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Effects of major fault zones on geothermal reservoirs – a case study at Villarrica Volcano, southern Chile

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ABSTRACT

Near Villarrica volcano, located in southern Chile, a high number of thermal springs indicate moderate geothermal activity with reservoir temperatures between 80 and 140 °C. Although being one of the most active volcanoes in Chile, high temperature geothermal manifestations are not observed. Moreover, the area is characterized by a complex tectonic pattern of two major fault zones intersecting each other.

Geochemical analysis disclose meteoric origin of the water with contributions >60 yrs and recent rain water. Local circulation patterns are characterised by low reservoir temperatures and low dilution along the LOFS and moderate reservoir temperatures and a higher amount of dilution away from the fault zones. A deep water component has not been detected. Strontium isotopy indicates equilibrium between the water and surrounding rock.

Geophysical data indicate mid- and upper crustal conductors that can be attributed to major fault zones. A connection between the structures in the different crustal levels cannot be excluded from geophysical measurements, but geochemical data point to a barrier between deep and meteoric fluids. We can conclude that the active faults govern the geothermal system by controlling the fluid movements in local small-scale circulation pattern.

1. INTRODUCTION

The study area is located in the vicinity of Villarrica Volcano (-39.42°S, -71.94°W) in southern Chile. The Volcano belongs to the Southern Volcanic Zone (SVZ) (Stern, 2004) of the Andes and is one of the most active volcanos in South America, possessing mostly strombolian activity (Ortiz, 2003). The southern part of SVZ is tectonically affected by the 1200 km long N-S striking Liquiñe-Ofqui fault system (LOFS), active under dextral strike-slip movement (Cembrano et al., 1996) induced by maximal horizontal stress of N60°E and sub-horizontal minimal stress (Lavenu and Cembrano, 1999). Stress field is related to the subduction of Nazca plate below the South American plate. In the southern part of SVZ volcanic centres are often located along the trace of LOFS or at secondary faults of NW or NE orientation allowing an accelerated magma ascend (Cembrano and Lara, 2009). In the northern sector of the study area (Figure 1) Holocene monogenetic cones have emerged along the LOFS trace.

Villarrica volcano is part of a NW-SE aligned volcanic lineament consisting of three stratovolcanos, Villarrica-Quetrupíllan-Lanin, with proven historic activity at Villarrica. The volcanic lineament highlights presumably the pre-Andean Mocha-Villarrica fault zone (MVFZ), striking from Chilean costal cordillera till Argentinian basins (e.g. Rapela and Pankhurst, 1992; Zaffarana et al., 2010) crossing the Andean cordillera. Within the research area the LOFS is offset by the MVFZ to the west, indicating sinistral movement (Lopez Escobar et al., 1995).

In the vicinity of Villarrica volcano ascending thermal fluids manifest in of hot springs (Figure 1). South of the Villarrica-Quetrupíllan-Lanin volcanic chain the hot springs follow the trace of LOFS, where north of the volcanos the springs occur more widespread. Reservoir temperature estimations were carried out using sulfate-geothermometry revealing reservoir temperatures of 130-140°C in the north and 80-90°C along the trace of LOFS south of the volcanic chain (Held et al., 2015).

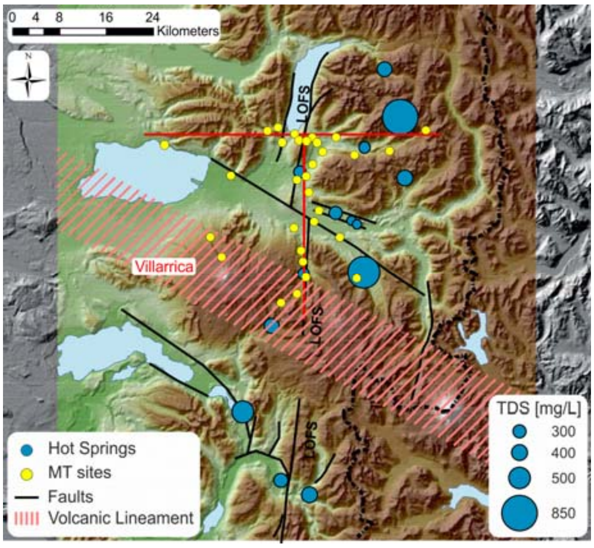

Figure 1: Shaded relief topographic map of the study area next to the Villarrica Volcano. Topography is based on SRTM data from NASA. Local fault zones according to (Lara and Moreno, 2004), (Moreno and Lara, 2008) and (Sánchez et al., 2013). Numbered yellow dots: MT stations, numbered cyan dots: magnetic field stations. MT profiles for inversion marked in red. Hot springs are marked by blue circles, size representing mineralization.

