Multidisciplinary approach for the exploration of remote geothermal fields: The Tocomar Geothermal System case study (Puna plateau, Argentina).

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Keywords: geotermal exploration, structural control, fluid circulation

ABSTRACT

The reconstruction of the stratigraphical–structural framework and the hydrogeology and hydrogeochemistry of geothermal areas is fundamental for understanding the relationships between cap rocks, reservoir and circulation of geothermal fluids and for planning the exploitation of geothermal fields. The Tocomar geothermal volcanic area (Puna plateau, Central Andes, NW Argentina) has a high geothermal potential. It is crossed by the active NW–SE trans-Andean tectonic lineament known as the Calama–Olacapato–Toro (COT) fault system, which favours a high secondary permeability testified by the presence of numerous springs.

This study presents new stratigraphic, structural and hydrogeological data on the geothermal field, together with preliminary geochemical and magnetotelluric data.

Our data suggest that the main geothermal reservoir is located within the Pre-Palaeozoic–Ordovician basement units, characterised by unevenly distributed secondary permeability. The reservoir is recharged by meteoric waters via infiltration in the ridges above 4500 m a.s.l. The reservoir is covered by Miocene–Quaternary units that allow a local circulation of shallow groundwater. Geothermal fluids upwell in areas with more intense fracturing, especially where main regional structures, particularly NW–SE COT-parallel lineaments, intersect with secondary structures associated with the development of the Tocomar basin. Preliminary data indicate a reservoir temperature of ~ 200 °C and a local geothermal gradient of ~ 130°C/km associated with the Quaternary volcanic activity in the Tocomar area.

The integration of field-based and geophysical analyses proved to be effective in approaching the exploration of remote geothermal fields, and in deepening the conceptual model for geothermal circulation.

1. INTRODUCTION

The exploration of geothermal systems in Andean regions is a very important issue, for the presence of significant thermal anomalies at accessible depths, associated with recent volcanism and widespread evidence of current and past geothermal activity. Exploration for these resources needs comprehensive multidisciplinary (geological, hydrological, geochemical and geophysical) surveys through the use of traditional methods and innovative techniques for the geothermal potential assessment. The Tocomar geothermal volcanic area, approximately 160 km east of the main volcanic arc, on the Calama Olacapato Toro lineament (COT; Norini et al., 2014), has a high geothermal potential. This area shows evidence of several geothermal manifestations, including active and fossil hot-springs and travertine deposits. Previous works presented only a general conceptual model for the Tocomar geothermal system (Aquater 1981, Ferreti and Alonso, 1993, Giordano et al. 2013). The future development of the Tocomar geothermal system requires a deepening in the knowledge of its conceptual model. This paper presents preliminary results of a multidisciplinary work which aims at: a) Defining the geometry and kinematics of the structural system at regional and local scale as well as identifying the structures that confine the reservoir; b) Mapping all the stratigraphic units, structural features and superficial manifestations at regional and local scale; c) Redefining the stratigraphy of the Tocomar volcanic center (TVC); d) defining the physical-chemical conditions into the reservoir by hydrogeochemical studies; e) Applying geophysical methods to determine the depth and geometry of the potential reservoir; f) Petrophysical characterization of the units that are involved in the geothermal system; g) Proposing a conceptual model to evaluate the geothermal potential.

2. GEOLOGICAL FRAMEWORK

The Puna (NW Argentina), located in the back-arc of the Central Andes, is an internally drained plateau with an average elevation of 3.8 km. The Puna is bordered to the west by the active magmatic arc (Western Cordillera) and to the east by the Eastern Cordillera and the Subandean Ranges (Fig.1). Since the Eocene–Oligocene the Puna Plateau formed by crustal shortening and thickening, with both orogen-parallel thrusting and orogen-oblique strike-slip faulting plus magmatic addition, delamination of the thickened lower crust and mantle lithosphere, and, subordinately, gravity-driven crustal channel flow

