**A Review of the Geodynamics Constraints on Central Andean Volcanic Zone (18º-28ºLat.S): Implications for the Development and Evolution of High-Enthalpy Geothermal Systems**

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**Supplementary Material**

Main characteristics of known/identified geothermal systems in the CAVZ

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| --- | --- | --- | --- | --- |
| Host-rock | Associated Volcano (quaternary activity unless stated) | Local Structures and Tectonics | Geothermal Manifestations, Water and Reservoir Temperatures and associated structures | References |
| Tacora (-17.698; -69.282) |
| Conglomerates, sandstones, shales and ignimbrites | Tacora | NW-trending left-lateral strike-slip faults, and minor compressional components (perhaps anachronic) | Outflow gas with temperatures between 82-93ºC; fumarolic field at the flank of the volcano; reservoir temperature calculated to be 270-310ºC. Other hot water manifestations (superficial) have temperatures of about 40ºC as acid-sulfate waters  | Salas et al., 1966; David, 2007; Capaccioni et al., 2011; Contreras, 2013. |
| Colpitas (-17.954; -69.440) |
| Rhyolitic ash flows, andesitic lavas and epiclastic sandstones interbedded with ash layers | Tacora and Lexone, plus several NW- and NNE-trending aligned volcanic centers | NW-trending left-lateral strike-slip and normal and thrust faults, NNE-to-NE trending normal faults, sharing the same orientation of folds and faults affecting (regionally) Miocene rocks | Water surface manifestations between 20ºC and (bubbling at) 55ºC, located along NW-trending structures (N20º-40ºW), and associated with the Tacora volcanic edifice; Chloride waters on northern and southern springs; Reservoir equilibrium temperatures about 200º-235ºC. Compositional trends indicate mixing of water brines. Heat source located most probably near the south flank of Lexone volcano | Garcia et al., 2004; Aguirre et al., 2011; Navarrete, 2012. |
| Jurase (-18.201; -69.530) |
| ¿? | Taapaca (?) | Thrust faults of the WVS located west of the geothermal field, and NW-trending lineaments and small faults | Hot springs of 65ºC, hydrothermal alteration and silica sinters. Thermal waters with pH of 7.04; SO4-Na waters and high Boron concentrations (up to 1350 mg/L) in thermal springs | Dias, 1983; Hauser, 1997; Chong et al., 2000; Farías et al., 2005; Tassi et al., 2008; Risacher et al., 2011; |
| Surire (-18.917; -68.983) |
| ¿? | Polloquere | Mostly covered yet associated with NNW trending anticlinal hinges of the WVS. NW-tending faults show left-lateral strike-slip displacements | Thermal discharges not clearly associated with N-to-NW-trending anticlinal hinges and thrust faults in the area (WVS), as well as NW-trending lineaments; Reservoir temperatures about 230ºC | Cusicanqui, 1979; Farías et al., 2005; Tassi et al., 2010 |
| Licancura (-19.141; -69.169) |
| Ignimbrites and andesitic volcani-clastic deposits | Isluga (?) | NW-trending left-lateral faults, N-to-NNW trending thrust faults (WVS?) and minor NE-trending faults | Hot and cold water discharges spatially associated with river and gullies that follow the direction of the main structures in the area, mostly along NW-trending faults and at the crossing of NW- and N-trending lineaments | Veloso et al., 2016; Maureira, 2013 |
| Berenguela (-19.247; -69.177) |
| Ignimbrites (?) | Isluga (?) | Mainly NNW-to-NW trending thrust faults (?) as well as right-lateral (?) NE-trending faults | Water discharges about 59ºC with pH 6.6, probably mixing between hydrothermal fluids and meteoric waters | Maureira, 2013 |
| Puchuldiza (-69.015; -19.382) |
| ¿? | Isluga  | NW-trending left-lateral strike-slip, NE-trending (right-lateral?) and NS-to-NNW-trending normal (?) faults | Constant fumarolic activity with associated bubbling and mud pools, thermal springs and geysers. Water discharges probably controlled by N-, NW- and NE-trending faults, on where thermal manifestations are spatially associated mostly with the intersection of N- and NW-trending faults; Deep temperatures (ca. 900m depth) of about 166ºC, and estimated reservoir temperatures of 210º-220ºC | Letelier, 1981; JICA, 1981; Céspedes et al., 2004; Tassi et al., 2010; Mahon and Cusicanqui, 1980. |
| Pampa Lirima (-19.851; -68.934) |
| Volcanic and sedimentary rocks covered by volcanic products and edifices | None (?) | NS-, NW-, and NE-trending faults | Water pools with temperatures between 38º-80ºC (pH 7.4); geothermal manifestations located on top of NW-trending lineaments; N-, NW- and NE-trending faults recognized on ZTEM surveys. There is a recognized conductive layer at >500-1000 m depth representing a clay-cap horizon. Reservoir temperatures estimated at 200ºC | Arcos et al., 2011; Legault et al., 2012; Procesi, 2014; Nicolau et al., 2015. |
