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Decadal gas monitoring for geothermal production and exploration: Andean experience

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INTRODUCTION

This review visits decadal gas monitoring datasets from the fumarolic areas as well as tested and raw geothermal fields, in order to identify the optimal conditions for recognising a high-enthalpy geothermal system in the Andean Cordillera. The geological environment under consideration covers the Central Volcanic Zone (CVZ) and the South Volcanic Zone (SVZ). Within the CVZ, the Cerro Pabellón (Apacheta Volcano) was implemented in 2017 for the production of a binary geothermal plant with inferred power resource estimations of 99 ± 58 MWe (Aravena et al., 2016; Morata et al., 2020a).

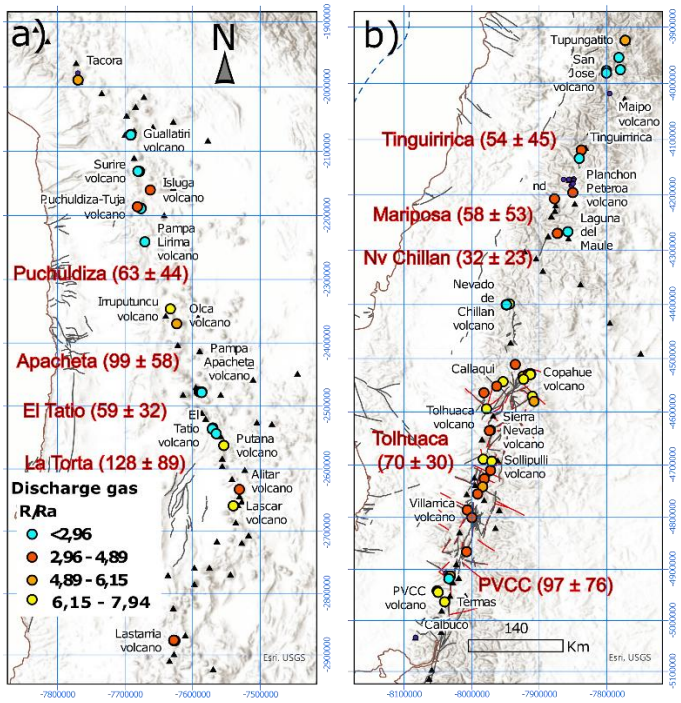


Figure 1. North-to-South Central and South Volcanic Zone of the Andes Volcanic centers and hydrothermal gas site noble gas ratio R/Ra ($^3He/^4He$, not corrected for atmospheric values). The geothermal estimated resources (MWe) in red color are from Aravena et al. (2016). PVCC stand for Puyehue–Cordón Caulle Volcanic Complex and Mariposa stand for a geothermal project near Laguna del Maule volcano.

Gas content strongly affects geothermal production and energy output because changing pressure and temperature conditions influence fluid properties and well performance (Cecioni et al., 2020; Arnórsson et al., 2007). Exploration methods depend on many factors, but this summary highlights the importance of gas chemistry in discovering new geothermal resources. Assessing fluid composition is challenging, especially at sites with fumarole fields, such as Tolhuaca (70 ± 30 MWe) and the blind field Cerro Pabellón, the first South American geothermal plant (Aravena et al., 2016; Taussi et al., 2021; Cecioni et al., 2020; Morata et al., 2020a). Gas species representing magmatic influence are normally oxidized at high-temperature equilibrium (e.g.; > 250 °C, SO_2, CO_2, HCl). Those are observed in CVZ active volcanoes, while gases that dominate in hydrothermal systems are reduced (high H_2/H_2O ratio) at lower temperatures conditions (< 150 °C; H_2S, H_2O).

Characterizing gases in most hydrothermal systems or binary geothermal plants is crucial in high enthalpy geothermal exploration because CO_2-rich phases provide key insights on vapor transport efficiency and mineral solubility into the broader volcanic-geothermal system (Arnórsson et al., 2007; Stimac, 2015). For this reason, a review of all gas samples taken from active and dormant volcanic-geothermal fields within the SVZ (**Fig. 1a**) and CVZ (**Fig. 1b**) of the Andes is presented here. The review covers gas geothermometers and the classification of gases within the geographical context of hydrothermal fields and sampling positions at documented volcanoes in both CVZ-SVZ (Aguilera et al., 2023). Finally, a multivariate analysis of the main reactive gases is performed to identify groups of gases that suggest whether or not the geothermal system is fertile, and whether drilling should continue. The geothermometer equations represent the gas species that are most prevalent in the gas database, allowing temperatures from reservoirs to be recalculated.

