3D Magnetotelluric Imaging of the Serra da Cangalha impact crater, Brazil

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Abstract

The results of the 3D finite-difference forward modeling of magnetotelluric data acquired around the Serra da Cangalha impact crater located northeastern Brazil, South America are presented. The 13 km impact structure has been investigated because of its explicit 3D shape. The central part of the model covers an area of approximately 169 Km^2. The model of the study area, constructed using a 3D mesh of 22 x 19 x 25 (29325 cells) was based on the a *priori* information of the geology of the region, and the results of the 2D inversion results. Eleven frequencies were calculated for the 3-D model (0.01, 0.03, 0.1, 0.3, 1, 3, 10, 30, 100, 300, 1000 Hz). The resistivity structure obtained suggests perturbations of the upper crust due meteorite impact; the base of the uplifted structure extending to 3.0 km depth was well delineated. The observed 3D effects are explained as a shallow resistive ring that represents a local 3D body embedded in a regional layered earth. The results confirm the importance of 3D forward modeling in impact crater studies. The three-dimensional model results indicate that a valuable picture of the regional electrical resistivity can be obtained from 3-D interpretation of the determinant impedance tensors using polar diagrams. The study has helped in providing an insight into the post-impact electrical signature of the upper crust.

Introduction

The necessity for the 3D forward modeling was imposed not only by the complex geology of the Serra da Cangalha impact crater region located on longitude 46°52'W and latitude S 8°5'S in northeast Brazil (Fig. 1 and 2) within the intra-cratonic Parnaiba basin consisting of Upper Silurian to Cretaceous sedimentary covers, but also by the result of our previous work that suggested the existence of 3D features around the impact crater region. The 2D electrical models earlier obtained by (Adepelumi et al, 2003) showed an uplifted basement that is due to impact structure effect. Furthermore, de Lugão et al (2002) suggested that MT interpretation based solely on 2-D formulations would lead to erroneous resistivity models. The main goal of this research is to use 3D forward modeling algorithm to determine if 3D effects is responsible for the anomalous behavior of the apparent resistivity observed at periods longer that 1s, or if it is basically due to a 2D structure. The 3D model (Fig. 2) comprised of a layer of 200 m thickness with a 30 ohm-m specific resistivity, a second layer of 100 ohm-m lying at depth ranging from 200 m to 1.2 Km, a third layer of 1000 ohm-m lying between 1.2 to 5.0 km represent the regional 2D structure in the area, the fourth layer has a resistivity of 4000 ohm-m and its depth vary from 5.0 to 10.0 Km. At the bottom lies an homogeneous half-space with a resistivity of 10 ohm-m. A 300 ohm-m resistivity body that represents the crater is embedded within these layersThe 3D structure is restricted to a very shallow band of period and we believe that this 3D character exhibited is due the heterogeneity of the upper crust (Adepelumi et al, 2003), which was caused by impact of a stony chondrite.

Turtle and Pierazzo (1998) and Amir et al (2002) demonstrated that a large impact by a meteorite usually releases an enormous amount of energy and fractures the surrounding rocks and, in-addition during this process, formidable shock waves are generated that intensely deform the crustal rocks. During impact, tensional failures in rock usually occur in the impacted rocks (Ahrens and Rubin, 1993) leading to an enhancement on the conductivity of the surrounding rocks and the fractured zones. Very high temperatures are induced by shock waves (Arakawa et al, 2000) thereby causing shock deformation of the brittle rocks, recrystallisation of the intrinsic minerals due to shock metamorphic (Bischoff and Stoffler, 1992) and causing mineralogical alterations as a result of high velocity impact reaction that the region is subjected to.

Figure 1:Landsat image of the Serra da Cangalha impact crater region. The red arrow shows the impact trajectory.

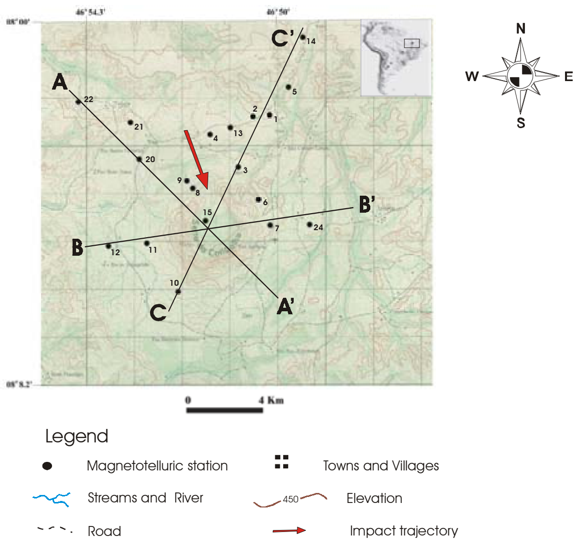

Figure 2-Topographic map of the Serra da Cangalha impact crater region. AA`, BB` and CC` shows the profiles used for the magnetotelluric data acquisition.

