JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. B3, PAGES 3351–3365, MARCH 10, 1992

UPPER CRUSTAL STRUCTURE OF THE NORTHEAST PARANÁ BASIN, BRAZIL, DETERMINED FROM INTEGRATED MAGNETOTELLURIC AND GRAVITY MEASUREMENTS

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Abstract. Eight magnetotelluric (MT) soundings were performed as a continuation of an earlier audiomagnetotelluric (AMT) survey conducted in the northeastern border of the Paraná basin, a large intracratonic basin located in central eastern South America and constituted by Silurian to Jurassic sedimentary rocks with Lower Cretaceous sill-type magmatic intrusions and overlying volcanics. Two of the MT stations were carried out near two deep petroleum wells. The remaining MT soundings were done on a profile traversing two important gravity features: a positive anomaly near the border of the states of São Paulo and Minas Gerais and a strong (trending NW-SE) linear gradient. Major findings of an integrated interpretation of the MT survey and of available gravity data are as follows: (1) inhomogeneities and/or strong magnetization of the superficial volcanics and diabase intrusions in the Paleozoic sedimentary rocks appearing to distort the MT results; and (2) identification of important structural discontinuities, including a possible different crustal structure beneath the Paraná basin compared to the region on the north, a thickening of the crust toward the NE, and the probable existence of a trough (graben?) within the basin, characterized by a thick accumulation of sediments and basalts.

Introduction

The intracratonic Paraná basin is located in central eastern South America, having an irregular oval shape with the major axis in the NNE-SSW direction. It covers an extensive area, about 1,700,000 km^2, mainly in southern Brazil but also in Uruguay, Paraguay, and Argentina, with a maximum thickness of sedimentary and volcanic rocks of 6000 m at its central part [Zalán et al., 1986].

Information on the main structural features of the Brazilian part of Paraná basin has been obtained through surface observations, sparse drilling, and a few geophysical surveys in the search for hydrocarbons. These subsurface investigations were largely located in the central region of the basin, whereas its margins have been less studied. Specifically, in the northeastern region, very little has been done in terms of geologic and geophysical studies; and, consequently the crustal characteristics of the area are mostly unknown.

In order to add new geophysical information to the northeastern region of the Paraná basin, it was decided to conduct a magnetotelluric (MT) study in the area, which began with a preliminary audiomagnetotelluric (AMT) survey in the frequency range from 4.1 to 2300 Hz. As a consequence of these measurements, Padilha et al. [1989] showed that it was possible to map the contact between the uppermost sedimentary layers and the underlain volcanic rocks. An observed undulated contact was interpreted as the result of a tectonic event that affected the basin border after the deposition of the volcanic rocks. Following these AMT studies, eight MT soundings, in the frequency range from 0.01 to 5 Hz, were done along the same AMT profile. An integrated interpretation of this MT survey and of the available gravity data is presented here.

Paper number 91JB02712.
0148-0227/92/91JB-02712$05.00

Geologic Setting

The Paraná basin is located on the South American platform which 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, the basin is filled by Silurian to Jurassic sedimentary rocks intruded by sill-type magmatic bodies and overlying volcanics, mainly of Lower Cretaceous age, whose thickness is greatest in the central part of the basin.

A generalized geological map of the Paraná basin is shown in Figure 1. The most important tectonic features are positive elongated structures ("arches") which outline the basin, except along the eastern parts where marginal Cenozoic basins occur. Notable are the NW structures, transversal to the main elongation of the basin, represented by several arches, the Torres syncline, and various tectonic and/or magnetic lineaments. The formation of the NW arches began in the Silurian, but developed mainly during the Triassic-Jurassic to Upper Cretaceous-Tertiary [Fúlfaro et al., 1982; Zalán et al., 1986].

The sedimentary development of the Paraná basin started in the Upper Ordovician [Zalán et al., 1986] and was characterized by three distinct phases of subsidence, separated by periods of uplift and erosion. The first stage of subsidence was responsible for the Silurian and Devonian sequences in gulf and epicontinental sea environments, respectively. The NW-SE tectonics was particularly active and a general uplift related to Andean Eo-Hercynian orogenesis caused the interruption of the sedimentation during Upper Devonian-Mississippian. The second phase of subsidence that occurred in the Pennsylvanian-Permian was related to a new transgressive-regressive depositional cycle. The sedimentation evolved from glacial to fluviodeltaic environments and finally to marine conditions. The NW-SE and NE-SW tectonics were alter-

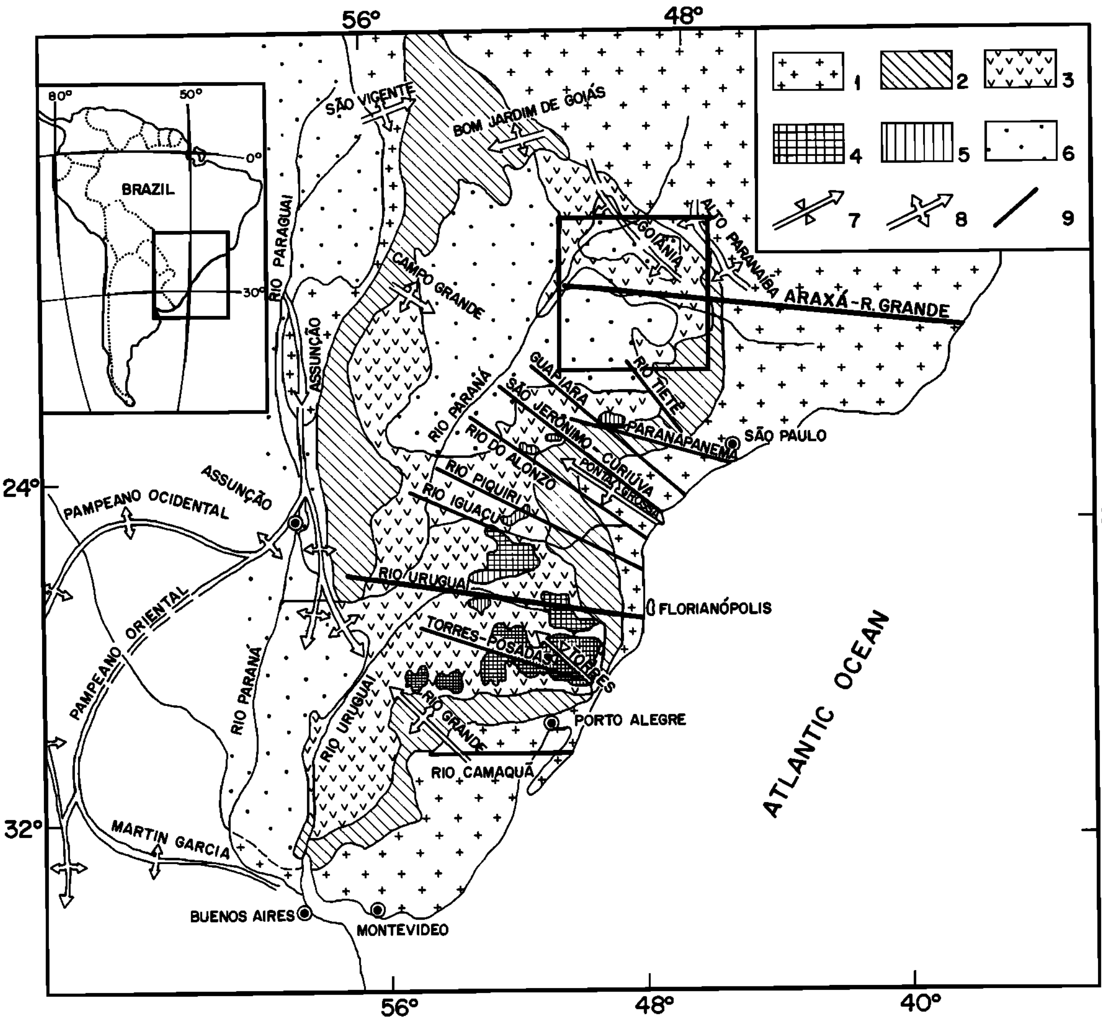

Fig. 1. Generalized geological sketch of Paraná basin (compiled by Bellieni et al. [1986] and Petrini et al. [1987]). 1, pre-Devonian crystalline basement; 2, prevolcanic sediments (mainly Paleozoic); 3, basic to intermediate flood volcanics (Serra Geral Formation: Lower Cretaceous); 4, Palmas-type acid lava flows (Serra Geral Formation); 5, Chapecó-type acid lava flows (Serra Geral Formation); 6, postvolcanic sediments (mainly Upper Cretaceous); 7, syncline-type structure; 8, arch-type structure; 9, tectonic and/or magnetic lineament.

natively active during this period, and a general uplift interrupted sedimentation in the Upper Permian-Lower Triassic.

During the Middle Triassic the sedimentation recommenced with the deposition of continental-fluvial sediments and in the Jurassic-Cretaceous desert conditions prevailed with the deposition of aeolic sandstones over the entire Paraná basin. The isopachs of the Triassic-Jurassic sediments indicate that the Ponta Grossa arch region (see Figure 1) was uplifted just before the onset of the Lower Cretaceous volcanic activity. Such uplift may be regarded as a thermal doming related to an elevation of the mantle [Zalán et al., 1986]. An important control on the Triassic-Jurassic sedimentation was provided by the NW-SE and E-W tectonics. A third phase of subsidence in Upper Jurassic-Lower Cretaceous was associated with the extrusion of a huge quantity of volcanics of the Serra Geral Formation and the emplacement of abundant sill-type intrusions. The volcanism, covering about 1,200,000 km^2, is dominated by tholeiitic basalt rock types (about 90% of the total volume) overlain by rhyodacites (3% of the volume) and sometimes by andesitic products (7% of the volume).