In the present study, we investigate the geothermal potential of the area using geophysical and geochemical methods. Furthermore, we address the question of the influence of the occurring fault zones on the formation of moderate geothermal systems. A multidisciplinary approach was used including among others broad band magnetotelluric measurements to investigate the structural setting as well as geochemical analysis including strontium isotopy and clorofluorocarbon concentration to address aspects on the origin and genesis of the thermal water.

2. GEOCHEMICAL EXPLORATION

Geochemical exploration involves the analysis of 15 samples from thermal waters (Figure 1) with temperature between 27 and 72 °C. For comparison two samples from Lake Pucon and rain water were analysed. Thermal water samples were taken closest to the discharge and in situ measurements such as pH, electric conductivity, temperature and alkalinity were carried out. The pH values are slightly alkaline and geochemical composition is Na-dominated. General low content in total dissolved solids does not exceed 850 mg/L (TDS, Figure 1). Samples were analyzed for cations, anions, trace elements, chlorofluorocarbon (CFC) species and strontium isotopy.

2.1 Strontium isotopy

In addition to the 50 ml water samples, 26 rock samples were analysed. Strontium isotopes signatures of thermal water and selected rock samples are analysed to deduce the reservoir rock. Rock samples were grinded with an agate mill and dissolved using aqua regia. Isotopes were measured with a Thermal Ionization Mass Spectrometer (TIMS) at IsoAnalysis (Berlin) on water and at the University of Tübingen on rock samples.

The results of strontium isotopy analysis are compiled in Figure 2. Strontium isotope signatures between 0.7041 and 0.7174 have been identified for both fluid samples and possible reservoir rocks. Recent volcanic and Cenozoic plutonic units possess isotope ratios <0.7045 typical for mafic rocks (without major Rb substitution in K-bearing minerals) of young age. Increase ratios >0.7045 are observed for plutonic rocks of Mesozoic or Paleozoic. Strontium isotope ratios of the fluids follow the pattern given by the outcropping rocks very closely and indicate relatively local fluid circulation.

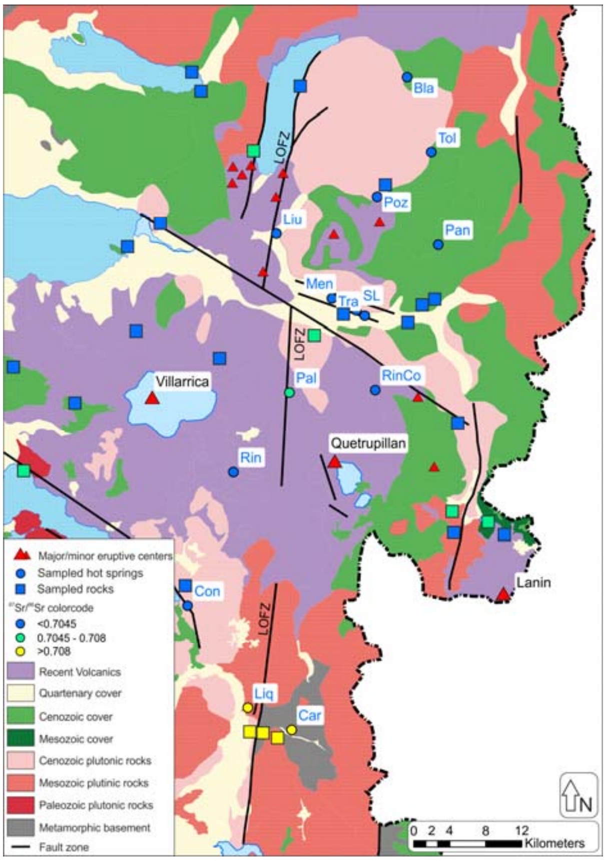

Figure 2: Geological map of study area including strontium isotopy analyses of thermal fluids and selected rock samples. Color code of thermal springs (circles) and rocks (squares) represents the Strontium isotope ratio.

2.2 Chlorofluorocarbons

Anthropogenic tracers with time-depended atmospheric concentrations are used to estimate subsurface residence time as well as shallow dilution by recent meteoric water. Estimation of residence time benefits from the time-depended CFC concentrations in the atmosphere, while dilution bases on the different evolution of the CFC species.