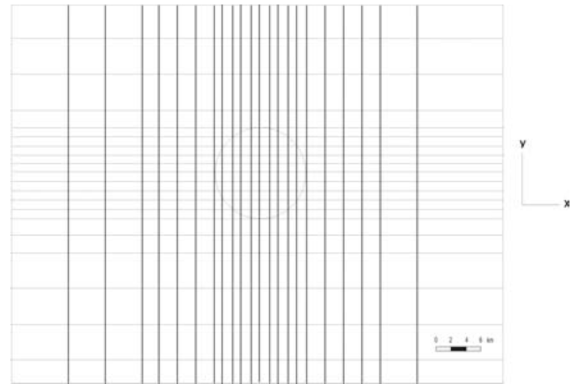

Figure 3: 3D mesh generated for the forward modeling of the MT data of the Serra da Cangalha impact crater region in the x (N30°E) and y (N60°W) coordiantes. The central region is finely discretised**.**

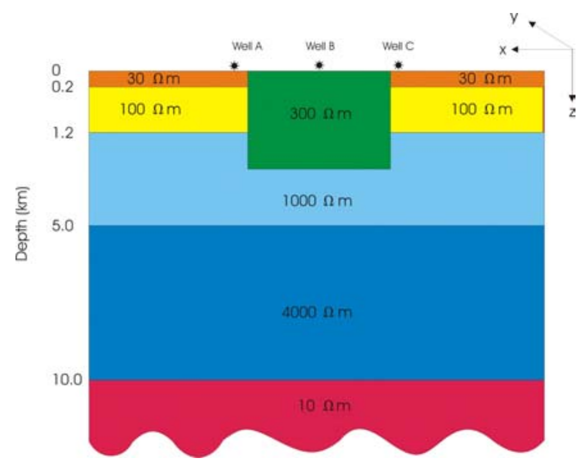

Figure 4- 3D model for the Serra da Cangalha impact crater region. The model is constraint by the results of the 2D inversion results and the borehole information obtained from Geological Survey of Brasil.

Method

The three-dimensional modeling was carried out based on the numerical approach proposed by Mackie et al (1994) with modifications by Mackie and Booker (1999). The central part of the model covers an area of approximately 70 × 70 km. The Serra da Cangalha and its surroundings were discretized into 22 blocks in the x-axis (N30°E) and 19 blocks in the y-axis (N60°W), and 25 horizontal layers. The model was further finely discretized in domains of strong resistivity contrast, mainly inside the outer and inner rings of the crater in area covering 13×13 km (Fig. 3). The 3D model (Fig. 4) comprises of a first layer of 200 m thickness with 30 ohm-m specific resistivity, a second layer of 100 ohm-m lying at depth ranging from 200 m to 1.2 Km, a third layer of 1000 ohm-m lying between 1.2 to 5.0 km which represents the regional 2D structure in the area, the fourth layer has a resistivity of 4000 ohm-m and its depth vary from 5.0 to 10.0 Km. At the bottom lies an homogeneous half-space with a resistivity of 10 ohm-m. A 300 ohm-m resistivity body that represents the crater is embedded within the first three layers. This model is based on the results of the 2D inversion (TE and TM modes) shown in chapter 2 and the borehole and geology of the region information obtained from CPRM (1972). The boreholes were drilled directly at the centre and edges of the crater. The model was graded in the horizontal and vertical direction using the geometric factors proposed by Mackie et al (1993) which is a factor of 2 in the vertical direction and factor of 3 in the horizontal direction.

At first we modified the model until we obtained a good fit with measured MT data and the calculated 3D response and then repeated the process until we achieved a very good fit between the two data sets. Furthermore, Reddy et al (1977) showed that the impedance polar plots could provide a measure of the MT data dimensionality. When 3D resistivity structures predominates in an environment, the additional impedance polar diagrams become elongate in one direction and their amplitudes are comparable to those of principal impedances. Vanyan et al (2000) suggested that the assymetry of the polar diagram is a clear evidence of the existence of 3D effects**.** In order to study the 3D dimensionality of the study area, we then used the inbuilt formulae for polar diagrams computation in Winglink™ version 1.59.