(Norini et al., 2013 and references therein). The Puna plateau basement is represented by the Puncoviscana Formation (Late Neoproterozoic), composed mainly of deformed meta-sedimentary rocks, and by the Mesón Group (Cambrian), made of siliciclastic sediments (Blasco et al., 1996 and references therein) (Fig.2). The Precambrian and Cambrian units are intruded by metagranitoid rocks of the Ordovician Faja Eruptiva Fm. and are covered through a marked unconformity by an Ordovician volcano-sedimentary sequence (Blasco et al., 1996 and references therein) (Fig.2). The Cretaceous–Paleocene syn- and post-rift sedimentary sequence of the Salta Group and the Oligocene–Miocene siliciclastic and evaporitic deposits of the Pozuelos Fm. crop out above the Pre-Cambrian and Palaeozoic local basement (Blasco et al., 1996 and references therein) (Fig.2). The basins of the Salta Group and Pozuelos Fm. were inverted during the subsequent orogenic phases started in the Eocene–Oligocene producing the present basin-and-range morphology of the Puna plateau (Salfity et al., 1993; Coutand et al., 2001; Hongn et al., 2007; Monaldi et al., 2008). The generated N–S trending intermontane depressions were filled by continental clastic sediments and volcanic rocks of Miocene–Quaternary age (Blasco et al., 1996 and references therein) (Fig.2).

The Puna plateau is characterized by an extensive magmatism since Neogene times (Kay and Coira, 2009, Guzman et al., 2014). The north-south volcanic arc was developed initially along Maricunga belts and finally stabilized 50 km to the west in the present day volcanic arc (Western Cordillera) (Kay and Coira, 2009). Shallowing of the subducting slab explains the eastward broadening of the arc magmatism along regional NW-SE, vertical, strike-slip faults systems (Viramonte et al., 1984; Viramonte y Petrinovic, 1990; Petrinovic et al., 1999; Riller et al., 2001; Matteini et al., 2002; Acocella et al., 2011). Also, a role played by the orogen-parallel thrust faults in the emplacement of polygenetic volcanoes in the back arc has been recently proposed by Norini et al. (2013, 2014). One of the main NW–SE tectonic structures is the Calama–Olacapato–El Toro Fault System (COT). The central portion of the COT is characterized by the development of a narrow basin (The Tocomar basin, Fig.2) filled during Pliocene-Holocene times by fluvial/alluvial sediments coevals whit small volume bimodal volcanism (Petrinovic et al., 2006).

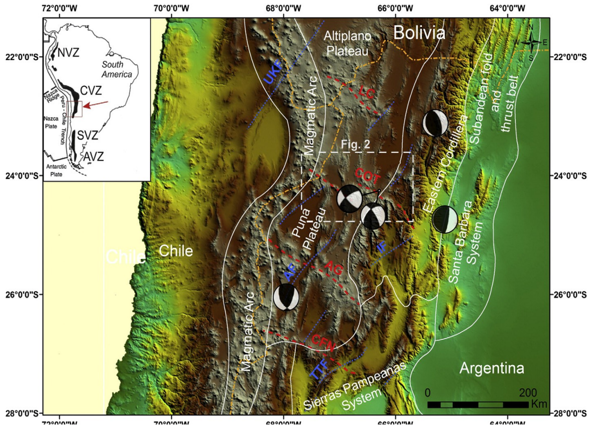


Fig. 1 Localisation of the study area (from Norini et al., 2013)

3. STRUCTURE

The structural style of the area is thick skinned, and consists of N-S thrusts planes involving the local basement (Puncoviscana and Faja Eruptiva Fms), the Cretaceous-Paleocene age sedimentary sequence and the Miocene-Holocene basin fill (clastic sediments and volcanic rocks). These orogen-parallel fronts are offset by the NW-SE trending COT transfer fault (Norini et al., 2013).

The Tocomar area is located along the COT fault zone, across two main, frontal N-S thrust systems (Fig. 2). The west-vergent thrusts system consists of at least three low angle reverse faults that uplifted the Ordovician Faja Eruptiva Fm. onto the Cretaceous

Pirgua Fm. This contact is repeated several times crossing the same thrust system, and usually it controls changes of the slope morphology. The geometry of the thrust planes seems to be controlled by the thickness variation of the Pirgua Fm suggesting an influence by the Cretaceous extensional tectonics. The east-vergent thrust system is a back thrust with the Pirgua Fm at the footwall covering unconformably the Puncoviscana and Faja Eruptiva Fms.

Both the thrust systems are complicated by the intrusion of magmatic rocks during Miocene. In the western sector, Miocene intrusive rocks are broadly E-W aligned, masking the thrust continuity, likely due to the interplay between the frontal thrusts and the transfer COT system; in the eastern sector, the Miocene intrusive rocks are aligned along the main thrust plane probably reactivated after the onset of the intrusion.

