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Electrical conductivity beneath the volcanoes of the NW Argentinian Puna

Pamela Lezaeta and Heinrich Brasse

Fachrichtung Geophysik, FU Berlin, Germany

Abstract. The detection of a high conductivity anomaly below the northern (Bolivian) part of the Altiplano-Puna plateau motivated a new analysis of magnetotelluric (MT) data which were formerly collected further south in NW Argentina. After appropriate dimensionality analysis from a profile located in the magmatic arc and backarc of the south-central Andean subduction zone, two-dimensional (2-D) electrical conductivity modelling of the crust and upper mantle in the eastern sector could be performed, i.e., in the eastern Puna and backarc zone. The 2-D conductivity models show a conductive zone beneath the eastern Puna shoshonitic volcanoes and nearby Tuzgle volcano, which reaches from the upper crust to the upper mantle. We suggest that this conductor is related to the Puna volcanism of enriched mantle composition. Whether the western Puna is also characterized by anomalous conductivities at crust-mantle depths, is still an open question.

Introduction

In the past several large zones of high electrical conductivity have been detected in the Southern Central Andes of Argentina, Bolivia and Chile [*Schwarz and Krüger*, 1997; *Lezaeta et al.*, 2000; *Brasse et al.*, 2001]. An especially pronounced anomaly was found below the Bolivian Altiplano, the northern part of the Altiplano-Puna high plateau. This motivated a new analysis of a data set previously collected in the Argentinian Puna in order to obtain a more general image of the spatial distribution of conductivity in the deep crust of the plateau.

Long period magnetotelluric (MT) and geomagnetic deep sounding (GDS) measurements were carried out in 1989 within as part of the Research Project "Mobility of Active Continental Margins" in the Southern Central Andes. In the present work, the stations located in the magmatic and backarc of the Andean system in NW Argentina at latitudes 23°S - 25°S (Fig. 1) are analyzed for dimensionality to investigate if two dimensional (2-D) modelling of the crust and upper mantle is appropriate. The sites to the west are distributed along the NW-SE oriented "El Toro" megafault which cuts across the whole Puna/Western Cordillera and probably extends until the Chilean Costal Cordillera. From NW to E, the sites extend from the Western Cordillera (the recent magmatic arc), over the Puna high plateau and the Eastern Cordillera until the Chaco lowlands (Fig. 2).

Krüger [1994] performed one-dimensional (1-D) modeling for the sites in the NW Argentinian Puna, using the MT data of the electric field component parallel to the profile trend (NW), regarding them as the TE-(tangential electric) mode. However, the 1-D model sections show no consistent image along the profile.

2-D conductivity models limited to the data east of the Puna (Fig. 1; transect B) have been previously obtained [*Schwarz and Krüger*, 1997; *Lezaeta et al.*, 2000], showing enhanced conductivity in the west, i.e., below the Eastern Cordillera. This high conductivity zone at upper mantle depths was interpreted as a rise of the asthenosphere that might be related to the Puna volcanism [*Lezaeta et al.*, 2000]. To support or modify this hypothesis, we scope here to obtain a complete image of conductivity structure from the Puna to the Chaco by performing 2-D inversion modelling of the MT data altogether.

Geological setting

Crustal depths vary between 65 and 50 km [e.g., *Götze et al.*, 1994] from W to E along the western MT profile (Fig. 1; A), with average regional elevations of 4.5 km, reaching a maximum of over 5.5 km at Tuzgle volcano. The seismicity of the downgoing slab below this region is observed until a depth of ∼200 km [*Cahill and Isacks*, 1992], while crustal seismicity is evident below Tuzgle volcano [*Sainato et al.*, 1993].

The Puna in the study area shows an active volcanic history since the Cretaceous. The most recent magmatism associated with a backarc source started about 2 Ma ago, namely the Tuzgle and shoshonitic magmas and the Tocomar ignimbrite (Fig. 1). The Tuzgle magma presents a mixture of mantle and crust-end members activity [*Coira and Kay*, 1993] whereas shoshonitic lavas are characterized by an enriched mantle composition with lower crustal contamination. Tuzgle volcanism is linked in time with young thrust faulting to the North, while the nearby shoshonitic centers and the Tocomar ignimbrite are connected with El Toro NW-trending sinistral strike-slip fault. The magma chamber for the Tuzgle eruption originated at mid-crust decollement levels (20-25 km depth) or alternatively at approx. 15-18 km depth beneath the sole of one of the N-S thrust faults [*Coira and Kay*, 1993]. Additionally, Tuzgle is described as the only major back-arc Quaternary stratovolcano of the Central Andes [*Coira and Kay*, 1993].