Geochemically, the Paraná basin may be subdivided into three main portions [Bellieni et al., 1984; Piccirillo et al., 1987]: south of the Rio Uruguay lineament, the volcanic sequence is characterized by low titanium content and combined acid and basic flows in the upper section; north of the Rio Piquiri lineament, the volcanics are dominated by high titanium content basic flows, sometimes overlain by acid flows (mainly rhyodacites); and the central part of the basin is a transition zone in which volcanic suites with high and low titanium content are present.

After the volcanism, in Upper Cretaceous, continental sediments of the Bauru Group were deposited. This sedimentation represents only 3-5% of the total volume of the basin and covers much of the volcanics of the northern Paraná basin.

In the region where this study is concentrated, the most prominent tectonic features are the Goiânia flexure and the Araxá-Rio Grande alignment. The Goiânia flexure constituted the northeastern tectonic border of the basin during most of its history, and the Araxá-Rio Grande has been proposed as a continental extension from the Vitória-Trindade alignment in the continental margin. Figure 2 shows more details of the geology of the study area, which is covered by the Bauru Group sediments and underlain by volcanic rocks of the Serra Geral Formation that crops out only along the principal rivers.

Previous Geophysical Surveys

As stated before, very little has been done in terms of geophysical studies in the northeastern border of the Paraná basin. The only available geophysical results for the area are based on vertical electrical sounding (VES) and gravity surveys.

Vertical electrical soundings have been carried out in the region as part of a groundwater study [Departamento de Águas e Energia Elétrica do Estado de São Paulo (DAEE), 1976]. These soundings showed that the Bauru Group has a mean resistivity of 16.3 ohm m, ranging from 10 to 25 ohm m, with a standard deviation of 1.7 ohm m, whereas the volcanic rocks of the Serra Geral Formation showed resistivity values ranging from 50 to 500 ohm m. These results are

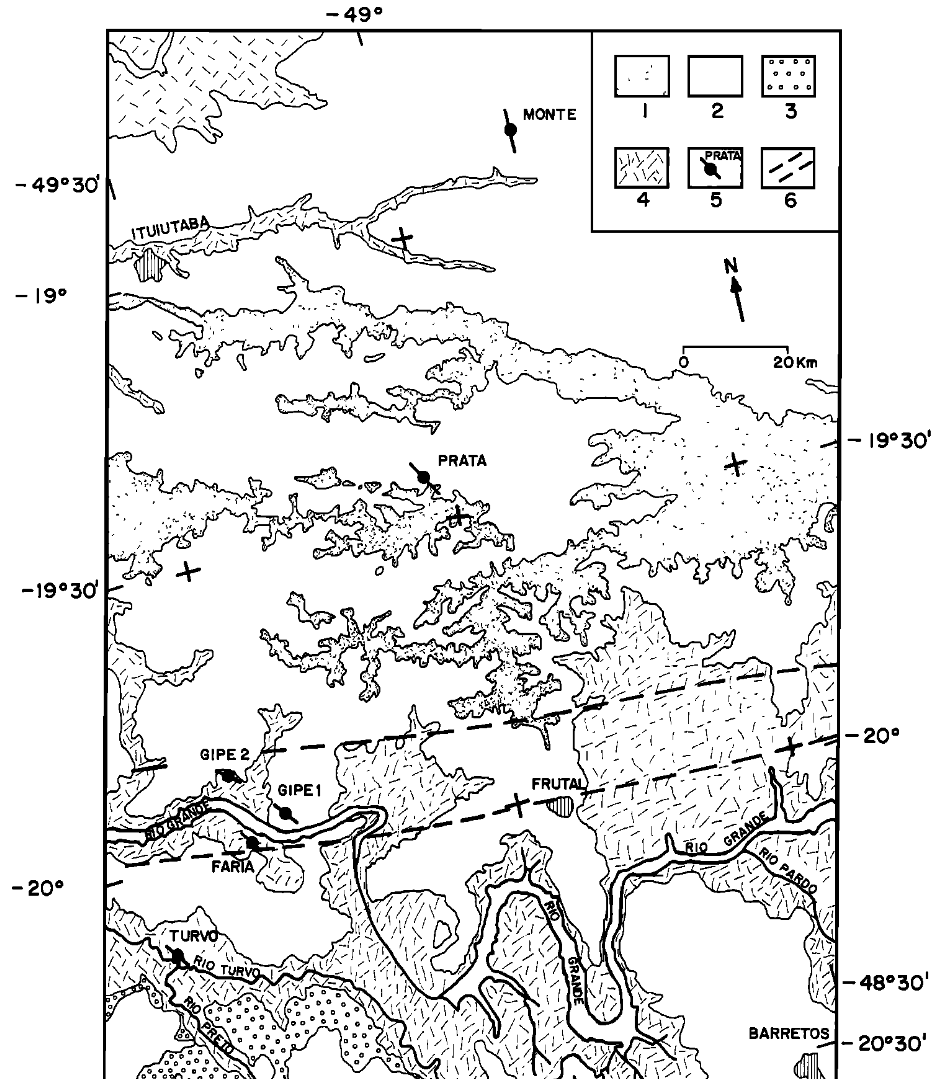

Fig. 2. Geological outline of northeast region of Paraná basin (after C.C. Liu, unpublished data, 1989), showing the location of the six northernmost MT stations with their principal directions. 1, Tertiary-Upper Cretaceous Marília Formation (Bauru Group); 2, Upper Cretaceous São José do Rio Preto-Uberaba Members (Bauru Group); 3, Upper Cretaceous Araçatuba Member (Bauru Group); 4, Lower Cretaceous Serra Geral Formation; 5, MT station; 6, Araxá-Rio Grande lineament.

used to constrain the resistivity values of the upper layers in our models.

Figure 3 depicts a Bouguer gravity anomaly map which covers the northeastern border of the basin. A strong linear gradient (approximately 3 mGal/km) trending NW-SE was interpreted by Lesquer et al. [1981] as due to a contact between two provinces, the Paramirim craton to the north and the southern rejuvenated crust where the Paraná basin developed. Other studies [Shiraiwa, 1985; Zalán et al., 1986; Santero et al., 1988] interpreted the same gradient as due to crustal thinning (about 20% in paper by Zalán et al. [1986]) under the Paraná basin. Another important feature of the gravity map is the sequence of local anomalies, positive to the west and negative to the east of the previously referred gravity gradient, with 10-20 mGal amplitude range and wavelength of a few tens of kilometers. The positive anomalies have not been fully interpreted and various hypotheses [see Haralyi and Hasui, 1981; Zalán et al., 1986; Molina et al., 1989] have been put forward to explain them, including thickening of the basalt layer, rise of the basement, or presence of basic intrusions in the sedimentary sequence. The negative gravity anomalies are probably associated with locally thicker sedimentary cover.

The geographic position of our MT survey in the region was selected on the basis of such gravity information. MT soundings were conducted along a profile starting in the interior of the Paraná basin, cutting across the most prominent of the positive anomalies and the gravity gradient, and terminating on the northeastern border of the basin. In terms of the basement tectonic framework of the basin, the profile begins on the southwest, on a marginal cratonic belt composed of ancient granitic, gneissic, and migmatitic

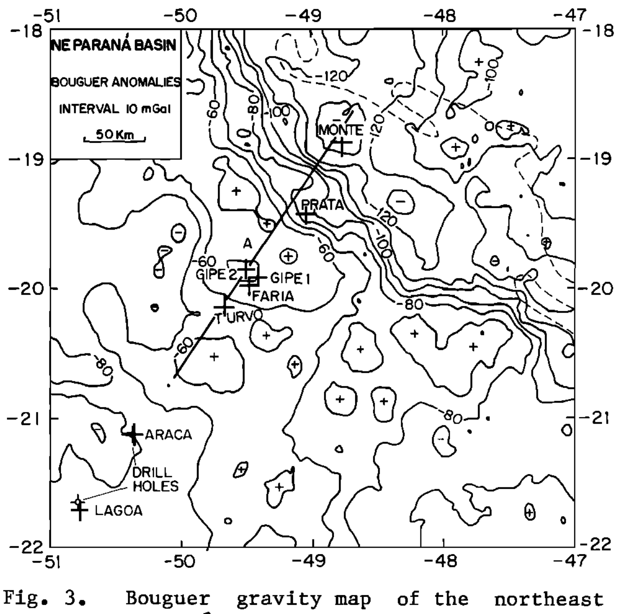

Fig. 3. Bouguer gravity map of the northeast region of Paraná basin, showing the location of the MT stations (large pluses), analyzed gravity profile (solid straight line, identified by the letter A), gravity lows (minuses) and highs (small pluses), drill holes, and northeast basin limit (dashed line).

terrains reworked during the Brazilian cycle, and ends on the northeast, over metasedimentary rocks related to the Uruaçuan episode of folding and deformation [Zalán et al., 1986]. A preliminary AMT study [Padilha et al., 1989] was carried out, and its results were used to select the sites for deeper MT soundings where superficial distortions were smaller; the AMT data also provided shallow information for the MT data inversion.