| Salar de Empexa (-20.361; -68.612) |
| Volcanic and sedimentary rocks covered by volcanic products and edifices | None (?) | NW-to-NNW trending normal faults, with small strike-slip displacements | Water thermal manifestations of about 88ºC, as well as a sulfur mine pit. Depth temperatures of 125ºC (60-165m); presence of sulfated water; Geothermal manifestations along NE-trending lineaments, commonly close or in the intersection of NE- and NW-trending lineaments. Reservoir temperature of 230º-240ºC, however, based on water chemistry is of 180ºC | Scandiffio and Cassis, 1992; Risacher and Fritz, 2009; JOGMEC et al., 2011; Ramos, 2015; Bona and Coviello, 2016. |
| Irruputuncu (-20.728; -68.581) |
| Ignimbrites | Irruputuncu | NW-trending lineaments probably associated with left-lateral/normal displacements | Permanent deposition of sulfur and gas emissions with SO2 as the main phase; outlet temperatures between 83º and 240º with highly concentrated SO2, H2S and abundant HCl, N2, HF, O2 y CH4; Volcanic craters at the summit are NW-SE aligned as well as hot springs and fumaroles; Reservoir temperature of >220ºC | Vergara and Thomas, 1984; Naranjo, 1985; Clavero et al., 2006; Reyes et al., 2011; Tassi et al., 2011; Rodriguez et al., 2015. |
| Olca (-20.940; -68.485) |
| Andesitic lava flows | Olca | Olca volcano lies on the westernmost end of an E-trending chain of Holocene volcanoes. Regional pattern dominated by N-to-NW-trending structures as well as local E-trending structures | Fumaroles at the crater and at a single warmspring at the base of the Olca volcano. Few geothermal manifestations aligned NW-SE. Estimated reservoir temperature of 230º-300ºC. Small native sulfur mining pits | Reyes et al., 2011; Gardeweg and Salas, 2011; Reyes et al., 2011. |
| Cerro Pabellón (-21.883; 68.119) |
| Eroded andesitic to dacitic stratovolcanoes and a series of younger porphyritic dacite domes and flows | San Pedro-San Pablo  | NNW-trending normal faults hosting a series of eroded volcanoes and young lava domes | Fumaroles with high steam-discharge in summit of Cerro Apacheta with 109º and 118ºC (superheated). Some water wells have bubble gas. Structures form a geomorphological graben ca. 3-5km wide (Pabelloncito graben), part of the NW-trending Paniri-Inacaliri-Azufre lineament. Reservoir temperature calculated at >320ºC with significant amounts of gas derived from a geothermal reservoir. Superficial alterations are clay and native sulfur around fumaroles and silica veins. | Francis and Rundle, 1976; Urzúa et al., 2002; Godoy et al., 2017. |
| El Tatio (-22.383; -67.994) |
| Ignimbrites, tuffs and lavas, covered by Holocene deposits  | Putana (?) (Uturuncu?) | NW-trending lineaments and N-trending normal/thrust (?) faults forming a geomorphological half-graben structure | Thermal manifestations developed in the hanging wall of N-trending half-graben. Surface thermal activity is mostly restricted to geysers, hot pools, fumaroles, mudpots, sinter aprons, salt incrustations and growth of microbes. Temperature at 600m depth is 253ºC. Most vents and thermal manifestations occur along N-to-NNE- and NW-trending lineaments. Discharged thermal waters at geysers have high Cl, Na, SiO2 and As and low SO4 concentrations. Water chemistry indicates complex mixing process between magmatic, meteoric and hydrothermal sources. Gas chemistry is dominant in CO2, N2, H2S and CH4. Increased fracturing on ignimbrite layers. MT surveys suggest a magmatic intrusion at 5-7 km depth | Ellis, 1969; Lahsen and Trujillo, 1975; Cusicanqui et al., 1976; Schwartz et al., 1984; Muñoz and Hamza, 1993; Cortecci et al., 2005; Tassi et al., 2005; Lucchi et al., 2009; Nicolau et al., 2014; Muñoz-Saez et al., 2015; Muñoz-Saez et al., 2018. |
| Sol de Mañana (-22.427; -67.819) |
| Ignimbrites, andesitic-dacitic lava sequences | Putana (?) Uturuncu (?) | NNW-trending faults forming small grabens and horsts, with measured seismic activity, and a second system with NNE- trending orientation | Fluids transported upwards through NNW- and NNE-trending fracture mesh. Surface manifestations along NNE-trending (?) faults and lineaments. Mature waters with neutral pH and high chloride concentration. Reservoir temperature between 280º-250ºC, located at a depth of ca. 800-900m. Springs in the area indicate mixture with cold groundwater. MT data indicates low resistivity areas related to the occurrence of a cap rock. Gravity and resistivity data indicate reservoir should be located within the fracture mesh | ENEL, 1991; Delgadillo and Puente, 1998; Cortecci et al., 2005; Villarroel, 2014; Ramos, 2015; Ramos, 2015; Bona and Coviello, 2016. |
