MAPPING OF HIGH ELECTRICAL CONDUCTIVITY ON THE TORRES SYNCLINE HINGE, SOUTHEASTERN PARANÁ BASIN

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ABSTRACT A preliminary interpretation of the electrical structures beneath the SE Paraná Basin is presented based on electromagnetic geophysical soundings carried out around the Torres Syncline. GDS induction arrows show a NW-trending conductive anomaly nearly coincident with the hinge of the syncline and strong "ocean effects" observed at longer periods in sites near the coastline. 1-D inversions of MT data at sites located inside this anomaly have distinguished a large electrical conduit, dipping to the NW from a depth of 500 m at the coast to 1000 m at a distance of about 100 km further inland. The conductor, located in the crystalline basement, could be possibly ascribed to residual metassomatic fluids concentrated along a fractured hinge of the downfolded Torres Syncline, as a fossil record of past magmatic activities in the Early Cretaceous that affected the Paraná Basin and underlying lithosphere.

Keywords: Structural Geology, Geophysics, Torres Syncline, Electromagnetic induction

INTRODUCTION Recently carried magnetotelluric (MT) and geomagnetic depth soundings (GDS) yield new information on the electrical conductivity distribution at crustal depths beneath the southeastern border of the Paraná Basin in Brazil. The surface geology of the area includes sedimentary units from the Permian/Carboniferous and basaltic and alkaline volcanic rocks from the Early Cretaceous, mostly intruded along geologically inferred NW-SE structures (Rio Uruguay and Torres-Posadas Lineaments, and the Torres Syncline; Zalán *et al.* 1986). During the Phanerozoic, the sedimentary evolution and related magmatic events were strongly controlled by these NW-SE structures, in contrast to the Precambrian basement that presents a tectonic grain in the orthogonal NE-SW direction, imprinted by the Upper Proterozoic Brazilian remobilization (Dom Feliciano fold belt). Few previous geophysical studies have been carried out at that basin border for the investigation of deep structures. Aeromagnetic data were used to characterize known lineaments in the central region of the basin (Ferreira 1982) and gravity data provided information on the Precambrian structural continuity under the basin (Hallinan *et al.* 1993). Consequently, most of the crustal characteristics have remained unknown. Hence, the focus of this geophysical research has been directed to the detection of electrical anomalies probably linked to local geologic structures and the identification of possible connections between such anomalies and magmatic activities.

GEOLOGY AND TECTONIC SETTING The oval-shaped intracratonic Paraná Basin is located on the southeastern section of the South American platform and covers an area of about 1,700,000 km^2, mainly in southern Brazil but also in Paraguay, Uruguay, and Argentina. Apparently, Paleozoic sedimentation took place in an almost undisturbed tectonic environment, and consequently the stratigraphic units have good lateral continuity and show very little facies variations (Northfleet *et al.* 1969). These Paleozoic sediments are covered by one of the most important events of continental flood volcanism in the world. The Early Cretaceous basalt complex (Serra Geral Formation) covers an area of about 1,200,000 km^2 and is formed predominantly by tholeiitic and andesitic basalts (90% of the total volume) accompanied by tholeiitic andesites and rhyodacites-rhyolites. The volcanism predates the continental breakup and spreading of the South Atlantic ocean floor which separated South America from Africa (Piccirillo *et al.* 1988a) and was almost entirely emplaced in less than 3 Ma (roughly 133-130 Ma; Renne *et al.* 1992, Turner *et al.* 1994). After the volcanism, Upper Cretaceous continental sediments were deposited on the northern part of the basin. The maximum thickness of sedimentary and volcanic rocks in the Paraná basin is of 6,000 m at its central part (Zalán *et al.* 1986).

To account for the short time-interval, within which the volcanic activity took place, it has been suggested that lava flows outpoured simultaneously from conduits established contemporaneously at different parts of the basin, probably fed from a thermally anomalous lithospheric mantle (Piccirillo *et al.* 1988b). Similarly, based on the great thickness of the lava flows, it has been proposed that the extrusion of volcanic rocks occurred preferentially along three main axes (e.g., Cordani and Vandoros 1967, Leinz *et al.* 1968, Petri and Fúlfaro 1983). One of these axes is the Torres-Posadas lineament, the extension to the WNW of the Torres syncline.

The section of the South American platform where the Paraná Basin is located was widely affected by events of the Brazilian orogenic cycle (Upper Proterozoic to Ordovician). According to Cordani *et al.* (1984), its basement is probably formed by a cratonic nucleus surrounded by mobile belts, essentially composed of igneous and metamorphic rocks of this Precambrian orogenic cycle. The most significant Paraná Basin tectonic features are elongated arch-type structures, which outline the limits of the basin, and distinct tectonic lineaments cutting the basin from its eastern edge towards its center. Some lineaments are characterized by aeromagnetic lineaments (Ferreira 1982), whereas others are represented by a set of faults. These tectonic features evolved since the Devonian and were particularly active during Triassic-Jurassic times (Fúlfaro *et al.* 1982).

