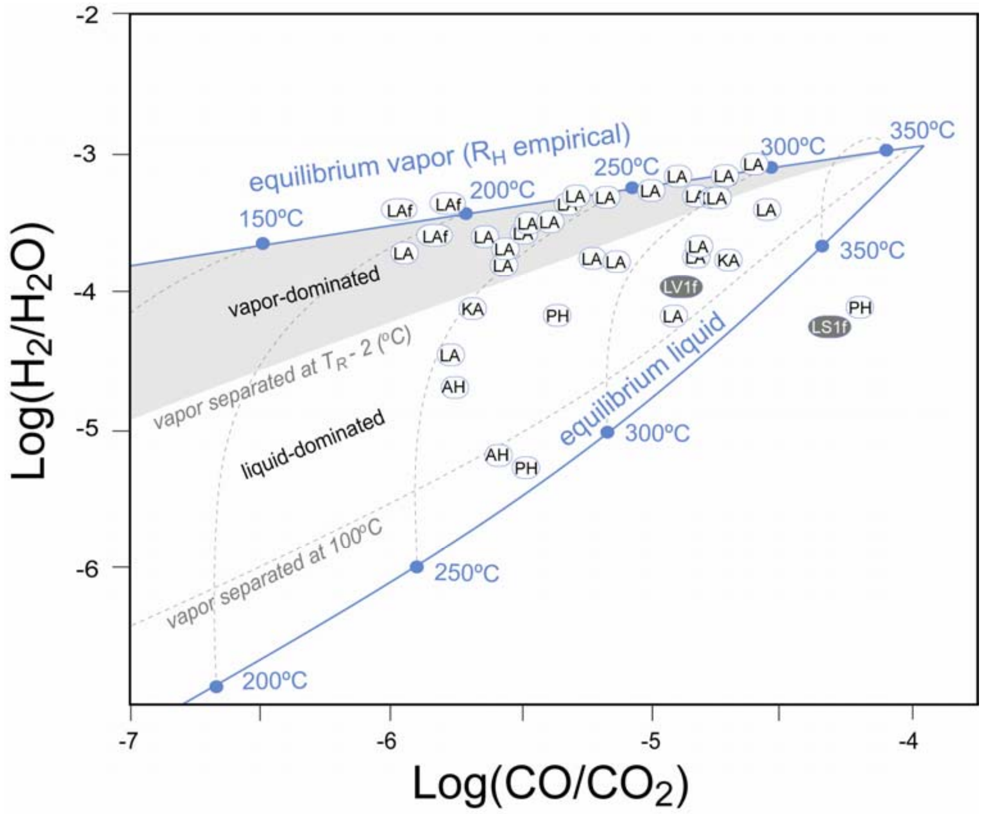

Figure 4 – The CO/CO_2-H_2/H_2O grid (Chiodini and Marini, 1998) showing gas samples of Cordón Caulle and elsewhere at empirical redox conditions. Caption as in Figure 3.

5. ACKNOWLEDGMENTS

The author thanks CONICYT-CHILE for funding through FONDEF Grant 1051 and Giovanni Chiodini, Fraser Goff and Alfred Truesdell for valuable comments on the former manuscripts.

6. REFERENCES

Arnórsson, S., 1985. Gas pressures in geothermal systems. Chemical Geology, 49, 319-328.

Chiodini, G. and Marini, L. 1998. Hydrothermal gas equilibria: the H_2O-H_2-CO_2-CO-CH_4 system. Geochimica et Cosmochimica Acta, 62, 2673-2687.

Gherardi, F., Panichi. C., Yock, A., Gerardo-Abaya, J. 2002. Geochemistry of the surface and deep fluids of the Miravalles volcano geothermal system (Costa Rica). Geothermics, 31, 91-128.

Giggenbach, W. F. 1980. Geothermal gas equilibra. Geochimica et Cosmochimica Acta, 44, 2021-2032.

Giggenbach, W. F. 1984. Mass transfer in hydrothermal alteration systems: a conceptual approach. Geochimica et Cosmochimica Acta, 48, 2693-2711.

Giggenbach, W. F. 1987. Redox processes governing the chemistry of fumarolic gas discharges from White Island, New Zealand. Applied Geochemistry, 2, 143-161.

Giggenbach, W. F. 1993. Redox control of gas compositions in Phillippine volcanic-hydrothermal systems. Geothermics, 22, No.5/6, 575-587.

