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Geochemical processes camouflaging original signatures in the thermal waters of south-central Chile

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ABSTRACT: Several geothermal systems have been delineated and characterized along the Liquiñe-Ofqui Fault Zone, in the South-Central Volcanic Zone of Chile, from the geochemical signatures of the thermal discharges and structural analysis of the lineaments. Based on the ways of heating up of meteoric water, which is the feeder to these geothermal systems, two distinct domains of thermal discharges have been identified – (i) structural (or non-volcanic) and (ii) volcanic, the latter being directly associated with the regional volcanic centres. The process of heating is through deep circulation of meteoric water in the case of former; and 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 camouflaged or subdued by the means of water-rock interaction and other near surface processes.

1 INTRODUCTION

In this paper, we discuss the structurally controlled geothermal systems along the Liquiñe-Ofqui Fault Zone (LOFZ) in Villarrica-Chihuio area (39°15′–40°15′S, 71°40′–72°10′W) of South-Central Volcanic Zone (SCVZ) of Chile, with a note on the processes camouflaging the original geochemical signatures of the thermal discharges. LOFZ is a major intra-arc transpressional dextral strike-slip fault running for over 1200 km between 38ºS and 47ºS, trending NNE-SSW (Lara & Cembrano 2009, Lange et al. 2008, Cembrano et al. 2007). The study area has several stratovolcanoes, viz. Villarrica, Quetrupillán and Mocho-Choshuenco and minor (mainly monogenetic) volcanic centres of SCVZ, whose location is apparently controlled by LOFZ (Stern 2004, and references therein). The conceptual model for these geothermal systems presented here is based on the geochemical and structural characterization of the geothermal manifestations of the area.

A simplified geologic map of the study area (Fig. 1), based on previous works (Lara & Moreno 2004, and references therein) 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.

2 GEOCHEMICAL CHARACTERISTICS

Here we outline only those aspects of the geochemistry of thermal waters (Table 1), which are of immediate significance for the present discussion. Details on the geochemistry will be reported in a following paper.

i. Thermal discharges are Na-SO_4 and Na-SO_4^- HCO_3 types.
ii. Low concentration range (~10–80 ppm) of chloride (Cl^-) largely indicates that these discharges are outflows, and not upflows of the system.
iii. Waters are relatively low in chloride (Cl^-, up to 80 ppm) and high in sulphate (SO_4^{2-}, up to 421 ppm), which is typical for steam-heated geothermal waters.
iv. All the sampled waters are slightly alkaline, which is unusual for steam-heated waters in the absence of additional neutralization processes.
v. Based on the concentration of conservative elements (viz. B, Cl^-), as well as on their ratio (B/Cl^-), two distinct domains (volcanic and structural domains) of thermal waters can be identified (Fig. 2), which is consistent with the spatial distribution of the thermal manifestations with respect to the Liquiñe-Ofqui fault zone and the volcanic centres in the area (Fig. 1).
vi. Variations of saturation indices of the mineral phases, viz. calcite, chalcedony and quartz, with temperature also support the

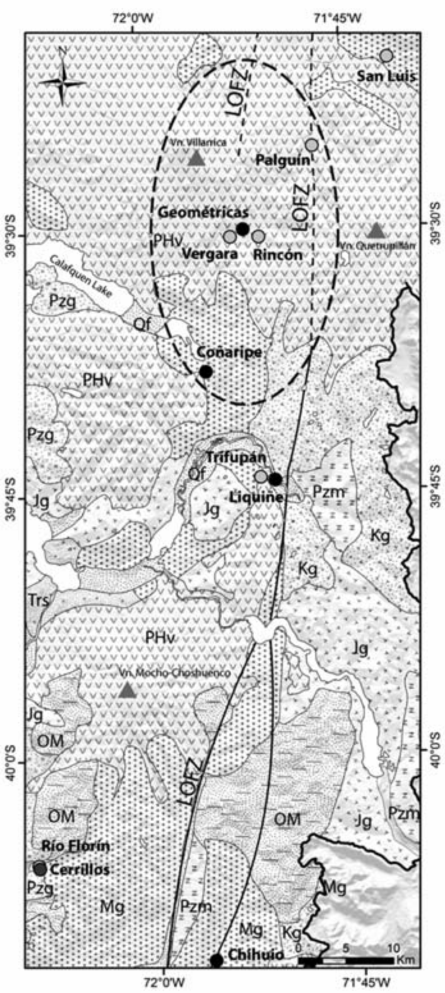

Figure 1. Geological map of the study area, with the locations of (i) geothermal manifestations (circles; darker circles represent higher temperatures of discharges), (ii) LOFZ, (iii) stratovolcanoes (solid triangles), and (iv) lithological units (Pzm: Palaeozoic Metamorphic Complexes; Pzg: Paleozoic 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 (please see Section 2).