MT Survey

Our MT equipment was constructed at the Instituto Nacional de Pesquisas Espaciais (INPE) [Dutra, 1984] and measures the electric field between two nonpolarizable electrodes at the surface of the Earth with a hundred meters separation, in two orthogonal directions (tensor), and the magnetic field by very sensitive induction magnetometers (CM11E). The analog signals are appropriately amplified and band-pass filtered. Subsequently, these signals are digitized with a precision of 12 bits, and the data are recorded in a digital cassette recorder for further analysis. Power spectral analyses of the time series data are done in our laboratory using Fourier techniques [Bendat and Piersol, 1971], and apparent resistivity and phase curves are then computed as a function of frequency [Madden and Nelson, 1964; Sims and Bostick, 1969].

In the present investigation, the signals were measured in a frequency band from 0.01 to 5 Hz for at least 6-8 hours per site in order to get useful data. The locations of the six northernmost stations are shown in Figure 2 with geological information, and the entire profile is seen in Figure 3 in relation to the gravity data. Two stations (identified as LAGOA and ARACA) on the southwest end of the MT profile, were near boreholes drilled for petroleum and served as guidelines for the interpretation of the other soundings. The remaining six stations composed a profile cutting across the positive gravity anomaly, with three stations (named FARIA, GIPE1, and GIPE2) situated inside the anomaly.

MT Interpretations

Figures 4 and 5 typify the MT results obtained in the northeastern border of the Paraná basin. In Figure 4, apparent resistivities and phases, with their confidence intervals, rotated on the principal directions of the impedance tensor and the responses (continuous and dashed lines) to the model from two-dimensional inversion, multiple coherences for the orthogonal electrical fields, the skew, and the angle of rotation (azimuth) that maximizes secondary diagonal terms of impedance tensor are shown for the analyzed frequency band for the FARIA site.

Multiple coherence and error bars obtained from the confidence intervals of apparent resistivity and phase estimates were used to verify the data quality. With the exception of ARACA, which was probably contaminated by artificial noises, multiple coherence results showed median values around 0.9, whereas error bars, obtained with a confidence limit of 68%, exhibited low deviations, which indicate good quality data for most of the stations.

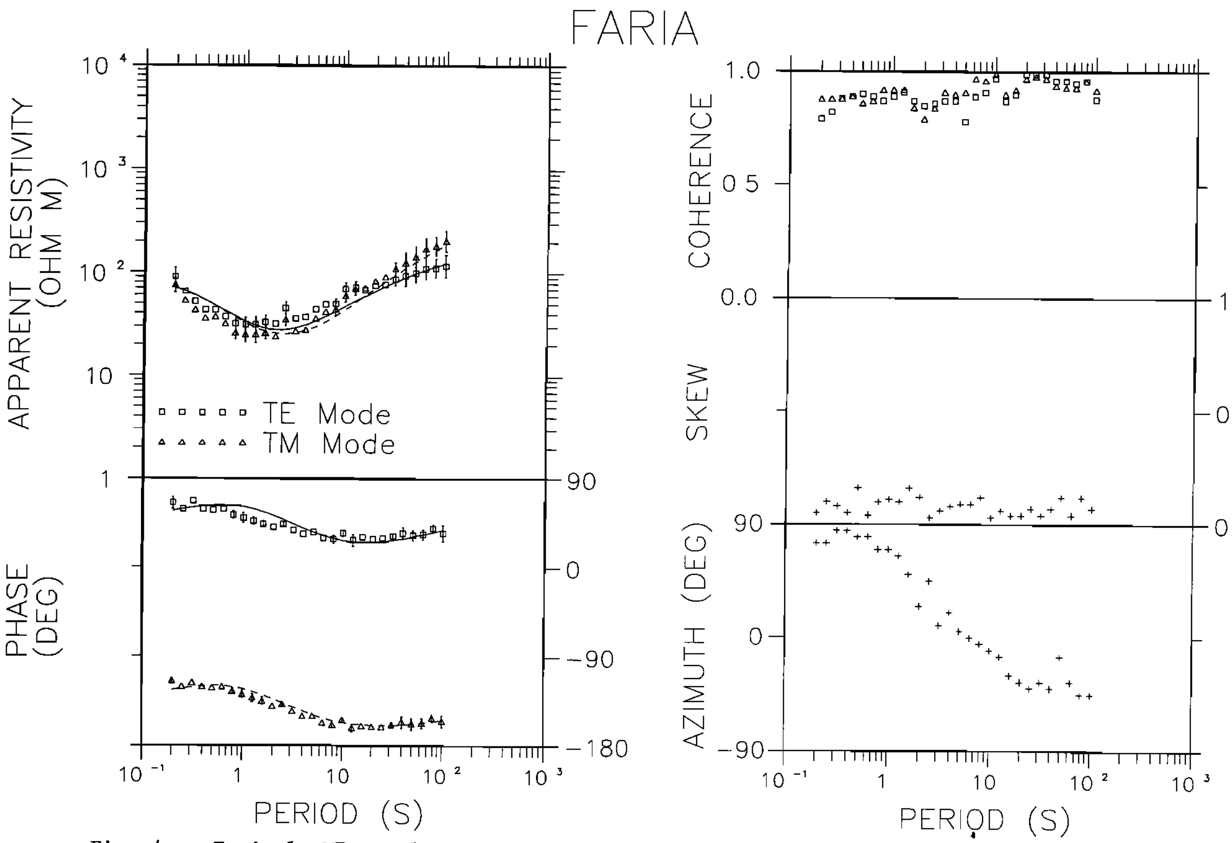

Fig. 4. Typical MT results in the northeastern border of the Paranã basin (FARIA station). Left side shows apparent resistivities and phases, both experimentally obtained (with error bars representing 68% confidence intervals, not plotted when smaller than the symbols) and generated by the two-dimensional adjusted model (continuous and dashed lines). The right side shows multiple coherences, skew, and angle of rotation (azimuth).

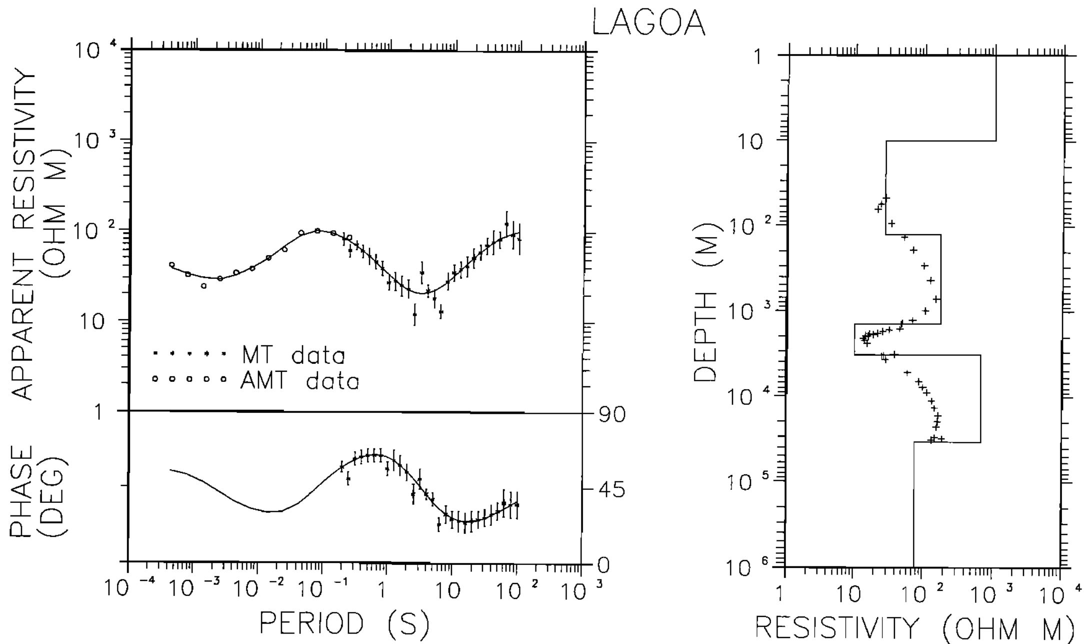

Fig. 5. Typical one-dimensional inversion results on invariant apparent resistivities and phases. The left side shows experimentally obtained data (with their 68% confidence intervals) and the responses (continuous line) to the model from inversion presented at the right. The right side also shows the Niblett-Bostick transform results (pluses).

Skew results, normally used as a structural dimension indicator, showed very low values in almost every frequency for all stations not disturbed by noise (i.e., excepting ARACA). The anisotropy between the two resistivity curves at each site can be also used to indicate local geological complexity. Table 1 presents averaged anisotropy factor (obtained through the ratio of the two apparent resistivity values at each frequency) in four frequency intervals. The anisotropy is very low, specially in the higher frequencies, showing good agreement to those observed in the northernmost stations of a previous survey in the central part of the basin [Paulipetro, 1982]. It can be concluded that the uppermost surficial geological layers (mainly volcanics) are seen as regionally homogeneous by individual MT soundings in northern region of the basin. The observed anisotropy factor (median of 1.29 for the two higher frequency intervals) can be interpreted as generated either by instabilities on the impedance tensor estimates (noise contamination) or by local superficial heterogeneities in the volcanic layer near the point of installation of the electrodes. The latter factor is commonly referred to as static shift. For the lower frequencies, anisotropy factors of the central stations on the profile (from TURVO to PRATA) indicate deep structures affecting the MT curves, illustrating the necessity of multidimensional modelling.