The Chaco province in the backarc margin is a wide, tectonically active sedimentary basin formed by intercalated deposits (∼5 km thick) derived from the Eastern Cordillera and the Subandean Ranges and bounded by the Brazilian craton to the east. The Sta. Barbara System (Fig. 1) is a N-S geological structure transition of the Subandean Ranges, an east verging fold and thrust belt running from Central Bolivia to NW Argentina. Crustal depths vary between 50

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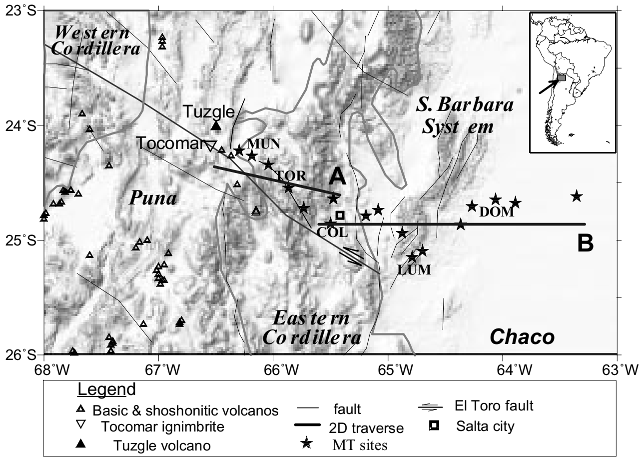

Figure 1. Map of the study area showing the geomorphological units, lineaments, volcanoes and the transects (A, B) considered for the magnetotelluric modelling (see legend).

and 35 km from west to east along the eastern profile (*Götze et al.* [1994]; Fig. 1; B).

Data analysis

Data were processed using a robust single-site least squares procedure to estimate MT impedances and magnetic transfer functions [*Rath*, 1984]. Most data are of good quality in the period range 90-7000 s, i.e., where errors are small and the curves of apparent resistivity and impedance phase are stable along this period band. This corresponds to mid crust/upper mantle investigation depths.

The skew parameter defined by *Bahr* [1988] has been treated to analyze dimensionality of the MT impedance data. Small skew values indicate that data can represent a regional 2-D conductivity model, whereas greater skews indicate that these are affected by non-negligible induction caused by 3-D structures. Skew can be subject to bias even under small errors of the impedances, therefore we have estimated the 95% confidence limit of skew to give a better credibility to this analysis of dimensionality [*Lezaeta*, 2001]. Fig. 3 shows a pseudo-section of the upper 95% confidence limit of skew interpolated between sites and plotted as a function of logarithmic period. Most of the sites to the west, between the Western Cordillera and western Puna, have great skew values with high probability, indicating that 3-D effects can be significant in this region (Fig. 3; AGC-CAM). The assumption of two-dimensionality is most feasible at the sites located in the Eastern Puna and Eastern Cordillera (Fig. 3; MUN-LUM), corresponding to transect A and to the western section of B (Fig. 1). In the Chaco, data are less affected by 3-D effects than the sites in the Western Cordillera.

The real parts of the magnetic transfer functions presented in the form of induction arrows using the convention of Wiese [cf., *Schmucker*, 1970], i.e., arrows point away from zones of higher conductivity, indicate that the lateral conductivity contrasts tend to strike along the El Toro lineament (and parallel to the profile trend) at the western sites (Fig. 2). Thus, under a 2-D assumption the strike of the conductivity structure is along the profile instead of striking perpendicular to it as should be to allow the 2-D modelling of the transect. These sites from the west can not be included in the 2-D modelling, considering also that their MT data are additionally affected by 3-D effects (Fig. 3; AGC-CAM). In contrast, at the sites to the east the induction arrows are more parallel oriented with respect to the profile trend, indicating a NNE-SSW strike of conductivity contrast in the Eastern Cordillera and a N-S one in the Sta. Barbara System (Fig. 2). Similar strike angles are found by applying the decomposition method of *Chave and Smith* [1994] to the impedance tensor and magnetic transfer functions.