| Tilocalar (-23.958; -68.117) |
| Ignimbrites | Possibly associated with Lascar, Miscanti or Aguas Calientes volcanoes | N-trending thrust faults and folds and scarce NW-trending lineaments | Scarce hot water manifestations commonly located at the hinges of N-trending folds (axes) or at the foot of N-trending thrust faults. Discrete water manifestations along N-trending thrust faults and at the intersection of these with NW-trending faults | Kuhn, 2002; Gonzalez et al., 2009. |
| Lazufre (-25.187; 68.533) |
| Andesitic-to-dacitic lava flows and domes, and dacitic ignimbrites | Lastarria | Mostly NW-trending lineaments and faults. Some minor occurrences of NE-trending and N-trending lineaments and faults, mostly bounded by NW-trending faults and lineaments | Geothermal manifestations on the flanks and summit of Lastarria volcano aligned NW-ward. Fumarolic fields with temperatures ranging between 80º-408ºC. Isotopic ratios on fumarolic gases are diagnostic of magmatic gas source. MT surveys indicate a conductive zone at 6km depth south of Lastarria volcano and interpreted as a magmatic heat source connected to a shallow conductor beneath the volcano | Naranjo and Cornejo, 1992; Aguilera et al., 2012; Diaz et al., 2015. |
| Juncalito (-26.534; -68791) |
| ¿? | Los Cuyanos-Sierra Nevada Volcanic Complex | NW-trending lineaments as well as N-trending thrust faults. Southward of the area, a series of subparallel ENE-trending lineaments are present | Five different thermal manifestations, with temperatures between 18-25º and 32-42ºC. Estimated reservoir equilibrium temperature of 160ºC. Thermal anomalies spatially associated with NNE- and N-trending faults and lineaments | Clavero et al., 1998; Mayorga, 2011; Lira et al., 2011. |
| Ojos del Salado (-27.081; -68.967) |
| Basaltic andesites, dacites and rhyolites | Spatially associated with the El Solo-Ojos del Salado-Tipas volcanic complex as well as with the Whellwright Caldera | N-to-NNE-trending thrust faults cut and displaced by NW-trending normal-left-lateral faults and lineaments, as well as a series of ENE-trending faults (left-lateral?) | Manifestations occur between two NW-trending, west-dipping normal-left-lateral faults | Baker et al., 1987; SERNAGEOMIN, 2003. |
| Uturuncu (-22.207; -67.233) |
| Ignimbrites | Uturuncu volcanic center, plus several calderas in the area (e.g. Panizos, Vilama and Coruto) | NW-trending normal-left-lateral faults of the Olacapato-El Toro-Calama lineament | Two active sulfur fumarole fields located near the summit of Uturuncu volcano, with temperatures slightly below 80ºC, spatially associated with the NW-trending normal (left-lateral) faults that of the Lipiz-Coranzuli (or Pastos Grandes-Cojina) lineament. Volcanic-tremors are aligned NW-ward. Five large domes outside the current dual-summit of Uturuncu volcano are approximately NE-SW aligned. Calculations suggests that heat flow at Uturuncu is larger than 200 mW/m2 | Sparks et al., 2008; Salisbury et al., 2011; Jay et al., 2012; Muir et al., 2015. |
| Tuzgle (-24.017; -66.543) |
| Ignimbrites | Tuzgle | N-to-NNE-trending thrust faults belonging to the Andean Foreland and NW-normal-left-lateral faults. NW-trending faults displace and deform (drag-folds) N-to-NNE-trending thrust faults | Fumaroles, water and water plus gases discharges. Fumaroles and other thermal manifestations are slightly NW-ward aligned. Field survey indicates that EW-to-NW trending structures favor upward fluid flow. Alkaline-chlorine type waters, with water temperatures between 21º-56ºC. Geothermal manifestations are rich in SiO2, SO4 and CO3 with a magmatic signature. Geoelectrical and MT surveys suggest the presence of a geothermal reservoir between 50-300m depth and with a variable thickness between 100-600m. A possible second, deeper, reservoir would be located at ca. 2km depth. Reservoir temperatures estimated between 134º and 143ºC | Aquater, 1980; Coira, 1995; Sainato and Pomposiello, 1997; Ferreti, 1998; Bonali et al., 2012; Giordano et al., 2013; Norini et al., 2013. |
| Tocomar (-24.233; -66.468) |
| Ignimbrites | Tuzgle Volcano ? | NNW-trending normal and left-lateral faults of the Calama-Olacapato-El Toro lineament | Hot and cold springs along the NW-trending faults | Giordano et al., 2013 |
| Antofalla (-26.104; -67.493) |
| Volcani-clastic deposits (?) | Antofalla Volcanic field as well as with the Cerro Blanco Caldera | N/A | N/A | Matteini et al., 2002; Gamonal, 2007; Richards et al., 2006; Tibaldi et al., 2009 |