1 METHODS AND RESULTS

The method developed here is based on classic gas field classification and provides a simplified overview of the application of gas geothermometry and multivariable analysis of a literature dataset. To simplify the collection of the most abundant regional data, reliable gas systems involving reactive carbon species and water are used (Chiodini et al., 2010). According to geothermometers by Chiodini and Marini (1998), there are two main equations that describe gas systems in natural hydrothermal fields where vapour is separated from the liquid phase:

$$(1)\ CO_2 + H_2 \rightarrow H_2O + CO$$
$$(2)\ 3CO_2 + CH_4 \rightarrow 2H_2O + 4CO$$

The equilibrium constants, which are independent of oxygen fugacity in both equations, do not deviate significantly from 1.0 within the typical P–T range of hydrothermal systems (100–374 °C and 1–220 bar). Therefore, the temperature dependence of the equilibrium constants in Equations (1) and (2) can be expressed as a function of the mole fraction ratios in the vapour phase (see Chiodini and Marini, 1998):

$$(3)\ \log(XH_2O\ /XH_2) + \log(XCO\ /XCO_2) = L1 = 2.485 - 2248/TK$$
$$(4)\ 3\log(XCO\ /XCO_2) + \log(XCO\ /XCH_4) = L2 = 19.605 - 17813/TK$$

where TK is the absolute temperature. In equation (4), the presence of liquid is assumed to be fixed water fugacity. However, the logarithmic H_2/H_2O fraction of the system is reinterpreted based on the RH isoclines designed to draw constant RH in most classification diagrams. Equations (3) and (4) are then used to calculate the theoretical L1 and L2 values for the equilibrium vapour phases. To maximise the reservoir temperature calculation, detected argon content (Ar) is also taken into account. The CO_2/Ar-H_2/Ar (CAR-HAR) gas geothermometer grid from Giggenbach (1987) is applied in such cases.

1.1 Geothermometer results

The **Figure 2** illustrates the along-arc CVZ and SVZ data to show the regional variations in reservoir temperatures. The altitude and geographic position are also shown to evaluate the topographic conditions of the major hydrothermal systems that were explored in Chile between the 1990s and 2020s. First, the gas geothermometer method of Chiodini and Marini (1998) is applied, with temperature median and standard deviation Md = 278 ± 68 °C (50/113 of these are equilibrated in a single vapor phase, reaching 374–436 °C; the rest are in liquid–vapour equilibrium). Only the range of 100–436 °C for hydrothermal systems is considered (Caliro et al., 2007), but temperatures outside of the vapor-liquid equilibrium are also noted in order to identify super-heated vapor conditions that may frequently be observed in volcanic areas and overpressured geothermal reservoirs. Where water is unavailable in the dataset, temperatures are used from Giggenbach (1987). The temperature median and standard deviation Md = 280 ± 64 °C (n = 99/119 in liquid equilibrium; the rest in the CAR-HAR model vapor-liquid field; Giggenbach, 1987).

Overall, field sampling temperatures average Md = 87±77 °C (7–431 °C). The results confirm that high-enthalpy systems reported in Aravena et al. (2016) correspond to several high-temperature profiles (**Fig. 2 a-b**). Many volcanic-related hydrothermal systems remain unexplored despite showing potential. Therefore, variables to assess their prospect are examined using distance and gas-chemistry characteristics based on known discriminators between geothermal and magma-related signatures. Temperature analysis is trivial for gas chemistry mixtures and can be compared with the major gas contents using Principal Component Analysis (PCA) (Greenacre et al., 2022). In this case PCA helps to evaluate the optimal conditions for gas mixture chemistry in geothermal applications. The list of Principal Component (PC) simplifies visualisation technique to analyse numerical variables and recognise patterns in gas chemical mixtures at fluid discharge sites, which in this methodological step may indicate high-enthalpy geothermal conditions in the vicinity of a volcanic system. The

results were obtained using the IoGAS 8.3 (IMDEX) and LithoModeleur (CONSOREM) software packages, which indicate linear correlations between the calculated variables, with Pearson correlation coefficient (PCC) scores ranging from -1 to +1 (Greenacre et al., 2022). High absolute PCC values indicate a strong correlation, while values near zero suggest a weak or absent correlation. (see Table 1).

