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# GEOELECTRICAL STUDIES OF THE COLÔNIA IMPACT STRUCTURE, SANTO AMARO, STATE OF SÃO PAULO - BRAZIL

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About 35 km South of Metropolitan São Paulo (SE Brazil), in the Precambrian cristalline basement, there is a striking circular morphological depression, with a diameter of 3.64 km. Based mainly on geological information, previous investigators suggested that the origin of the Colônia ring-structure is due to an impact of a meteorite. The depression is filled with Quaternary deposits. In order to estimate the depth to the basement, a total of 29 scalar audiomagnetotelluric (AMT) soundings (spectral frequency range: 1-5000 Hz) were carried out. Results from 1D modelling using both Niblett-Bostick transformation and Occam inversion show a basin-like shape of the sediment-basement interface. The AMT maximum depth of this interface is 440 m and is located approximately at the centre of the depression.

**ESTUDOS GEOELÉTRICOS DA ESTRUTURA DE IMPACTO DE COLÔNIA, SANTO AMARO, ESTADO DE SÃO PAULO - BRASIL** - Aproximadamente 35 km ao sul da Grande São Paulo existe uma proeminente depressão morfológica circular, com um diâmetro de 3,64 km, no embasamento cristalino. Baseando-se fundamentalmente em considerações geológicas, investigadores anteriores sugerem que a origem da depressão circular de Colônia seja devida ao impacto de um meteorito. A depressão está preenchida por sedimentos quaternários. Para estimar a profundidade do embasamento foram realizadas um total de 29 sondagens audiomagnetotelúricas (AMT) cobrindo a faixa espectral 1 Hz - 5000 Hz). O modelamento 1D usando a transformação de Niblett-Bostick e a inversão de Occam mostram como resultados a forma de uma bacia para a interface sedimento-embasamento cristalino e aproximadamente no centro da depressão uma profundidade máxima de 440 m.

## 1. INTRODUCTION

Meteorite craters are structures usually found among planets of the solar system. It is accepted that cratering was a fundamental process in the evolution of the terrestrial planets. Therefore, they are important in comparative planetology, e.g., the use of crater counts to estimate the age of unsampled surface units on the planets is a well established technique (Grieve and Robertson, 1979). The number of recognized impact craters on the Earth is relatively small, compared for example to the heavily cratered surfaces of Mercury and the Moon. Systematic telescopic surveys carried out over the last two decades show that the flux of asteroids and comets nuclei in the Earth's neighbourhood is sufficiently high so that the effects of occasional collisions should be recognizable in the geological record (Shoemaker, 1983). However, tectonical and erosional processes alter the Earth's surface gradually, affecting also the impact structures in such a manner that they may loose their original morphology or even disappear as recognizable features in a geologically short time interval. Dietz (1961) proposed the designation astrobleme for all structures which have their origins associated to an ancient impact. The term astrobleme is derived from the Greek astro for star and bleme for wound.

On the Earth, there are about 150 known impact structures, divided into three categories: (1) proven impact structures with associated meteorites, (2) probable impact crater with shock metamorphism present in target rocks and (3) possible impact crater with shock metamorphism not established (Grieve and Robertson, 1979). Six of these impact sites (mixed categories) are presently recognized on Brazilian territory and it is very possible that their number might be even greater (Crosta, 1982).

Based on morphological arguments, Kollert e.at. (1961) were the first to propose that the origin of the Colônia depression was due to an impact of a meteorite. However, the lack of direct evidence, such as associated meteorite fragments and shock metamorphic features in the affected country rock (shatter-cones, shock-minerals), classifies the Colônia structure as a possible impact site (Grieve and Robertson, 1979).

The Colônia depression has a diameter of 3.64 km and it is the smallest of the six impact sites existent in Brazil. The central plain is practically circular and surrounded by a ring-shaped wall of hills rising up to 125 m above the centre. The depression is filled with Quaternary deposits, rich in clay and organic components (Kollert et al., 1961). Its high sediment accumulation makes it a good site for paleoclimatic studies. According to early gravity and electrical resistivity studies undertaken by Kollert et al. (1961), the minimum depth of the basement is in the center of the depression between 285 m and 400 m deep.

Only a few magnetotelluric studies were undertaken in areas of meteorite impact craters. They usually investigated the effects in the structure of the upper crust due to the impact. Apart from possible conducting fractures, scalar audiomagnetotelluric investigations in the Charlevoix Crater (Canada) show a large variation in conductance (conductivity x thickness) in the superficial cover (Chouteau, 1986). Recent magnetotelluric investigations in the same crater (Marecshal and Chouteau, 1990) and in the Siljan Crater in Sweden (Zhang, 1989) show a complex fracturing of the upper crust.

The main objective of this study is to estimate the depth of the sediment-basement interface of the Colônia crater. For this purpose, several AMT soundings were carried out. Niblett-Bostick transformation (Jones, 1983) and Occam inversion (Constable et al., 1987) were employed to model the data. The high level of cultural noise, due to the relative proximity of the crater to the city of São Paulo, affected strongly the soundings in the lower frequencies. It thus prevented further investigation of structures in the upper crust caused by the possible impact of a meteorite.

## 2. GEOLOGY

The Colônia structure is located in the Precambrian cristalline of the Ribeira Fold Belt, which is composed of metamorphic rocks of the Transamazonic Cycle (1800 - 2200 my), later remobililized during the Brazilian Cycle (450 - 650 my) and penetrated by granites of several ages (Hasui et al., 1975). The regional structure of the basement is characterized by blocks formed by a system of faults, with a general trend in the ENE-WSW direction. After Macedo (1989), the Ribeira Fold Belt represents a zone of lithospheric convergence ocurring during the 'Brasiliano' Cycle, so that the fault-system is constituted by deep crustal discontinuities.

A series of small taphrogenic basins, e.g., São Paulo, Taubaté, Resende, are found along the regional trend in the Ribeira Fold Belt. The formation of this taphrogenic system is of Oligocene age (Riccomini et al., 1987).

A simplified version of Coutinho's geological map of the area around Colônia (Coutinho, 1980; In: Riccomini et al., 1989) shows a great variety of basement rocks (Fig. 1). The main types are gneisses, migmatites, diorites, mica schists, quartzites, mylonites, metabasites and granites.

Sandstones outcroping along the S and SE border of the structure are attributed to the São Paulo Formation, an Oligocene deposition of the São Paulo Basin (Riccomini et al., 1989). The interior of the depression is filled with Quaternary alluvial and colluvial deposits rich in clay and organic components (Kollert et al., 1961, Riccomini et al., 1989).