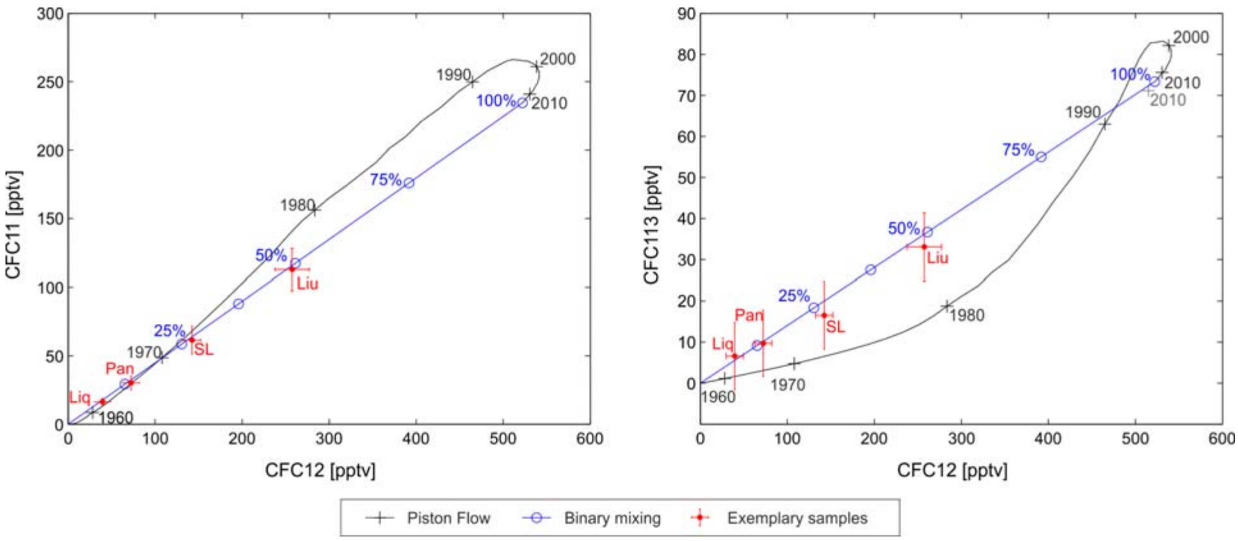

Figure 3: Comparison of CFC concentrations in thermal fluids with atmospheric concentrations assuming piston flow model inside the reservoir. In addition binary mixing between a pre-1940, CFC-free reservoir water, and recent meteoric water are presented.

CFC samples were collected in 1L glass bottles with metal lined caps. Protection from atmospheric contamination bottles was achieved by sealing using tight copper containers. During sampling bottle and cooper container were submerged and filled from inside. CFC analysis were performed at the Spurenstofflabor Dr. Harald Oster, Wachenheim, Germany using a purge and trap gas chromatography with an electron capture detector (GC-ECD).

For comparison with atmospheric concentrations, CFC concentrations of thermal waters were converted using the procedure described by Plummer and Busenberg (2006). Comparison is presented in Figure 3. Atmospheric concentrations (black line) assuming piston flow in the reservoir are compared to concentrations measured in the hot springs (red dots). Distribution of CFC-12 and CFC-113 species (Figure 3) excludes simple piston flow model to be valid for the reservoirs around Villarrica volcano. Instead the thermal fluids plot along a line connecting recent water of meteoric origin with CFC-free waters of pre-1940 age. This line (blue) represents binary mixing between a CFC-free reservoir fluid, leaving atmospheric sphere of influence before 1940, and modern groundwater. Mixing can occur during ascend or at the level of a shallow, secondary reservoir. Note that springs south of the volcanic chain, located along the distinct run of LOFS, reveal lower rates of meteoric dilution than waters from springs north of the volcanic chain.

3. GEOPHYSICAL EXPLORATION

Magnetotelluric (MT) campaigns disclose subsurface conductivity distribution with depth by measuring the electric and magnetic field over a broad frequency range. Geothermally relevant conductivity anomalies in shallow-intermediate depth are best investigated using broad-band frequencies between 10^{-3} and 10^{3} Hz and minimizing inter-station distance above the expected target. They mostly origin from hydrothermal alteration products (clay minerals) or the presence of saline fluid. In Nov.-Dec. 2013 15 MT stations were measured along a profile across the LOFS (Figure 1) with small inter-station distances of about 500 m at the fault zone. MT data were processed and analysed using WinGLink. MT data were inverted for apparent resistivity and phase using 2-D nonlinear conjugate gradients algorithm of Rodi and Mackie (2001) considering TM, TE and vertical magnetic field data. Modelling parameters were set to 5% error for phases compared to a higher error of 15% for apparent resistivity TM and 70% apparent resistivity TE. Smoothing parameter τ was determined to 7.5 using the L-curve technique (Hansen and O'Leary, 1993).

