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A MAGNETOTELLURIC SURVEY IN THE NORTHERN BOLIVIAN ALTIPLANO

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Abstract. Magnetotelluric (MT) measurements were performed at 9 sites on the northern Bolivian Altiplano in a attempt to determine thicknesses of the Cainozoic sedimentary infill and to characterize the underlying crust. At some of the sites the MT soundings show complications due to static shift effects caused by local, surficial heterogeneities. Preliminary one-dimensional (1D) modeling of the data based on the impedance tensor determinant parameters was undertaken for sites considered to be free of static effects, and was followed by 2D modeling. The model obtained indicates, from the surface downward, three important geoelectrical units, namely (1) a very low-resistivity layer (1-6 ohm- m) consisting of Late Cainozoic volcanic rocks and/or Tertiary-Cretaceous sedimentary rocks 1-4 km in thickness, (2) a crustal resistive zone (about 200 ohm-m), and (3) a lower crustal or uppermost mantle conductor (less than 10 ohm-m) at depths of 40-45 km which might be related to partial melting. This model is consistent with the geological model according to which the Altiplano formed as a synorogenic basin showing abrupt changes in depositional thicknesses across thrust faults.

Introduction

In the central Andes, the Altiplano plateau is an essential peculiarity of the structural and orogenic system. The Altiplano extends from southern Peru to northwestern Argentina (where it is called the Puna), with a length of 1500 km and width of 200 km approximately, and has an average altitude of 3650 m [Isacks 1988]. This high plateau contains several sedimentary basins filled by thick detrital strata accumulated during the Tertiary Andean orogeny. The nature and age of these sedimentary rocks are relatively well known [Ascarrunz 1973; Rodrigo and Castano 1975; Martinez 1980; Lavenu 1986], and some data exist about the deep structure of the Altiplano for southwestern Bolivia and northwestern Argentina [Schwarz et al. 1984; Haak and Giese 1986; Götze et al. 1988; Reutter et al. 1988; Wigger 1988]. In contrast, except for some recent works [Baby et al. 1990], the geometry at depth of the sedimentary infill and the characteristics of its contact with its basement are poorly known, especially in the northern Altiplano.

In order to obtain data permitting an interpretation of the structure of the northern Bolivian Altiplano, 9 MT recording sites (in the period range 10-5000 s) were established along a SW-NE line approximately 200 km-long, which is roughly perpendicular to the main surface structures and stretches from the Chilian border to the foot of the Cordillera Oriental (Figure 1). The purpose of this paper is to present the obtained data and to discuss their implication for our knowledge of the structure of this part of the Altiplano.

Data and Modeling Results

The field tapes were analyzed following a procedure described by Vozoff [1972], and tensor apparent resistivities and phases were rotated to their principal directions. At most of the sites the determination of the principal axes of the impedance tensor has revealed directions more or less parallel (TE mode) and normal (TM mode) to the structural strike. However, for soundings 1-4 on the west end of the profile the angles of rotation were site and frequency dependent. The rotation direction of the data from these sites is somewhat different from the rest of the line and could be an artefact produced by local, shallow 2D or 3D features (discussed below). MT responses across the profile appear to fall into three distinct groups which leads to separation of the sites into a western group with sites 1, 2, 3, and 4, a central group with sites 5, 6, and 7, and an eastern group with sites 8 and 9. Figure 2 illustrates typical soundings curves for sites 2, 7, and 9, where the coordinate systems are independent of period.

At all sites the apparent resistivity curves are separated by up to several orders of magnitude, but the central group, represented here by site 7, shows very low apparent resistivities which are different from those calculated at typical sites 2 and 9, representing the western and eastern groups, respectively. In addition, the MT responses at the 4 western sites show very pronounced parallel splits between the TE and TM curves, which are caused by small, local, near-surface heterogeneities [Berdichevsky and Dimitriev 1976]. This bilateral splitting is seen only on the amplitude data, whereas the phase data are unaffected as shown at typical site 2 on Figure 2; it indicates that a variable amount of static shift is present. This is of no major concern for the other groups, which appear to be free of static shift effects as indicated in Figure 2 for typical sites 7 and 9. This distortion is difficult to process; the phase of the impedance tensor remains unaffected, but an interpretation based completely upon phase gives no information regarding absolute depths. Methods have been proposed to correct for this effect in the MT data [Zhang et al. 1987; Jones 1988]. However, without complete knowledge of the characteritics of the heterogeneity, it is not possible to correct for this effect at any site.