The probable age of an impact is based on morphological preservation parameters of impact craters, which are divided into seven levels. The degree of preservation of the Colônia structure lies between 3 and 4, i.e., the structure has partly preserved craterfill products and a partly preserved rim, although deeply eroded (Riccomini et al., 1989). According to an empirical relationship between age, diameter and preservation level (Grieve and Robertson, 1979), the Colônia impact crater, with its 3.64 km of diameter and preservational degree between 3 and 4, has a maximum age of impact between 36.4 ma (Eocene-Oligocene boundary) and 5.2 ma (Miocene-Pliocene boundary). The existence of oligocene sedimentary rocks from the São Paulo Formation inside the crater agrees well with an Oligocene timing for the maximum age of the impact.

## 3. THE AUDIOMAGNETOTELLURIC METHOD

The magnetotelluric (MT) sounding method allows the determination of subsurface conductivity distributions, based on the propagation of natural electromagnetic signals. When applied for frequencies in the audiofrequency range, this technique is called the audiomagnetotelluric (AMT) sounding method. Detailed discussions about the theory and application of the AMT method is given elsewhere, e.g. Strangway et al. (1973), Hoover et al. (1976) and Strangway and Koziar (1979).

The main source of signals in the audiofrequency range are worldwide lightning storms, which are particularly concentrated in the tropics. The energy generated, referred to in the literature as spherics, propagates around the world inside a waveguide lying between the Earth's surface and the bottom of the ionosphere (Strangway et al., 1973). The energy is reflected many times between the lowest layer of the ionosphere (D-layer) and the surface of the Earth. During the night, the D-layer disappears and the waveguide changes the height from 60 km to 90 km; this creates a diurnal variation in the nature of the signal deriving from the activity of distant storm centres (Keller and Frischknecht, 1966). The source of the spherics contains a wide spectrum of frequencies, but the waveguide has a preference for certain frequencies, the so called Schumann resonances at 8, 14, 20, 25 and 32 Hz, where fairly strong energy peaks are observed (Strangway et al., 1973).

The electromagnetic signal is assumed to be a plane wave propagating vertically downward into the Earth. This condition is valid when both the energy source is several wavelenghs away from the point of measurement and the displacement currents in the Earth can be neglected (Hoover et al., 1976). For the subsurface this energy is like a fluctuating magnetic field inducing electric currents (Faraday's law) called telluric currents. These currents are responsible for the horizontal electric field (E) measured at the surface, which is orthogonal to the associated horizontal magnetic field ($H$). The ratio of the induced electric field ($E$) to the associated inducing magnetic field (H) is the surface impedance (Z) and the apparent resistivity $\rho_a$ is determined by the following equation (e.g. Hoover et al., 1976):

$$\rho_a = \frac{1}{5f}\frac{|E|^2}{|H|^2} \qquad (1)$$

where f is the frequency in Hertz, E is the electric field in microvolts per meter, B is the magnetic field in nT, and $\rho_a$ is the apparent resistivity in ohm-meters. Two steel stakes - usually a few tens of meters apart - are used as electrodes to measure the horizontal electric field (E). An induction coil placed orthogonally to the electrodes is used to measure the horizontal magnetic field (H). Each AMT sounding consists of measuring simultaneously the electric and magnetic fields in two perpendicular directions (XY and YX). For a one-dimensional (1D) Earth, the resistivity varies only with depth and the apparent resistivities assume the same values for any orientation of the electrodes and the induction coil. Distinct apparent resistivity responses for the two perpendicular directions in the same station are an indication of lateral variation of the conductivity of the subsurface, i.e., two (2D) or three- dimensional (3D) structures yield distinct responses depending on the measuring directions of the horizontal electric and magnetic fields.

The phase between the horizontal electric and the magnetic field signals is another important response parameter and for a one- dimensional Earth, is given by the ratio of the imaginary to the real part of the surface impedance (e.g. Szarka and Fischer, 1989):

$$\varphi_{1D} = \tan^{-1}[ImZ_{1D}(\omega)/ReZ_{1D}(\omega)] \qquad (2)$$

($\omega = 2\pi f$ is the angular frequency, Z is the impedance).

For a uniform conductor of resistivity $\rho$, the surface impedance is reduced according to Fischer (1985) to

$$Z(\omega) = [\omega\mu_0\rho]^{1/2} \exp(i\pi/4) \tag{3}$$

It is well known that for a uniform medium the electric field is 45° ahead of the magnetic field, as is easily seen in equation (3). In a layered Earth, the phase will differ from 45°. The surface impedance can be expressed according to Fischer (1985) by an apparent resistivity $\rho_a(\omega)$ and a phase $\varphi(\omega)$ between 0° and 90°, if a time dependence of $exp(+i\omega t)$ is assumed:

$$Z(\omega) = [\omega\mu_0\rho_a]^{1/2} \exp[i\varphi(\omega)] \tag{4}$$

## 4. FIELD WORK

The field work was done in two campaigns and a total of 29 scalar AMT soundings were carried out. Most of the first 17 soundings were obtained following a profile roughly orthogonal to the regional strike of the cristalline basement, cutting the structure radially. Twelve other stations were distributed inside the depression aiming to reveal possible lateral variations (the stations location are shown in Fig. 1). The relatively small number of stations is due both to the dense and thick vegetation and to the large swamp areas inside the depression. Most of the tracks, including the profile cutting the depression, had to be opened by machete and sickle during the field work operation.

A SAGAX scalar AMT equipment (Canada) was used in the investigation. It is similar to the one described by Strangway et al. (1973). The electrical field was measured at each station in two perpendicular directions by two electrodes made of steel stakes, generally separated by 20 m. An induction coil placed orthogonally to the direction of the two electrodes was used to measure simultaneously the horizontal magnetic field. The measuring directions were N60E and N30W, respectively parallel and perpendicular to the regional strike of the basement outside the depression. Both directions are related to the magnetic North, which is presently about 17 West of the geographical North in the Colônia area.

## 5. FIELD DATA

The measurements were carried out at selected discrete frequencies in the range between 4600 and 1 Hz. The sounding results are presented in double logarithmic plots of frequeny versus apparent resistivity.

The equipment used in this work does not provide information about the phase, but the employed inversion schemes require the phase for calculating the conductivity structures. These schemes are usually more efficient than those operating only with the apparent resistivity. According to Fischer and Schnegg (1980), the phase can be calculated from a smoothed single-valued function $\rho_a$, so that the computed phase and the corresponding apparent resistivity are compatible with a tabular structure and suitable as input for 1D inversion schemes.

For a 1D Earth the phase $\varphi$ can be deduced from the apparent resistivity $\rho_a$ through the approximation

$$\varphi(T) = \frac{\pi}{2} - \frac{\pi}{4}\left(1 + \frac{d\log\rho_a(T)}{d\log T}\right) \tag{5}$$

where T is the period in seconds (Weidelt, 1972). Since double logarithmic plots of $\rho_a$ are used, the phase can be obtained from the slope, i.e., from the first derivative of the sounding curves.