idea of two different domains, as mentioned earlier.

vii. 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.

viii. Water-rock interaction is indicated by partial equilibrium (Fig. 3) for some mineral phases, viz. calcite, chalcedony and quartz.

ix. The values of SO_4^{2-}/Cl^- and SO_4^{2-}/HCO_3^- ratios decrease with increasing distance from the volcanic centres 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.

x. Oxygen and hydrogen isotopes (not reported here) attest conclusively the meteoric origin of the thermal waters. The absence of a considerable shift in the $\delta^{18}O$ values from the local meteoric line suggests limited water-rock interaction.

3 STRUCTURAL ANALYSIS

From the structural analysis of the thermal areas, relation between the geothermal systems and fracture density (FD) is quite evident. FD correlates with the existence and location of the surface geothermal manifestations, as well as with recharge areas of meteoric water of these superficial geothermal systems. This association is particularly pronounced particularly in areas with crystalline rocks (granitic batholiths). 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.

Although the lineaments scatter in a wide range, it is evident the absence of lineaments between N 60°E and N100°E (Fig. 4), which is consistent with displacement and stress data (Cembrano et al. 2007, Lavenu & 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 a secondary permeability that facilitates the subsurface flow particularly in NW-SE and N-S directions. This association will be discussed in detail elsewhere.

4 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,

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

Sample	Location	T °C	pH	TDS ppm	SiO_2	Na	K	Mg	Ca	B	Br^-	F^-	HCO_3^-	CO_3^{2-}	SO_4^{2-}	Cl^-	NO_3^-
1	San Luis	39	9.4	170	49	55	1.0	0.2	5.2	0.1	0	1.8	29	12	77	8	1.4
2	Palguin	35	8.7	110	47	42	1.9	1.3	4.2	0.4	1.3	1	67	0	32	10	1.4
3	Palguin	36	8.7	110	52	53	2.5	1.5	4.2	0.7	1.3	1.5	81	0	38	12	1.5
4	Geométricas	72	8.4	540	83	160	9.6	0.1	47	5.0	1.3	1.2	29	0	421	49	1.3
5	Rincón	36	8.0	250	69	62	4	2	10	1.4	1.3	0.9	52	0	103	17	1.5
6	Vergara	41	7.8	240	68	72	5.0	2.6	17	1.9	1.3	0.5	48	0	151	18	1.6
7	Coñaripe	55	7.9	230	55	82	2.7	0.9	7.2	4.7	1.4	0.9	78	0	61	50	1.6
8	Coñaripe	68	8.6	350	78	136	3.6	0.3	5.6	7.3	1.4	1.5	94	0.6	103	81	1.4
9	Coñaripe	60	8.3	330	61	99	3.2	0.2	6.9	5.4	1.4	1.1	83	0	78	62	1.3
10	Trifupán	37	8.9	160	42	60	1.4	0.9	9.8	0.5	1.3	0.7	42	0	77	23	1.7
11	Liquiñe	71	9.4	210	83	73	2.2	0	3.7	0.2	1.3	1.3	24	22	78	16	0
12	Liquiñe	71	9.5	260	87	71	2.2	0	3.7	0.2	1.3	1.5	67	0.9	81	16	1.3
13	Liquiñe	70	8.8	130	41	26	1.1	0.7	5.2	0	0	0.3	35	0	30	7.1	1.4
14	Liquiñe	70	9.4	210	84	69	2.2	0.1	3.8	0.2	1.3	1.4	40	1.2	80	16	1.3
15	Rio Florín	54	9.7	180	57	60	1.0	0	7.7	0.5	1.3	0.5	26	0	78	26	1.3
16	Cerrillos	41	9.4	330	54	55	0.8	0.1	8.3	0.4	1.3	0.4	29	8	75	21	1.5
17	Cerrillos	32	8.0	330	42	42	0.7	0.7	12	0.2	1.3	0.3	47	0	58	15	1.4
18	Chihuio	82	9.4	450	96	107	4.2	0.1	9.9	0	1.3	0.9	25	1.1	213	14	1.5
19	Chihuio	82	9.4	450	97	106	4	0	9.9	0	1.3	0.9	24	2.1	213	13	1.5