Preliminary layered models for sites 5-9 considered to be free of static shift effects were established using 1D inversions [Jupp and Vozoff 1975] based on the impedance tensor determinant parameters [Ranganayaki 1984], which according to Berdichevsky and Dimitriev [1976] will generally give more robust results than interpretations based on the TE and TM resistivity and phase responses. However, any static shift effects in the MT tensor elements will also be present in the determinant resistivity. Hence, in such a

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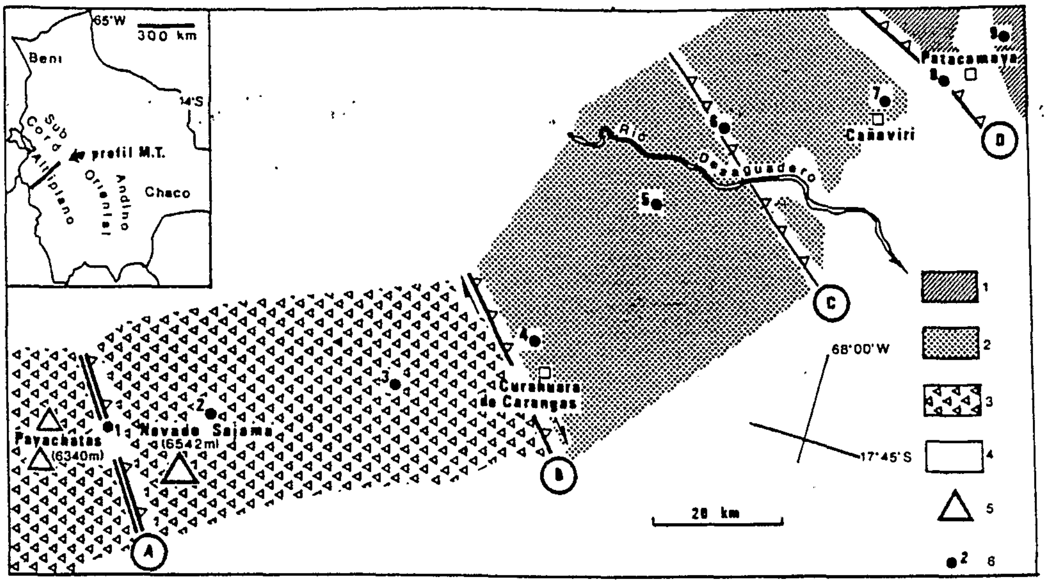

Fig. 1. Simplified geologic map and MT site locations in the northern Bolivian Altiplano. 1, Paleozoic, 2, Mio-Pliocene sediments, 3, Plio-Quaternary volcanics, 4, Quaternary sediments and unmapped area, 5, Major volcanoes, 6, Location of MT sites. A, Intra-Andean Boundary Fault (FLIA), B, San Andrés Fault, C, Sivinca Fault, D, Coniri thrust.

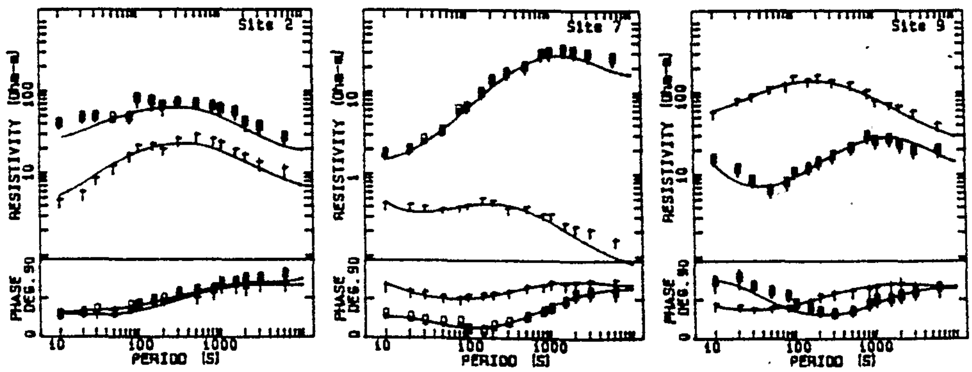

Fig. 2. Examples from two sites (7 and 9) of the tensor resistivity and phase data for the TE (dots) and TM (crosses) directions. At site 2 data represent tensor parameters calculated in a fixed coordinate system which is parallel (dots) and perpendicular (crosses) respectively to the regional strike in agreement with the rest of the line. Solid lines on the data are the responses of the 2D model shown in Figure 4.

situation, 1D modeling of the determinant resistivity response involves the risk of erroneous interpretation.

