Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Geophysical Characterization of Medium and Low Temperature Geothermal Systems Using MT: an Example of the Villarrica Area

Maximiliano Pavez[1], Eva Schill[1,4], Sebastian Held[2], Daniel Díaz[3], Thomas Kohl[3]

[1]Karlsruhe Institute of Technology, Institute of Nuclear Waste Disposal, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

[2]Karlsruhe Institute of Technology, Institute of Applied Geosciences, Adenauerring 20B, 76131 Karlsruhe, Germany

[3]Departamento de Geofísica, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Blanco Encalada 2002, Santiago, Chile

[4]Technical University Darmstadt, Institute of Applied Geosciences, Schnittspahnstraße 9, 64287 Darmstadt

maximiliano.pavez@partner.kit.edu

Keywords: geophysical characterization, magnetotelluric, geothermal system, Villarrica volcano

ABSTRACT

The mostly untapped geothermal potential in Chile has been estimated to about up to 16 GWel (Lahsen et at., 2010). Besides this potential for electric power, in particular, in southern Chile applications for heat supply from low to medium temperature resources may be beneficial to the development of the rural areas. In this respect, the thermal spring areas around the Villarrica volcano have been investigated geochemically (Held et al., 2018) and geophysically (Held et al., 2016) with the aim to visualize and improve the understanding of such types of reservoirs.

In this study, we combine findings from 3D inversion of magnetotelluric (MT) data. The MT inversion was carried out with the data collected from 31 MT stations that were measured along two profiles, one in an E-W orientation and perpendicular to the branches of the Liquiñe-Ofqui Fault System (LOFS) and a second one in the N-S orientation along the LOFS and sub-perpendicular to an Andean Transverse Fault (ATF) and the Villarrica-Quetrupillán-Lanín volcanic chain. 3D inversion results can be interpreted as two anomalies of maximum electrical conductivity at shallow depth; one of these is located on the eastern branch of LOFS and links to a number of thermal springs and the second maximum is located below the volcanic chain. Additionally, intermediate resistivity minima along the LOFS coincide with the thermal sources and the monogenetic volcanic activity in the northern and the active rise of magma near the volcano in the southern part of the profile.

1. INTRODUCTION

The Andes mountain range is located on an active, compressive plate boundary that has varied in its position over time (Pardo-Casas and Molnar 1987). It controls the volcanic activity and geological structures and generates geothermal systems of different types.

In the south of Chile, the Andes is characterized by a high number of thermal sources of intermediate temperature (Sánchez et al. 2013), bordering volcanic chains and several fault zones and forming a high geothermal potential.It is the case for the area around Villarrica volcano, which we call Villarrica geothermal system, located in the volcanic arc of southern Chile next to the active Villarrica volcano (39.42°S, 71.93°W).

The research area is characterized by major intersection fault zones. The Liquiñe-Ofqui Fault System (LOFS) is a N-S aligned, 1200km long, intra-arc fault system of dextral strike-slip movement (Cembrano et al. 1996). The fault system is intersected in the research area by the WNW-ESE aligned oblique-to-the-arc Mocha-Villarrica Fault Zone (MVFZ) and several small oblique faults, all of them belong to the Andean transversal fault system.

The MVFZ accompanies the N50°W alignment of the main middle Pleistocene to Holocene Villarrica-Quetrupillán-Lanín volcanic chain (Lara et al., 2004). All of these three volcanoes have erupted during Holocene times. Villarrica volcano has a constant and frequent activity with >20 major eruptions per century (Petit-Breuilh & Lobato 1994), being the most active of the volcanic chain. In the vicinity of the volcanic chain >20 geothermal springs discharge (Sanchez et al. 2013, Held et al. 2017) indicate enhanced geothermal potential.

Field geophysical surveys are used to investigate and characterize the morphology of a geothermal system. One of the geophysical methods used to generate a visualization of the geothermally relevant depth is magnetotellurics (MT), which measures the electric and magnetic field variations simultaneously, to obtain information of the resistivity distribution of the subsurface (Simpson and Bahr 2005).

In the Villarrica geothermal system, low resistivity values were associated with fault systems due to the presence of hydrothermal fluid or hydrothermal alteration products such as clay minerals (Held et al. 2016). The objective of this study is to characterize of medium and low temperature geothermal systems along the LOFS using 3D inversion of MT data.

2. MT DATA ACQUISITION AND PROCESSING

Magnetotelluric data were collected by 31 stations along two profiles were orientated perpendicular to the major tectonic features. E-W profile across to the LOFS and N-S crosscuts MVFZ and VCV (Figure 1b).

For MT acquisition, a period band of 10^{-3} - 512s was chosen. The data were processed using the routine by Egbert and Booker (1986). Details of data acquisition, processing and 2D inversion are given by Held et al. (2016).