For this purpose, a polynomial fit of the apparent resistivity

$$\log\rho_a(T) = a_0 + \sum_{k=1}^{M} a_k(\log T)^k \tag{6}$$

using general linear least square criteria (Press et al., 1987). The resulting polynomial fit, i.e., the coeficients $a_k$ and their uncertainties $\delta_k$ are obtained by minimizing the $\chi$- square function

$$\chi^2 = \sum_{i=1}^{N}\left[\frac{\log\rho_a(T_i) - \sum_{k=1}^{M} a_k(\log T_i)^k}{\sigma_i}\right]^2 \tag{7}$$

using the method of normal equations (Press etal., 1987). The variable $\sigma_i$ is the error of $\rho_a$. Since the polynomial fit is a good approximation of the $\rho_a$ data curve, the phase can thus be obtained by analytically differentiating the above polynomial fit of degree M, therefore originating another polynomial fit of degree M-1.

$$\frac{d\log\rho_a(T)}{d\log T} = a_1 + \sum_{k=2}^{M} ka_k(\log T)^{k-1} \tag{8}$$

The uncertainty associated with the calculated phase can now be determined using the errors of the coeficients of the second polynomial. The standard error $\sigma_u$ of a function of variables $Y_i$ and constants $k_i$ of the form $u = k_o + k_i Y_i$ is given by

$$\sigma_u = \left[ \sum_{i=1}^{M} k_i \sigma_i^2 + 2 \sum_{i=1}^{M-1} \sum_{j=i+1}^{M} k_i k_j \sigma_{ij} \right]^{1/2} \tag{9}$$

where $\sigma_i$ are the uncertainties of $Y_i$ and $\sigma_{ij}$ the covariances between the variables; Rektorys, 1969).

Typical sounding curves and the approximated phase values are shown in Fig. 2, for stations 4 and 20.

Station 20 is located near the centre of the structure (Fig. 1) and is representative of most stations inside the depression. The sounding curves for the telluric lines in the XY- direction (N60E) and in the YX- direction (N30W) are nearly equal (Fig. 2b), indicating a 1D structure of the subsurface. Station 4 is located on the border of the depression (Fig. 1). The apparent resistivity values of station 4 are clearly higher than the ones in station 20. The homogeneous behaviour of both sounding directions in station 20 is not observed in station 4. The apparent resistivity data for the YX- direction in this latter station presents higher values than the ones in the XY- direction, indicating a lateral variation of resistivity. This is mainly due to the fact that station 4 is directly above the cristalline basement. The basement reaches the surface at the border of the structure forming the rim. The cristalline rocks of the rim and the sediments filling the depression build a steep electrical interface. The most simple 2D model corresponding to such a situation is the vertical fault. The effect of higher apparent resistivities in the YX- direction of station 4 is due to its perpendicular orientation relatively to the border of the structure, i.e. H polarization mode. Oppositely, the XY- direction shows lower values for the apparent resistivity because it is orientated parallel to the border - the E polarization mode.

## 6. PSEUDOSECTIONS

Pseudosections are plots representing the distribution of the apparent resistivity as a function of frequency along a traverse. The ordinate is proportional to the logarithm of the frequency (decreasing downward) and the abscissa is the distance along the traverse. Pseudosections allow the observation of lateral and vertical variations simultaneously (Strangway et al., 1973).

In Fig. 3 the pseudosection for both sounding directions (XY and YX) show a similar behaviour in the middle of the depression, but distinct depth distributions of $\rho_a$ at the border, which is related to the steep resistivity contrast between sediments filling the depression and the cristalline rocks of the rim.

Pseudosections calculated for the most simple 2D structure - the vertical fault - are presented by Vozoff (1972). For a profile crossing the fault, they present a smooth spatial variation in the apparent resistivity values in the direction parallel to the strike of the fault and a jump in the apparent resistivity for the perpendicular direction. This behaviour is seen in Fig. 3, where the XY- direction - parallel to the border - shows a smoother variation of the apparent resistivity compared to the YX- direction, perpendicular to the border.

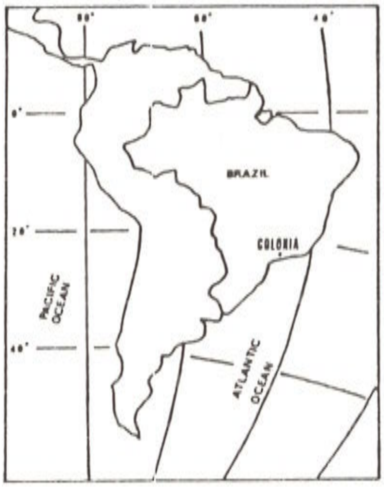
## 7. DEPTH OF PENETRATION OF THE ELECTROMAGNETIC (EM) FIELD

The depth of penetration of the EM field is naturally controlled by the greater penetration of the lower frequencies and by the conductivity of the medium in which the waves propagate. It can be related to the frequency and resistivity - inverse of conductivity - by the concept of the skin-depth, given as

$$\sigma = 500(\rho T)^{1/2} \tag{10}$$

where $\sigma$ is the skin-depth in meters and T is the period in seconds. The skin-depth is defined as the depth where both electric and magnetic fields are reduced to 1/e of their surface values. The concept of skin-depth is not synonimous, as often assumed, but closely related to the depth of penetration (Spies, 1989).

Due to the relative proximity of the studied structure to the city of São Paulo, the natural EM signals can be much influenced by the high level of cultural noise characteristic of populated areas. This behaviour is well reflected on the high gradient of the apparent resistivity curves at the lower frequencies.