Along the COT fault all the thrusts curve and merge with the fault plane. This geometry indicates that the COT works mainly as transfer fault, at least during the main phase of thrust development.

The Tocomar basin is a 30 km^2 wide, roughly triangular depression that interrupts locally the COT, and hosts a sedimentary and volcanic succession of Pliocene (?) - Quaternary age. Extensional, transcurrent and reverse faults affect the recent deposits suggesting for this basin a pull-apart origin (Petrinovic et al., 2006; Giordano et al., 2013).

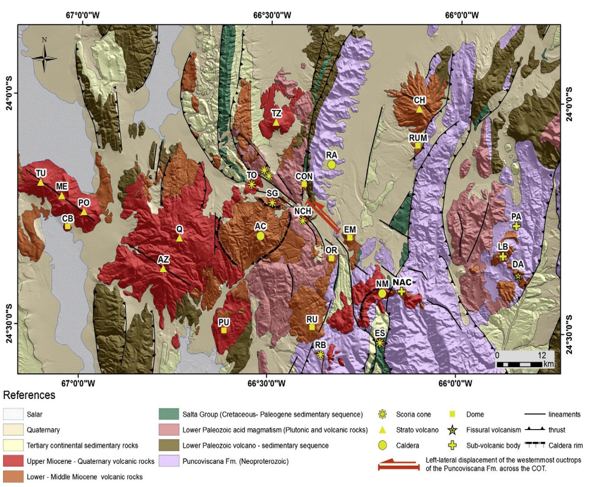


Fig. 2 Regional structural framework of the Tocomar area (from Norini et al., 2013).

4. STRATIGRAPHY

The Fig.3 shows a revised stratigraphy of the Tocomar geothermal volcanic area, indicating pre-Tocomar basin units and the volcano-sedimentary basin fill. The oldest basement unit outcropping in the Tocomar area is the Faja Eruptiva Fm. formed by Ordovician metagranites and minor mafic intrusive rocks that intrude the Pre-Paleozoic metasedimentary Puncoviscana Fm. Above the Palaeozoic basement rocks, the oldest rocks preserved are the Cretaceous–Oligocene syn-rift and post-rift sediments (Salta Group) that were deposited along narrow grabens in rapid subsidence (Salfity and Monaldi, 2006). The main lithofacies outcropping in the study area are poorly sorted conglomerates and breccias, and fluvial–lacustrine sandstones, with a typical red-purple colour (syn-rift Pirgua Subgroup). The youngest pre-Tocomar basin unit is represented by extensive dacitic crystal rich ignimbrite sheets sourced between 17 and 10 Ma from the Aguas Calientes Caldera (Petrinovic et al. 2010). The ignimbrites are extensively lithified with diffuse vapour phase crystallisation of the matrix (low primary permeability). Also the secondary permeability due to fractures is low (Giordano et al., 2013).

The Tocomar basin fill starts with a 12 m thick (minimum thickness) tabular and internally stratified medium to coarse sandstone, inter-bedded with thin mudstone levels, related to distal alluvial fans sedimentation (Red Sandstone unit). Middle Pleistocene mafic lava flows from San Geronimo monogenetic cone (0.78 Ma; Petrinovic et al., 2006) show a stratigraphic relationship with the Red Sandstone unit. Coarse alluvial/fluvial sediments (Green Conglomerate unit) with a minimum thickness of 40 m filled the basin after a tectonic?-erosional phase. A coeval mafic phreatomagmatic activity is evidenced by pyroclastic surge deposits inter-bedded with the Green Conglomerate unit. Also, the presence of ~ 5m thick travertine at the top of the Green conglomerate unit point out the onset of the geothermal activity into the Tocomar basin. The Tocomar 1 pyroclastic sequence (fall/surge/flow deposits) related to a rhyoltic phreato-plinian eruption (0.55 Ma; Petrinovic and Colombo, 2006; Petrinovic et al., 2006) covers by a mild angular unconformity the Green Conlgomerate unit. This felsic volcanism was followed by other two rhyolitic phreatomagmatic eruptions associated with different vents that formed the pyroclastic sequences (dominantly surge deposits) of Tocomar 2 and Tocomar 3. Previous works interpret the rhyolitic magmatism in the Tocomar basin as related to an anatectic crustal source (Petrinovic et al., 2006). Finally, thin alluvial, fluvial and eolian recent deposits covers largely the Tocomar basin.