3. 3D INVERSION

The 3-D inversion of the magnetotelluric data was carried out using the "Modular System for Inversion of Electromagnetic Geophysical Data, ModEM" developed by Kelbert et al. (2014). A subset of the data has been chosen to efficiently use the 3-D inversion program, calculated in 43 periods, logarithmically distributed between 0.0026s and 512s, with 7 periods per decade. All the elements of impedance tensor Z and vertical magnetic component are relevant. In this study, we established a data error of 10% of |ZxyZyx|1/2 and 10% of |TyTx|1/2, starting from a homogeneous half-space of 100 Ωm. A regular grid centered at the crossing of the E-W and N-S profiles was defined. The grid extends over 70 (E-W, positive towards the east) x 90 (N-S, positive towards the north) cells with a uniform size of 500 m x 500 m with 10 padding cells in each direction increasing gradually. To avoid lateral boundary effects, these padding cells with increasing size of the factor 1.3 were added. Topography relief was included using 50 m cells of linear increase up to 2000 m to continue with an increase factor of 1.1.

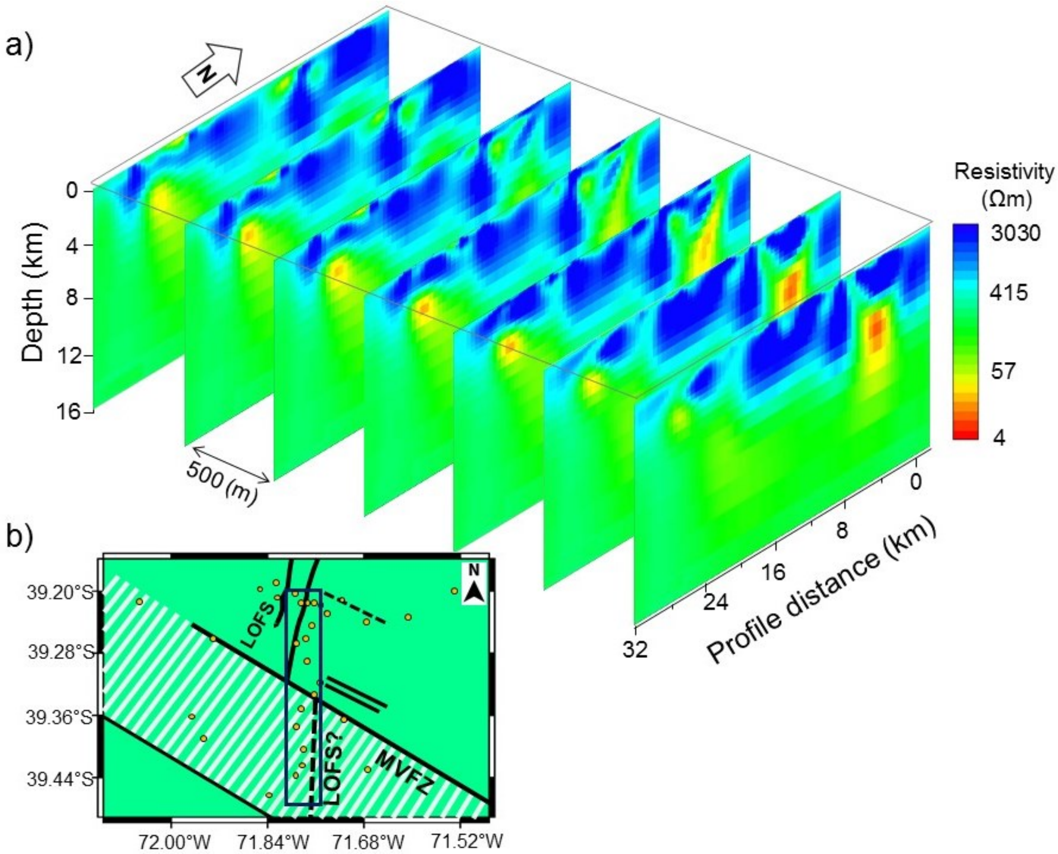

Figure 1: a) Resistivity distribution model of the subsurface from N-S crosscutting section across the major fault zone in the study area including the majority of the measured MT stations. b) Regional overview map showing: Fault traces (black lines); MT stations (yellow dots). LOFS denotes Liquiñe-Ofqui Fault System; MVF, Mocha Villarrica Fault Zone. Blue rectangle indicate the seven sections of the 3-D inversion of magnetotelluric data across the LOFS with an offset of 500 m to each other, including the majority of the measured MT stations.

4. INTERPRETATION

4.1 Resistivity changes

The 3D inversion model shows that largest resistivity changes occur in the near surface down to about 7 km depth. This change in the electric response from highly variable resistivity to a rather homogenous distribution of a few hundreds of Ωm may be associated with the expected brittle-ductile transition zone (Bertrand et al. 2012). Typically, the brittle-ductile transition zone in the Earth's crust occurs between 10 and 15 km Sibson (1990). However, it is well-known from volcanic areas that the upper limit can be influenced by the presence of volcanism. However, at similar depth changes in the magnetic properties were interpreted as the boundary between the upper and middle crust (Hernandez-Moreno et al., 2014).