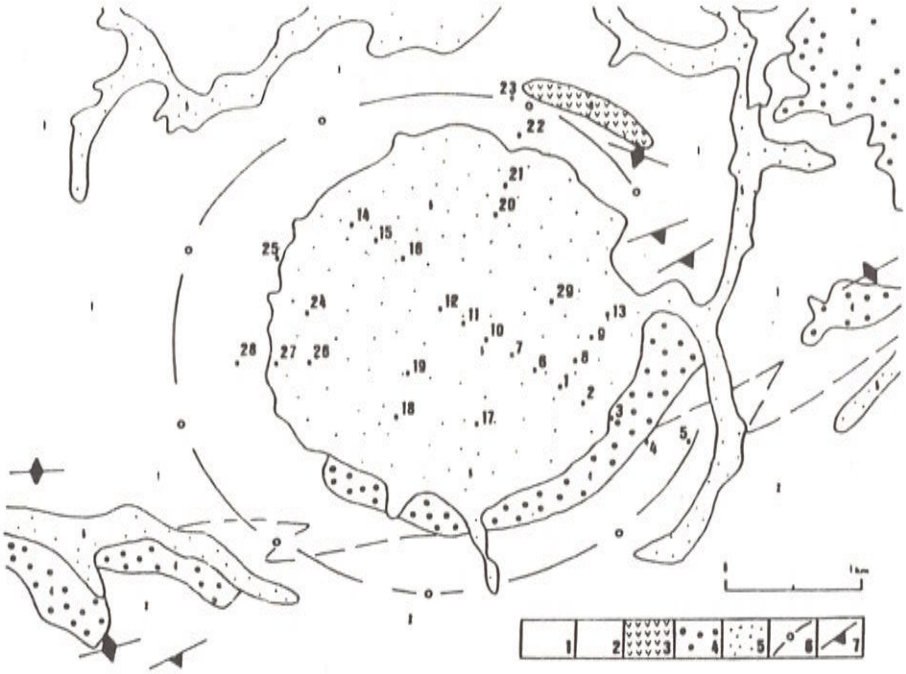


**Figure 1.** Simplified geologic map of the Colônia impact area, showing mica schists, quartzites, locally mylonites (1), migmatites, also locally mylonites (2), diorites (3), sedimentary rocks from the São Paulo Formation (4), Quaternary alluvial deposits (5), crater rim (6), structural trend of the Precambrian basement (7), and the location (1-29) of the AMT sounding sites (after Coutinho, 1980; In: Riccomini et al., 1989).

*(Mapa geológico simplificado da área de impacto Colônia, mostrando chistos de mica, quartizito, milonitas locais (1), migmatitas, milonitas locais (2), dioritas (3), rochas sedimentares de formação de São Paulo (4), depósitos aluviais Quaternários (5), crateras (6), estrutura de base Precambriana (7), e as locações (1-29) dos sondadores AMT (segundo Coutinho, 1980; em Riccomini et al., 1989).)*

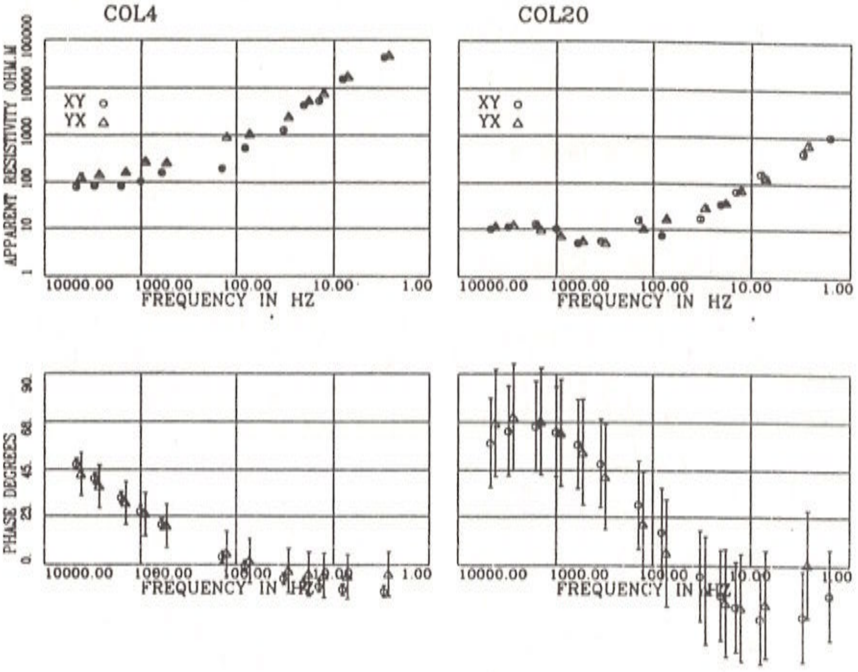


**Figure 2.** Apparent resistivity and phase data curves for stations 4 and 20.
*(Curvas de dados para a resistividade e fases aparentes para as estações 4 e 20.)*

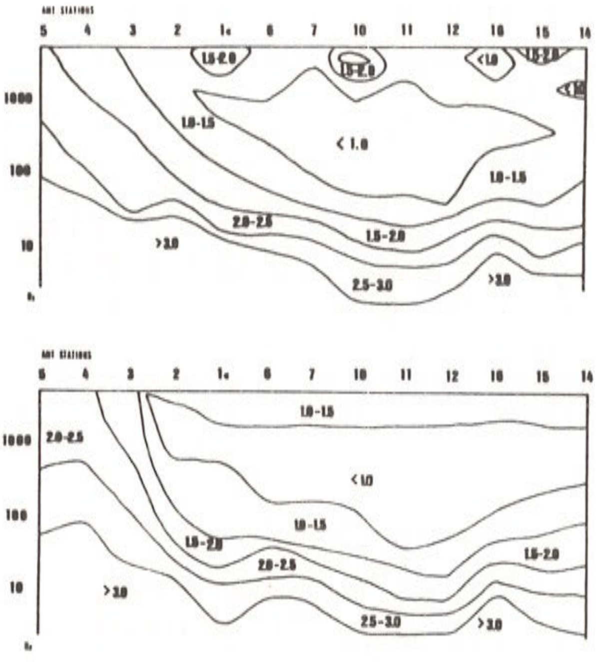


**Figure 3.** Pseudosections in both XY- and YX- sounding directions. Resistivity values in logarithmic scale. Horizontal axis: distribution of the AMT stations on the surface along a profile. Vertical axis: frequency in Hz.
*(Pseudoseções nas direções XY e YX. Valores de resistividade em escala logaritmica. Eixo horizontal: distribuição das estações AMT na superfície ao longo de um perfil. Eixo vertical, freqüência em Hz.)*

Below a particular frequency - in the case of station 20 for frequencies smaller than 80 Hz (Fig. 2) - the slope has an inclination exceeding 45°. Recent studies using industrial noise as a signal for investigating the Earth's structure reveal in the near field, i.e., source is within the range of one-half skin-depth, a slope in the apparent resistivity curve of 45° and the phase value equal to zero (Fontes, 1991; Qian and Pedersen, 1991). According to Weidelt (1972), the gradient of the apparent resistivity data curve cannot exceed unity for a 1D Earth. Consequently, the phase varies between 0° and 90° (Weidelt, 1972; eq. 2.30).

Below a particular frequency which varies slightly for each site, all the sounding curves of Colônia exhibit gradients greater than the unity. This is strongly believed to be caused by cultural noise affecting the lower frequencies (i.e. frequencies lower than 30 Hz in most measured sites). Supporting that idea is the fact that the depression is located in Precambrian resistive cristalline rocks, which implies that the natural signal is disturbed by the cultural noise being originated in São Paulo, due to the greater skin- depths of the EM signals. However, the depression is filled with fairly conductive Quaternary deposits, rich in clay and organic components. In this environment the depth of penetration of the EM signal is strongly reduced, thus building a good shield against remote disturbances of the EM field. As mentioned earlier, the Colônia depression and its surroundings are covered by thick vegetation, which makes it a fairly noise free region. It is therefore reasonable to assume that in the higher frequency range natural sources and/or man- made plane waves dominate the EM signals.

