Interplay of Volcanism and Structural Control in Defining the Geothermal System(s) along the Liquiñe-Ofqui Fault Zone, in the South-Central Chile

Mohammad Ayaz Alam, Pablo Sánchez, Miguel Ángel Parada

Departamento de Geología, Universidad de Chile, Santiago, Chile

Keywords

Geothermal, Liquiñe-Ofqui Fault Zone, Chile, meteoric water, volcano, structure, lineaments, direct use, Chile

ABSTRACT

Two distinct domains of the geothermal systems, viz. structural (or non-volcanic) and volcanic have been identified in the south-central Chile, based on the chemistry of the thermal discharges and structural analysis of the lineaments. These two domains are distinct in their ways of heating up of meteoric water, which is the feeder to these geothermal systems. The geothermal system(s) of the volcanic domain are associated with the regional volcanic centers. The process of heating is through deep circulation of meteoric water in the case of the geothermal system(s) of the structural (non-volcanic) domain. In the case of the geothermal system(s) of volcanic domain, the heating of the meteoric water is through absorption of heat and condensation of steam and gases by meteoric water during lateral circulation. However, these thermal discharges do not exhibit the typical signatures of steam heated waters, which are subdued through water-rock interaction and other near surface processes

Introduction

In this paper, we discuss the possible roles of volcanism and structural control in defining the geothermal system(s) in the Villarrica-Chihuio area (39°15´–40°15´S, 71°40´–72°10´W) of the South-Central Volcanic Zone (SCVZ) of Chile. Geothermal manifestations in the area are largely structurally controlled and are located along the Liquiñe-Ofqui Fault Zone (LOFZ), which is a major intra-arc transpressional dextral strike-slip fault running for over 1200 km between 38ºS and 47ºS, trending NNE-SSW (Cembrano et al., 1996; Cembrano et al., 2000; Lara and Cembrano, 2009; Lange et al., 2008; Cembrano et al., 2007). However, some manifestations are apparently associated with the stratovolcanoes, viz. Villarrica, Quetrupillán and Mocho-Choshuenco and minor (mainly monogenetic) volcanic centers of SCVZ. The location of SCVZ itself is apparently controlled by LOFZ (López-Escobar et al., 1995; Stern, 2004).

A simplified geologic map of the study area (Figure 1), based on previous works (Lara and Moreno 2004; Moreno and Lara, 2008) and inputs from the field observations during this study, shows two distinct lithological units - an impermeable basement (comprising crystalline rocks, please see the caption of Figure 1 for details) and a relatively permeable cover, comprising pre- and post-glacial volcanic and sedimentary deposits associated with the erosion of the volcanic centers. Two geothermal domains can be defined: (a) Volcanic, comprising of the geothermal areas close to volcanic centers and (b) Structural (or Non-volcanic), with the geothermal areas located over the LOFZ. Although the primary basis of this classification is their disposition, it is also justified by the chemical signatures of the thermal waters, as discussed in the next section.