Inversion results of magnetotelluric data are presented in Figure 4 containing three important electromagnetic features: 1) a widespread resistive layer present in both profiles down to a depth of 8-10 km. This rather homogenous layer is interrupted by 2) a narrow <3 km sub-vertical conductor (Con1). Inside the underlying more conductive lower layer a 3) zone of increased conductivity (Con2) can be detected in the eastern part of E-W profile. High conductivities of <20 Ωm are evident also observed by Brasse et al. (2009).

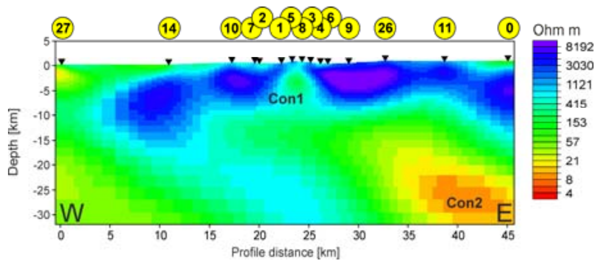

Figure 4: Inversion of MT data along the E-W.

Thus, LOFS can be described as a sub-vertical fault zone. Limitation of LOFS at brittle-ductile-transition cannot be excluded from MT data.

4. DISCUSSION AND CONCLUSION

Geophysical and geochemical results lead to the conceptual model presented in Figure 5. The Liquiñe-Ofqui fault system, displaced by MVFZ, is a sub-vertical, narrow fault zone, presumably developing a flower structure next to Caburgua lake. Thermal springs are mostly located along the run of LOFZ or related secondary fault system. South of the volcanic system, where the hot springs follow the distinct run of LOFZ inside the batholith complex, local circulation along the fault zone without minor meteoric dilution occur, indicated from small scale strontium isotope ratio variations and low binary mixing rates. North of the volcanic lineament, where the batholith is replaced by a more complex pattern of volcanic and volcano-sedimentary units as well as limited plutonic intrusions, subsurface is characterized by a less distinct run of LOFS and a higher amount of secondary fault. As a consequence geothermal fluids mix over broader area, indicated by more homogenous strontium isotopes. Due to the higher number of possible flow path higher dilution rated and high variations of meteoric dilution rates are observed. Hot springs directly related to MVFZ are sparse, only one spring, located north of Quetrupíllan volcano (RinCo), lies in the area affected by MVFZ and cannot be related to LOFS.

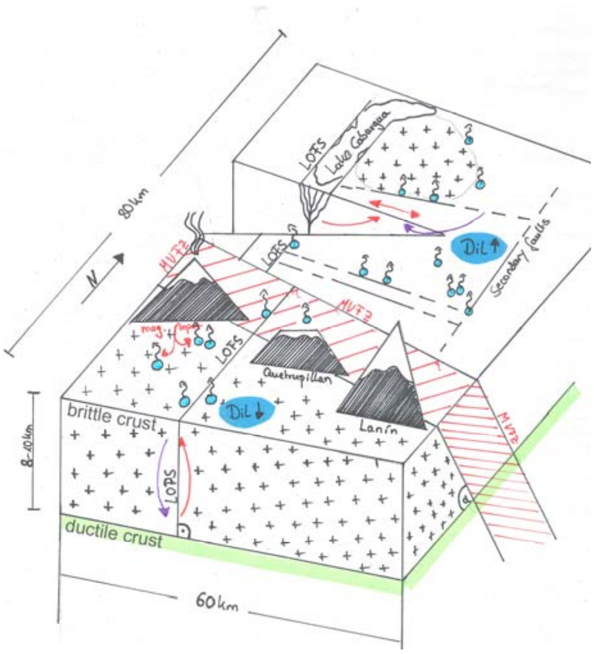

Figure 5: Conceptual model of the study area including results from geophysical and geochemical surveys.