The azimuth angles (measured positive in the clockwise direction from north to east) indicate the directions of the principal axes of the structures and can be grouped into two different regions in the profile (Figure 2): from LAGOA to PRATA and at MONTE. In the first region, there are two distinct principal directions, quite similar at every station: about 80° for the higher frequencies, involving volcanic rocks and probably Paleozoic sediments, and -35° for the lower frequencies, related to the crystalline basement, with a smooth transition between both directions. At MONTE, there is only one direction (aligned with the geographic north) probably indicating small thicknesses of rocks generating the observed structural orientation for the higher frequencies and a different crystalline basement. It should be noted that with the absence of the vertical component of the magnetic field, the choice of one of the two possible orthogonal directions was done considering observed superficial trends (specially rivers directions), general NW-SE direction of the tectonic and magnetic alignments, and long-wavelength gravity features.

On the basis of these analyses, it was necessary to employ two-dimensional modelling to fit the MT data. The interpretation began with the inversion of the observed apparent resistivity and phase results for each sounding to obtain a one-dimensional resistivity distribution. The determinant invariant impedances [Berdichevsky and Dmitriev, 1976; Ranganayaki, 1984] were chosen to represent the MT data, and previous AMT data, available at each station, were also used in the inversion to obtain information on the surficial layers. The starting model for the inversion, using the routine given by Jupp and Vozoff [1975], was based mainly on information from wells 2-LA-1-SP and 2-AR-1-SP (adjacent to LAGOA and ARACA, respectively). Figure 5 shows the results of the inversion for LAGOA, using both Niblett-Bostick continuous depth-versus-resistivity curve [Niblett and Sayn-Wittgenstein, 1960; Bostick, 1977; Jones, 1983] and Jupp-Vozoff's discrete-layered inversion. The two methods gave similar results, with the continuous inversion showing that the first and last discrete layers are not well defined for the available data.

The results from one-dimensional models were pieced together to construct an electrical cross section (Figure 6a), from which a simplified, two-dimensional starting model was constructed (Figure 6b). Normally, a consistent two-dimensional model is only possible if the stations are identically rotated, perpendicular to the direction of the profile [Wannamaker et al., 1984]. From Figure 2, it can be seen that MONTE does not satisfy this condition. However, as the anisotropy at MONTE is very low and almost the same throughout the entire frequency range (see Table 1) and the skew values are also very low, the error is not large when considering the station as identically oriented as the others.

TABLE 1. Anisotropy Factors for the MT Curves of the Northeast Region of the Paraná Basin

Station	Interval			
Code	>1 Hz	0.2-1 Hz	0.04-0.2 Hz	<0.04 Hz
LAGOA	1.50 (0.11)	1.30 (0.23)	1.31 (0.08)	1.26 (0.05)
ARACA	2.26 (0.59)	3.50 (0.40)	3.64 (0.42)	2.43 (0.40)
TURVO	1.19 (0.06)	1.33 (0.07)	1.33 (0.10)	0.99 (0.11)
FARIA	1.20 (0.02)	1.27 (0.05)	1.08 (0.12)	0.70 (0.09)
GIPE1	1.29 (0.06)	1.31 (0.06)	0.87 (0.15)	0.45 (0.07)
GIPE2	1.24 (0.05)	1.27 (0.05)	0.85 (0.16)	0.43 (0.07)
PRATA	1.14 (0.12)	1.23 (0.07)	0.86 (0.09)	0.57 (0.06)
MONTE	1.37 (0.05)	1.39 (0.08)	1.46 (0.10)	1.66 (0.30)

Values in parentheses correspond to one standard deviation.

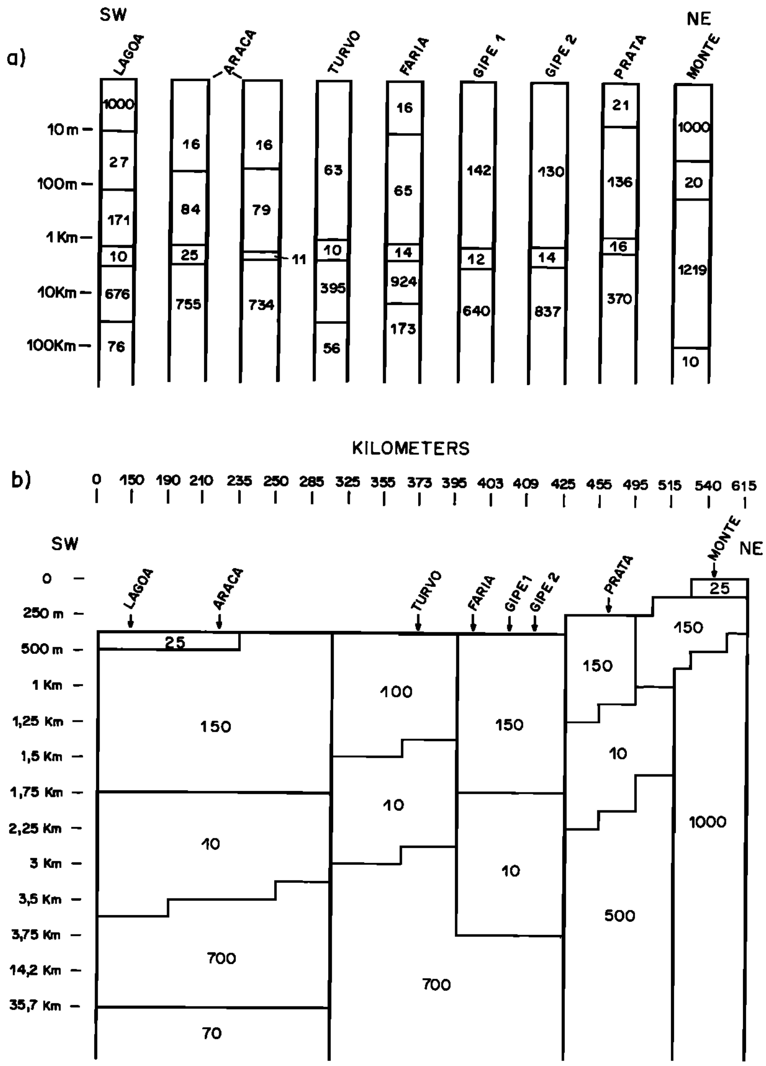

Fig. 6. Construction of the starting model for the two-dimensional inversion. (a) One-dimensional inversions of the invariant model for each site along the profile (in ARACA two possible models are shown). (b) Simplified, two-dimensional starting model derived from Figure 6a. Numbers in model are resistivity values inside the blocks in ohm m.

Also, due to the large distance from the profile, LAGOA and ARACA could not be interpreted conjointly to the others. Their utilization is justified because they provide a more regional vision of the basin. For ARACA, the original MT values contaminated by noise were not used for the modelling. Instead, the electrical results from the well 2-AR-1-SP were used for the starting model in the inversion.

The two-dimensional inversion code developed by Jupp and Vozoff [1977] was used on the starting model of Figure 6b. Apparent resistivities and phases at six frequencies (3.163, 1, 0.3163, 0.1, 0.0316, and 0.01 Hz) for the two modes of polarization of the electric field were modelled. The results from the model, which is presented in Figure 7, provide a good fit to the experimental curves.

To analyze if the key features of the model of Figure 7b are required by the data, we consider an alternate structure. Figure 8 shows the results of a model without the postulated "graben" under the region of the gravity anomaly. In this model, the thicknesses of the different layers decrease slowly in the direction of the margin, so that the data must be fitted by resistivity variations alone. Figure 9 presents a direct comparison between both models at GIPE1, the station located at the center of the gravity anomaly. It can be seen that the values obtained from the model of Figure 7 are substantially better than those of the model of Figure 8. It can be concluded that the data cannot be fitted by resistivity variations alone, which shows that the data require thickness variations as in Figure 7b, our preferred structure.

A few details of the model of Figure 7b have special geologic significance. The blocks that can be associated with the basaltic complex show a great variation in their resistivities, from 53

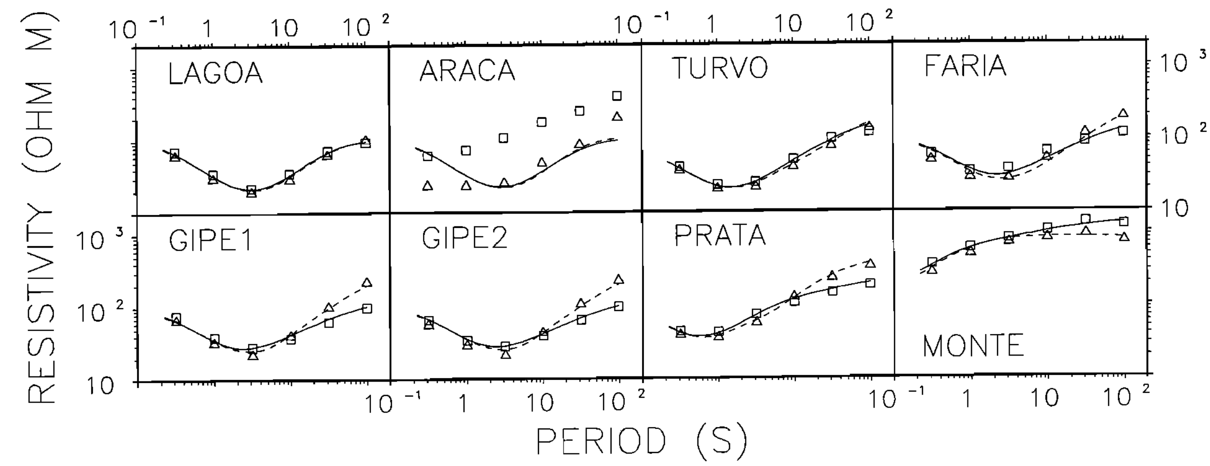

Fig. 7a. Two-dimensional electrical model for the northeastern region of the Paraná basin. Smoothed, observed TE (squares) and TM (triangles) data and computed values are shown for all soundings.