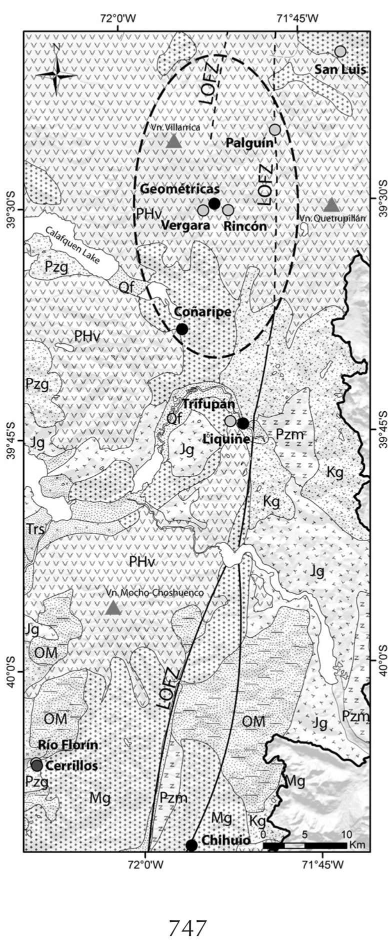

Figure 1. Geological map of the study area, with the locations of (i) geothermal manifestations (circles; darker circles represent higher temperatures of discharges), (ii) LOFZ, (iii) stratovolcanoes (solid triangles), and (iv) lithological units (Pzm: Paleozoic Metamorphic Complexes; Pzg: Paleozoic Granitoids; Trs: Triassic Sedimentary Rocks; Jg: Jurassic Granitoids; Kg: Cretaceous Granitoids; OM: Oligocene Sedimentary Rocks; Mg: Miocene Granitoids; PHv: Pleistocene to Holocene Volcanic Deposits; Qf: Unconsolidated Quaternary Sediments). Geothermal manifestations in the encircled area belong to the volcanic domain; while the rest of them belong to the structural domain.

Table 1. Physical parameters and chemical composition of thermal water discharges.

	Location	T °C	pH	TDS	SiO_2	Na	K	Mg	Ca	B	F^-	HCO_3^-	CO_3^{2-}	SO_4^{2-}	Cl^-
				ppm											
1	San Luis	39	9.4	170	49	55	1.0	0.2	5.2	0.1	1.8	29	12	77	8
2	Palguin	35	8.7	110	47	42	1.9	1.3	4.2	0.4	1	67	0	32	10
3	Palguin	36	8.7	110	52	53	2.5	1.5	4.2	0.7	1.5	81	0	38	12
4	Geométricas	72	8.4	540	83	160	9.6	0.1	47	5.0	1.2	29	0	421	49
5	Rincón	36	8.0	250	69	62	4	2	10	1.4	0.9	52	0	103	17
6	Vergara	41	7.8	240	68	72	5.0	2.6	17	1.9	0.5	48	0	151	18
7	Coñaripe	55	7.9	230	55	82	2.7	0.9	7.2	4.7	0.9	78	0	61	50
8	Coñaripe	68	8.6	350	78	136	3.6	0.3	5.6	7.3	1.5	94	0.6	103	81
9	Coñaripe	60	8.3	330	61	99	3.2	0.2	6.9	5.4	1.1	83	0	78	62
10	Trifupán	37	8.9	160	42	60	1.4	0.9	9.8	0.5	0.7	42	0	77	23
11	Liquiñe	71	9.4	210	83	73	2.2	0	3.7	0.2	1.3	24	22	78	16
12	Liquiñe	71	9.5	260	87	71	2.2	0	3.7	0.2	1.5	67	0.9	81	16
13	Liquiñe	70	8.8	130	41	26	1.1	0.7	5.2	0	0.3	35	0	30	7.1
14	Liquiñe	70	9.4	210	84	69	2.2	0.1	3.8	0.2	1.4	40	1.2	80	16
15	Rio Florín	54	9.7	180	57	60	1.0	0	7.7	0.5	0.5	26	0	78	26
16	Cerrillos	41	9.4	330	54	55	0.8	0.1	8.3	0.4	0.4	29	8	75	21
17	Cerrillos	32	8.0	330	42	42	0.7	0.7	12	0.2	0.3	47	0	58	15
18	Chihuio	82	9.4	450	96	107	4.2	0.1	9.9	0	0.9	25	1.1	213	14
19	Chihuio	82	9.4	450	97	106	4	0	9.9	0	0.9	24	2.1	213	13