In the study region, the complex basement is generally composed of metamorphic rocks of the NE-trending Dom Feliciano fold belt, extensively deformed during the Brazilian event. Saddled between the Ponta Grossa Arch to the north and the Rio Grande Arch to the south, the NW-plunging Torres Syncline has been characterized mainly through surface observations of faults that vertically moved the sediments of the basin. Figure 1 shows the distribution of the MT/GDS

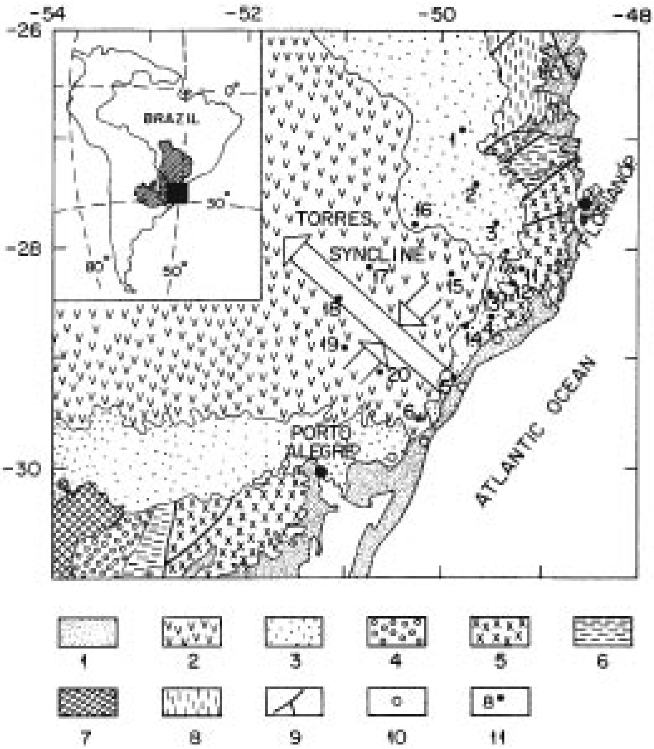

Figure 1 - Geological units around the Torres syncline in the Brazilian southern region. In the inset, the Paraná Basin (shaded zone) and the studied area (filled rectangle) on a map of South America. 1 - Quaternary sedimentary rocks; 2 - Upper Jurassic-Lower Cretaceous volcanic rocks; 3 - Upper Paleozoic-Triassic sedimentary rocks; 4, 5, and 6 - Upper Proterozoic metamorphic rocks (Dom Feliciano belt molassic, granite-gneiss and metasedimentary facies, respectively); 7 - Upper Proterozoic metamorphic rocks; 8 - Lower Proterozoic metamorphic rocks; 9 - shear zones; 10 - coal mines; 11 - MT/GDS stations.

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sites placed against a simplified geology of the SE Paraná Basin and contiguous tectonic features.

GEOPHYSICAL DATA Two electromagnetic methods of geophysical prospecting were used in this study: the MT (magnetotelluric) and the GDS (geomagnetic deep sounding). Both methods use natural time-varying electromagnetic fields due to solar activity and electric storms to investigate the electrical conductivity structure of the earth. In the MT method, two horizontal components of the electric field and three orthogonal components of the magnetic field are simultaneously recorded at the earth's surface over a large range of frequencies. The horizontal electric and magnetic fields are related through transfer functions (impedance) used to calculate apparent resistivity and phases as functions of the measured frequencies. Plots of apparent resistivity and phase against frequency are the results of a MT sounding at a given site. These plots resemble a highly smoothed electrical log with an axis of frequency rather than depth. The information concerning the depth is obtained thanks to the skin-depth effect, which implies that the electromagnetic wave amplitude decays as it diffuses down through the earth depending on the frequency of the wave and the subsurface conductivity. The geological structures responsible for the MT curves are determined from comparisons of the experimental data with synthetic data computed from models. Vozoff (1991) has presented the state-of-the-art of the MT method up to the early 1990's.

The GDS method is used to investigate the subsurface conductivity distribution by employing the natural magnetic field variations alone. Two complex transfer functions, which relate the vertical magnetic field component to the horizontal magnetic components, are derived and represented by real and imaginary induction arrows. The real arrows, when reversed, generally point towards zones of enhanced conductivity and can be used to locate lateral changes in conductivity. By being relatively unaffected by small-scale anomalies that can distort electric field amplitudes, the GDS method is an excellent mapping tool for locating regional anomalous structures. A full description of the analysis and interpretation techniques can be found in Arora (1997).