Results

As a first step towards confirming the three-dimensionality of the Serra da Cangalha impact crater region, we analyse the result of the polar diagrams shown figures 5a and 5b. The impedance polar diagrams for the rotated principal impedance tensor (Z_{xy}) and the additional impedance tensor (Z_{xx}) components for two periods of interest (0.1 and 1.0 s) are shown. The shape and orientation of these elements depicts 2D and/or 3D structures. From figure 5a and 5b we could see that only 2D and 3D structures predominates in the period range analyses, since additional impedance tensor (Z_{xx}) exists for all the twenty MT stations and they are non-zero. We found the suggestion of Hermance (1982) and Vanyan et al (2000) that the asymmetry of the Z_{xx} tensor is a strong evidence for the occurrence of 3D effects to be true in the period range (0.1 and 1.0 s) studied. Generally, Z_{xy} is larger than Z_{xx} but the modulus of Z_{xx} is found to be large and comparable in magnitude to the Z_{xy} for most of the MT stations, this observation point to the fact a mixture of 2D and 3D structures predominates in this region. At 10 Hz, the depth of penetration that we obtained does not exceed 2.74 Km inside the crater and 0.87 Km, 1.58 Km and 5.00 Km outside the crater if we consider 300 Ωm, 30 Ωm, 100 Ωm, and 1000 Ωm homogeneous earth respectively (see figure 2), From this, we conclude that the polar diagrams pattern (Figs 5a and 5b) obtained at sites located within and outside the crater indicate the region structurally controlled by the regional geology of the area having a strike of N30^{o}E and the circular and radial pattern of the impact crater structure. The structural features delineated from the 10 Hz polar diagrams are maintained at the 1 Hz frequency with very slight variation. At 1Hz, if we use the same homogeneous earth as 10 Hz, the skin depths of 8.6 km, 2.74 km, 5 km and 15 km are obtained. From the above, we infer that the features seen at Serra da Cangalha crater region could only be best explain by 3D effects of the subsurface structures.

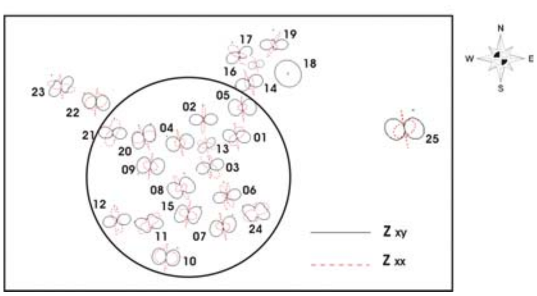

Figure 5a: Polar diagrams of the impedance elements (Z_{xy} and Z_{xx}) at 10 Hz.

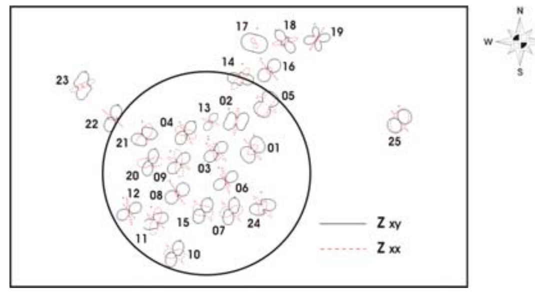

Figure 5b: Polar diagrams of the impedance elements (Z_{xy} and Z_{xx}) at 1 Hz.

The calculated 3D model, apparent resistivity and phase of both polarizations (TE and TM) for the entire impact crater region are presented in figure 6 and 7. From the depth slices (Fig. 6), it is observed that the apparent resistivities of the upper crust as defined by the apparent resistivities for all the period greater than 1 s is far below the known resistivity of dry basement rocks. The presence of faults and fractures in the basement is favored as the most plausible explanation for these low values. Zhang et al (1987) showed that resistivity in such a region is controlled by the shunting conductance of the fractured zones. Also, Grieve (1984a) argued that the shock waves created by the impact event would fracture the crust possibly down to the upper mantle levels. Another explanation for the moderately resistive upper crustal rocks observed around the Serra da Cangalha impact structures (Fig. 6 and 7) are given in terms of the presence of free fluids in the lower crust earlier suggested by Haak and Hutton (1986). Bjørn et al (2000) proposed the mechanism of fluid introduction to dry rocks in the lower crust as due to stress perturbations. This observation clearly fit the Serra da Cangalha model since the rocks in these regions have undergone some sort of stress pertubations as a result of the meteorite impact. If the impact generated fractures are kept open by the pore pressure of the lower crust fluids, it would mean that a pathway would exist for the migration of these fluids to upper crustal levels and fill the fractures and pores generated by the impact thereby reducing the bulk resistivities of the host rocks.