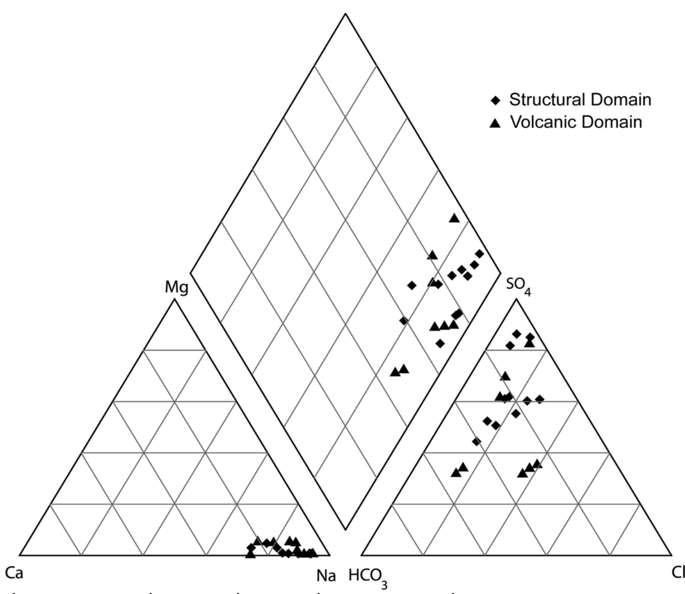

Figure 2. Piper diagram, showing the $Na-SO_4$ and $Na-SO_4-HCO_3$ water types.

Geothermal Discharges

Geothermal discharges in the area are in the form of thermal springs and pools, a large number of which are modified anthropologically. Undisturbed natural thermal discharges are quite scarce in the study area. The physicochemical nature of the thermal waters (Table 1) is discussed here in brief. Details on the chemical and isotopic signatures of thermal waters and gas geochemistry will be reported in a subsequent paper. Outlines of the chemistry of the thermal waters are as follows:

(i) The temperature of the geothermal discharges varies from 30 to 82°C.

(ii) Discharged waters are $Na-SO_4$ and $Na-SO_4-HCO_3$ types (Figure 2).

(iii) Low concentration (~10-80 ppm) of chloride (Cl^-) largely indicates that these discharges are not the upflows of the geothermal system.

(iv) Waters are relatively low in chloride (Cl^-, up to 80 ppm) and high in sulfate (SO_4^{2-}, up to 421 ppm), which is typical for steam-heated geothermal waters.

(v) Slight alkaline nature of these waters is not typical of the steam-heated waters (Giggenbach, 1991) in the absence of additional neutralization processes, which indicates the role of water-rock interaction and other near surface processes in camouflaging the original geochemical signatures of these waters (Alam et al., 2010).

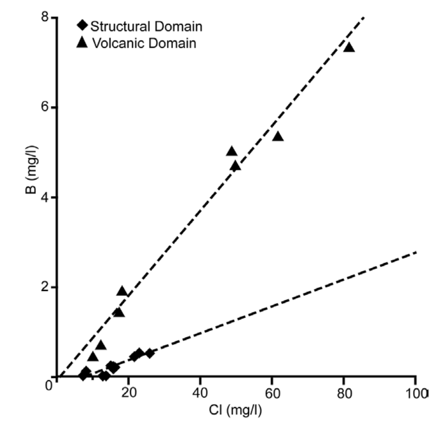

Figure 3. Cl-B relationship shows two distinct domains.

(vi) The concentration of conservative elements (viz. B, Cl^-), as well as on their ratio (B/Cl^-) form two different clusters (Figure 3) corresponding to the two distinct domains mentioned in the earlier section, which is consistent with the spatial distribution of the thermal manifestations with respect to the Liquiñe-Ofqui fault zone and the volcanic centers in the area (Figure 1).

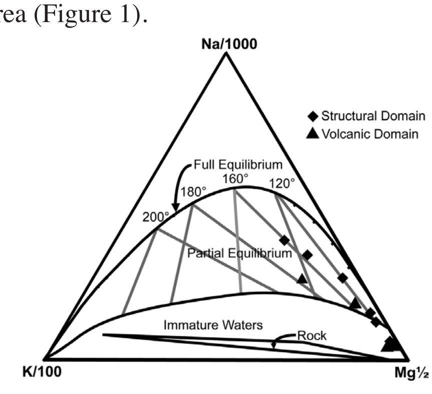

Figure 4. Na-K-Mg diagram (Giggenbach, 1988) shows partial equilibrium in most of the cases.