References Cited

*Aguilera, F., Tassi, F., Darrah, T., Moune, S and Vaselli, O. 2012. Geochemical model of a magmatic-hydrothermal system at the Lastarria volcano, northern Chile. Bulletin of Volcanology 74, 119-134.*

*Aguirre, I., Clavero, J., Simmons, S., Giavelli, A., Mayorga, C. and Soffia, J. 2011. Colpitas - a new geothermal project in Chile. Geothermal Resources Council Transactions 35, 1141-1145.*

*Aquater. 1980. Exploración geotérmica en el área del Cerro Tuzgle, Provincia de Jujuy, República Argentina, estudio de prefactibilidad inédito, Secretaria de Minería de la Provincia de Jujuy, 123pp.*

*Arcos, R., Clavero, J., Giavelli, A., Simmons, S., Aguirre, I., Martini, S., Mayorga, C. ,Pineda, G., Parra, J. and Soffia, J. 2011. Surface exploration at Pampa Lirima geothermal project, Central Andes of northern Chile. Geothermal Resources Council Transactions 35, 689-693.*

*Baker, P., González-Ferran, O. and Rex, D. 1987. Geology and geochemistry of the Ojos del Salado volcanic region, Chile. Journal of the Geological Society of London 144, 85-96*

*Bona, P. and Coviello, M. 2016. Valoración y gobernanza de los proyectos geotérmicos en América del Sur: Una propuesta metodológica. Documentos de Proyecto, Naciones Unidas, Santiago, 176pp.*

*Bonali, F., Corazzato, C. and Tibaldi, A. 2012. Elastic stress interaction between faulting and volcanism in the Olacapato-San Antonio de Los Cobres area (Puna plateau, Argentina). Global and Planetary Change 90-91, 104-120*

*Capaccioni, B., Aguilera, F., Tassi, F., Darrah, T., Poreda, R. and Vaselli, O. 2011. Geochemical and isotopic evidences of magmatic inputs in the hydrothermal reservoir feeding the fumarolic discharges of Tacora volcano (northern Chile). Journal of Volcanology and Geothermal Research 208, 77-85*

*Céspedes, L., Clavero, J. and Cayupi, J. 2004. Hazard management at Isluga volcano, Northern Chile: preliminary results. IAVCEI General Assembly, Pucón, Chile, 11447-a.*

*Chong, G., Pueyo, J. and Demergasso, C. 2000. Los yacimientos de boratos de Chile. Revista geológica de Chile 27, 99-119.*

*Clavero, J., Gardeweg, M. and Mpodozis, C. 1998, Mapa Geológico Preliminar del Area del Salar de Piedra Parada, Escala 1:100.000, Región de Atacama. Servicio Nacional de Geología, Chile.*