All the arguments outlined in this section lead us to a main working hypothesis. For each AMT sounding in the Colônia depression, the transition between sediments and basement occur in the range of frequencies for which the gradient of the apparent resistivity assume values higher than one, corresponding to a change in signal of the phase from positive to negative.

## 8. DEPTH ESTIMATION AND ONE-DIMENSIONAL (1D) MODELLING

The Niblett-Bostick transformation (Jones, 1983) associates the apparent resistivity data with a resistivity $\rho_B$ to a depth $h$

$$h = \left[\frac{\rho_a(T)T}{2\mu_0}\right]^{1/2} \tag{11}$$

$$\rho B = \rho_a(T)\left[\frac{1+m(T)}{1-m(T)}\right] \tag{12}$$

where $T$ is the period and $m(T)$ is the gradient of the apparent resistivity curve in double logarithmic plots and $m(T) = \frac{d\log\rho_a}{d\log T}$. The depth $h$ is equivalent to a penetration depth in a half-space medium of resistivity equal to the apparent resistivity at that particular period.

The Nibblet-Bostick transformation is a particularly good depth estimator in a situation of increasing conductivity with depth. However, the depth resolution is poor for the opposite situation of decreasing conductivity with depth. To alleviate this problem, Jones and Foster (1986) propose considering the $2^{nd}$ derivative of the apparent resistivity data curve,

$$m'(T) = \frac{d^2\log\rho_a}{d\log T^2} \tag{13}$$

According to the same authors, when $m(T)$ and $m'(T)$ are both positive, the apparent resistivity curve at the period of interest indicates a diffusion of the EM signals into an increasingly resistive medium. If $m(T)$ and $m'(T)$ are both negative, the opposite holds true. For the former case, Jones and Foster (1986) introduce a modified version of the Niblett-Bostick transformation in terms of generating sharper variations in resistivity at a depth $h$:

$$\rho B = \rho_a\frac{1+\operatorname{sign}(m)|m|^q}{1-\operatorname{sign}(m)|m|^q} \tag{14}$$

for $\operatorname{sign}(m) = \operatorname{sign}(m')$, where $q = \frac{1}{1+m}$ for $m(t) > 0$ or $q = \frac{1}{1-m}$ for $m(T) < 0$.

When $\operatorname{sign}(m) \neq \operatorname{sign}(m')$ the Niblett-Bostick transformation remains unaltered (eq. 12).

To estimate the depth to the basement, both versions of the transformation were employed for all stations. The transition from sediments to cristalline rocks is given by the change of signal of the gradient $m(T)$, which is equivalent to an unphysical negative phase. This transition, due to noise signals travelling long distances in the resistive cristalline basement, increased the gradient $m(T)$ to values higher than one (as discussed in section 7). According to Weidelt (1972), the gradient of the apparent resistivity data curve (the $m(T)$ value) does not exceed unity for a consistent response of a one-dimensional Earth.

For each sounding (both directions) in Colônia obtain a set of $m(T)$ values, the first few negatives followed by positive ones. The minimum depth to the basement was associated with the last of the negative $m(T)$ values while the maximum depth to the basement was associated with the first positive $m(T)$ value. Considering that the working hypothesis is correct, the minimum depth estimation is clearly a low estimation of the true depth to the sediment-basement interface, as it is derived from an investigation circle still inside the sediments.

Tab. 1 shows results for both versions of the Niblett-Bostick transformation for station 24, located in the central plain of the depression (see Fig. 1). For both XY- and YX- directions, the basement is estimated to be at a depth between 149 m and 358 m, and between 147 m and 219 m, respectively.

For the XY- direction, the associated Niblett-Bostick resistivity at the maximum depth of 358 m could not be calculated, because the gradient $m(T)$ is less than one, thus indicating a strong presence of cultural noise in the natural electromagnetic signal. The minimum estimation for the depth to the basement lies 149 m and the relatively low resistivity value stands well for the sediment-filling of the depression. A smaller depth-estimation is obtained from the data of the YX- direction. The basement lies at a maximum depth of 219 m and the associated Niblett-Bostick resistivity is very high. As can be seen in Tab. 1, the result of the modified Niblett-Bostick transformation gives an even higher resistivity value, showing a sharp increase with depth on entering the higher resistivity zone representing the basement. Both resistivity values are due to the $m(T)$ value, which is nearly one, generating a phase close to 0 and therefore high resistivities.

The Niblett-Bostick transformation for all other stations thus resulted in a series of minimum and maximum depths for the basement interface inside the depression. Despite the sparse quantity of data yielding depth estimations inside the depression, one was tempted to plot the resulting spatial distribution, thus resulting in a topographic view of a minimum and maximum surface for the basement (Figs. 4 and 5).

**Table 1.** Depths and resistivities for both versions of the Niblett-Bostick transformation for the XY and YX sounding directions of station 24.

*(Profundidades e resistividades para as duas versões da transformações Niblett-Bostick para as direções de sondagens XY e YX, na estação 24.)*

| DEPTH m | | RES. Ω m | | RES. (mod. vers) Ω m | |
|---|---|---|---|---|---|
| XY | YX | XY | YX | XY | YX |
| 30 | 19 | 43 | 6 | 43 | 5 |
| 36 | 23 | 19 | 5 | 17 | 5 |
| 47 | 29 | 8 | 5 | 6 | 5 |
| 46 | 29 | 4 | 5 | 4 | 5 |
| 86 | 41 | 11 | 8 | 11 | 8 |
| 56 | 61 | 4 | 18 | 4 | 27 |
| 117 | 147 | 23 | 150 | 30 | 441 |
| 149 | 219 | 54 | 4277 | 132 | 16868 |
| 358 | - | *** | - | *** | - |

Although exhibiting distinct pattern for each case, the circular shape of the depression is well depicted in all plots. It is therefore consistent with the hypothesis of an impact crater. For both XY- and YX- directions, the minimum and maximum estimated depth to basement in the centre of the depression is around 200 m and 440 m, respectively (Figs. 4 and 5).

Based on a theoretical relationship between depth and diameter given by Grieve and Robertson (1979), a depth value of 436 m is obtained for the basement at the centre of the Colônia depression (Riccomini et al., 1989). This value is very close to the maximum depth estimation obtained in this study.