(vii) Geothermal waters of the area fall in the partial equilibrium field of the Na-K-Mg triangular plot (Figure 4).

(viii) Base temperatures calculated by conventional water geothermometers (Giggenbach 1991, and references therein) also indicate the presence of two distinct domains, with base temperatures in the range 130-150°C for the volcanic domain and 100-120°C for the structural domain.

(ix) The values of SO_4^{2-}/Cl^- and SO_4^{2-}/HCO_3^- ratios decrease with increasing distance from the volcanic centers for discharges of the volcanic domain. This is particularly evident in the case of Coñaripe, which has the highest Cl^- content of all thermal discharges of the area.

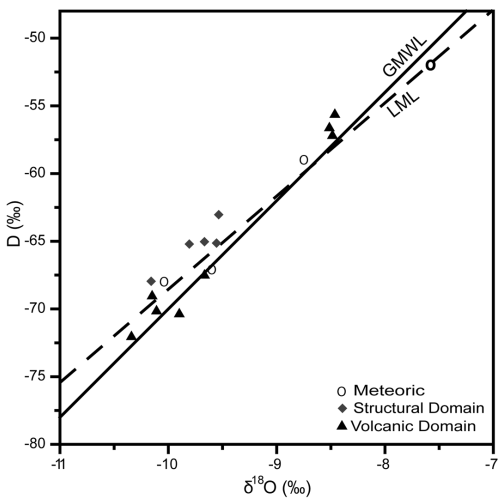

Figure 5. Variation of δD with δ¹⁸O shows meteoric origin of the thermal waters.

(x) The meteoric origin of the thermal waters is established conclusively from oxygen and hydrogen isotopes (Figure 5). The absence of a considerable shift in the $\delta^{18}O$ values from the local meteoric line suggests limited isotopic exchange in the water-rock interaction process.

Structural Analysis

The relation between the geothermal systems and fracture density (FD) is quite evident from the structural analysis of the thermal areas. FD correlates very well with the existence and location of the surface geothermal manifestations, as well as with the recharge areas of these superficial geothermal systems. This association is pronounced particularly in areas with crystalline rocks. In order to be consistent with this observation, the conceptual model must consider a considerable increase in the (secondary) permeability in the uppermost 200-300 m in the areas of relatively high values of FD, which is consistent with the lithology and structure in the area.

Although the lineaments scatter in a wide range, the absence of lineaments between N60°E and N100°E (Figure 6) is noticeable, and is consistent with displacement and stress data (Cembrano et al., 2007; Lavenu and Cembrano, 1999) of LOFZ segment in the study area. This indicates that such lineaments, which represent fractures and faults, are the result of recent deformation, causing secondary permeability that facilitates the subsurface flow particularly in NW-SE and N-S directions. This association will be discussed in detail elsewhere.

Discussion

The process of heating of the meteoric water is (i) through their deep circulation for discharges of the structural domain and/or (ii) through absorption of heat and condensation of steam and gases during their lateral circulation, for discharges of the volcanic domain (steam-heated waters). Steam, rich in CO_2 and H_2S but low in Cl^-, generates bicarbonate-sulfate type waters. The acidity of the water is neutralized and further modified to alkaline by water-rock interaction.

The conceptual model (Figure 7) for the two distinct domains of the geothermal systems presented here is based on the geochemical and structural characterization of the geothermal manifestations of the area. In the case of discharges of the structural domain, infiltrated and percolated meteoric water gets heated by conduction after reaching considerable depth and is driven by convection. The waters thus heated are separated in two phases through adiabatic decompression, allowing the ascent of a gaseous phase. Chemical speciation in such thermal waters is controlled by the leaching of the host rock, without any contribution of magmatic fluids, as supported by low Cl^- concentrations. On the other hand, the geochemical signature of discharges of the volcanic domain is modified by limited interaction with magmatic fluids, as indicated by ongoing investigations on gas geochemistry.