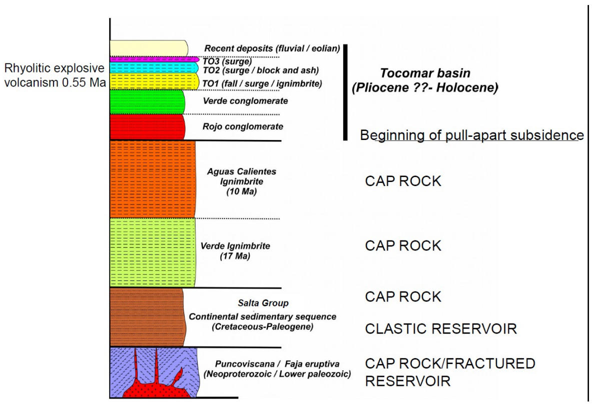


Fig. 3 Mechanical stratigraphy of Tocomar area and role in the geothermal system

5. HYDROGEOLOGY

The area has an arid climate, characterised by very low precipitation, less than 100 mm/yr, distributed from January to April.

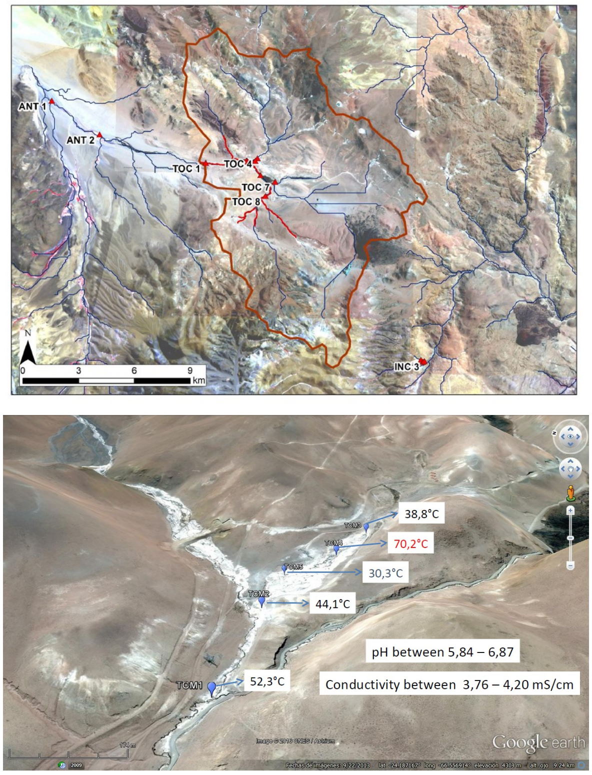
The few main permanent springs which feed permanent rivers are located at the bottom of incised valleys at elevations comprised between 4400 and 4200. It is the case of Tocomar watershed, in which permanent flow is located between 4360 and 4248 elevation.

Four hydrogeological surveys (from November 2014 until now) have been carried out in the Tocomar watershed, measuring eight gauging stations (Fig. 4a), to quantify the water flow regime in different seasons of the year.

Comparison of the four water flux surveys shows that the shallow aquifer piezometric surface fluctuates, with outflow ranging between 40 and 108 l/s (Fig. 4a, TOC 1 gauging station).

Other flux measurement were carried out in other nearby geothermal watershed systems at Antuco, Incachule and Tuzgle. These measurements were carried out to have a basis for comparison with surrounding situations.

The aim of this study is to calculate the hydrogeological balance of the area and to understand if the actual perennial stream can be addressed only to the direct recharge (infiltration) or if there is an amount of deep waters which feed Tocomar geothermal springs.



ig. 4 a) Tocomar watershed and location of main geothermal springs (TOC for Tocomar; ANT for Antuco; INC for Incachule, see text for explanation); b) Oblique view of the area of the Tocomar geothermal springs and their main physical characteristics