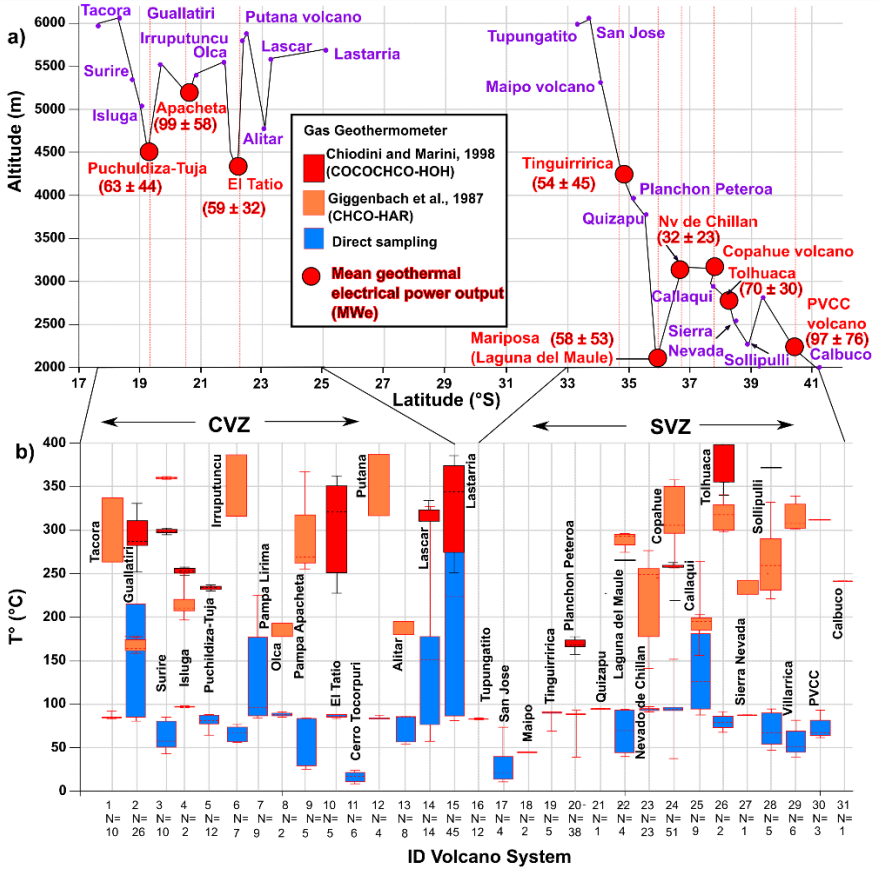


Figure 2. Geothermometer results: cross section. a) Altitude vs. latitude cross section of volcanic systems and calculated resources, as indicated by Aravena et al. (2016). b) Temperature (°C) vs. ID of volcanic systems in the original database, classified by latitude from north to south.

1.2 Discussion

The results of reservoir temperature, sampling distance and gas chemistry are reviewed with PCA technique. The interpreted description of each PC is described below **Table 1**. In such cases, PC represent proportion of variables by group of samples from the originally projected dataset (**Fig. 1**). Inverse correlation between gas pairs normally used in geothermometers reflect direct effects from reservoir temperature calculations (e.g. CO vs. CO_2 vs CH_4; **Equations 1**, **2**). The ratio N_2/Ar represent cooling and/or heating induce strong effects on gas mixture equilibrium according to CAR-HAR geothermometer (Giggenbach, 1987). Extreme fluctuations in heating and cooling are observed at active volcanoes (**Table 1**: PC1, PC5, PC6), for example where N_2/Ar ratio increase, the following ratios H_2S/SO_2 and H_2/H_2O, and CH_4/CO_2 might also vary (Giggenbach, 1987). Those gas ratios discriminate hydrothermal gases from volcanic gases, because they often represent different PCCs in the Pearson Matrix (**Table 1**), thus the gas-ratio pairs represent typical potentiometers (for oxydo-reduction) and natural geothermometers. This is independent of the noble gas ratio indicators of the fluid source (**Fig. 1**; $^3He/^4He$), which are usually closer to the values of the mantle in the southern part of Chile ($^3He/^4He \sim 7.0 – 9.0$) due to fewer interactions with the crust (Barry et al., 2025; Lages et al., 2021).