In both the cases, steam absorption and condensation occurs in a permeable zone, with constant circulation of thermal water,

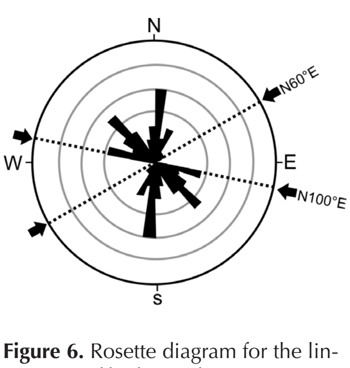

Figure 6. Rosette diagram for the lineaments of higher order representing major structural discontinuities.

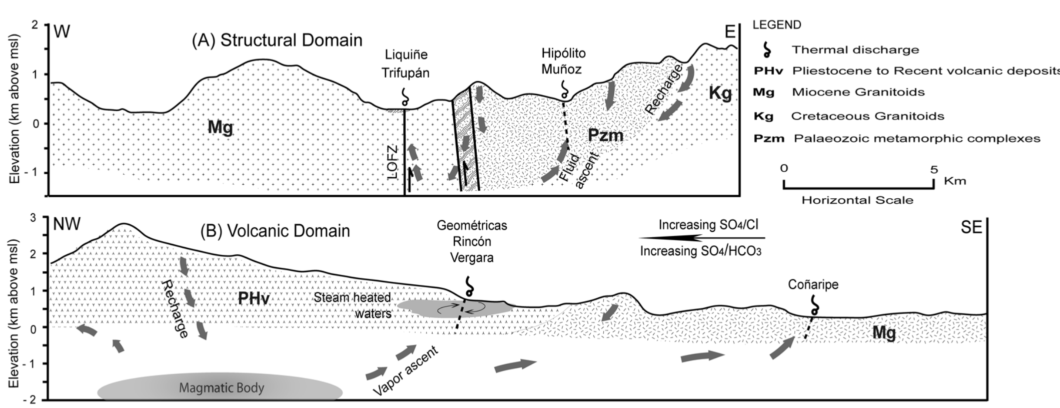

Figure 7. Conceptual model of the geothermal systems for the (a) structural and (b) volcanic domains.

to form convective cells of heated up water. In the structural domain, this zone is likely to have a dominantly vertical extension, with reservoir(s) restricted to sectors with high fracture density. In the volcanic domain, on the other hand, due to the primary permeability of the volcano-sedimentary sequences, it is likely to have a more pronounced horizontal extension, with predominant lateral flow. In the uppermost zones of these geothermal systems, heated meteoric water is mixed with superficial waters, causing further dilution and cooling. This is particularly evident for the discharges in Vergara, Rincón and Geométricas.

Conclusions

Based on the geochemical signature of the thermal discharges and on the structural analysis of the lineaments, two distinct ways of heating of meteoric water, and thus two domains of thermal waters, have been identified: a structural (or non-volcanic) and a volcanic domain. It can be concluded that the thermal discharges in the studied area are largely superficial phenomena and do not represent high-enthalpy system(s) expected in the study area. However, they do indicate the presence of deep seated (blind) high-enthalpy geothermal system(s) that contributes to the superficial geothermal systems in the study area.

Conclusively, the geothermal discharges in the study area are associated with the shallow low-enthalpy systems, which can be used for direct applications, viz., district heating, greenhouses, food processing and drying, industrial processes requiring heat, improving livestock productivity, melting of snow (Lund et al., 2005). Most of the geothermal manifestations in the study area have already been converted into commercial spas and resorts. However, use of these low-enthalpy geothermal sources for power generation, viz. 400 KWe geothermal plant in Chena, Alaska (USA), can be ascertained only after proper feasibility studies (Chandrasekharam and Bundschuh, 2008).