Between the eastern Puna and the Eastern Cordillera a 2-D strike in NNE direction – and thus perpendicular to the WNW-ESE profile – has been calculated (Fig. 1; profile A). This profile together with the already modelled Chaco data (Fig. 1; profile B) have been treated together for the 2-D inversion. The impedances from transect A are rotated by 15° cw with respect to north, while data from transect B remain in their measured coordinate system (N-S; Fig. 1).

2-D electrical conductivity model

2-D modelling has been performed by inverting the MT impedance data through a relaxation field gradient code [*Rodi and Mackie*, 2001]. After several tests a homogeneous half-space with a resistivity of 200 Ωm was used as starting model. Here we show the model that gives the best fit and favoring smoothed structures, selected from various inversion tests (Fig. 4a). The roughness of the model structures is controlled by a regularization parameter, which we set to 10 after several tests. The criterion for choosing the best inversion result was a minimum root mean square error (rms) for the phases at single sites, shown in Fig. 4b. We assigned an error floor of 20% to the apparent resistivities (ρ_a) and 2% to the phases; this gives more weight to the phases than to the ρ_a data during the inversion. Fig. 4 (bottom) shows the fit between model responses and data of apparent resistivity (ρ_a in Ωm) and impedance phases of the electric field component tangential (red; TE-mode) and perpendicular (blue; TM mode) to the 2-D strike. Six representative sites distributed along the profile are shown. A parallel shift of the ρ_a curves between model response and data is occasionally observed and reflects a static telluric effect, which does not influence the model result because more weight on impedance phases was considered during the inversion.

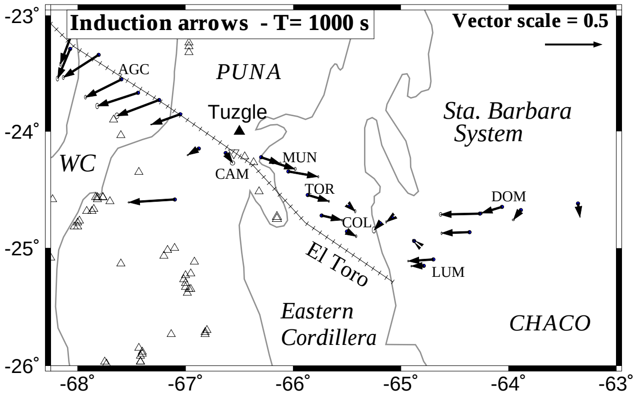

Figure 2. Real part of induction arrows at period 1000 s, sensitive to lateral conductivity contrasts. Arrows point away from zones of higher conductivity. Hatched line is the strike-slip El Toro fault. *WC*: Western Cordillera.

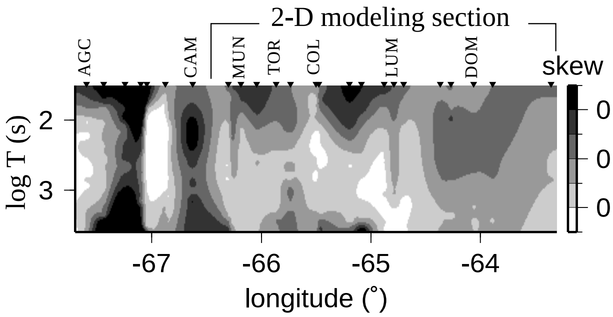

Figure 3. W-E section of the upper 95% confidence limit of skew interpolated between sites and as function of (log) period (s). Greater values are indicative of 3-D induction effects (dark grey). Location of sites is shown in Fig. 2.

The good conductor tracing vertically from shallow depths at the western border of the model (Fig. 4; MUN) spatially correlates with a thrust fault that runs to the north and south of the profile. The fault to the north is related to the Tuzgle volcano activity, as was outlined previously.