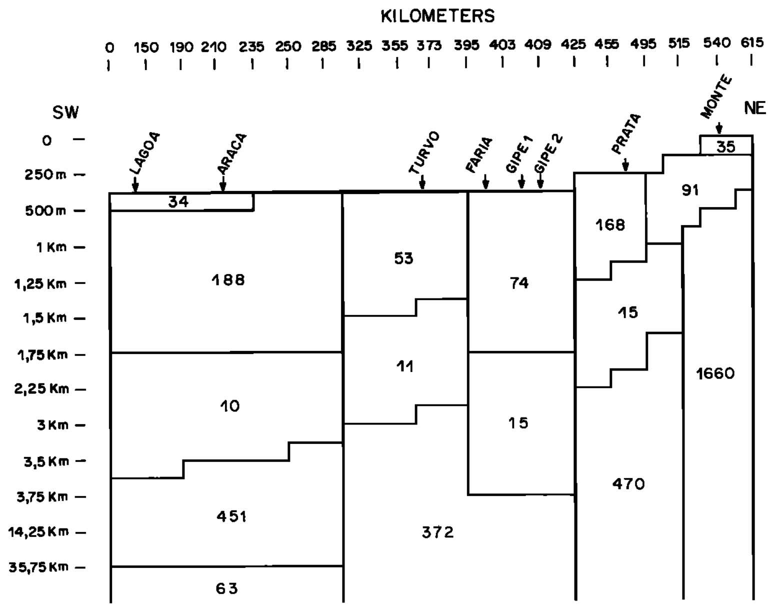

Fig. 7b. Model obtained from the Jupp-Vozoff inversion, using Figure 6b as its starting model.

to 188 ohm m, confirming the heterogeneity of the Serra Geral Formation at scales of hundred of kilometers. The sedimentary rocks beneath the Serra Geral Formation have a peculiar characteristic of increased resistivity toward the basin border. A comparison of the values observed in this survey (interval from 10 to 15 ohm m) to those reported by Stanley et al. [1985] for the central part of the basin (variation from 3 to 12 ohm m) seems to confirm this tendency. A possible explanation for this behavior could be in terms of a depositional system in which coarse basal sediments (sandstones) would be overlain by finer type sediments (siltstone and claystone) concentrated in the central region. Model resolution parameters show that the resistivity of the basement is more accurate for the northern end of the profile than beneath the Paleozoic sediments of the basin. Resistivity values give some indication of two basement units with distinct electric properties, one under the southweastern part (deviation from 275 to 713 ohm m) and the other under the northeastern part of the basin (from 1480 to 1880 ohm m). However, these dissimilarities are not well enough constrained since a difference in resistivity by a factor of only 2, such as in this case, can be ascribed to many other sources, including subtle three-dimensional effects. Additional information must be used to distinguish the two possible basements. Parameters of the Bauru Group (surface sediments) presented at both extremes of the profile are not significant, because the highest frequency used in modelling (3.163 Hz) is too low to permit us to study this unit.

An additional conductive layer appears on the

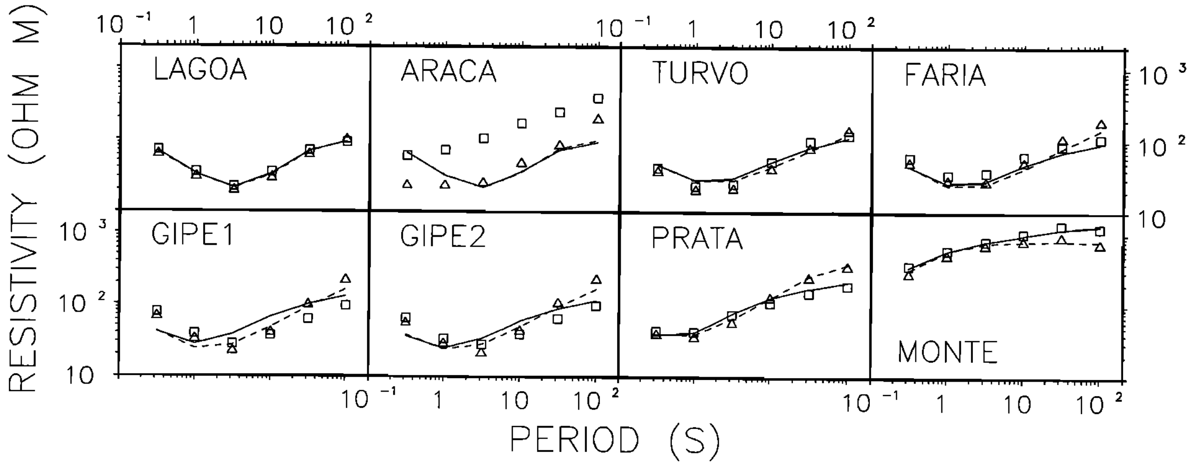

Fig. 8a. The same as Figure 7a using a starting model without the "graben" under the gravity anomaly region.

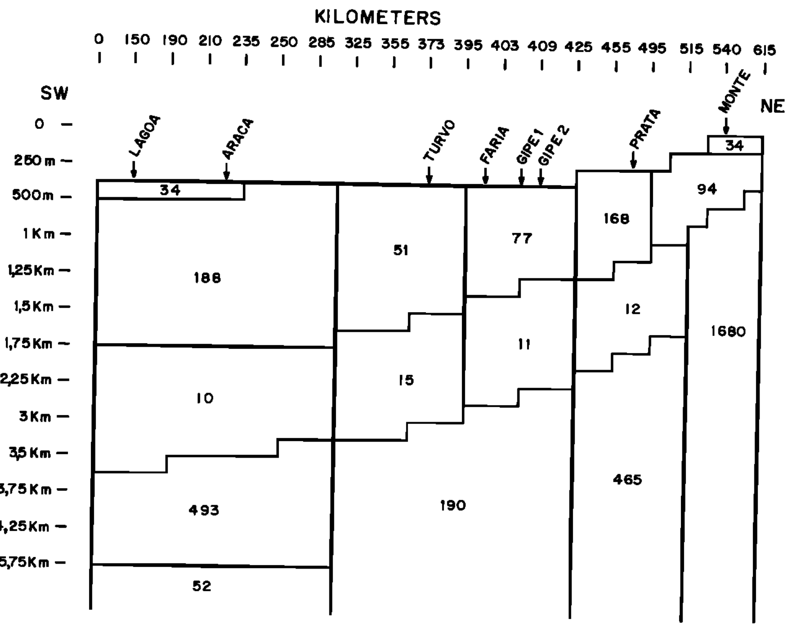

Fig. 8b. The same as Figure 7b using a starting model without the "graben" under the gravity anomaly region.

southwestern end of the model, near the basin center, at depths of the lower crust. A similar layer, situated deeper than 30 km, had already been observed in the previous MT survey reported by Stanley et al. [1985]. Saline fluids are normally considered as the origin of low resistivities at such depths [e.g., Shankland and Ander, 1983]. In extensional regimes, water from the mantle released in devolatilization processes is suggested as a source of water for the lower crust and may also be associated with widespread crustal underplating [Hyndman and Shearer, 1989]. In the context of the Paranã basin, Molina et al. [1989] interpreted a large 30-40 mGal amplitude gravity anomaly high situated in the central part of the basin as generated by underplating of basic material.

Distortions on MT Results

An evaluation of the degree of accuracy of our model is possible through the two soundings carried out near the wells 2-LA-1-SP and 2-AR-1-SP. Figure 10 presents a comparison of some of principal characteristics of well 2-LA-1-SP with the results of MT sounding referred to as LAGOA (about 7 km distant from the well). This comparison ought to be considered an approximation because both the depths to the different formations and the electric resistivity log for the well are in reference to values restricted to the vicinity of the hole, whereas the MT results provide information on electrical property variations on a broader scale. The thickness of the Bauru Group and the resistivities of the Serra

