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The potential of audiomagnetotellurics in the study of geothermal fields: A case study from the northern segment of the La Candelaria Range, northwestern Argentina

Hernan Barcelona [a,*], Alicia Favetto [a], Veronica Gisel Peri [a], Cristina Pomposiello [a], Carlo Ungarelli [b]

[a] Instituto de Geocronología y Geología Isotópica, Universidad de Buenos Aires-Consejo Nacional de Investigaciones Científicas y Tecnológicas, Buenos Aires, Argentina
[b] WesternGeco Geosolutions — Integrated EM Center of Excellence, Milan, Italy

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A B S T R A C T

Despite its reduced penetration depth, audiomagnetotelluric (AMT) studies can be used to determine a broad range of features related to little studied geothermal fields. This technique requires a stepwise interpretation of results taking into consideration diverse information (e.g. topographic, hydrological, geological and/or structural data) to constrain the characteristics of the study area. In this work, an AMT study was performed at the hot springs in the northern segment of the La Candelaria Range in order to characterize the area at depth. Geometric aspects of the shallow subsurface were determined based on the dimensional and distortion analysis of the impedance tensors. Also, the correlation between structural features and regional strikes allowed us to define two geoelectric domains, useful to determine the controls on fluid circulation. The subsurface resistivity distribution was determined through 1D and 2D models. The patterns of the 1D models were compared with the morpho-structure of the range. Shallow and deep conductive zones were defined and a possible shallow geothermal system scheme proposed. A strong correlation was found between the AMT results and the geological framework of the region, showing the relevance of using AMT in geothermal areas during the early stages of subsurface prospecting.

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1. Introduction

The magnetotelluric (MT) method is widely applied in geothermal exploration due to its manifested sensitivity to detect the presence of fluids. The main target is to determine the geometry of the geothermal system, including its extent in depth and the location of the source. The audiomagnetotelluric (AMT) method is usually used to improve the resolution of MT at shallow subsurface levels because of the higher frequencies detected. The seminal works of Hoover et al. (1976), Sandberg and Hohmann (1982) and Berktold (1983) adapted AMT for use to study geothermal areas. The main goal of AMT in geothermal systems is to define the distribution of conductive and resistive zones associated with fluids and cap rocks in the first few hundred meters (Arango et al., 2009; Monteiro Santos et al., 1996). However, issues such as dimensionality, distortion and geoelectric strike are usually not considered to infer any geothermal field characteristics. Although geothermal studies normally require a deeper penetration, a detailed analysis of the signal properties and data inversion can convert AMT into an efficient and relatively inexpensive method during the early stages of exploration, prospection or subsequent geothermal characterization.

The La Candelaria mountain range (LCR) is located between morphotectonic units of the Cordillera Oriental and Santa Bárbara system, in Salta province, northwest Argentina. Geothermal activity manifestations at the northern end including several hyperthermal hot springs have been described by Pesce and Miranda (2003). Seggiaro et al. (1997) proposed a geothermal water circulation model based on percolation and infiltration of meteoric water in the upper highland areas where permeable rocks are exposed. Several discontinuities allow the conduction of water in depth where its temperature rises and emerges at lower topographic levels in the northern apex range. However, in the hot springs zone there are no geophysical studies to define the shallow structure features, the structure–fluid relation, the local geometry of the geothermal system and the nature and extent of the occurrence.

Here, we present AMT results from the northern segment of the LCR in order to define the resistivity distribution at depth and infer some aspects related to the hot springs. We characterized the regional and local geology to determine the possible geoelectric response of the stratigraphic column. Also, structural analysis was helpful to define structures that could have potentially strong effects on the local electromagnetic field. Dimensional and distortion analyses were performed to focus on aspects that could contribute to detecting the geometry of the geothermal field. The data were processed to obtain the resistivity distribution at depth in one and two dimensional models. The geoelectric structures defined were contrasted with the local geology, main structures and hydrogeological, geomorphological

* Corresponding author at: Pabellón INGEIS, Ciudad Universitaria, Ciudad Autónoma de Buenos Aires, Argentina. Tel.: +54 11 4783 3021/3; fax: +54 11 4783 3024.
E-mail address: h.lidenbrock@gmail.com (H. Barcelona).

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and hydrological variations in order to constrain the interpretation. Finally, we classified the conductive anomalies based on their deduced sources.

2. Geological settings

The LCR is part of an N–S fault and thrust system evolved in response to the stress transference from the Western Cordillera to the foreland during the final stages of Andean deformation (Mon and Gutierrez, 2007; Ramos, 1999). In particular, it represents a thick-skinned deformation front with a Miocene–Pliocene main event (Mon, 2001), but gently folded Pleistocene deposits reveal possible minor stages of subsequent compressive deformation. The stratigraphic column shows the basement deformation and describes a sequence of tectonic events associated with the evolution of the cretaceous rift system until the thermal subsidence stage interrupted by Andean orogeny deposits (Abascal, 2005; Iaffa et al., 2011).