The determinant MT response from one site (site 6) unaffected by static shift and the 1D model curves are shown in Figure 3. The layered model (not shown) for site 6 indicates an overburden layer 1.7 km thick of resistivity as low as 0.6 ohm-m underlain by a more resistive layer (80 ohm-m). Beneath the resistive layer is a significant low resistivity zone (<10 ohm-m) with its upper boundary at a depth of less than 45 km. Within the central group the data are generally consistent with a three-layered section made up of a thick conductive surface layer (<2 ohm-m) thickening from west to east to reach a maximum thickness of about 4 km at site 7, and a high resistivity layer of 80-300 ohm-m succeeded by a drop in resistivity to 5-10 ohm-m at about 40-45 km. Models at sites 5-7 differ from those calculated at sites 8 and 9 (eastern group) by the existence of a 1.5-2.5 km-thick low resistivity layer of about 2 ohm-m at depths of 2.5-3.5 km. For the eastern group the low resistivity layer (2 ohm-m) is sloping downwards to the east under a more resistive thick stack.

A initial 2D model was constructed from 1D models fitting the impedance tensor determinant parameters at sites 5-9 as described above. For each site of the western group, where static shift effects are present, the elements of the impedance tensor were computed in a fixed coordinate system which was parallel and perpendicular to the average strike of the study area (N 140°E) in order to interpret all data in a consistent reference frame. Very few geophysical and geological surveys have been conducted in the northern Altiplano to provide us independent structural controls. No controls from wells are available to constrain the shallow structure. However, an assumption was made that the strong anisotropy present in the MT data arises mainly from significant resistivity contrasts near the major geological faults (Figure 1). The general shape of the data curves and the knowledge that sites 1-4 are located in a sedimentary basin have been used as a starting point for 2D modeling [Wannamaker et al. 1987] at most westerly sites. The initial model was then modified in order to obtain the final 2D model response of Figure 4. Examples of the fit of the model and observed responses are given in Figure 2 for typical

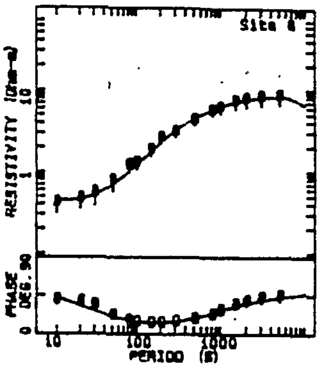

Fig. 3. An example from site 6 of impedance tensor determinant parameters. Solid lines are layered responses.

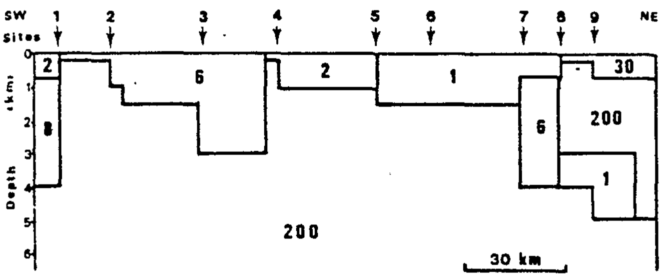

Fig. 4. 2D resistivity model along the Altiplano traverse. Resistivities are given in ohm meters. See Figure 1 for MT site locations.

sites. The most serious misfit of the model of Figure 4 occurs at sites 1-4 in the resistivity data as shown for site 2 in Figure 2. This is compatible with the comments above regarding near-surface inhomogeneities which are likely to have shifted the apparent resistivity curves vertically. For this reason the model at these four sites has been constructed to provide an adequate fit to phase data first.

Discussion and Conclusions

The model we obtain shows (Figure 4) from southwest to northeast the existence of three basins filled with low-resistivity (1-8 ohm-m) material. These basins are bounded by N 140°E-striking faults.