The favourable component PC1 (hot hydrothermal, magmatic) and PC8 (hot hydrothermal, weak magmatic) is present in 29% of the samples as typical hot hydrothermal systems (Callaqui, Apacheta, Irruputuncu, Alitar, Tacora, El Tatio, Sollipulli, Puchuldiza-Tuja, Guallatiri, Tinguiririca, Nevado de Chillán, Planchón-Peteroa, PVCC and Lascar). Hot hydrothermal systems without clear magmatic signature are also present (PC8), but still for fewer volcanic centers (Callaqui, Irruputuncu, Apacheta, Tolhuaca, Alitar, Tacora, El

Tatio, Puchuldiza-Tuja, Sollipulli, Guallatiri, Tinguirririca, Planchon Peteroa, Nevado de Chillan, PVCC). A dominantly high H_2S/SO_2 ratio (or anticorrelatioin with PCCs) indicates that the hydrothermal system lacks the typical oxidised SO_2 magmatic gases or detected halogen (e.g. Nevado de Chillan; Tardani et al., 2025) present in the following cases: Callaqui, Apacheta, Tolhuaca, Tacora, El Tatio and Nevado de Chillán. The sulfur proportion (H_2S/SO_2) has only been measured in these systems; therefore, we caution that other gas discharges may contain both species depending on laboratory techniques.

Table 1. Component Analysis Results: Pearson Matrix

Components	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
horizontal distance "HARVERSINE" (km)	-0,41	0,11	-0,70	0,08	0,03	-0,29	-0,47	-0,06
vertical distance (km)	-0,26	0,08	-0,73	-0,22	0,40	-0,13	0,38	0,01
$[CO_2]$	0,12	**0,85**	0,23	-0,25	0,18	-0,11	-0,16	0,07
$[SO_2]$	**0,57**	-0,57	0,20	0,30	0,04	-0,31	-0,03	-0,23
$[H_2S]$	0,28	-0,37	-0,44	**0,48**	0,05	**0,56**	-0,08	0,11
$[N_2]$	-0,57	-0,49	-0,04	0,09	-0,47	-0,31	0,11	0,09
$[O_2]$	-0,77	-0,36	0,25	-0,05	0,04	-0,06	0,05	0,06
$[H_2]$	-0,04	-0,72	-0,19	-0,46	-0,17	0,23	0,01	-0,21
$[CH_4]$	-0,69	0,29	0,30	-0,10	0,04	0,37	-0,06	-0,09
[CO]	0,20	-0,71	0,18	-0,29	**0,45**	-0,02	-0,14	-0,17
[He]	-0,47	-0,42	0,28	0,39	**0,47**	-0,12	0,01	0,19
[Ar]	-0,87	-0,26	0,03	-0,10	0,02	0,14	-0,15	0,01
Reservoir temperature (°C)	**0,52**	-0,54	-0,01	-0,42	-0,04	-0,03	-0,14	**0,45**
Proportion variables%	**25,75**	**24,65**	**12,41**	**8,43**	**6,79**	**6,46**	**3,68**	**3,15**
Description	**Hot hydrothermal, magmatic**	**Warm hydrothermal**	**Distant mixed gases**	**Cold hydrothermal, crater is near**	**Low altitude mixed**	**Hydrothermal H_2S dominant**	**Distant, low altitude, no gas anomalies**	**Hot hydrothermal, weak magmatic**

* Values in bold highlight the unique characteristics when the PCC score is > 0,5.

Conclusion

Key variables for assessing practical drilling conditions at CVZ-SVZ geothermal sites are N_2/Ar, H_2S/SO_2 CO/CO_2, CO/CH_4, and H_2/H_2O due to their reactive behaviors during cooling, with N_2/Ar value higher in active volcanic centers compared to geothermal fields. According to PCA, the volcanoes and hydrothermal areas with gas mixtures most suitable for geothermal development at distance from eruptive centers include Irruputuncu, Apacheta, Tolhuaca, Tacora, Tinguirririca, and PVCC. Accessibility also improves at lower elevations, with sites below 4000 meters offering better drilling potential; hydrothermal discharges distant from Tolhuaca, Tinguirririca, and PVCC support this.

These measurements are essential for targeting hot hydrothermal prospects with gas pathfinders while evaluating overpressure conditions and atmospheric gas mixing. Such key geochemical parameters should be supported by water chemistry analysis to indicate safe exploration conditions and can be used as efficient pathfinders for sustained heated reservoirs representing low permeability and minimal cold fluid recharge.