6. GEOCHEMISTRY

Water and gas samples were collected from five hot springs in the Tocomar area to investigate the source regions of thermal fluids and to provide insights into the chemical–physical conditions of the hydrothermal reservoir for a preliminary estimation of its geothermal potential. Spring water temperatures range from 30.3 to 70.2 ºC (Fig. 4b), whereas pH values vary in a narrow range between 5.84 and 6.87. Water samples show relatively high Electrical Conductivity (EC > 6.43 mS/cm) and are sodium chloride in composition. The values of the isotopic ratios of water vary from -10.2 to -9.0, and from -84 to -81‰ V-SMOW, respectively. These isotopic data show that hot springs plot close to the Local Meteoric Water Line (LMWL) proposed by Panarello et al. (1990) for the Central Puna area, suggesting a predominantly meteoric origin for these fluids. The slight $\delta^{18}O$ enrichment shown by the samples was probably produced by prolonged water–rock interactions at temperatures >150 °C (Truesdell and Hulston, 1980). The relatively high concentrations in ammonium ion (up to 6.5 mg/l) together with the chemical composition of the gas phase indicate a hydrothermal environment at depth (e.g. Martini et al., 1984; Giggenbach, 1991; Arnósson y Andresdottir, 1995; Aggarwal et al., 2000). Estimations carried out using different geothermometers indicate temperatures in the range of 131–235 °C for the deep hydrothermal reservoir.

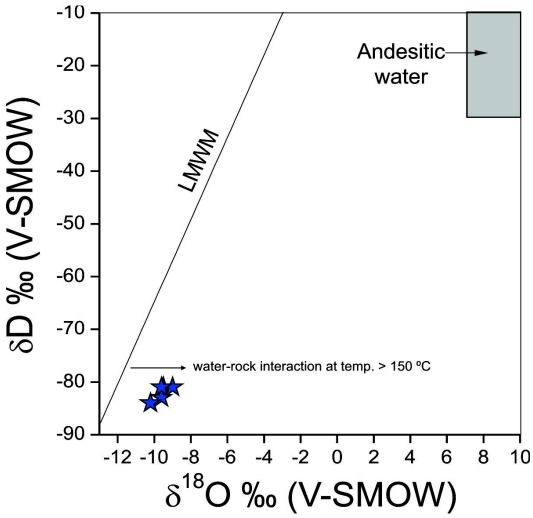


Fig. 5. δD-H_2O vs. $\delta^{18}O$-H_2O (‰ vs. V-SMOW) binary diagram for thermal spring from Tocomar geothermal system. The Local Meteoric Water Line (LMWL; Panarello et al., 1990) is reported.

7. MAGNETO-TELLURICS

Two magnetotelluric surveys (30 sites, during 2014 and 2016) were carried out around the Tocomar volcanic area to detect electric structures possible related to reservoir and heat source. A regional geological strike around N20ºE was applied to data and a 3D MT model was found by MODEM code. We found two conductive anomalies, a shallower (~5-1

Ω.m) from 90 m to 800 m, and a deep conductor (< 4 Ω.m) from 1200 to 2500 m and very resistive structure from 1000 m to ~5000 m deep (Fig.6).

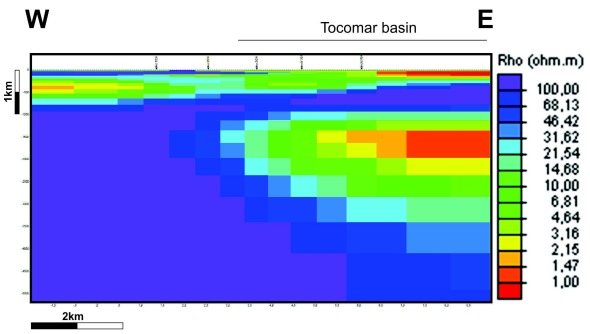


Fig. 6. Vertical cross section of the Tocomar geothermal area (magneto-telluric model) showing two main conductive anomalies.

8. DISCUSSION AND CONCLUSIONS

The mechanical stratigraphy and the role of each unit in the geothermal system are shown in the Fig. 3, in agreement with knowledge from other nearby areas (e.g. the thermal areas of Rosario de la Frontera; Maffucci et al., Chiodi et al., Invernizzi et al.,). The Pre-Cambrian and Ordovician rocks are generally low permeable but locally intensely fractured and faulted, which may promote an important secondary permeability. The location at ~ 1500 m depth of the deeper MT conductive anomaly (Fig.7) suggests that the main geothermal reservoir is located within the Pre-Palaeozoic–Ordovician basement units that we interpret as locally highly fractured, possibly across a main fault zone.

Hydrothermal water isotopy shows a predominantly meteoric recharge for the main geothermal aquifer, suggesting that the deep heat source only provides conductive heat to the geothermal reservoir, likely because the anatectic heat source is well within a ductile zone not prone to development of secondary permability (Fig.7).

The recharge of the main geothermal reservoir may therefore be associated with rain and snowmelt infiltration either in the basement rocks outcropping to the north of the COT or in the Miocene volcanics that crop out to the south (Fig. 3), though in both cases in localized areas of intense fracturing, as in general these units are low permeable.