Acknowledgements

Authors would like to thank the Universidad de Chile for the necessary facilities to carry out this work and acknowledge the financial support through PBCT PDA-07 project of CONICYT and the Geothermal Program of the Department of Geology of the university.

The authors would like to thank the reviewers Bob Young and Ali Khan for their invaluable comments and suggestions. Thanks are also due to Anh Lay for efficient handling of the manuscript.

References

Alam, M.A., P. Sánchez and M.A. Parada, 2010. Geochemical processes camouflaging original signatures in the thermal waters of south-central Chile. In: P. Birkle (Ed) *Water-Rock Interaction 13*, A.A. Balkema, Rotterdam, in press.

Cembrano, J. and L. Lara, 2009. The link between volcanism and tectonics in the southern volcanic zone of the Chilean Andes: A review. *Tectonophysics*, v. 471, p. 96–113.

Cembrano, J., A. Lavenu, G. Yañez (coordinators), R. Riquelme, M. Garcia, G. González and G. Herail, 2007. Neotectonics. In: T. Moreno and W. Gibbons (Eds), *The Geology of Chile*, The Geological Society, London, p. 147–178.

Cembrano, J., E. Schermer, A. Lavenu and A. Sanhueza, 2000. Contrasting nature of deformation along an intraarc shear zone, the Liquiñe-Ofqui fault zone, Southern Chilean Andes. *Tectonophysics*, v. 319, p. 129–149.

Cembrano, J., F. Hervé and A. Lavenu, 1996. The Liquiñe-Ofqui fault: a long-lived intra-arc fault system in southern Chile. *Tectonophysics*, v. 259, p. 55–66.

Chandrasekharam, D. and J. Bundschuh, 2008. *Low-enthalpy geothermal resources for power generation*. Taylor & Francis Group, London, UK, 172 p.

Giggenbach, W.F., 1988. Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators. *Geochimica et Cosmochimica Acta*, v. 52, p. 2749–2765.

Giggenbach, W.F., 1991. Chemical techniques in geothermal exploration. In: F. D'Amore (Ed), *Applications of Geochemistry in Geothermal Reservoir Development*, UNITAR/UNDP Centre on Small Energy Resources, Rome, p. 119–142.

Lange, D., J. Cembrano, A. Rietbrock, C. Haberland, T. Dahm and K. Bataille, 2008. First seismic record for intra-arc strike-slip tectonics along the Liquiñe-Ofqui fault zone at the obliquely convergent plate margin of the southern Andes. *Tectonophysics*, v. 455, p. 14–24.

Lara, L.E., and H. Moreno, 2004. Geología del área Liquiñe-Neltume, *Carta Geológica de Chile*, Serie Geología Básica 83, Servicio Nacional de Geología y Minería, Santiago, 23 p.

Lavenu, A. and J. Cembrano, 1999. Compressional and transpressional-stress pattern for Pliocene and Quaternary brittle deformation in forearc and intra-arc zones (Andes of Central and Southern Chile). *Journal of Structural Geology*, v. 21, p. 1669–1691.

López-Escobar, L., J. Cembrano and H. Moreno, 1995. Geochemistry and tectonics of the Chilean Southern Andes basaltic Quaternary volcanism (37º-46ºS). *Revista Geológica de Chile,* v. 22, p. 219–234.

Lund, J., D.H. Freeston and T.L. Boyd, 2005. Direct application of geothermal energy: 2005 worldwide review. *Geothermics*, v. 34, p. 691–727.

Moreno, H. and L. Lara, 2008. Geología del área Pucón-Curarrehue, *Carta Geológica de Chile*, Serie Geología Básica 115, Servicio Nacional de Geología y Minería, Santiago, 36 p.

Stern, C., 2004. Active Andean volcanism: its geologic and tectonic setting. *Revista Geológica de Chile*, v. 31, p. 161–206.