*Clavero, J., Pocoaca, G., Godoy, B., Godoy, E. and Rojas, C. 2006. Influencia del sustrato en el transporte y emplazamiento de la avalancha del volcán Tata Sabaya, Andes Centrales. XI Congreso Geológico Chileno, Actas 2, 439-442.*

*Coira B. 1995. Cerro Tuzgle Geothermal Prospect, Jujuy, Argentina. World Geothermal Congress Transactions 2, 1161-1165.*

*Contreras, A. 2013. Caracterización de la mineralogía de alteración hidrotermal en superficie del volcán Tacora y sus alrededores, Región de Arica y Parinacota. Universidad de Chile [Undergraduate Thesis], 89pp.*

*Cortecci, G., Boschetti, T., Mussi, M., Herrera-Lamelli, C., Mucchino, C. abnd Barbieri, M. 2005. New chemical and original isotopic data on waters from El Tatio geothermal field, northern Chile. Geochemical Journal 39, 547-571.*

*Cusicanqui, H., Mahon, W. and Ellis, A. 1976. The geochemistry of the El Tatio geothermal field, northern Chile. Proceedings of the 2nd United Nations Symposium on Geothermal Fields, Berkeley, California, 140-156.*

*Cusicanqui, H. 1979. Estudio geoquímico del área termal de Surire - provincia de Arica - I Región, Technical Report Comité Geotérmico CORFO, Santiago.*

*David, C. 2007. Comportamiento actual del ante-arco y del arco del codo de Arica en la orogénesis de Los Andes Centrales. Ph.D. Thesis, Universidad de Chile, 299p.*

*Delgadillo, T. and Puente, G. 1988. The Laguna Colorada (Bolivia ) Proyect: A Resevor Engineering Arsessment*

*Días, F. 1983. Present state of geothermal research and development in Chile. Technical Report Servicio Nacional de Geología y Minería, Santiag, Chile.*

*Diaz, D., Heise, W. and Zamudio, F. 2015. Three-dimensional resistivity image of the magmatic system beneath Lastarria volcano and evidence for magmatic intrusion in the back arc (northern Chile). Geophysical Research Letters, 42, 5212-5218, doi:10.1002/2015GL064426.*

*Ellis, A. 1969. Survey for geothermal development in Northern Chile. Preliminary geochemistry report, El Tatio geothermal field. UNDP-Report.*

*ENEL. 1991. Estudio de Factibilidad Geotérmica en el área de Laguna Colorada. Informe Inédito*

*Farías, M., Charrier, C., Comte, D., Martinod, J. and Hérail, G. 2005. Late Cenozoic deformation and uplift of the western flank of the Altiplano> Evidence from the depositional, tectonic, and geomorphologic eolution and shallow seismic activity (northern Chile at 19º30´S). Tectonics 24, TC4001, doi:10.1029/2004TC001667*

*Ferretti, J., 1998. Caracterización de las Fuentes termales asociadas a los complejos volcánicos Quevar-Cerro Verde-Aguas Calientes. Relevamiento e interpretación de datos gravimétricos y geoeléctricos. Informe Final, FOMEC-Universidad Nacional de Salta, (inédito), Salta, 123pp.*

*Francis, P. and Rundle, C. 1976. Rates of production of the main magma types in the Central Andes. Geological Society of America Bulletin 87, 474-480.*

*Gamonal, S. 2007. Volcanic stratigraphy and epithermal mineralization of the La Coipa district, Maricunga Belt, Chile. Universidad de Chile, Santiago [Master’s thesis].*

*García, M., Gardeweg, M., Clavero, J. and Hérail, G. 2004. Hoja Arica, Región de Tarapacá. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 84, 150 p.*

*Gardeweg, M. and P. Salas. 2011. Estudio Geológico-Estructural sector volcán Irruputuncu, Región de Tarapacá, Chile. A report prepared for Collahuasi, Aurum Consultores. 119 pp.*

*Giordano, G., Pinton, A., Cianfarra, P., Baez, W., Chiodi, A., Viramonte, J., Norini, G. and Gropelli, G. 2013. Structural control on geotermal circulation in Cerro Tuzgle-Tocomar geotermal volcanic área (Puna plateau, Argentina). Journal of Volcanology and Geothermal Research 249, 77-94*