Giggenbach, W. F. 1995. Variations in the chemical and isotopic composition of fluids discharged from the Taupo Volcanic Zone, New Zealand. Journal of Volcanology and Geothermal Research, 68, 89-116.

Giggenbach, W. F. and Goguel, R. L. 1989. Collection and analysis of geothermal and volcanic water and gas discharges, Unpublished Report. Chemistry Division, DSIR-Petone, New Zealand, 81 p.

Giggenbach, W. F., Tedesco, D., Sulistiyo, Y., Caprai, A., Cioni, R., Favara, R., Fisher, T. P., Hirabayashi, J.-I., Korzhinsky, M., Martini, M., Menyailov, I., Shinohara, H. 2001. Evaluation of results from the fourth and fifth IAVCEI field workshops on volcanic gases, Vulcano island, Italy and Java, Indonesia. Journal of Volcanology and Geothermal Research, 157-172.

Goff, F. and Janik, C. J. 2002. Gas geochemistry of the Valles caldera region, New Mexico, and comparisons with gases at Yellowstone, Long Valley and other geothermal systems.

Grant, M. A. 1979. Water content of the Kawah Kamojang geothermal reservoir. Geothermics, 8, 21-30.

Harper, M. A., Singer, B. S., Moreno, H., Lara, L., Naranjo, J. 2004. $^{40}Ar/^{39}Ar$ constraints on the evolution of the Puyehue-Cordón Caulle Volcanic Complex, Andean Southern Volcanic Zone, Chile. Abstracts IAVCEI General Assembly 2004 (CD Volume, Symposium 12b).

Hedenquist, J. W. 1990. The thermal and geochemical structure of the Broadlands-Ohaaki geothermal system, New Zealand. Geothermics, 19, 151-185.

Lahsen, A. 1988. Chilean geothermal resources and their possible utilization. Geothermics, 17, 401-410.

Lara, L., Moreno, H., Naranjo, J. 2004. Rhyodacitic fissure eruption in Southern Andes (Cordón Caulle; 40.5°S) after the 1960 (Mw: 9.5) Chilean earthquake: a structural interpretation. Journal of Volcanology and Geothermal Research, 138, 127-138.

Lara, L., Moreno, H., Naranjo, J., Matthews, S., Pérez de Arce, C. 2006. Magmatic evolution of the Puyehue-Cordón Caulle Volcanic Complex (40ºS), Southern Andean Volcanic Zones: from shield to unusual rhyolite fissure volcanism. Journal of Volcanology and Geothermal Research, Article in Press.

Lowenstern, J. B., Janik, C. J., Fahlquist. L. S., Johnson, L. S. 1999. A new compilation of gas and steam analyses from The Geysers geothermal field, California, USA. Proceedings 21st New Zealand Geothermal Workshop, 55-60.

Mannington. W., O'Sullivan, M. Bullivant, D. 2004. Computer modelling of the Wairakei-Tauhara geothermal system, New Zealand. Geothermics, 33, 401-419.

Powell, T. 2000. A review of geothermal gas geothermometry. Proceedings 25th Workshop of Reservoir Engineering. University of Stanford, California.

Sepúlveda, F., Dorsch, K., Lahsen, A., Bender, S., Palacios, C., 2004. The chemical and isotopic composition of geothermal discharges from the Puyehue-Cordón Caulle area (40.5°S), Southern Chile. Geothermics, 33/5, 655-673.

Sepúlveda, F., Lahsen, A., Bonvalot, S., Cembrano, J., Alvarado, A., Letelier, P., 2005. Morphoestructural evolution of the Cordón Caulle geothermal region, Southern Volcanic Zone, Chile: insights from gravity and Ar-Ar dating. Journal of Volcanology and Geothermal Research, 148, 165-189.

Sepúlveda, F. 2006. The Cordón Caulle Geothermal System: Geological and Geochemical Characterization. Unpublished PhD Thesis, Department of Geology, University of Chile, 290 p.

Tassi, F., Martinez, C., Vasello, O., Capaccioni, B., Viramonte, J. 2005. Light hydrocarbons as redox and temperature indicators in the geothermal field of El Tatio (northern Chile). Applied Geochemistry, 20, 2049-2062.

Truesdell, A. H., Haizlip, J. R., Box, W. T., D'Amore, F. 1992. A geochemical overview of The Geysers geothermal reservoir. In Monograph on The Geysers Geothermal Field, GRC Special Report. No. 17, 121-132.