In this study, the five electromagnetic field components were recorded in the full period range of 0.0008-2048 s by commercial MT/GDS systems, deployed along some of the accessible roads of the region. Modern techniques of data processing were used to derive transfer functions and remove distortions from the data but their descriptions are beyond the scope of this paper. Further information can be found elsewhere (Padilha and Vitorello 2000).

Figure 2 displays the maps of real induction arrows for periods of 114 s and 1130 s. At the period of 114 s, the most conspicuous induction pattern is the NE-pointing induction arrows at the southernmost stations (sites 5, 6, 19, and 20), in contrast with the SW-pointing arrows at the nearby northernmost stations (sites 4, 13, 14, and 15). Such pattern constitutes the major evidence of the presence of an inland conductive zone running approximately in the NW direction, bounded by these two parallel groups of stations. Also, the near-vanishing arrows at sites 17 and 18, with the vertical component tending to zero, indicate that the resistivity distribution under these sites varies mainly only with depth (a near 1-D situation) and suggest the proximity of these stations to the axis of the anomaly. The shaded area in the background of Figure 2(a) indicates qualitatively the area extent of this high conductance zone, henceforth-named GDS anomaly. At a longer period (1130 s), the induction arrows, especially on the eastern part of the array, shift to a direction roughly perpendicular to the nearest coastline, 20 to 50 km away from the sites. This behavior suggests that electric currents in the Atlantic Ocean (coast effect) control the induction features at long periods.

MT apparent resistivity and phase were inverted to an assumed layered structure under each site. Rotationally invariant data were used, as they have proved useful in reducing the effects of local structures. Figure 3 shows one-dimensional inversions at two stations inside the GDS anomaly, chosen for their near 1-D behavior. Site 14 is representative of the stations over the pre-volcanic sediments, closest to the coast. It can be seen that below the sedimentary layers (mean resistivity of 16.5 W.m and thickness of 470 m) a strong conductor is observed with conductance of about 2300 S (resistivity around 1 W.m and depths from 470 to 2800 m). Site 18 is representative of the more inland group of stations. It shows that the same conductor is also present under the basalt-sediment assemblage (total depth of 1060m; resistivity of 280 W.m for the basalt and 13.1 W.m for the Paleozoic sediments) with a conductance of about 2000 S (resistivity around 2.5 W.m and depths from 1060 m to 6100 m).

DISCUSSION AND CONCLUSIONS According to our results, the EM fields for periods longer than 1000 s are strongly influenced by the coast effect to the east, whereas at shorter periods the data are primarily sensitive to inland conductive structures at depths shallower than a few kilometers. The NW direction was identified as the dominant electrical strike. This direction indicates that the NW Paleozoic lineaments rather than the NE structural direction of the Upper Proterozoic crystalline basement, in SE Paraná Basin locally control the conductivity contrasts.

A main conductive anomaly has been detected in the upper crust, nearly coincident with the Torres Syncline, and plunging towards the center of the basin. The detection of this conductor by both GDS and MT data represents the first geophysical evidence on the extension of the Torres Syncline to greater depths. The deepening of the top of the conductor to the NW is well matched by the isopachs of integrated sediments and basalt presented in Figure 2. Consequently, the source of the anomalous conductivity is considered to be seated in the upper part of the basement underneath the Paraná Basin, yet its identification is not straightforward. Due to the low resistivity of this conductor (less than 1 W.m), it is unlikely to be the result of cracks and pores filled with saline fluids alone, related to meteoric water. Nevertheless, the shallow crustal depths of few kilometers confine the possibilities to the presence of a large volume of interconnected highly mineralized fluids of low temperature deposition. Thus, we speculate that the conductor is related to trapped metassomatically-enriched highly mineralized