Above the basement rocks, some levels in the Pirgua Subgroup probably host minor geothermal clastic reservoirs. The low primary and secondary permeability of the Miocene ignimbrites indicates that these units act mainly as a seal in the geothermal system. The Tocomar basin sequence probably does not play any major role to the structure and circulation of the deep geothermal systems due its superficial stratigraphic position and limited spatial distribution. However, this sequence hosts the shallow aquifer mainly into the Green Conglomerate unit (Fig.7). The location of the hot springs above the intersection of the NW–SE main regional structures with secondary structures associated with the development of the Tocomar basin suggests that hot fluid upwelling occurs in areas intensely fractured. The deeper hot fluid subsequently mixed with the shallow aquifer to form the hot springs. The large temperature variability exhibited by the very close springs of the Tocomar field (30° to 70°C) suggest that hydrothermal fluid fracture flows in the basement reach the shallow clastic aquifer at very shallow depths preventing thermal equilibration.

The coeval evolution of the Tocomar basin with bimodal magmatism in a narrow area is responsible for generating the local heat anomaly (Fig.7). Our preliminary data from fluids geochemistry indicate a reservoir temperature of ~ 200 °C and a local geothermal gradient of ~ 130°C/km (Fig.7).

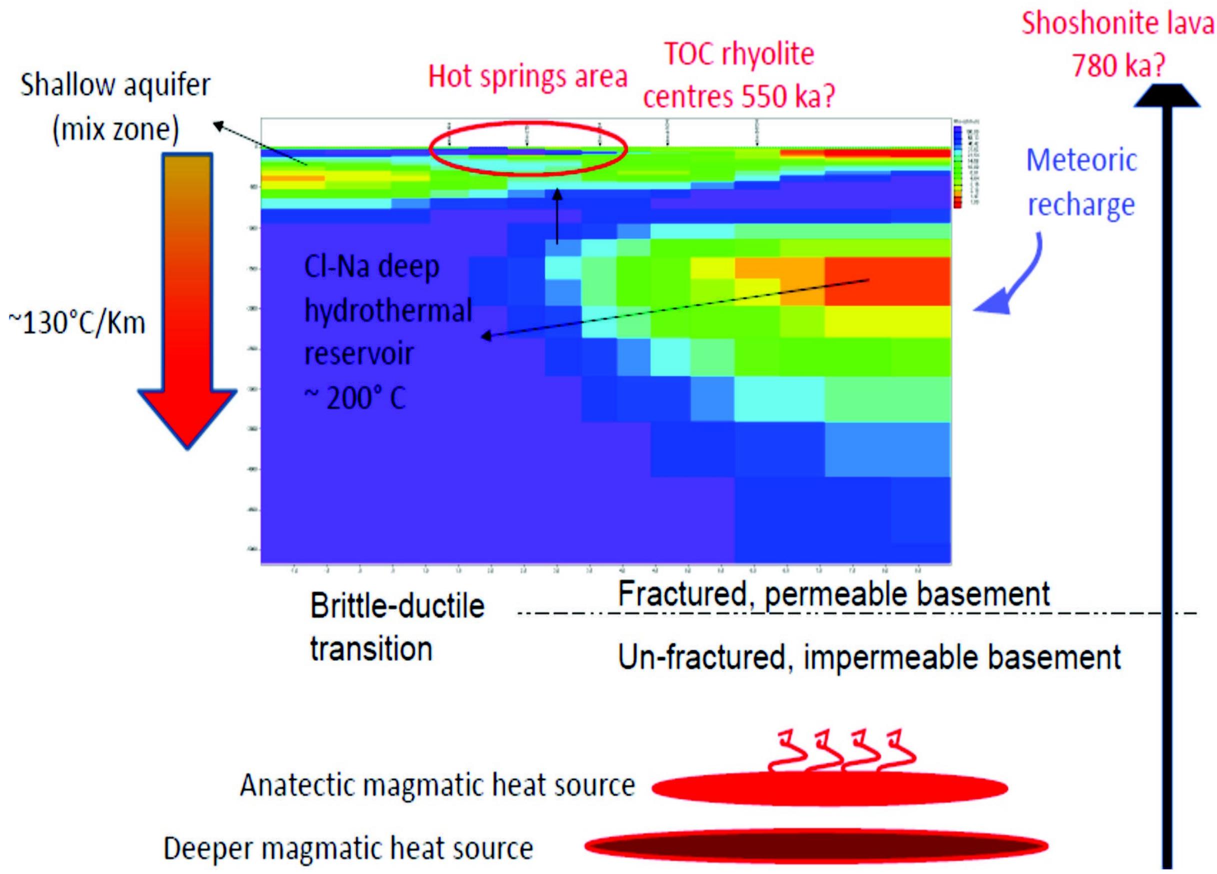


Fig. 7. Preliminary conceptual model of the Tocomar geothermal system.