*Godoy, B., Wörner, G., Le Roux, P., de Silva, S., Parada, M.A., Kojima, S., González-Maurel, O., Morata, D., Polanco, E., and Martínez, P., 2017. Sr- and Nd- isotope variations along the Pleistocene San Pedro – Linzor volcanic chain, N. Chile: Tracking the influence of the upper crustal Altiplano-Puna Magma Body. Journal of Volcanology and Geothermal Research, 341, 172-186.*

*González, G., Cembrano, J., Aron, F., Veloso, E. and Shyu, B. 2009. Coeval compressional deformation and volcanism in the Central Andes, case studies from northern Chile (23ºS-24ºS). Tectonics 28, doi: 10.1029/2009TC002538*

*Hauser, A. 1997. Catastro y catacterización de las fuentes de aguas minerales y termales de Chile. Servicio Nacional de Geología y Minería 50, Santiago.*

*Jay, J., Pritchard, M., West, M., Christensen, D., Haney, M., Minaya, E., Sunagua, M., McNutt, S., and Zabala, M. 2012. Shallow seismicity, triggered seismicity, and ambient noise tomography at the long-dormant Uturuncu volcano, Bolivia. Bulletin of Volcanology 74, 817-837, doi:10.1007/s00445-011-0568-7.*

*JICA. 1981. Report on Geothermal Power Development in Puchuldiza Area, Republic of Chile. March 1981.*

*JOGMEC, Sumitomo Corporation, Mitsubishi Corporation, Nittetsu Mining Consultants CO, Ltd. 2011. Estudio sobre Recurso Geotérmico para Suministro de Calor y Energía en la Región de Uyuni del Estado Plurinacional de Bolivia. Reporte Final. Estudio de Proyectos de Infraestructura de Iniciativa Privada en Países en Desarrollo en el Año Fiscal 2010. Report prepared for Ministry of Economy, Trade and Industry. www.meti.go.jp/meti\_lib/report/2011fy/ E001624.pdf.*

*Kuhn, D. 2002., Fold and thrust belt structures and strike-slip faulting at the SE margin of the Salar de Atacama Basin, Chilean Andes, Tectonics, 21(4), 1026, doi:10.1029/2001TC901042.*

*Lahsen, A. and Trujillo, P. 1975. El Tatio Geothermal Field. Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, California, 157-178.*

*Legault, J., Lombardo, S., Zhao, S., Clavero, J., Aguirre, I., Arcos, R. and Lira, E. 2012. ZTEM airborne AFMAG EM and ground geophysical survey comparisons over the Pampa Lirima geothermal field in northern Chile – a) Z-axis tipper electromagnetic system. Geothermal Resources Council Transactions 36, 1001-1008.*

*Letelier, M. 1981. Geoquímica de las manifestaciones termales de Puchuldiza y sus alrededores. Technical Report Comité Geotérmico CORFO, Santiago.*

*Lira, E. 2011. Estudio de sismicidad, tomografía sísmica y modelo de física de rocas: Potencial sistema geotermal asociado al complejo volcánico Tinguiririca. Universidad de Chile, Santiago [Master’s thesis].*

*Lucchi, F., Tranne, C., Rossi, P. Gallardo, C. De Astis, G. and Pini, G. 2009. Volcanic and tectonic history of the El Tatio area (central Andes, northern Chile): Explanatory notes to the 1:50,000 scale geological map. In: Rossi, P (ed.), Geological constraints on the onset and evolution of an extreme environment: The Atacama area. GeoActa Special Publication 2, 1-29.*

*Mahon, W. and Cusicanqui, H. 1980. Geochemistry of the Puchuldiza and Tuja hot springs, Chile. New Zealand Journal of Science 23, 149-159.*

*Matteini, M. Mazzuoli, R., Omarini, R., Cas, R. and Maas, R. 2002. Geodynamical evolution of Central Andes at 24ºS as inferred by magma composition along the Calama-Olacapato-El Toro transversal volcanic belt. Journal of Volcanology and Geothermal Research 118, 205-228.*

*Maureira, G. 2013. Alteración Hidrotermal y Geoquímica de las Aguas Termales en el Área de la Concesión Geotérmica Licancura III, I Región de Tarapacá, Chile. Tesis de Licenciatura. Universidad de Chile, 125pp.*

*Mayorga, C. 2011. Geoquímica de Fluidos del área de Juncalito, Proyecto Juncalito. Energía Andina S.A., Unpublished, Chile, 26p.*