The most prominent structure is the conductor at upper mantle depths in the Eastern Cordillera (EC), which rises to shallow depths (∼10 km) beneath the Eastern Puna (Fig. 4; site TOR). The mantle conductor beneath EC (>60 km) is similar to that obtained from the 2-D inversion modelling constrained to the sites east of the Puna (see introduction). The new result here is the connection of the former (of 5-20 Ωm) with a crustal conductivity enhancement underneath the Puna shoshonitic volcanic zone (<5 Ωm at 15-60 km depth).

The sub-vertical *resistive* zone beneath the eastern Puna encountered between the crustal conductor of the western border of the model and that next to the east may well be an artificial feature (Fig. 4; between MUN and TOR), because the data from the only site of this sector have large error bars and large skew values. This means that such feature is not well constrained in the inversion model. Given also the large skew values observed in the sites of the Western Cordillera and western Puna (Fig. 3; sites AGC to CAM), 3-D modelling is apparently required to resolve the conductivity structure of the western Puna, which could be then integrated into the 2-D model obtained in the east. This

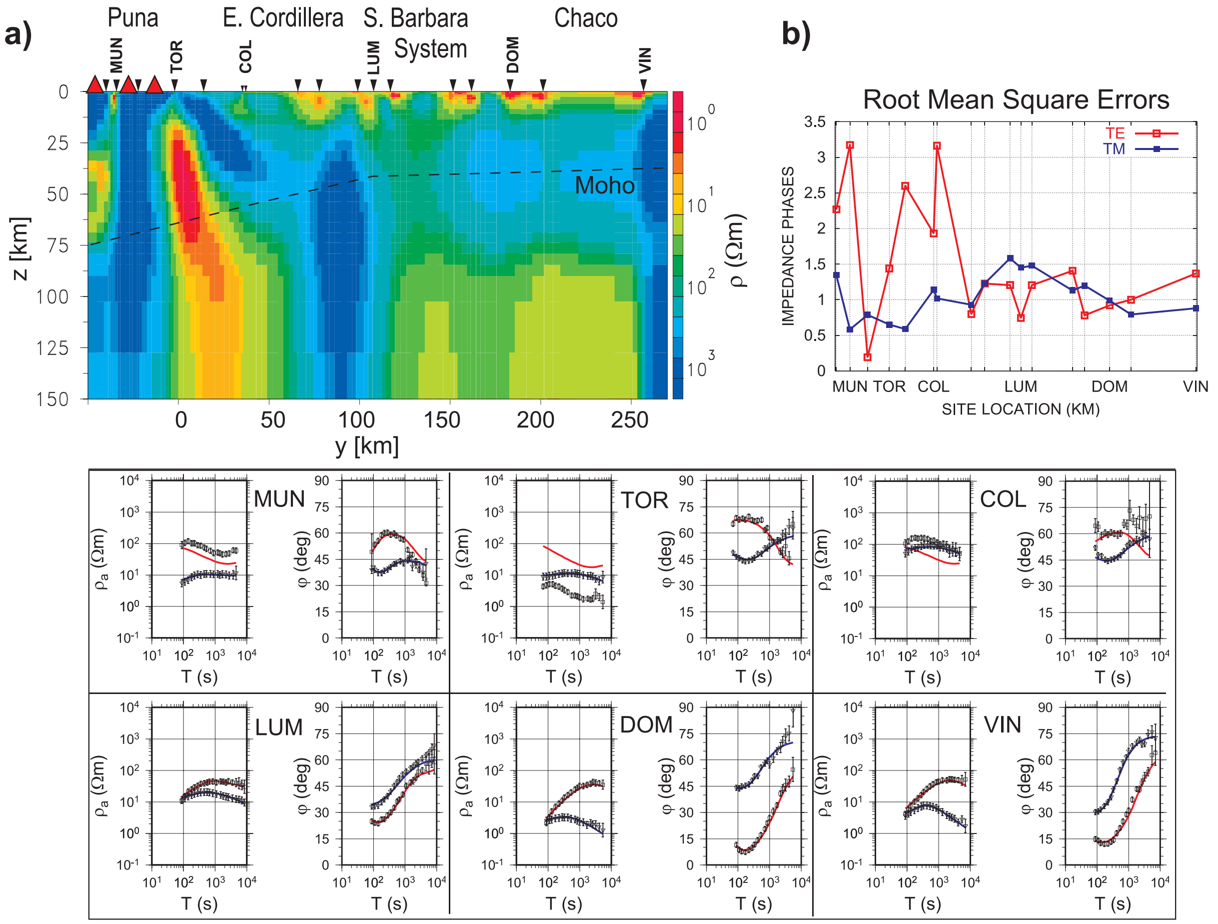

Figure 4. *a)* 2-D inversion model of electrical resistivity of transect A and B (Fig. 1) projected on W-E direction. Red triangles indicate the shoshonitic volcanoes, black inverse triangles the site locations. Anomalous (high) conductivity zones are shown in red-orange. The depth of the Moho (dashed line) is after *Götze et al.* [1994]. *b)* Root mean square errors of impedance phases. *Bottom:* Apparent resistivities (ρ_a) and phases (in degrees) of the model response (*lines*) for the sites labelled on top of the model and the corresponding measured data (*dots*). TE-polarization mode is in red, TM in blue. A static effect in the TE-mode is observed at sites TOR and COL.

would demand additional MT measurements in the Puna, on an array covering the NW-trending El Toro Lineament (Fig. 2).

Discussion and outlook

The conductivity enhancement beneath the Eastern Cordillera uprising westward to the eastern Puna (15-80 km depth) can be due to partial melts with a mantle source, considering the young shoshonitic volcanism in the region. Also, the surface heat flow on the whole Puna is very high (>100 mW/m^2), which might be caused by heat transfer from the mantle [*Hamza and Muñoz*, 1996].