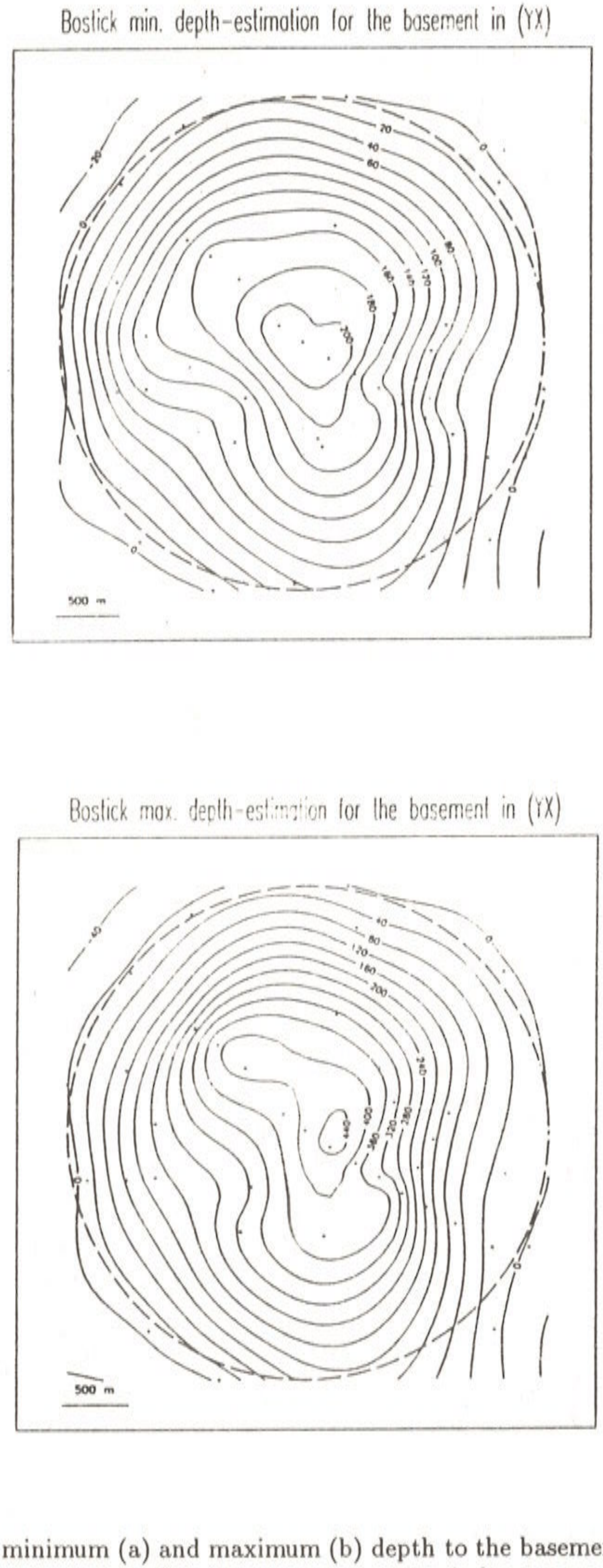
Another attempt to model the data was performed using OCCAM's 1D inversion algorithm (Constable et al., 1987), which uses an arbitrary starting model and a set of sounding data to generate a smooth and simple final model. This final

Bostick min. depth-estimation for the basement in (XY)

Bostick max. depth-estimation for the basement in (XY)

**Figure 4a,b.** Curves of the minimum (a) and maximum (b) depth to the basement (in meters), obtained after the Niblett-Bostick transformation of the XY- direction data. The circle corresponds to the crater rim.

*(Curvas de mínimo (a) e máximo (b) de profundidade à base, em metros, obtidas com a transformação dos dados da direção XY do método de Niblett-Bostick. O círculo corresponde à beirada da cratera.)*



Bostick min. depth-estimation for the basement in (YX)

Bostick max. depth-estimation for the basement in (YX)

**Figure 5a,b.** Curves of the minimum (a) and maximum (b) depth to the basement (in meters), obtained after the Niblett-Bostick transformation of the YX- direction data. The circle corresponds to the crater rim. *(Como acima, para os dados da direção YX.)*

model does not necessarily represent the best possible fit to the data. OCCAM's inversion searches for the smoothest possible model, which fits the data according to a required tolerance. It is well known that discrete models obtained from discontinuous 1D inversion schemes, e.g. Jupp and Vozoff (1975) or Fischer et al. (1981), would indeed reveal more detailed structures, but they would also most probably be strongly influenced by the noise in the data, caused by the proximity of metropolitan São Paulo. The smooth and rather continuous models obtained in this work with the 1D Occam inversion scheme do not define a sharp transition between sediments and cristalline. As a matter of fact, the application of the 1D Occam inversion in this study was more an attempt to create simple and smooth models, thus avoiding the extra structures that could be caused by the presence of noise in the data and are in no way related to the geology.

According to Parker (1982), there exists a critical depth for each modelling of MT data, below which it is not possible to obtain additional information about the conductivity distribution. The 1D OCCAM algorithm requires, for the starting model, a definition of a minimum and maximum depth in the sense of Parker (1982). In this work, they were chosen from the Niblett-Bostick depths (see eq. 11). All frequencies up to the first negative phase value and mostly also the first negative one were included in the inversion. The OCCAM's inversion algorithm was applied to all the data of the Colônia depression. Figs. 6-10 show some results of the 1D OCCAM inversion along with Niblett-Bostick transformation for several stations. The models illustrate typical results from the depression's interior (COL7, COL20, COL17) and from the border of the depression (COL4, COL28). The obtained models do not define a sharp transition between the sediments and the basement. They generally show a gradual and smooth increase of the resistivity with depth and are normally in good accordance with the depths and resistivity values obtained from the Niblett-Bostick transformation.

The final models for most stations in the interior of the depression present a near-surface conductor. The apparent resistivity data curves have a minimum (Fig. 2b), which could represent the presence of a more conductive layer. According to Spies and Eggers (1986), the apparent resistivity is nothing more than a normalization process with little physical significance, except for the rather unrealistic case of a homogeneous half- space. The same authors show that the minimum of an apparent resistivity curve for a two-layer structure, with an underlying more resistive half-space, is due to the presentation of the curve in the frequency domain, since the minimum disappears when the same data is presented in the time domain. The amplitude of this minimum depends on the resistivity contrast between the half-space and the overlying more conductive layer (Spies and Eggers, 1986). Therefore, the presence of a more conductive layer in both final models of this study could merely be an artifact.

Stations located on the rim of the depression, or close to it, usually do not present this near-surface conductive layer. The resistivity increases gradually with depth and the initial values are clearly higher than those measured in the interior of the depression. This agrees well both with the shortage of highly conductive sediments and with a rim of cristalline rocks.

## 9. CONCLUSIONS

An estimate of the depth to the basement in the Colônia depression was obtained by using the AMT method. It was accomplished by using both the Nibblet-Bostick tranformation and the Occam 1D inversion algorithm. The resulting minimum and maximum estimations of the basement-depth using the Nibblet-Bostick transformation is approximately at the centre of the depression and lies between 200 m and 440 m. The resulting models using OCCAM's 1D inversion algorithm are in good accordance with the Nibblet-Bostick transformation.

