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Preliminary data on the structure and potential of the Tocomar geothermal field (Puna plateau, Argentina)

G. Giordano*[,a], F. Ahumada[b], L. Aldega[c], W. Baez[b], R. Becchio[b], S. Bigi[c], C. Caricchi[a], A. Chiodi[b], S. Corrado[a], A.A. De Benedetti[a], A. Favetto[d], R. Filipovich[b], A. Fusari[e], G. Groppelli[f], C. Invernizzi[e], R. Maffucci[a], G. Norini[f], A. Pinton[a], C. Pomposiello[d], F. Tassi[g], S. Taviani[a], J. Viramonte[b]

[a]*Università Roma Tre, Largo S. L. Murialdo 1, 00146 Roma, Italy*
[b]*Universidad Nacional de Salta, Avenida Bolivia 5150, 4400 Salta, Argentina*
[c]*Università La Sapienza, Piazzale Aldo Moro, 5, 00185 Roma, Italy*
[d]*CONICET, Godoy Cruz 2290 (C1425FQB) Buenos Aires, Argentina*
[e]*Università di Camerino, Piazza Cavour 19/f, 62032 Camerino (MC), Italy*
[f]*CNR IDPA, Via Mario Bianco, 9, 20131 Milan, Italy*
[g]*Università di Firenze, Piazza di San Marco, 4, 50121 Firenze, Italy*

Abstract

This study presents new stratigraphic, structural and hydrogeological data on the Tocomar geothermal volcanic area (Puna plateau, Central Andes, NW Argentina), together with preliminary geochemical and magnetotelluric data.
The main geothermal reservoir is located within the fractured Pre-Palaeozoic–Ordovician units. The reservoir is recharged by meteoric waters. Geothermal fluids upwell where main regional structures intersect 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.

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Keywords: geothermal exploration; structural control; fluid 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

* Corresponding author. Tel.: +39 06 5733 8004.
E-mail address: guido.giordano@uniroma3.it

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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; [1]), 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 [2, 3, 4]. 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 ([5] 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 ([6] and references therein) (Fig. 1).

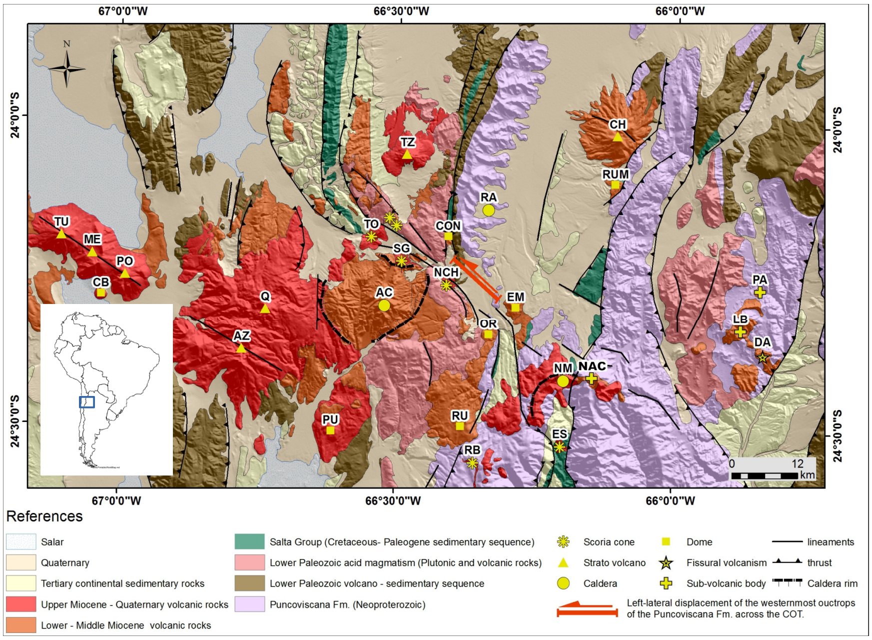

Fig. 1 Regional structural framework of the Tocomar area (from [5]).

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 ([6] and references therein) (Fig. 1). 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 ([6] and references therein) (Fig. 1). 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 [7, 8, 9, 10]. The generated N–S trending intermontane depressions were filled by continental clastic sediments and volcanic rocks of Miocene–Quaternary age ([6] and references therein) (Fig. 1).

The Puna plateau is characterized by an extensive magmatism since Neogene times [11, 12]. 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) [11]. Shallowing of the subducting slab explains the eastward broadening of the arc magmatism along regional NW-SE, vertical, strike-slip faults systems [13, 14, 15, 16, 17, 18]. 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 [5, 1]. One of the main NW–SE tectonic structures is the COT Fault System. The central portion of the COT is characterized by the development of a narrow basin (The Tocomar basin, Fig. 1b) filled during Pliocene-Holocene times by fluvial/alluvial sediments coevals whit small volume bimodal volcanism [19].

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 [5].

The Tocomar area is located along the COT fault zone, across two main, frontal N-S thrust systems (Fig. 1b). 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 [19, 4].

4 Stratigraphy

Fig. 2 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 [20]. 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 [21]. 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 [4].