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REFERENCES

- Aguilera, F., Grosse, P., Guzmán, S., Michelfelder, G., and Taussi, M.: Volcanism in the Central Volcanic Zone of the Andes, Frontiers in Earth Science, 11, (2023), 1130976.
- Aravena, D., Muñoz, M., Morata, D., Lahsen, A., Parada, M. Á., and Dobson, P.: Assessment of high enthalpy geothermal resources and promising areas of Chile, Geothermics, 59, (2016), 1–13.
- Arnórsson, S., Stefánsson, A., and Bjarnason, J. O.: Fluid-fluid interactions in geothermal systems, Reviews in Mineralogy and Geochemistry, 65, (2007), 259–312.
- Barry, P. H., de Moor, J. M., Broadley, M. W., Seltzer, A. M., Bekaert, D. V., Patil, K., Bartels, C. G. E., Young, E. D., Longworth, B. E., Barosa, B., and Bastianoni, A.: Carbon, nitrogen, and noble gas isotopes reveal deep volatile signatures in thermal springs in the Central Volcanic Zone (CVZ) of the Andes, Earth and Planetary Science Letters, 651, (2025), 119169.
- Caliro, S., Chiodini, G., Moretti, R., Avino, R., Granieri, D., Russo, M., and Fiebig, J.: The origin of the fumaroles of La Solfatara (Campi Flegrei, South Italy), Geochimica et Cosmochimica Acta, 71, (2007), 3040–3055.
- Cecioni, M., and Cei, M.: Numerical Simulation of Cerro Pabellon Geothermal Field (Chile) with TOUGH-2®, Proceedings World Geothermal Congress, 1, (2020), 1.
- Chiodini, G., and Marini, L.: Hydrothermal gas equilibria: the H2O–H2–CO2–CO–CH4 system, Geochimica et Cosmochimica Acta, 62, (1998), 2673–2687.
- Chiodini, G., Caliro, S., Cardellini, C., Granieri, D., Avino, R., Baldini, A., and Minopoli, C.: Long-term variations of the Campi Flegrei volcanic system as revealed by the monitoring of hydrothermal activity, Journal of Geophysical Research: Solid Earth, 115, (2010), B3.
- Giggenbach, W. F.: Redox processes governing the chemistry of fumarolic gas discharges from White Island, New Zealand, Applied Geochemistry, 2, (1987), 143–161.
- Greenacre, M., Groenen, P. J., Hastie, T., d'Enza, A. I., Markos, A., and Tuzhilina, E.: Principal component analysis, Nature Reviews Methods Primers, 2, (2022), Article 100.
- Lages, J., Rizzo, A. L., Aiuppa, A., Robidoux, P., Aguilar, R., Apaza, F., and Masias, P.: Crustal controls on light noble gas isotope variability along the Andean Volcanic Arc, Geochemical Perspectives Letters, 19, (2021), 45–49.
- Morata, D., Aravena, D., Lahsen, A., Muñoz, M., & Valdenegro, P. (2020a). Chile Up-Date: The First South American geothermal power plant after one century of exploration. In Proceeding of the World Geothermal Congress (Vol. 1).
- Robidoux, P., Tardani, D., Sánchez-Alfaro, P., Liuzzo, M., Morata, D., Moussallam, Y., and Francofonte, V.: Relationship of magmatic fluids to high-enthalpy geothermal systems: New insights from the Tolhuaca Geothermal System (TGS), Southern Andes, Chemical Geology, 681, (2025), 122583.
- Stimac, J., Goff, F., and Goff, C. J.: Intrusion-related geothermal systems, The Encyclopedia of Volcanoes, 2, (2015), 799–822.
- Tardani, D., Taussi, M., Tassi, F., Romero, J., Robidoux, P., Poblete-Gonzalez, C., Álvarez-Amado, F., Manosalva, L., Pinti, D. L., Morata, D., Mura, V., and Arancibia, G.: Temporal evolution of fumarolic gas geochemistry at the Nevados de Chillán Volcanic Complex (NCVC): Signals of volcanic unrest and insights into the geothermal resource, Journal of Volcanology and Geothermal Research, (2025), 108467.
- Taussi, M., Nisi, B., Pizarro, M., Morata, D., Veloso, E. A., Volpi, G., and Renzulli, A.: Sealing capacity of clay-cap units above the Cerro Pabellón hidden geothermal system derived by soil CO_2 flux and temperature measurements, Journal of Volcanology and Geothermal Research, 384, (2019), 1–14.