REFERENCES

Acocella, V., Gioncada, A., Omarini, R., Riller, U., Mazzuoli, R., Vezzoli, L., 2011. Tectonomagmatic characteristics of the back-arc portion of the Calama–Olacapato–El Toro Fault Zone, Central Andes. Tectonics 30, TC3005.

Aquater, 1980. Exploración geotérmica del área del Cerro Tuzgle, Provincia de Jujuy, Argentina. Secretaría de Estado de Minería. Unpublished report.

Aggarwal, J.K., Palmer, M.R., Bullen, T.D., Arnosson, S. y Ragnarsdottir, K.V. 2000. The boron isotope systematic of Icelandic geothermal waters: 1. Meteoric water charged systems. Geochimimica et Cosmochimica Acta 64: 579-585.

Arnósson, S. y Andresdottir, A. 1995. Processes controlling the distribution of boron and chlorine in natural waters in Iceland. Geochimimica et Cosmochimica Acta 59: 4125-4146.

Blasco, G., Zappettini, E., Hongn, F., 1996. Hoja Geológica 2566-I, San Antonio de los Cobres, provincias de Salta y Jujuy, 1:250,000. ServicioGeológico Minero de Argentina, Buenos Aires, Boletín, 217.

Coutand, I., Cobbold, P.R., de Urreiztieta, M., Gautier, P., Chauvin, A., Gapais, D., Rossello, E. A., López Gamundí, O., 2001. Style and history of Andean deformation, Puna plateau, northwestern Argentina. Tectonics 20, 210–234.

Ferretti, J., Alonso, R., 1993. Geoquímica del campo geotérmico Tocomar (Salta). XII Congreso Geológico Argentino. II Congreso de Exploración de Hidrocarburos. Buenos Aires, Argentina.

Giggenbach, W. 1991. Chemical techniques in geothermal exploration. En Application of Geochemistry in Geothermal Reservoir Development, UNITAR, 253 – 273, Nueva York.

Giordano, G., Pinton, A., Cianfarra, P., Baez, W., Chiodi, A., Viramonte, J., Norini, G., Groppelli, G., 2013. Structural control on geothermal circulation in the Cerro Tuzgle–Tocomar geothermal volcanic area (Puna plateau, Argentina). J. Volcanol. Geotherm. Res. 249, 77–94.

Guzmán, S., Grosse, P., Montero López, C., Hongn, F., Pilger, R., Petrinovic, I.,Seggiaro, R. &

Aramayo, A. 2014. Spatial–temporal distribution of explosive volcanism in the 25–28° S segment of the Andean Central Volcanic Zone. Tectonophysics, 636, 170-189, doi: 10.1016/j.tecto.2014.08.013

Hongn, F., Del Papa, C., Powell, J., Petrinovic, I., Mon, R., Deraco, V., 2007. Middle Eocene deformation and sedimentation in the Puna-Eastern Cordillera transition (23-26S): control by preexisting heterogeneities on the pattern of initial Andean shortening. Geology 35, 271–274.

Kay, S.M., Coira, B.L., 2009. Shallowing and steepening subduction zones, continental lithospheric loss, magmatism, and crustal flow under the Central Andean Altiplano– Puna Plateau. In: Kay, S.M. (Ed.), Backbone of the Americas: shallow subduction, plateau uplift, and ridge and terrane collision. Geological Society of America Memoir. 204, pp. 229–259.

Martini, M., Cellini, Legittimo, P., Piccardi, G. y Giannini, L. 1984. Low temperature manifestations in volcanic areas. Rendiconti della Societa Italiana di Mineralogia e Petrologia 39: 401-405.

Matteini, M., Mazzuoli, R., Omarini, R., Cas, R., Maas, R., 2002. Geodynamical evolution of the central Andes at 24°S as inferred by magma composition along the Calama–Olocapato–El Toro transversal volcanic belt. J. Volcanol. Geotherm. Res. 118, 225–228.