The relatively poor depth-estimation must be explored further.

Firstly, the presence of cultural noise in the data due to the proximity of Metropolitan São Paulo is indisputable. Secondly, the AMT/MT method does not resolve well the depth in a situation of increasing resistivity with depth. This assertion is particularly valid when comparing the achieved AMT results with the resolution possibly attained by the seismic method when applied to an environment like Colônia.

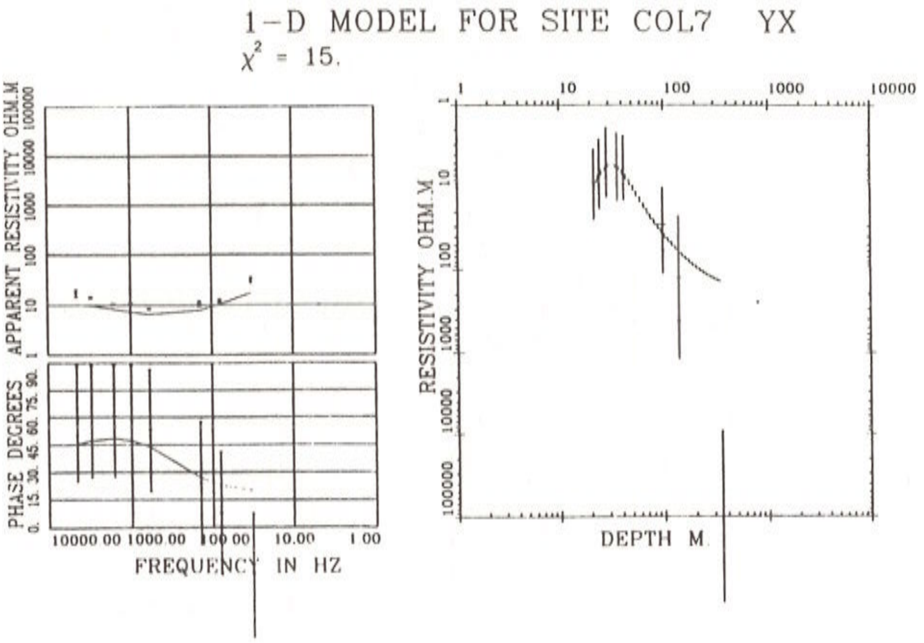


**Figure 6.** Resulting model for the 1-D OCCAM inversion and the Niblett-Bostick transformation of station 7 in the YX measuring direction.

*(Modelo resultante da inversão 1-D OCCAM da transformação Niblett-Bostick da estação 7 na direção YX de medida.)*

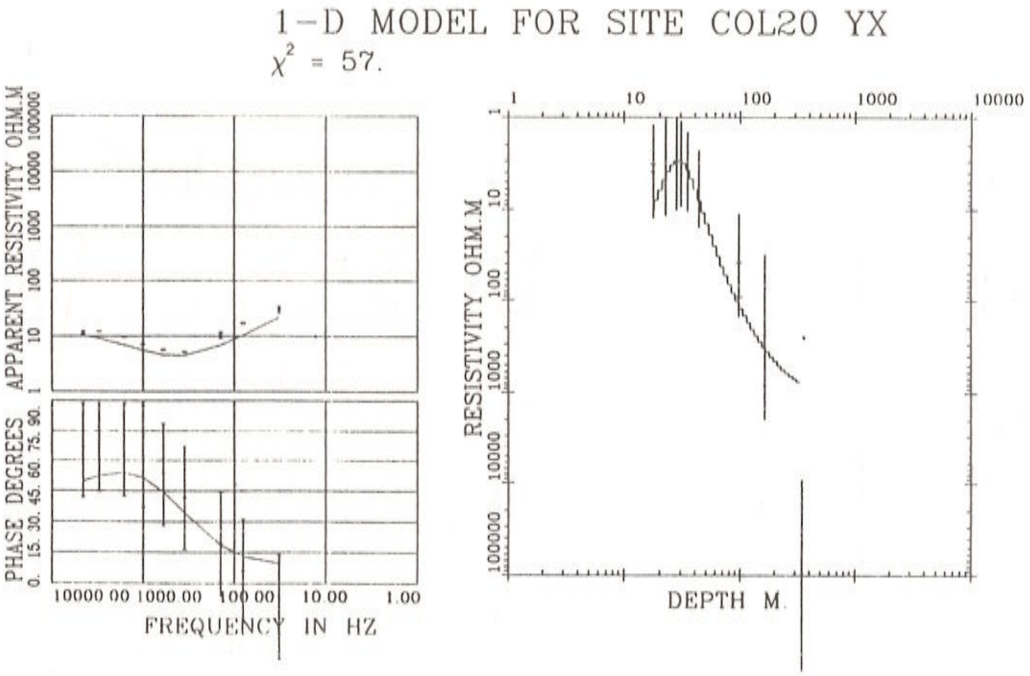


**Figure 7.** Resulting model for the 1-D OCCAM inversion and the Niblett-Bostick transformation of station 20 in the YX measuring direction.

*(Como acima, para a estação 20.)*

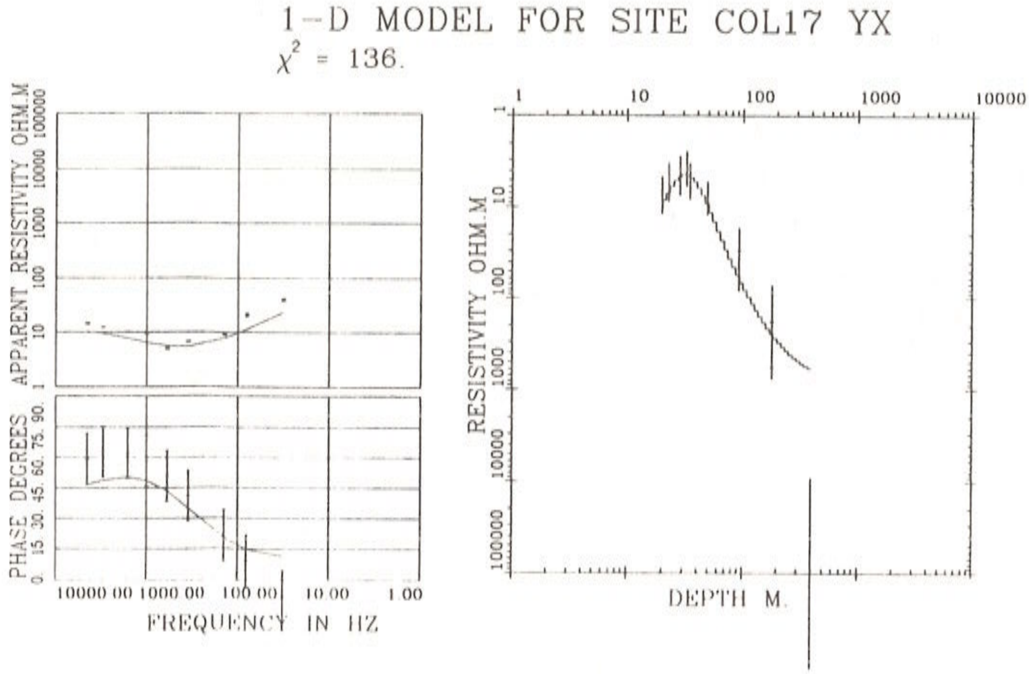


**Figure 8.** Resulting model for the 1-D OCCAM inversion and the Niblett-Bostick transformation of station 17 in the YX measuring direction.