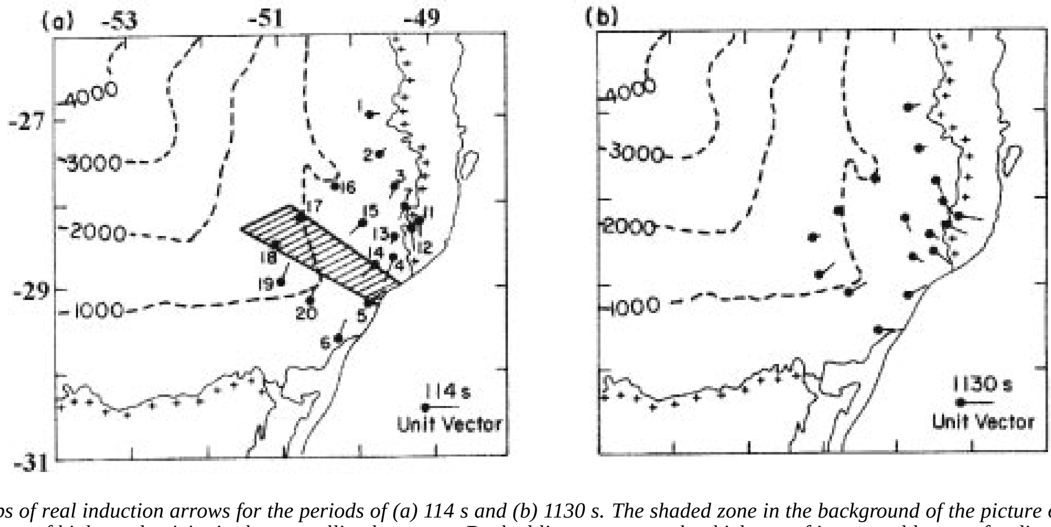

Figure 2 - Maps of real induction arrows for the periods of (a) 114 s and (b) 1130 s. The shaded zone in the background of the picture on the left side shows the probable area of high conductivity in the crystalline basement. Dashed lines represent the thickness of integrated layers of sediments and basalts from boreholes in the Paraná Basin (Zalán et al. 1986).

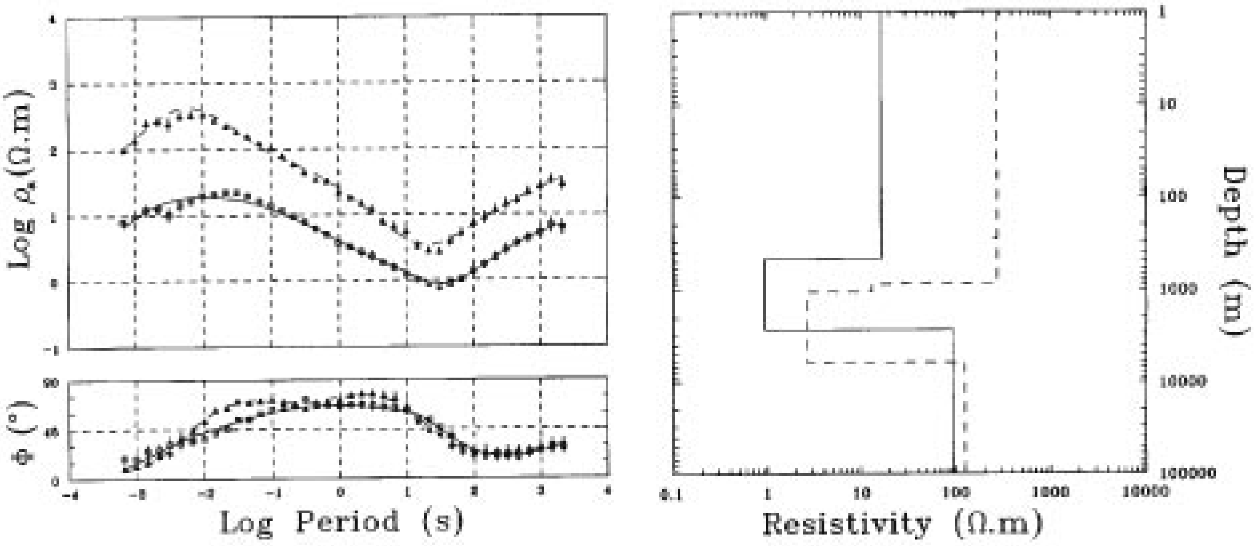

Figure 3 - 1-D inversion of rotationally invariant MT data at sites 14 and 18. At left, the observed data represented by the apparent resistivity and impedance phase responses (squares for site 14, triangles for site 18). Error bars are one standard deviation. At right, the best-fitting 1-D layered-Earth models, with the solid line corresponding to site 14 and the dashed line to site 18.

fluids likely emplaced in a vertically-fractured fold hinge, possibly in synchronism with magmatic events and sealed off by plugged conduits at upper layers by mineral deposition in the shallower and colder environment.

Evidence for this conclusion comes from the occurrence of abundant fluorite veins dated from 147-76 Ma and possibly until relatively recent periods of mineralizations (Jelinek *et al.* 1999). Temperatures between 70^o and 170^{o}C required to constrain such mineral deposition (Jelinek *et al.* 1999) are compatible with the present day gradient of 26.7^{o}C/km (weighted mean least squares) at the Torres Syncline and of 28.1-24.1^{o}C/km in adjacent areas (Vitorello *et al.* 1980), when projected to depths of 1-6 km (interval within which the electrical conductivity anomaly is confined) from a mean surface temperature of 21^{o}C. Furthermore, there are no geological indications of later major events that would disrupt the initial conditions required for the long-term preservation of the interconnected fractures.

Due to the shallow depths involved, a denser MT/GDS survey would be needed to delineate the finer-scale patterns in detail, with sites separated by hundreds of meters in the region where the conductors are located, and expanded NW in order to detect the conductors' extension towards the center of the basin.

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