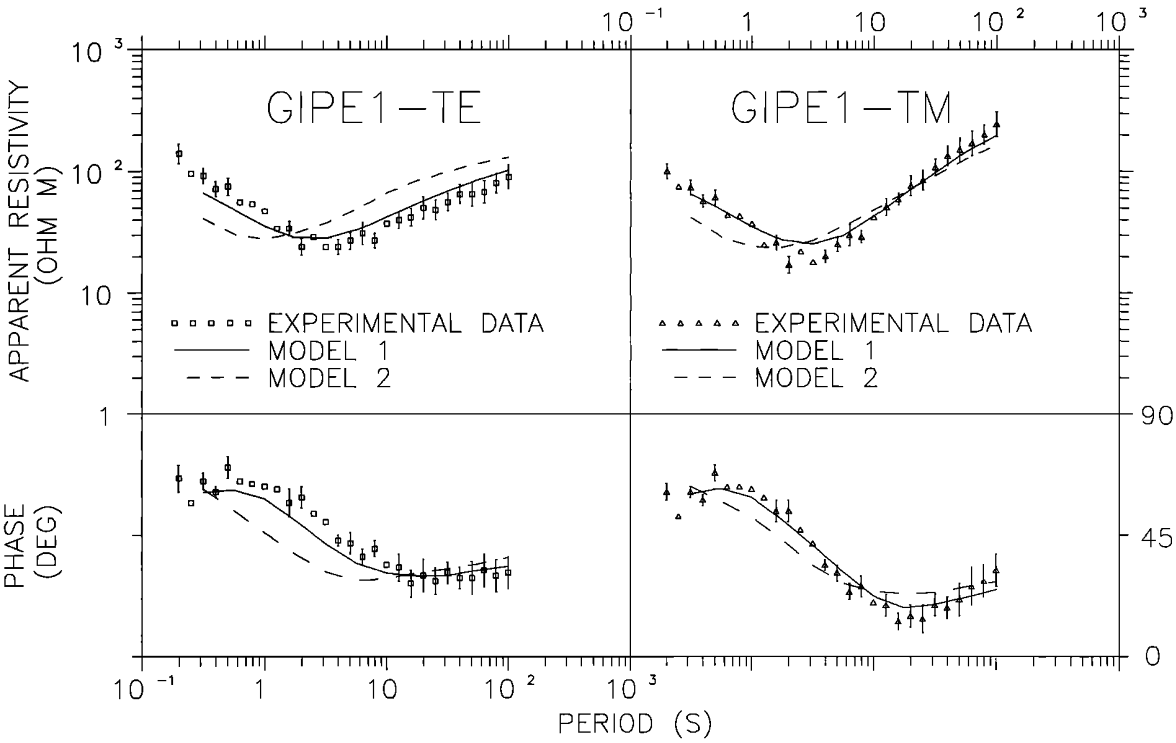

Fig. 9. Comparison of apparent resistivity and phase values generated by two different models at GIPE1 station in both TE and TM modes. Model 1 is referred to a structure with the postulated "graben" (Figure 7) and model 2 without it (Figure 8).

Geral Formation and underlying sedimentary rocks seem well determined in our measurements. The depth to electrical basement (diabase intrusions at the base of the Paleozoic sediments) is similar on both the electrical log and the MT inversion. On the other hand, the MT sounding indicates a thickness which is 15% larger for the volcanic rocks.

In a study of another basalt covered area (Columbia river plateau), Katterjohn and Hopkins [1984] reported that the MT data determined the base of the basalts at a depth 8.3% deeper than the actual depth encountered at a nearby well and the basement at a depth more than 13.5% shallower than the actual depth of the crystalline basement. Similarities between the two studies, specially in the determination of the basaltic layer, brings on the suspicion of a geologic factor, common to volcanic covered areas, distorting the measurements. Strong magnetization of basaltic layers can be suggested as a possible cause for this uncertainty in the MT results. According to Kao and Orr [1982], a magnetized layer could be interpreted as more resistive or thicker than an unmagnetized equivalent layer. From the relation between magnetic susceptibility and permeability, it can be shown that a misinterpretation of 15% in the basaltic layer thickness could be generated by a magnetic susceptibility of 0.15 (in S.I. units) for the basalts. This value is a little greater than those commonly observed for basalts (interval from 0.00002 to 0.145 of Telford et al. [1976]) but does not completely rule out this hypothesis.

Another possible source of distortion on our MT data may be ascribed to the presence of three-dimensional lateral inhomogeneities in the volcanic rocks. These surficial inhomogeneities can modulate the inferred depth to deeper layers, causing an underestimation or overestimation by factors arbitrarily large [Hermance, 1983]. Observation of exposed sections of Serra Geral volcanics in large dams [Souza Júnior, 1986] and the large resistivity variations observed in the well log of Figure 10 in the interior of that formation confirm these inhomogeneities which can be attributed to several causes: generation of different lava flows; variable cooling conditions; or the presence of intercalated sediments on the basaltic complex.

In reference to the electrical basement, the coincidence of the depth in which it is obtained from MT measurements and the one where the diabase intrusions are found had also been reported for some of the MT stations in the central part of the basin by Stanley et al. [1985]. This fact permits us to infer that these intrusions may be locally important (probably sills). The presence of these factors, magnetization and/or local inhomogeneities on basaltic layer and intrusions in sedimentary rocks may generate distortional effects that must be considered in the interpretation of the MT data in Paraná basin as well as in any other area with basaltic volcanics.

The noise that disrupted the signals of the ARACA station makes impracticable the comparison of the MT results from this station to those supplied from the 2-AR-1-SP well. The noise source can be assigned to either a strong wind

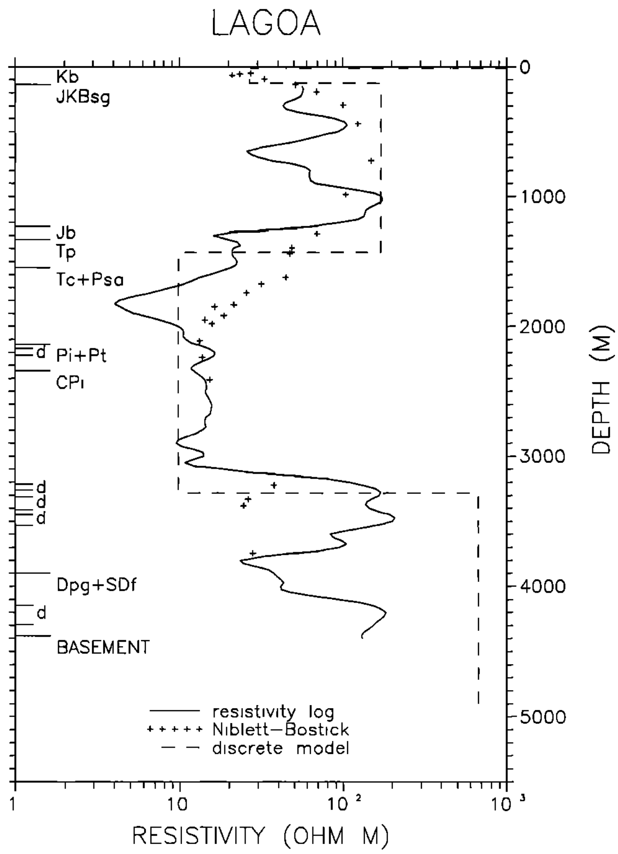

Fig. 10. Comparison of MT results for LAGOA with geological and geophysical data for the well 2-LA-1-SP. At the left side are presented contact depths between different units: Kb, Bauru Group; JKBsg, Serra Geral Formation; Jb, Tp, Tc, Psa, Pi, Pt, Cpi, Dpg, and SDf, prevolcanic sedimentary units; d, major diabase intrusions.

during the data acquisition or to an artificial noise generated in the nearby relatively large town of Araçatuba. Furthermore, the low conductivity of the surficial basaltic layer probably contributed to the problem by disseminating such local noise to the surrounding areas.

Gravity Data

A gravity profile was taken from the Bouguer anomaly map of the northeastern border of the Paraná basin (Figures 3 and 11), located nearly coincident to the MT survey profile. The principal features along the gravity profile are the highs and lows situated to the SW of the strong gradient (from 0 to 170 km distance on the profile), the gradient itself with superimposed short wavelength signatures (jumps indicated with an arrow in Figure 11a), and the negative anomaly in the northeastern end of the profile (from 240 to 255 km).

A two-dimensional model of the profile was developed using an interactive programme whose algorithm is based on work by Talwani et al. [1959]. In our interpretation, the gravity highs and lows originate from undulations in the contact between prevolcanic sedimentary rocks and the basalts of the Serra Geral Formation. The short-wavelength variations over the gravity gradient and the negative anomaly on the northeastern end of the profile were not included in the model, but we ascribe them to the presence of faults in the Goiânia flexure region and to superficial sedimentary deposits on the Uruaçuan folded rocks, respectively. For the interpretation of the gravity gradient, given the nonuniqueness of the inverse problem, there is an infinite number of models that can be adjusted to the observed data. Three of these models are discussed here in more detail (Figure 11).

Figure 11b presents a model in which the gravity features are interpreted with only a crustal thickening from the interior to the exterior of the basin. This model does not consider the possibility brought up by the MT results which give some indication that the crystalline basement can present different properties along the profile, with two possible distinct provinces within (granitic rocks) and outside (metasedimentary rocks) the basin. Figure 11c shows another model, which assigns the gradient only to density variations between the two geologic provinces and eliminates the possible problem of compatibility between the two geophysical methods. However, this model does not explain the gradient features, which extends itself outside the basin traversing different geologic units and does not show any obvious correlation with the surface geology. With this behavior, the gravity gradient must have a deeper source, such as a crustal thickness variation, besides being located in the contact between two different provinces. A preferred model, shown in Figure 11d, is a hybrid of the two preceding ones. It adopts an Airy's model of local compensation to compensate topographic variations observed at Earth's surface as due to undulations in the crust-mantle contact, and it also accounts for lateral variations of density in the crust between the two provinces traversed by the profile. The model details a crustal thickening of less than 10% at the interface of the basin to its northeastern border and a difference of 0.02 g/cm^3 between the denser crystalline rocks under the basin and the marginal metasedimentary rocks. Additional evidences for this model come from seismic [Giese, 1975] and gravity [Blitzkow et al., 1979] analyses in the region between 42°-45°W and 18°-20°S (about 700 km to the northeast of the study area). These studies show mean crustal thicknesses from 38 to 40 km in agreement to the 38 km modelled for the thicker part of our profile.