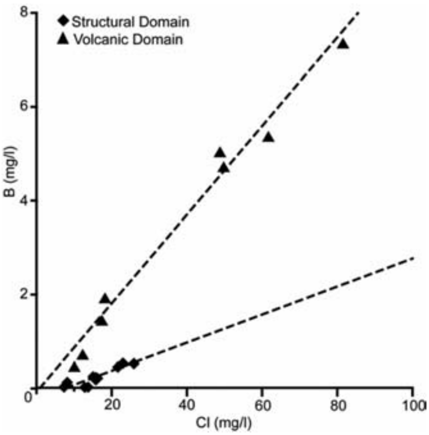

Figure 2. Cl-B relationship shows two distinct domains.

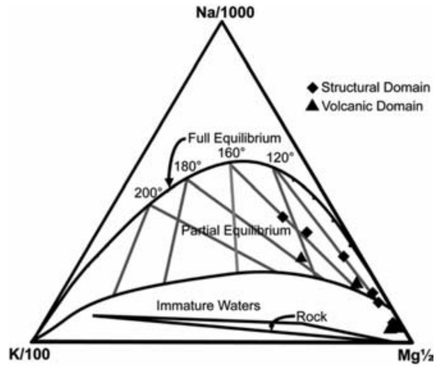

Figure 3. Na-K-Mg diagram (Giggenbach 1988) shows partial equilibrium in most of the cases.

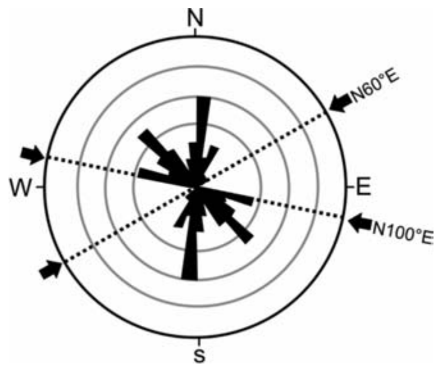

Figure 4. Rosette diagram for the lineaments of higher order representing major structural discontinuities.

rich in CO_2 and H_2S but low in Cl^-, generates bicarbonate-sulphate type waters. The acidity of such water is neutralized and further modified to alkaline by water-rock interaction.

In the case of discharges of the structural domain, infiltrated and percolated meteoric water get heated by convection as well as conduction, after reaching considerable depth. 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

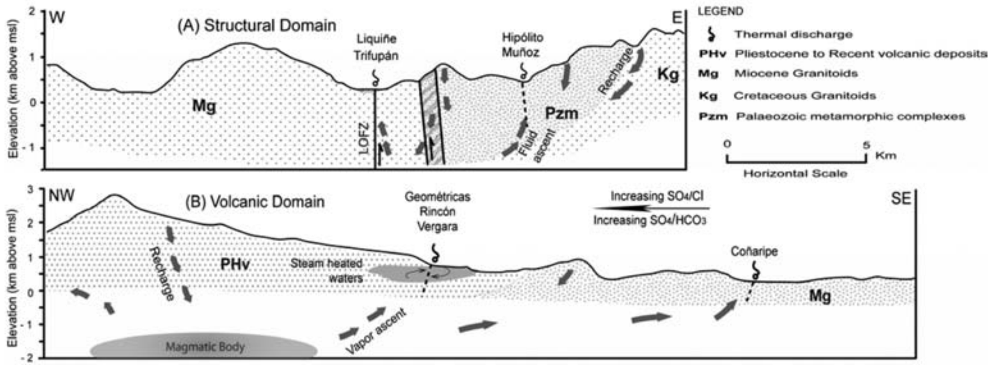

Figure 5. Conceptual model of the geothermal systems for the (a) structural and (b) volcanic domains.

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, 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 (Fig. 5). 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 (Fig. 5), 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.

5 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.

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