The general low resitivity values obtained is explain in terms of the fractured and breciated basement in the upper crust due to the bolide impact. The forward modeling results shown in figures 4 and 5 (TE and TM mode) suggests that the impact crater is relatively a shallow tectonic structure that extends from a depth of about 0.2 km to about 1.2 km. This corresponds to the depth obtained from the 2-D model. The central impact structure is conductive to 0.6 km and after this depth, the structure shows basically resistive signature. The main features of the resistivity structure presented in Fig. 4 are consistent with the basement structure derived from 2-D modeling by Adepelumi et al (2003). A relatively conductive zone (100 ohm-m or less) extends to about

1.5km. This zone seems to correspond to the impact-induced altered zone and Paleozoic sedimentary rocks, which are widely distributed at these levels. The resistivity distribution of the uppermost domains is strongly influenced by the crater structure and the Paleozoic sediments. The distinct resistivity contrast observed on figure 4 and 5 represents inhomogeneities in the upper crust to mid-crust formed due to the impact of the meteorite in this region that resulted in the formation of impact induced fractures, microfractures with interconnected pore spaces and brecciation. Masero et al (1997) for the Araguainha crater site in Brazil reported a similar occurrence of this low resistivity effect in the upper crust.

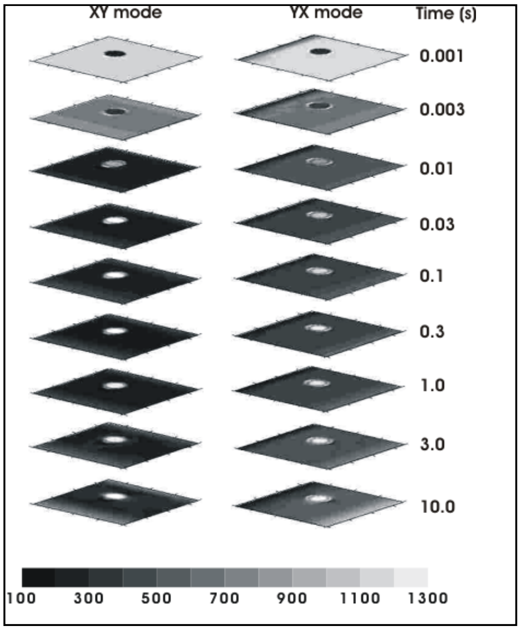

Figure 6- Calculated apparent resistivity (Ωm) horizontal time slices. The crater lateral extent is well defined.

Conclusions

We have modeled and characterized the 3D structures that produced crater morphology observed at the Serra da Cangalha impact crater site. From the analysis of the 3D forward modeling calculations, it is concluded that the resistivity structure detected are due to a 3D effect and not 2D structure. The modeled structures clearly delineated the apparent resistivity distribution of the actual deeper geological structure present in the impact crater area. The 3D forward modeling results was very useful in explaining the resistivity contrast seen at the impact crater region. We also conclude that the 3D modeling results obtained supports the resistivity model for the area obtained from the previous work (Adepelumi et al, 2003). In addition, the calculated 3-D MT response reveals a significant reduction in the basement rock resistivity around the center of the crater, which we believe was caused by the impact-induced fracturing of the upper crust. Another plausible explanation for the calculated resistive anomaly in the upper crustal to mid-crust is given in terms of the presence of free fluids in the crust due to stress perturbations caused by the impact of the meteorite in the region. This low resistivity zone is estimated to reach a depth of about 3 Km. The real polar diagram of the impedance also helped in defining the 3D dimensionality of the crater structure at the chosen periods of 0.1 and 1.0 s. We conclude that the 3D forward modeling carried out has led to having an insight into the post-impact geodynamic characteristics of the electrical signature of the upper crust around the Serra da Cangalha impact crater region, northeastern Brazil, South America .

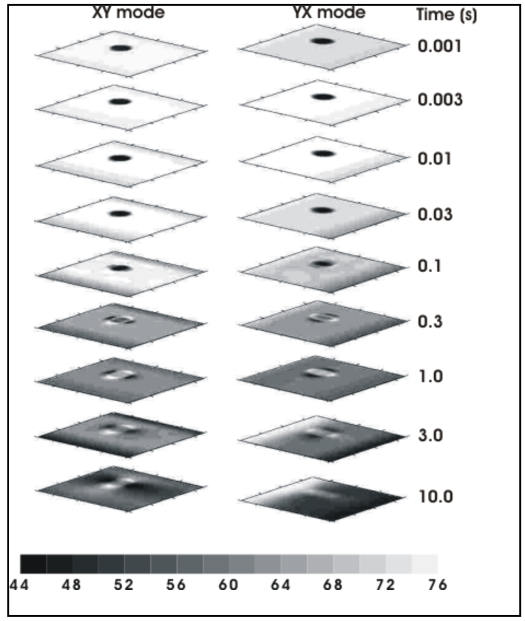

Figure 7: Calculated phase horizontal time slices. Note the low phase in the TM relative to the TE mode.

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