Discussion on the Tectonic Aspects

To facilitate the visualization of our geoelectrical results, Figure 12 presents a smoothed version of the two-dimensional model obtained in this survey. It can be observed that the region underneath the studied positive gravity anomaly, which corresponds to the area about 100 km of distance on the profile, is characterized by a thickening of both prevolcanic sediments and basaltic rocks. Another aspect evident from Figure 12 at PRATA and MONTE, the two northernmost sites, is the drastic reduction

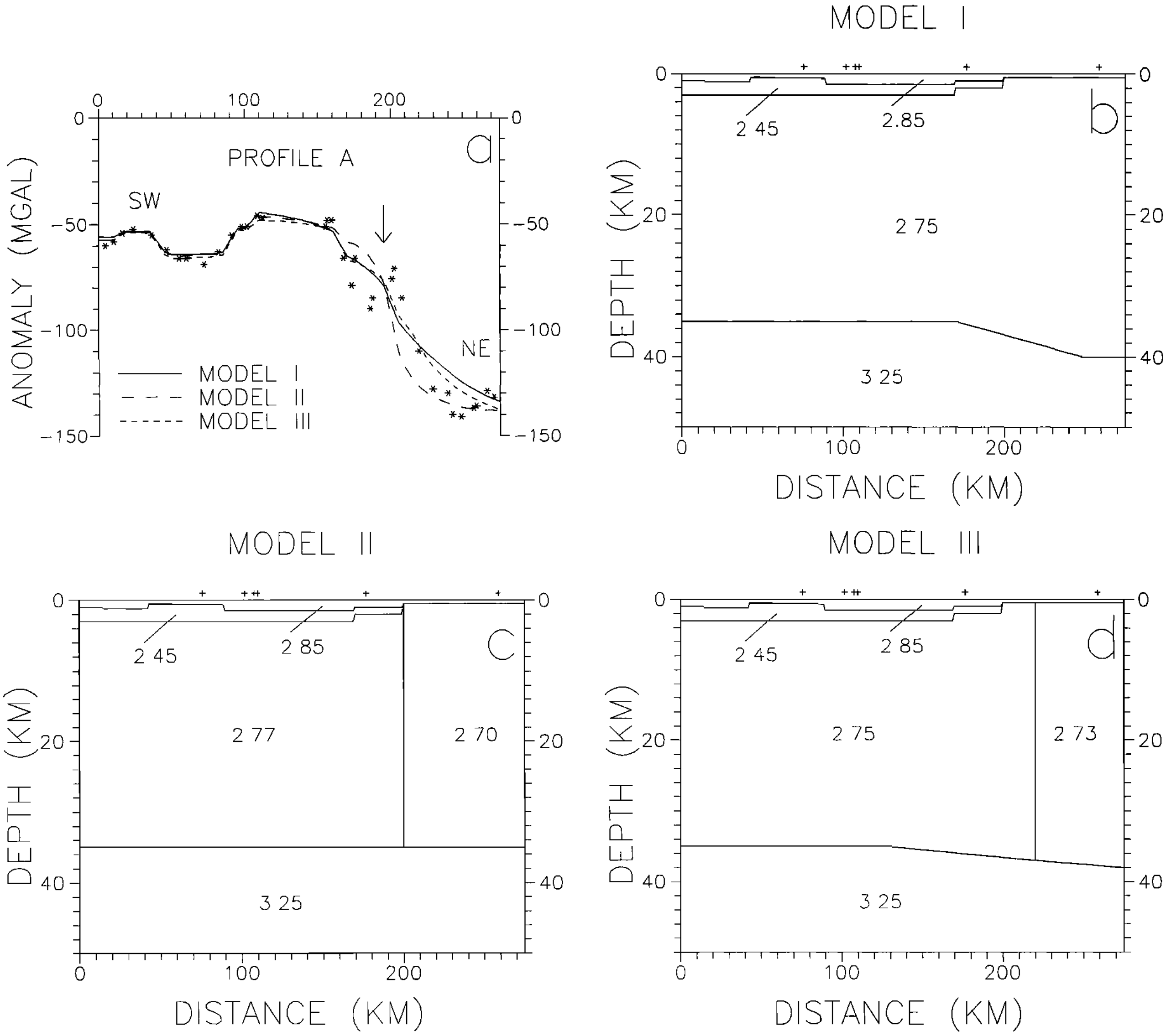

Fig. 11. Three possible gravity models of Profile A in Figure 3. (a) Measured Bouguer values along the profile (dots) and the responses to the models in Figures 11b, 11c, and 11d. The arrow in Figure 11a indicates the short-wavelength jump superimposed on the gravity slope. The numbers in the models are densities (in grams per cubic centimeter) of the different geologic units and the MT station sites are represented by plus signs. Density values were estimated from discussions of Molina et al. [1989].

or termination of the Paleozoic sediment thickness. This abrupt structure may imply a steeply inclined boundary for the basin, probably limited by faults in the Goiânia flexure region. Additional evidence for this fault comes from the gravity profile and the variation in altitude of the base of the Marilia Formation, a subunit of the Bauru Group mapped in Figure 2. The gravity profile shown in Figure 11 indicates a short-wavelength oscillation (a jump) superimposed on the gradient (between 190 and 200 km of distance on the profile, about 20 km NE of PRATA), probably related to faulting. Furthermore, the Marilia Formation, which is assumed to have been deposited as an horizontal layer over flat terrains from the analysis of the lower formation contact, is presently found with a sudden elevation jump from an elevation of 600 m south of the Rio da Prata (nearby PRATA) to an elevation of 700 m north of the same river, again suggesting the presence of faults in the Goiânia flexure region. Moreover, the previous AMT survey showed another possible deep fault zone on the Araxá-Rio Grande alignment (Figures 1 and 2). Except for local major bendings of Rio Grande (see Figure 2) that cause great divergences from surface structural directions, there is no other additional evidence for this fault zone.

In summary, the region of the positive gravity anomaly is characterized by the local occurrence

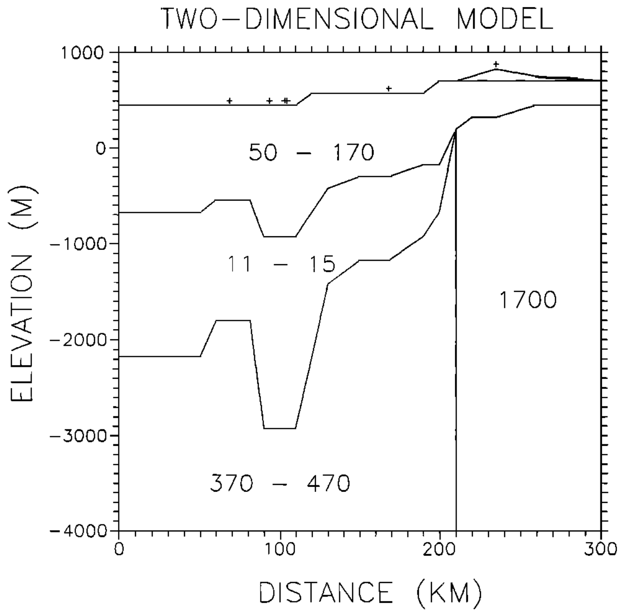

Fig. 12. Smoothed two-dimensional MT modelling results for the northeastern region of the Paraná basin, presenting the locations of MT sites on the surface (pluses) and the distribution of the resistivities for each layer. Not shown is the resistivity of the first layer under the northernmost station which is 35 ohm m. Numbers are resistivity intervals in ohm m.

of a larger thickness of the sedimentary-volcanic basinfill, limited to the north by faults in the Goiânia flexure and to the south by more poorly defined faults in the region of the Rio Grande. The basin margin in its northeastern region seems to be a crustal weakness zone with the format of a "trough", constituting a deposition center of both sediments and basalts with final subsidence after the magmatic event. A key question concerns the lateral extension of this "trough". Is it only a local feature or does it extends along the whole northeast basin border? The answer to this question requires additional information from other parallel MT profiles.

Summary and Conclusions

The main contribution of this study is the recognition of important structural discontinuities in the northeastern region of the Paraná basin. Besides the irregularities in the contact surface of the Bauru Group and Serra Geral Formation mapped in the preliminary AMT survey, we observed the plausible existence of a trough (graben?) characterized by the accumulation of sediments and basalts, probably limited by faults at its borders, the possible presence of different crustal provinces under the basin and outside it, and a thicker crust in NE direction, external to the basin.

Another important aspect observed in this work was the difficulty in the interpretation of the MT results due to inhomogeneities and/or strong magnetization of the superficial volcanics and the presence of diabase intrusions on sedimentary pre-volcanic rocks. As a consequence of these effects, the quantitative interpretation of the MT data may present severe bias, which complicates the utilization of the method in volcanic covered areas. A detailed survey, as the one carried out in Cuiabá Paulista county near the center of the Paraná basin (65 sites with 1-km interval, according to Paulipetro [1982]), might be used to verify the extent of the distortions. Also, a survey with more spatial sampling facilitates the use of nearby soundings in the development of more refined data treatment to reduce the effects of static shifts. Unfortunately, to date published interpretations of that survey [Paulipetro, 1982; Stanley et al., 1985] did not explore yet its full potentiality. It should be noted that the interpretations presented here were only possible through the use of MT and gravity data, which are complementary geophysical techniques. In general, MT data are more sensitive to vertical resistivity changes whereas gravity data are more sensitive to lateral rock property changes. As shown by Prieto et al. [1985], this complementary character is especially useful in the study of volcanic covered areas, due to their geologic complexity.

In conclusion, this study shows the importance of gathering additional geophysical data in the Paraná basin margins. The quantity of information obtained with only one survey shows that these margins are much more complex than previously thought. In addition, our results demonstrate the need to extend these studies to verify the lateral continuity of the inferred structures.

Acknowledgments. This work was supported by Financiadora de Estudos e Projetos (FINEP) and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP). The MT data acquisition were successfully completed through the efforts of Francisco Ogura and Domingos Fonseca, to whom we are most grateful. The writers also thank the gravity group of the IAG/USP for access to their gravity data bank and W.D. Stanley and P.E. Wannamaker for critical reviews and many useful suggestions on the manuscript.