In addition, a significant seismic anomaly in the crust and upper mantle was found beneath the Tuzgle volcano, i.e., high seismic attenuation and high velocity ratios v_p/v_s (due to a low v_s), and a low v_p velocity in the upper mantle [*Schurr*, 2001]. These results indicate a ductile regime which favors the hypothesis about interconnected partial melt zones and hence of high conductivity. It is noteworthy to point out that the volcanism at Tuzgle – higher degrees of crustal contamination [*Coira and Kay*, 1993] – is different from the shoshonitic volcanoes. A local magnetotelluric study performed with 1-D inversion modeling of sites measured at Tuzgle and close to it shows a shallow high conductivity layer (∼2 km depth) that might be related to the magma chamber of the volcano [*Sainato et al.*, 1993], while the 1-D inversion models from the sites located adjacent to the volcano show in addition a deeper conductive layer. The latter can be linked with the high conductivity zone beneath the eastern Puna of the 2-D model presented here because the corresponding adjacent sites employed in the former study overlap the two most western sites of our 2-D profile. Thus the crustal conductor in the eastern Puna may also be related to the Quaternary Tuzgle volcano.

The NW-SE trending El Toro lineament and a complex of east and west verging thrust fault systems are surrounding the area, crossing the MT profile as well. Saline fluids in the fault planes can also be a candidate to enhance conductivity at upper crustal levels.

The model presented here is in rough accordance with the hypothesis of a rising asthenosphere below the Eastern Cordillera and Puna as was shown in *Lezaeta et al.* [2000], although a horizontally continuous zone of high conductivity in the upper mantle (Fig. 4; >60 km depth) beneath the whole eastern Puna is not expressed here. However, the idea of an upper mantle conductor can not be discarded given the not well-constrained model structures at this section of the profile (between MUN and TOR) due to partly bad data quality and/or 3-D induction effects. In addition, it has been shown that data from the Western Cordillera and western Puna are strongly affected by 3-D effects. Additional MT data are required to achieve a 3-D conductivity image in the deep crust of the western Puna, which could be integrated into the conductivity model resulting from the inversion presented here.

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P. Lezaeta[1], H. Brasse, Fachrichtung Geophysik, FU Berlin, Malteserstr. 74-100, 12249 Berlin, Germany (e-mail: lezaeta@gfz-potsdam.de).[1]Now at: GFZ Potsdam, Telegrafenberg, 14473 Potsdam, Germany.

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