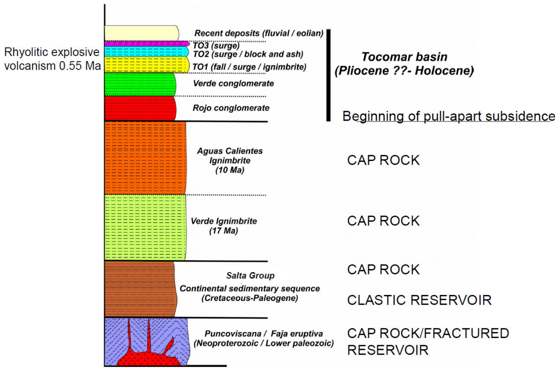

Fig. 2 Mechanical stratigraphy of Tocomar area and role in the geothermal system

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; [22]) 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; [19, 22]) 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 [22]. Finally, thin alluvial, fluvial and eolian recent deposits covers largely the Tocomar basin.

5 Hydrogeology

The area has an arid climate, characterized 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. 3a), 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. 3a, 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.

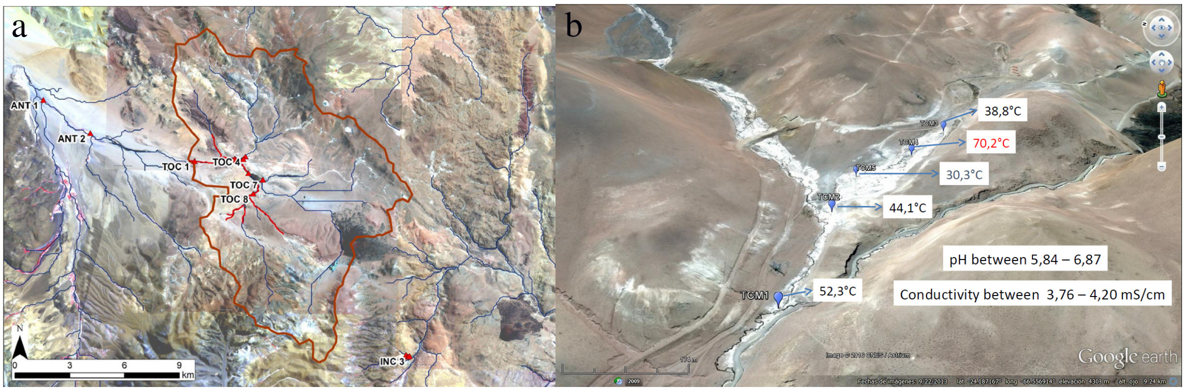

Fig. 3 a) Tocomar watershed and location of main geothermal springs (TOC for Tocomar; ANT for Antuco; INC for Incachule, see text for explanation); b) Oblique view of the area of the Tocomar geothermal springs and their main physical characteristics

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. 3b), 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 (Fig. 4) 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 [23] for the Central Puna area, suggesting a predominantly meteoric origin for these fluids. The slight δ18O enrichment shown by the samples was probably produced by prolonged water–rock interactions at temperatures >150 °C [24]. 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.* [25, 26, 27]). Estimations carried out using different geothermometers indicate temperatures in the range of 131–235 °C for the deep hydrothermal reservoir.

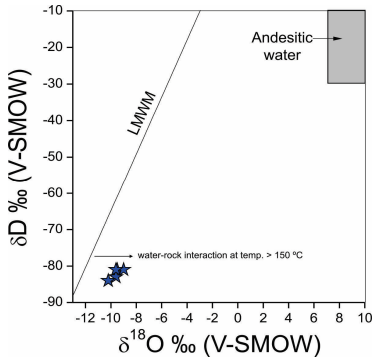

Fig. 4 δD-H_2O vs. $\delta^{18}O$-H_2O (‰ vs. V-SMOW) binary diagram for thermal spring from Tocomar geothermal system. The Local Meteoric Water Line (LMWL; [23]) is reported.

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 (Fig. 5), 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.

8 Discussions and conclusions

The mechanical stratigraphy and the role of each unit in the geothermal system are shown in the Fig. 2, in agreement with knowledge from other nearby areas (*e.g.* the thermal areas of Rosario de la Frontera; [28, 29, 30]). 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. 5) suggests that the main geothermal reservoir is located within the Pre-Paleozoic–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 permeability (Fig. 5).

The recharge of the main geothermal reservoir may therefore be associated with rain and snowmelt infiltration either in the basement rocks cropping out to the north of the COT or in the Miocene volcanics that crop out to the south (Fig. 2), 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. 5). 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. 5). Our preliminary data from fluids geochemistry indicate a reservoir temperature of ~ 200 °C and a local geothermal gradient of ~ 130°C/km (Fig. 5).

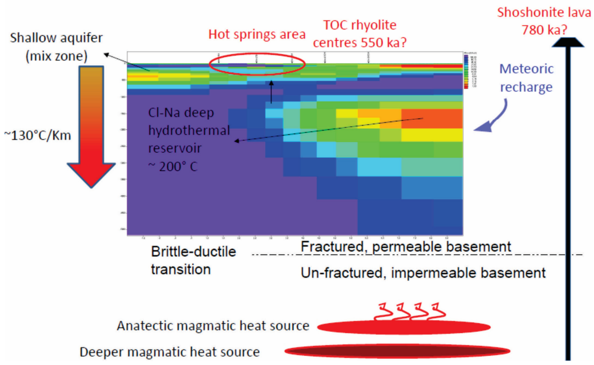

Fig. 5 Preliminary conceptual model of the Tocomar geothermal system.

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