Monaldi, C.R., Salfity, J.A., Kley, J., 2008. Preserved extensional structures in an inverted Cretaceous rift basin, northwestern Argentina: outcrop examples and implications for fault reactivation. Tectonics 27, TC1011.

Norini, G., Baez,W., Becchio, R., Viramonte, J., Giordano, G., Arnosio, M., Pinton,A., 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.

Norini, G., Cogliati, S., Báez, W., Arnosio, M., Bustos E., Viramonte J.G. y Groppelli, G. 2014. The geological and structural evolution of the Cerro Tuzgle Quaternary stratovolcano in the back-arc region of the Central Andes, Argentina, *Journal of Volcanology and Geothermal Research*, 285, 214-228.

Panarello, H. O., Sierra, J.L., Pedro, G, 1992. Flow patterns at the Tuzgle-Tocomar Geothermal system, Salta Jujuy, Argentina: an isotopic and geochemical approach. IAEA-Technical Document, Costa Rica, 641: 57-75.

Petrinovic, I.A. and Colombo, F., 2006. Phreatic to Phreatomagmatic eruptions in the Tocomar volcanic centre, Puna, Argentina. J. Volcanol. Geotherm. Res. 158 (1–2), 37–50.

Petrinovic, I.A., Riller, U., Alvarado, G., Brod, J.A., Arnosio, M., 2006. Bimodal volcanism in a tectonic transfer zone: evidence for tectonically controlled magmatism in the southern Central Andes, NW Argentina. J. Volcanol. Geotherm. Res. 152, 240–252.

Petrinovic, I.A., Martí, J., Aguirre-Díaz, G.J., Guzmán, S., Geyer, A., Salado Paz, N., 2010. The Cerro Águas Calientes caldera,NWArgentina: an example of a tectonically controlled, polygenetic collapse caldera, and its regional significance. J. Volcanol. Geotherm. Res. 194, 15–26.

Riller, U., Petrinovic, I., Ramelow, J., Strecker, M.R., Onken, O., 2001. Late Cenozoic tectonism, collapse caldera and plateau formation in the Central Andes. Earth Planet. Sci. Lett. 188, 299–311.

Salfity, J.A. and Monaldi, C.R., 2006. Hoja Geológica 2566-IV: Metán (1:250,000). Programa Nacional de Cartas Geológicas de la República Argentina, boletin, 319, Buenos Aires, 80 pp.

Salfity, J.A., Monaldi, C.R., Marquillas, R.A., Gonzalez, R.E., 1993. La inversion tectonica del Umbral de Los Gallos en la cuenca del Grupo Salta durante la Fase Incaica. paper presented at 12th Congreso Geológico Argentino and 2nd Congreso Nacional de la Exploracion Hidrocarburos, Asociacion Geol. Argentina and Inst. Argentino del Petroleo y del Gas, Mendoza, Argentina.

Truesdell, A.H., Hulston, J.R., JCh, F., 1980. Isotopic evidence on environments of geothermal systems. In: Fritz, P. (Ed.), Handbook of Environmental Isotopes Geochemistry. The Terrestrial Environment A 1. Elsevier, Amsterdam, pp. 179–226.

Viramonte, J.G., Petrinovic, I.A., 1990. Cryptic and partially buried calderas along a strikeslip fault system. In: Inst. Français de Rech. Sci (Ed.), the Central Andes, ISAG Grenoble. Ed. De l'Orstom, Paris, pp. 317–320.

Viramonte, J.G., Galliski, M.A., Araña Saavedra, V., Aparicio, A., Garcia Cacho, L.Y., Martín Escorza, C., 1984. El finivolcanismo básico de la depresión de Arizaro, provincia de Salta. IX Congreso Geológico Argentino Actas I, pp. 234–251.

Acknowledgements

This work has been funded by the Italian Minstry of Foregn Affairs Progetto AR00197 di Grande Relevanza *"Sviluppo dei sistemi sostenibile geotermici Associati della ai sistemivulcanici Puna di nelle Salta Province (2014-2016)"* directed by Guido Giordano and Jose G. Viramonte, and by PIO No. 3320140100015CO "*Caracterización del Sistema Geotermal Tocomar y evaluación de su potencial como recurso energético no convencional sustentable para la Puna Argentina (2015-2017)*", financed by CONICET and YPF S.A. , Y-TEC