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REFERENCES

Brasse, H., Kapinos, G., Li, Y., Mütschard, L., Soyer, W., and Eydam, D., 2009, Structural electrical anisotropy in the crust at the South-Central Chilean continental margin as inferred from geomagnetic transfer functions: Physics of the Earth and Planetary Interiors, v. 173, no. 1-2, p. 7–16, doi: 10.1016/j.pepi.2008.10.017.

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

Cembrano, J., and Lara, L.E., 2009, The link between volcanism and tectonics in the southern volcanic zone of the Chilean Andes: A review: Tectonophysics, v. 471, doi: 10.1016/j.tecto.2009.02.038.

Hansen, P.C., and O’Leary, D.P., 1993, The use of the L-Curve in the regularization of discrete ill-posed problems: SIAM Journal on Scientific Computing, v. 14, no. 6, p. 1487–1503.

Held, S., Schill, E., Sanchez, P., Neumann, T., Emmerich, K., Morata, D., and Kohl, T., 2015, Geological and Tectonic Settings Preventing High-Temperature Geothermal Reservoir Development at Mt. Villarrica (Southern Volcanic Zone): Clay Mineralogy and Sulfate-Isotope Geothermometry, *in* World Geothermal Congress 2015,.

Hickey -Vargas, R., Moreno-Roa, H., Lopez-Escobar, L., and Frey, F., 1989, Geochemical variations in Andean basaltic and silicic lavas from the Villarrica-Lanin volcanic chain (39.5° S): an evaluation of source heterogeneity, fractional crystallization and crustal assimilation: Contributions to Mineralogy and Petrology, v. 103, no. 3, p. 361–386, doi: 10.1007/BF00402922.

Lara, L.E., and Moreno, H., 2004, Geología del Área Liquine-Neltume: Carta Geológica de Chile - Servicio Nacional de Geológia y Minería,.

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

Lopez Escobar, L., Cembrano, J., and Moreno, H., 1995, Geochemistry and tectonics of the Chilean southern Andes basaltic Quaternary volcanism

(37-46°S): Revista Geologica de Chile, v. 22, p. 219–234.

Moreno, H., and Lara, L.E., 2008, Geología de Àrea Pucón-Curarrehue: Carta Geológica de Chile - Servicio Nacional de Geológia y Mineria,.

Ortiz, R., 2003, Villarrica volcano (Chile): characteristics of the volcanic tremor and forecasting of small explosions by means of a material failure method: Journal of Volcanology and Geothermal Research, v. 128, no. 1-3, p. 247–259, doi: 10.1016/s0377-0273(03)00258-0.

Plummer, L.N., and Busenberg, E., 2006, Chorofluorocarbons in Aquatic Environments, *in* Use of Chlorofluorocarbons in Hydrology : A Guidebooks, International Atomic Energy Agency.

Rapela, C.W., and Pankhurst, R.J., 1992, The granites of northern Patagonia and the Gastre Fault System in relation to the break-up of Gondwana: Geological Society, London, Special Publications, v. 68, no. 1, p. 209–220, doi: 10.1144/GSL.SP.1992.068.01.13.

Rodi, W., and Mackie, R.L., 2001, Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion: Geophysics, v. 66, no. 1, p. 174, doi: 10.1190/1.1444893.

Sánchez, P., Pérez-Flores, P., Arancibia, G., Cembrano, J., and Reich, M., 2013, Crustal deformation effects on the chemical evolution of geothermal systems: the intra-arc Liquiñe–Ofqui fault system, Southern Andes: International Geology Review, v. 55, no. 11, p. 1384–1400, doi: 10.1080/00206814.2013.775731.

Stern, C.R., 2004, Active Andean volcanism: its geologic and tectonic setting: Andean Geology, v. 31, no. 2, p. 161 – 206.

Unsworth, M., 2004, Crustal and upper mantle structure of northern Tibet imaged with magnetotelluric data: Journal of Geophysical Research, v. 109, no. B2, p. B02403, doi: 10.1029/2002JB002305.

Wannamaker, P.E., 1984, Magnetotelluric responses of three-dimensional bodies in layered earths: Geophysics, v. 49, no. 9, p. 1517, doi: 10.1190/1.1441777.

Zaffarana, C.B., López de luchi, M.G., Somoza, R., Mercader, R., Giacosa, R., and Martino, R.D., 2010, Anisotropy of magnetic susceptibility study in two classical localities of the Gastre Fault System, central Patagonia: Journal of South American Earth Sciences, v. 30, no. 3-4, p. 151–166, doi: 10.1016/j.jsames.2010.10.003.