References

Bellieni, G., P. Brotzu, P. Comin-Chiaramonti, M. Ernesto, A.J. Melfi, I.I.G. Pacca, E.M. Piccirillo, and D. Stolfa, Flood basalt to rhyolite suites in the southern Paraná plateau (Brazil): Paleomagnetism, petrogenesis and geodynamic implication, J. Petrol., 25(3), 579-618, 1984.

Bellieni, G., P. Comin-Chiaramonti, L.S. Marques, A.J. Melfi, A.J.R. Nardy, C. Papatrechas, E.M. Piccirillo, A. Roisenberg, and D. Stolfa, Petrogenetic aspects of acid and basaltic lavas from the Paraná plateau (Brazil): Geological, mineralogical and petrochemical relationships, J. Petrol., 27, 915-944, 1986.

Bendat, J.S., and A.G. Piersol, Random Data: Analysis and Measurements Procedures, 407 pp., John Wiley, New York, 1971.

Berdichevsky, M.N., and V.I. Dmitriev, Basic principles of interpretation of magnetotelluric sounding curves, in Geoelectric and

Geothermal Studies, edited by A. Ádám, pp. 165-221, Akademiai Kiado, Budapest, 1976.
Blitzkow, D., P. Gasparini, N.C. de Sá, and M.S.M. Mantovani, Crustal structure of southeastern Minas Gerais, Brazil, deduced from gravity measurements, Rev. Bras. Geociênc., 9(1), 39-43, 1979.
Bostick, F.X., Jr., A simple almost exact method of MT analysis, paper presented at the Workshop on Electrical Methods in Geothermal Exploration, Dep. of Geol. and Geophys., Un. of Utah, Logan, 1977.
Cordani, U.G., B.B.B. Neves, R.A. Fuck, R. Porto, A. Thomaz Filho, and F.M.B. Cunha, Estudo preliminar de integração do Pré-Cambriano com os eventos tectônicos das bacias sedimentares brasileiras, Bol. Ciênc. Técn. Petról., 15, 1-70, 1984.
Departamento de Águas e Energia Elétrica do Estado de São Paulo (DAEE), Estudo de águas subterrâneas: Regiões administrativas 7, 8, 9, Bauru, São José do Rio Preto e Araçatuba, technical report, vol. 2, Gov. Est. São Paulo, São Paulo, 1976.
Dutra, L.S.V., Desenvolvimento de um sistema automático de tratamento de dados magnetotelúricos, M.S. thesis, 201 pp., Inst. de Pesqui. Espac., São José dos Campos, Brazil, 1984.
Fúlfaro, V.J., A.R. Saad, M.V. Santos, and R.B. Vianna, Compartimentação e evolução tectônica da Bacia do Paraná, Rev. Bras. Geociênc., 12(4), 590-611, 1982.
Giese, P., Preliminary report on the results of seismic measurements in the Brazilian coastal mountains in March/April 1975, technical report, Brazil-Germany Sci. Agreement, Freiburg, Germany, 1975.
Haralyi, N.L.E., and Y. Hasui, Anomalias gravimétricas e estruturas maiores do Sul de Goiás, paper presented at the Primeiro Simpósio de Geologia do Centro-Oeste, Atas, Soc. Bras. Geol., Goiânia, Brazil, 1981.
Hermance, J.F., Electromagnetic induction studies, Rev. Geophys., 21(3), 652-665, 1983.
Hyndman, R.D., and P.M. Shearer, Water in the lower continental crust: Modelling magnetotelluric and seismic reflection results, Geophys. J. Int., 98(2), 343-365, 1989.
Jones, A.G., On the equivalence of the "Niblett" and "Bostick" transformations in the magnetotelluric method, J. Geophys., 53(1), 72-73, 1983.
Jupp, D.L.B., and K. Vozoff, Stable iterative methods for the inversion of geophysical data, Geophys. J.R. Astron. Soc., 42(3), 957-976, 1975.
Jupp, D.L.B., and K. Vozoff, Two-dimensional magnetotelluric inversion, Geophys. J.R. Astron. Soc., 50(2), 333-352, 1977.
Kao, D., and D. Orr, Magnetotelluric response of an uniformly stratified earth containing a magnetized layer, Geophys. J.R. Astron. Soc., 70(2), 339-347, 1982.
Katterjohn, M., and G. Hopkins, Comparison of magnetotelluric data with northern Columbia River Plateau wells in Kattitas County, Washington, paper presented at the Fifty Fourth Annual International Meeting and Exposition, Soc. of Explor. Geophys., Atlanta, Ga., 1984.
Lesquer, A., F.F.M. de Almeida, A. Davino, J.C. Lachaud, and P. Maillard, Signification structurale des anomalies gravimétriques de la partie sud du craton de São Francisco (Brésil), Tectonophysics, 76(3/4), 273-293, 1981.
Madden, T.R., and P. Nelson, A defense of Cagniard's magnetotelluric method, Tech. Rep. ONR Proj. NR-371-401, 12 pp., Office of Nav. Res., Cambridge, Mass., 1964.
Molina, E.C., N. Ussami, N.C. de Sá, and D. Blitzkow, Interpretação dos dados gravimétricos da parte norte da Bacia do Paraná, Rev. Bras. Geociênc., 19(2), 187-196, 1989.
Niblett, E.R., and C. Sayn-Wittgenstein, Variation of electrical conductivity with depth by the magneto-telluric method, Geophysics, 25(5), 998-1008, 1960.
Padilha, A.L., N.B. Trivedi, J.M. da Costa, I. Vitorello, A. Dupis, and C. Cavoit, Audiomagnetotelluric study in northeast region of Paraná basin, South America, Geophysics, 54(7), 824-831, 1989.
Paulipetro (Consórcio IPT-CESP), Levantamento geofísico magnetotelúrico: área de Cuiabá Paulista—Estudo regional e de detalhe, Tech. Rep. RT-106/81, 2 vols., Consórcio Geotron.-Hidroserv., São Paulo, 1982.
Petrini, R., L. Civetta, E.M. Piccirillo, G. Bellieni, P. Comin-Chiaramonti, L.S. Marques, and A.J. Melfi, Mantle heterogeneity and crustal contamination in the genesis of low-Ti continental flood basalts from the Paraná plateau (Brazil): Sr-Nd isotope and geochemical evidence, J. Petrol., 28(4), 701-726, 1987.
Piccirillo, E.M., A.J. Melfi, P. Comin-Chiaramonti, G. Bellieni, M. Ernesto, L.S. Marques, A.J.R. Nardy, I.G. Pacca, A. Roisenberg, and D. Stolfa, Continental flood volcanism from the Paraná basin (Brazil), in Flood Basalts, edited by J.D. Macdougall, pp. 195-238, Kluwer Academic, Boston, Mass., 1987.
Prieto, C., C. Perkins, and E. Berkman, Columbia River Basalt Plateau—An integrated approach to interpretation of basalt-covered areas, Geophysics, 50(12), 2709-2719, 1985.
Ranganayaki, R.P., An interpretative analysis of magnetotelluric data, Geophysics, 49(10), 1730-1748, 1984.
Santero, P., M. Zadro, D. Blitzkow, and N.C. de Sá, Gravimetric analysis of the Goiânia flexure, Northern Paraná basin, in The Mesozoic Flood Volcanism From Paraná Basin (Brazil): Petrogenetic and Geophysical Aspects, edited by E.M. Piccirillo and A.J. Melfi, pp. 257-269, Instituto Astronômico e Geofísico, São Paulo, 1988.
Shankland, T.J., and M.E. Ander, Electrical conductivity, temperatures, and fluids in the lower crust, J. Geophys. Res., 88(11), 9475-9484, 1983.
Shiraiwa, S., Modelo de estrutura crustal entre 19,5°/22,6° S e 45°/51° W calculado a partir de dados gravimétricos, M.S. thesis, 106 pp., Univ. São Paulo, São Paulo, 1985.
Sims, W.E., and F.X. Bostick Jr., Methods of magnetotelluric analysis, technical report, 86 pp., Univ. of Texas at Austin, 1969.
Souza Júnior, N.N. de, Feições lito-estruturais de interesse geológico e geotécnico em maciços

basálticos, M.S. thesis, 180 pp., Univ. São Paulo, São Carlos, Brazil, 1986.
Stanley, W.D., A.R. Saad, and W. Ohofugi, Regional magnetotelluric surveys in hydrocarbon exploration, Paraná basin, Brazil, AAPG Bull., 69(3), 346-360, 1985.
Talwani, M., J.L. Worzel, and M. Landisman, Rapid gravity computations by two-dimensional bodies with application to the Mendocino submarine fracture zones, J. Geophys. Res., 64(1), 49-59, 1959.
Telford, W.M., L.P. Geldart, R.E. Sheriff, and D.A. Keys, Applied Geophysics, 860 pp., Cambridge University Press, New York, 1976.
Wannamaker, P.E., G.W. Hohmann, and S.H. Ward, Magnetotelluric responses of three-dimensional bodies in layered earths, Geophysics, 49(9), 1517-1533, 1984.
Zalán, P.V., et al., Análise da Bacia do Paraná, Tech. Rep. DEPEX-CENPES GT-OS-000/85, 195 pp., Petrobrás, Rio de Janeiro, 1986.

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(Received October 19,1990;
revised September 11, 1991;
accepted September 30, 1991.)