*(Como acima, para a estação 17.)*

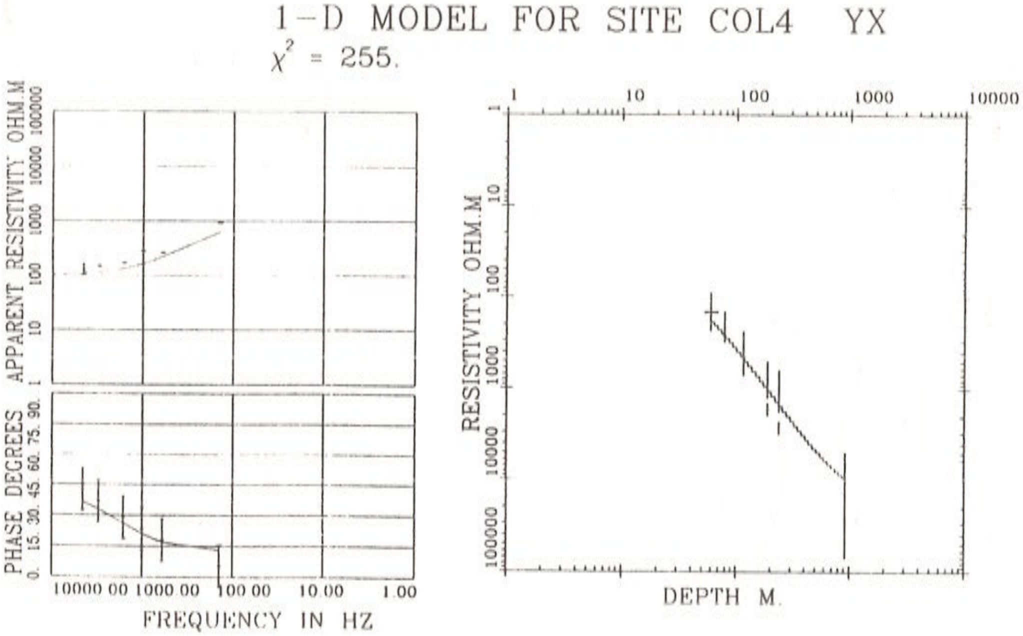


**Figure 9.** Resulting model for the 1-D OCCAM inversion and the Niblett-Bostick transformation of station 4 in the YX measuring direction.

*(Como acima, para a estação 4.)*

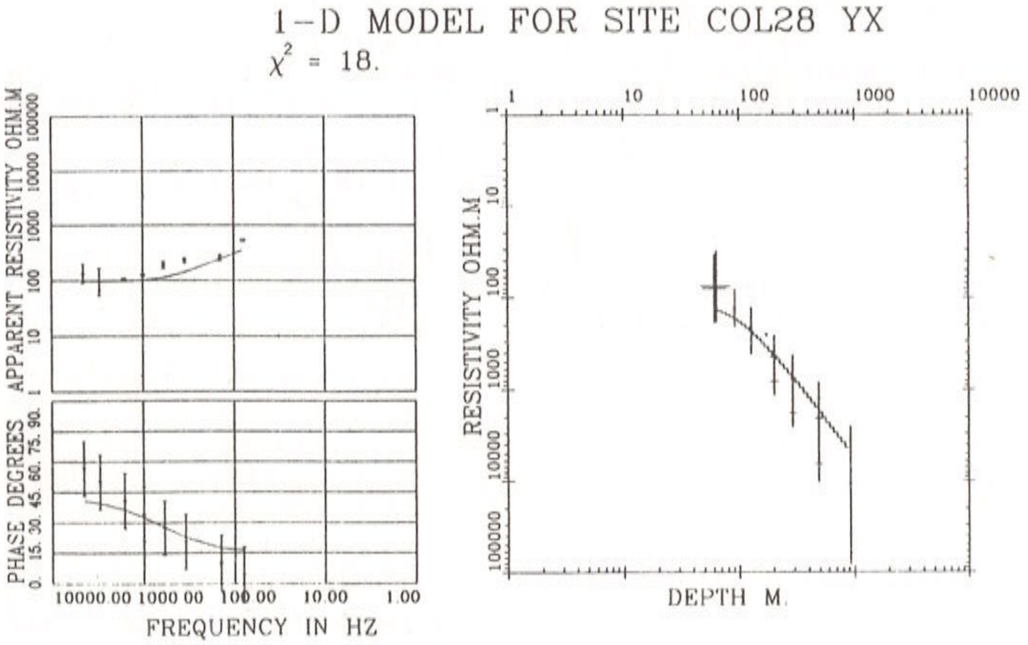


**Figure 10.** Resulting model for the 1-D OCCAM inversion and the Niblett-Bostick transformation of station 28 in the YX measuring direction.

*(Como acima, para a estação 28.)*

A third structural reason may contribute to question of resolution. For both the Nibblet-Bostick and OCCAM 1D inversion, the modelling results did not show a sharp transition of the interface between the sediment-fill and the basement. Actually, a rather gradual and smooth increase of the resistivity with the depth was obtained in most models. Notwithstanding, one should bear in mind that the Colônia depression was probably caused by an impact of a meteoritic body with the Earth; the depression should thus not have an original simple surface. There are several studies in the literature discussing the effects of an impact on the surface and subsurface of sites. For instance, Regan and Hinze (1975) believe in the ocurrence of a strongly brecciated zone on the subsurface of the famous and well studied Meteor Crater, in the desert of Arizona. As other examples, magnetotelluric investigations undertaken in both the Siljan crater in Sweden (Zhang, 1989) and in the Charlevoix crater in Canada (Mareshal and Chouteau, 1990) show a fracturing of the upper crust due to the impact. The Colônia crater has not the dimensions of the two above mentioned craters, but it is very reasonable to assume that the impact affected superficially the local basement in the form of brecciation and fracturing. The interface between sediments and cristalline basement is therefore most probably a transition zone and not a sharp interface.

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