*Muir, D., Barfod, D., Blundy, J. Rust, A., Sparks, R. and Clarke, K. 2015. The temporal record of magmatism at Cerro Uturuncu, Bolivian Altiplano. In: Caricchi, L. and Blundy, J. (eds.) Chemical, Physical and Temporal Evolution of Magmatic Systems, Geological Society of London Special Publications 422, doi: 10.1144/SP422.1*

*Muñoz, M. and Hamza, V. 1993. Heat flows and temperature gradients in Chile. Studia Geophysica et Geodaetica 37(3), 315-348, doi: 10.1007/BF01624604.*

*Muñoz-Saez, C., Manga, M., Hurwitz, S., Rudolph, M., Namiki, A. and Wang, C. 2015. Dynamics within geyser conduits, and sensitivity to environmental perturbations: Insights from a periodic geyser in the El Tatio geyser field, Atacama Desert, Chile. Journal of Volcanology and Geothermal Research 292, 41-55.*

*Muñoz-Saez, C., Manga, M. and Hurwitz, S. 2018. Hydrothermal discharge from the El Tatio basin, Atacama, Chile. Journal of Volcanology and Geothermal Research 361, 25-35.*

*Naranjo, J. and Cornejo, P. 1992. Hoja Salar de la Isla, Carta Geológica de Chile 72 escala 1:250.000. Servicio Nacional de Geología y Minería, Chile.*

*Naranjo, J. 1985. Sulphur flows at Lastarria volcano in the North Chilean Andes. Nature 313, 778-780.*

*Navarrete, Á., 2012. Origen y comportamiento del CO2 difuso del suelo en los sistemas geotérmicos de Juncalito (68◦55`–68◦38`20``W y 26◦25`–26◦31`30``S,Región de Atacama) y Colpitas (69◦29`30``–69◦23`30``W y 17◦50`30``S–18◦S,región de Arica y Parinacota), Chile. Bachelor thesis, Departamento de Geología, Universidad de Chile, 132 pp. http://www.tesis.uchile.cl/handle/2250/112064.*

*Nicolau, C., Blank, J. and Clavero, J. 2015. PaleoEnvironmental Conditions Revealed by Fossil and Geochemical Features at Pampa Lirima, a High Altitude Geothermal System in the Andes. American Geophysical Union Fall Meeting 2015, V13C-3153.*

*Nicolau, C., Reich, M. and Lynne, B. 2014. Physico-chemical and environmental controls on siliceous sinter formation at the high-altitude El Tatio geothermal field, Chile. Journal of Volcanology and Geothermal Research 282, 60-76, doi: 10.1016/j.jvolgeores.2014.06.012.*

*Norini, G., Baez,W., Becchio, R., Viramonte, J., Giordano, G., Arnosio, M., Pinton,A. and Groppelli, G. 2013. The Calama–Olacapato–El Toro Fault System in the Puna Plateau, Central Andes: geodynamic implications and stratovolcanoes emplacement. Tectonophysics 608, 1280-1297.*

*Procesi, M. 2014. Geothermal potential evaluation for northern Chile and suggestions for new energy plans. Energies 7, 5444-5459, doi:/10.3390/en7085444.*

*Ramos, P. 2015. Well data analysis and volumetric assessment of the Sol de Mañana geothermal field, Bolivia. United Nations University, Geothermal Training Programme, Reports (30).*

*Reyes, N., Vidal, A., Ramirez, E, Arnason, K., Richter, B., Steiingrimson, B., Acosta, O. and Camacho, J. 2011. Geothermal exploration at Irruputuncu and Olca volcanoes: Pursuing sustainable mining development in Chile. GRC Transactions 35, 983-986.*

*Richards, J., Ullrich, T. and Kerrich, R. 2006. The late Miocene-Quaternary Antofalla volcanic complex, southern Puna, NW Argentina: Protracted history, diverse petrology, and economic potential. Journal of Volcanology and Geothermal Research 152, 197-239.*

*Risacher, F. and Fritz, B. 2009. Origin of salts and brine evolution of Bolivian and Chilean Salars. Aquatic Geochemistry 15, 123-157.*

*Risacher, F., Fritz, B. and Hauser, A. 2011. Origin of components in Chilean thermal waters. Journal of South American Earth Sciences 31, 153-170.*

*Rodriguez, I., Roche, O., Moune, S., Aguilera, F., Campos, E. and Pizarro, M. 2015. Evolution of Irruputuncu volcano, central Andes, northern Chile. Journal of South American Earth Sciences 63, 385-399.*