The basement exposed at the LCR is represented by the highly fractured Upper Precambrian–Lower Cambrian metasedimentary rocks of the Medina Formation (Bossi, 1969; Ramos, 2008). Overlying this unit the partially cemented and fractured lower Cretaceous red sandstones of the Pirgua Subgroup lie unconformably (Galliski and Viramonte, 1988; Reyes and Salfity, 1973; Viramonte et al., 1999). These continental deposits are related to the cretaceous synrift associated with crustal stretching and Gondwana break up. The Late Cretaceous Balbuena Subgroup overlies the Pirgua Subgroup (Moreno, 1970). It is constituted by conglomeratic sandstones, lutites and mudstones from the Lecho Formation and limestones from the Yacoraite Formation (Reyes and Salfity, 1973; Turner, 1959). These units, together with the Paleocene continental deposits of the Santa Bárbara Subgroup, correspond to the thermic subsidence rifting stage (Iaffa et al., 2011; Viramonte et al., 1999). Eocene to Oligocene continental sedimentation events related to different pulses during the rise of the Andes Cordillera after the Incaic tectonic phase are grouped as the Metán subgroup. Fluvial and fluvio-lacustrine deposits of Río Seco and Anta formations are exposed at the northern extreme of the LCR (Gebhard et al., 1974). Finally, the sequence is crowned by Miocene to Pliocene deposits of the Jujuy Subgroup (Gebhard et al., 1974). At the top, quaternary deposits do not exceed 50 m thickness (Bercheñi, 2003). The complete sedimentary sequence has a maximum thickness of 4500 m in adjacent basins and towards the LCR presents a significant decrease in thickness due to the stacking basement (Cristallini et al., 1997).

The main structural feature of LCR is an east verging high angle thrust exposed at the eastern margin and its associated fold (Moreno Espelta et al., 1975). LCR also presents a strong segmentation indicated by a NNE to NNW rotation of the longitudinal axis from south to north. Four segments separated by E–W and ENE–WSW lineaments can be recognized and the northernmost, probably the most modern one, correspond to the study area (Fig. 1).

The southern margin of the northern segment of LCR is delimited by an E–W inverted high angle fault dipping to the north, responsible for the northward stepwise thickness increase of the permeable Pirgua Formation (Salfity and Monaldi, 2006). This segment is formed by two anticlines with different strikes, both dipping to the north. According to Seggiaro et al. (1997) these anticlines and the associated faults system are the structural framework of the geothermal system. The N–S Balboa anticline is characterized by the cretaceous sandstone outcropping at its core. Also, the fold is dissected to the east by the main thrust or the intersection of two younger faults. The gentle NNW–SSE Termas anticline was developed partially overlapping the preexisting structures and its formation is related to a high angle thrust with west trend (Seggiaro et al., 1997). The stratification at both sides of the anticline adopts an N–S strike and presents a strong inflection, probably controlled by a regional E–W lineaments system defining a rearrangement or interference zone. Furthermore, N–S, NE–SW and E–W lineaments are present and some direct faults delimit the eastern anticline margin (Moreno Espelta et al., 1975).

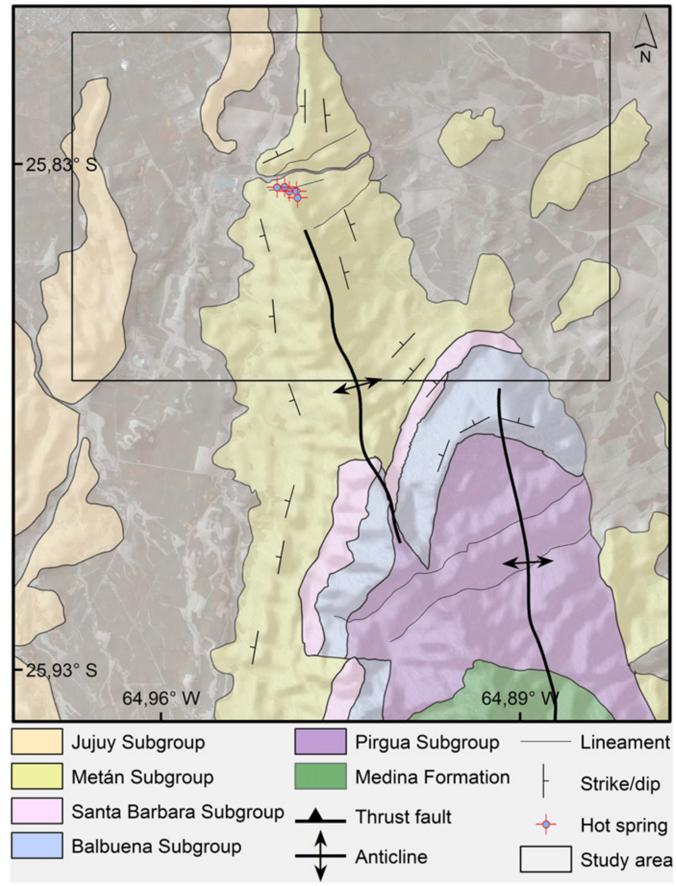

Fig. 1. Geological map of the northern segment of La Candelaria Range and the location of the study area.
Based on Salfity and Monaldi (2006).

3. Data acquisition and signal processing

Thirty AMT sites were collected using Geometrics STRATAGEM with two BF6 sensors to measure the magnetic horizontal field and two 60 m long dipoles with steel electrodes oriented N–S and E–W to measure the electric field. The frequency used during the study ranged from 10 Hz to 1000 Hz, but depending on the curve features obtained, it eventually increased up to 7000 Hz to obtain good detail in the first few tens of meters.

The site locations were organized according to the structure and geological characteristics of the area. Consequently, the geometry of the grid was designed to be approximately rectangular (Fig. 2). In general, the nodes of the grid are approximately 1 km apart, but on the summit of the range the sampling distances were shorter to better describe the hot springs. On the flanks of the range there is a lower density of sampling due to access difficulties.

The Geometrics Image software was used to control the registration and the data pre-processing and processing. These steps included filtering of the signal, manual gain setting for each channel, calculation of the complex tensor impedance (**Z**), resolution of transfer functions and acquisition of values for apparent resistivity and phase of the signal. More than thirty time series segments from each frequency band were stacked automatically for robust analysis in order to enhance the signal-noise ratio. The value of coherence threshold selected for electric and magnetic fields was 0.8, which allowed us to obtain high quality data.

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