The basin evidenced at site 1 (the Tambo Quemado basin) must extend southwest of the study traverse into Chilean territory, but its geometry cannot be described by this study. Northeast of site 1, the Sajama-Kellkhata basin (between sites 1 and 4) and the Canaviri basin (between sites 4 and 8) are clearly visible. Both basins are asymmetrical and deepen toward the northeast, to 3 and 5 km, respectively, whereas their southwestern edges only bear a thin cover (Figure 4). The sedimentary infill of these basins shows low resistivities (1-6 ohm-m) certainly corresponding to Cainozoic sands and clays (and volcanoclastics), whereas the more resistive (200 ohm-m) basement is likely to consist of Paleozoic schists and/or Precambrian gneisses and granitoids.

The existence of the Canaviri basin and the Sivinca fault had been known for a long time, but the Cainozoic strata west of the San Andrés Fault (Figure 1) were traditionally thought to be thin [Martinez 1980; Lavenu 1986]. It is only by tectonostratigraphic considerations of regional scale [Sempéré et al. 1989] that the existence of the Intra-Andean Boundary Fault (Figure 1) and the Tambo Quemado and Sajama-Kellkhata basins had been inferred. The MT data permit us to confirm the existence of these structures and to describe the gross geometry of the Sajama-Kellkhata basin. At the northeastern tip of the traverse (sites 8 and 9) below a resistive zone (200 ohm-m), a low-resistivity (1-6 ohm-m) unit is detected which extends to depths of approximately 5 km (Figure 4). In this area the Paleozoic of the Cordillera Oriental is thrust westward onto the Cainozoic of the Altiplano by the Coniri Fault, which is exposed more to the northwest.

At all sites along the traverse, the 2D model indicates a transition from a resistive layer (200 ohm-m) to a conductive one (5-10 ohm-m) at a depth of about 40-45 km. This low-resistivity material with an unknown thickness which is detected beneath the Altiplano may represent the upper mantle or an anomalous layer in the lower crust. Götze et al. [1988] infer a crustal thickness of about 70 km in the Bolivian Altiplano from gravity data. If we accept the Götze et al. [1988] depth to the Moho discontinuity of 70 km, the conductive layer probably represents an anomalous lower crust. High values of heat flow, with an average of 84 mW/m^2, are observed in the Altiplano and Cordillera Oriental of Bolivia [Henry and Pollack 1988], and the lower crust anomaly could be associated with partially molten material. However, the heat flow values are averaged results over a large region and therefore cannot be used to favor this alternative uniquely for the sites presented here. The solution of this problem must await additional investigations. Schwarz et al. [1984] observed a similar general decrease in resistivity at about 40 km beneath the southern Bolivian Altiplano, which may be explained by an 8% partial melting.

Our MT and geologic data show (Figure 5) that the Altiplano consists of asymmetrical, SW-tapering, sedimentary basins in the study area. Each basin is bounded

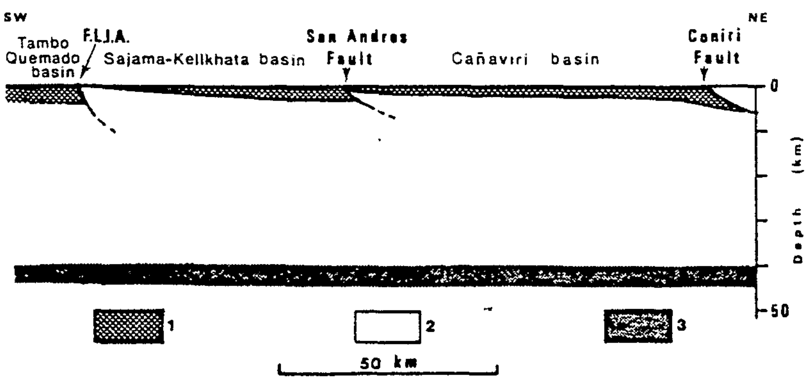

Fig. 5. Schematic cross section of the northern Bolivian Altiplano crust along a SW-NE profile derived from combined MT and surface geology data. 1, Cainozoic basins of very low resistivities (<8 ohm-m), 2, Resistive upper crustal unit (200 ohm-m), 3, layer of enhanced conductivity in the lower crust (or upper mantle).

on its northeastern edge by SW-verging thrusts (or faults with a strong thrust component). This is in good agreement with the model that proposes that the northern Altiplano as a foreland basin related to the development of thrusts transporting the Cordillera Oriental toward the southwest [Sempéré et al. 1989]. The significance of the conducting zone beginning at 40-45 km is not fully understood, and the ongoing study should permit a more precise understanding of its nature and its relations with such western thrusts.

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