*Sainato, C. and Pomposiello, M. 1997. Two-dimensional magnetotelluric and gravity models of the Tuzgle volcano zone (Jujuy province, Argentina). Journal of South American Earth Sciences 10 (3-4), 247-261.*

*Salisbury, M., Jicha, B., de Silva, S., Singer, B., Jiménez, N. and Ort, M. 2011. 40Ar/ 39Ar chronostratigraphy of Altiplano-Puna volcanic complex ignimbrites reveals the development of a major magmatic province. Geological Society of America Bulletin 123, p. 821-840, doi:10.1130/B30280.1.*

*Scandiffio, G. and Cassis, W. 1992. Geochemical report on the Empexa geothermal area, Bolivia. Estudios Geotérmicos con Técnicas Isotópicas y Geoquímicas en América Latina, 115-139, IAEA-TECDOC 641, Vienna.*

*Schwarz, G., Chong, G., Krüger, D., Martinez, E., Massow, W., Rath, V. and Viramonte, J. 1994. Crustal High Conductivity Zones in the Southern Central Andes. In: Reutter, K., Scheuber, E. and Wigger, P. (eds.) Tectonics of the Southern Central Andes. Springer, Berlin, Heidelberg. doi: 10.1007/978-3-642-77353-2\_3*

*SERNAGEOMIN. 2003. Mapa geológico de Chile: versión digital. Digital Geological Publishing 4 (CD-ROM, version 1.0, 2003).*

*Sparks, R., Folkes, C., Humphreys, M., Barfod, D., Clavero, J, Sunagua, M., McNutt, S. and Pritchard, M. 2008. Uturuncu Volcano, Bolivia: volcanic unrest due to mid-crustal magma intrusion. American Journal of Science 308, 727-769.*

*Tassi, F., Martinez, C., Vaselli, O., Capaccioni, B. and Viramonte, J. 2005. Light hydrocarbons as redox and temperature indicators in the geothermal field of El Tatio (northern Chile). Applied Geochemistry 20, 2049-2062, doi: 10.1016/j.apgeochem.2005.07.013.*

*Tassi, F., Aguilera, F., Vaselli, O. and Medina, E. 2008. A geochemical survey of geotermal resources in the Tarapacá and Antofagasta regions (northern Chile). International Symposium in Andean Geodynamics (ISAG) 2008.*

*Tassi, F., Aguilera, F., Darrah, T., Vaselli, O., Capaccioni, B., Poreda, R. and Delgado-Huertas, A. 2010. Fluid geochemistry of hydrothermal systems in the Arica-Parinacota, Tarapacá and Antofagasta regions (northern Chile). Journal of Volcanology and Geothermal Research 192, 1-15.*

*Tassi, F., Aguilera, F., Vaselli, O., Darrah, T. and Medina, E. 2011. Gas discharges from four remote volcanoes in northern Chile (Putana, Olca, Irruputuncu and Alitar): a geochemical survey. Annals of Geophysics 54, doi: /10.4401/ag-5173.*

*Tibaldi, A., Corazzato, C. and Rodiva, A. 2009. Miocene–Quaternary structural evolution of the Uyuni–Atacama region, Andes of Chile and Bolivia. Tectonophysics 471, 114-135.*

*Urzúa, L., Powell, T., Cumming, W.B., and Dobson, P. 2002. Apacheta, a new geothermal prospect in northern Chile. Geothermal Resources Council Transactions, v. 26, pp. 65-69.*

*Veloso, E., Aron, F., Camus, E., Morata, D., Arancibia, G., Del Valle, F. and Cembrano, J. 2016. Understanding the geodynamic role of structural elements and their influence on (paleo)fluid flow at the Licancura Geothermal Field, Central Andean Volcanic Zone, northern Chile. AGU Fall Meeting 2016, San Francisco, United States, T43A-3018.*

*Vergara, H. and Thomas, A. 1984. Hoja Collagua: región de Tarapacá, escala 1:250.000. Servicio Nacional de Geología y Minería, Nº 59, 79pp.*

*Villarroel, D. 2014. Geochemical studies of geothermal fluid and evaluation of well test results from well SM-01, SM-02 and SM-03, Sol de Mañana field, Geothermal Project, Laguna Colorada, Bolivia. United Nations University, Geothermal Training Program Reports 32.*