4.2 Fault zones effects

In the northern part of the N-S section (Figure 1a) two structures with lower resistivity (~100 Ωm) intersect the resistive structures in shallow depth. The larger structure is situated at the location where Cembrano and Lara (2009) located the LOFZ. Thus, enhanced conductivity is associated with effects produced in the fault zone. From the 3D inversion, the LOFZ can be characterized as a sub-vertical fault zone dipping towards while penetrating the ductile lower crust. The smaller conductor can be related to a smaller NW-SE oriented fault zone, located just north to MVFZ, which has been described by Sánchez et al. (2013).

4.3 Volcanic arc influence

In the south of the sections, conductive structure (Figure 1a) with a resistivity < 40 Ωm is identified below the NE slope of the Villarrica volcano at a depth of 4km. Due to the location underneath the Villarrica volcano, this may be associated to the magmatic system being part of a surface reservoir (Morgado et al., 2015). Around to this anomaly, a rim of about 100 Ωm resistivity is observed, that reveals a dip towards to the north. Structurally, this corresponds to the MVFZ.

5. CONCLUSIONS

By means of geophysical characterization that includes the medium and low temperature geothermal systems, we distinguish different anomalies of high electric conductivity along the strike of the LOFS through magnetotelluric measurements. They may be associated to both, tectonic and volcanic features, i.e. the MVFZ in the north of the sections and the expected shallow magma chamber in the south, close to Villarrica-Quetrupillán-Lanín volcanic chain. The brittle-ductile transition zone appears to occur at shallow depth of about 7 km. For future, new MT stations will be deployed in order to provide a full 3D inversion, allowing a complete characterization of this unconventional geothermal system.

REFERENCES

Bertrand, E. A., Caldwell, T. G., Hill, G. J., Wallin, E. L., Bennie, S. L., Cozens, N., ... & Wameyo, P. (2012). Magnetotelluric imaging of upper-crustal convection plumes beneath the Taupo Volcanic Zone, New Zealand. Geophysical Research Letters, 39(2).

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

Cembrano, J., & Lara, L. (2009). The link between volcanism and tectonics in the southern volcanic zone of the Chilean Andes: a review. Tectonophysics, 471(1), 96-113.

Egbert, G., & Booker, J. 1986. Robust estimation of geomagnetic transfer functions. Geophysical Journal International, 87(1), 173–194.

Held, S., Schill, E., Pavez, M., Díaz, D., Muñoz, G., Morata, D., & Kohl, T. (2016). Resistivity distribution from mid-crustal conductor to near-surface across the 1200 km long Liquiñe-Ofqui Fault System, southern Chile. Geophysical Journal International, 207(3), 1387-1400.

Held, S., Schill, E., Schneider, J., Nitschke, F., Morata, D., Neumann, T., & Kohl, T. (2018). Geochemical characterization of the geothermal system at Villarrica volcano, Southern Chile; Part 1: Impacts of lithology on the geothermal reservoir. Geothermics, 74, 226-239.

Hernandez-Moreno, C., Speranza, F., & Di Chiara, A. (2014). Understanding kinematics of intra-arc transcurrent deformation: Paleomagnetic evidence from the Liquiñe-Ofqui fault zone (Chile, 38–41° S). Tectonics, 33(10), 1964-1988.

Kelbert, A., N. Meqbel, G. D. Egbert and K. Tandon (2014), "ModEM: A modular system for inversion of electromagnetic geophysical data", Computers & Geosciences, v. 66, p. 40-53, doi:10.1016/j.cageo.2014.01.010

Pardo-Casas, F., Molnar, P., 1987. Relative motion of the Nazca (Farallon) and South American plates since late Cretaceous time. Tectonics 6, pp. 233-248.

Petit-Breuilh, M., & Lobato, J. (1994). Análisis comparativo de la cronología eruptiva histórica de los volcanes Llaima y Villarrica (38-39 LS). In Congreso Geológico Chileno (No. 7, pp. 366-370).

Sánchez, P., Pérez-Flores, P., Arancibia, G., Cembrano, J. & Reich, M.,2013. Crustal deformation effects on the chemical evolution of geothermal systems: the intra-arc Liquiñe–Ofqui fault system, Southern Andes, Int. Geol. Rev., 55(11), 1384–1400.

Sibson, R. H. (1990). Conditions for fault-valve behaviour. Geological Society, London, Special Publications, 54(1), 15-28.

Simpson, F., & Bahr, K. 2005. Practical magnetotellurics. Cambridge University Press. R.N.: Boiling Flow in a Horizontal Fracture, Geothermics, 29, (1999), 759-772.