Three dimensional resistivity structure of the Serra da Cangalha crater inferred from magnetotelluric modeling

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Abstract

In view of the circular geometry of the Serra da Cangalha impact crater, we have carried out a 3D forward modeling computation for twenty-five MT data in order to obtain the 3D resistivity forward model for the crater region. The 3D resistivity forward model revealed a five-layer model, showing a significant reduction in the basement resistivity. We suggest that this, perhaps, could be due to the structural disturbances that have been caused by the meteorite impact on the crater about 220 million years ago resulting in brecciation, fracturing, alteration and shocked zone filled with fluids. Also, the sensitivity analysis of the 3D model chosen indicates that 3D models having a crater diameter greater than 15 km are inconsistent with our data because the 3D model responses are very sensitive to changes in the diameter beyond 15 km. This analysis also reveals that, the depth limits (for the 3D body) causing the anisotropic effects seen on some of our apparent resistivity curves maximally does not extend beyond 1.2 km depth.

Introduction

The Serra da Cangalha crater (SDC) structure (Figure 1 and 2) is located on longitude 46°52' W and latitude 8°05' S in northeast Brazil is a confirmed impact structure having a diameter of 13 km (McHone, 1986). SDC structure was formed in the intracratonic Parnaíba basin that comprises a stratigraphy of Upper Silurian to Cretaceous sedimentary rocks. Target rocks include upper Permian Pedra do Fogo sandstones, Permian/Carboniferous sandstones, Carbonaceous shales, Poti Formation, and the dark shales of the Longá Formation. A regional NE-SW depositional direction controls the sedimentary rocks found in the crater region. The necessity for the 3D forward modeling was imposed not only by the complex geology of the SDC, but also by the result of our previous work that suggested the existence of 3D features around the impact crater region. The main goal of this research is to use 3D forward modeling method to determine if 3D effects are responsible for the anisotropic behavior of the apparent resistivity observed at periods shorter than 0.1s since 3D MT forward modeling is deemed more appropriate than 2D inversion. Moreso, the 3D effects observed in the crater region could not have been accounted for in the 2D inversion results obtained by Adepelumi et al. (2004).

Geology of the Serra da Cangalha crater

Serra da Cangalha impact scar is imprinted on undisturbed Permian sediments (Pedra de Fogo Formation) of the Parnaíba Palaeozoic sedimentary basin. Within the central bowl occur deformed, steep dipping Carboniferous marine deposits of the Poti Formation (Dietz and French, 1973). The local stratigraphy involves 1.2 km sedimentary units locally covering the impact structure. Field evidences (Shatter cones boulders, shock breccia, lamellae and few impact melt, rhombic fractures and joints, unsual micro-fracturing of the quartz grains, shock-induced optical planar elements (1012 and 1013) and shock wave overpressures of over 100 Kilobar) provided by McHone (1986) lead to the conclusions that the impact could have occurred around 220 million of years ago. Shallow borehole drilled by CPRM (1972) showed that the annular inner depression of the crater is filled with impact-derived materials made up of an allochtonous monomictic breccia and as well as minor impact melt bodies.

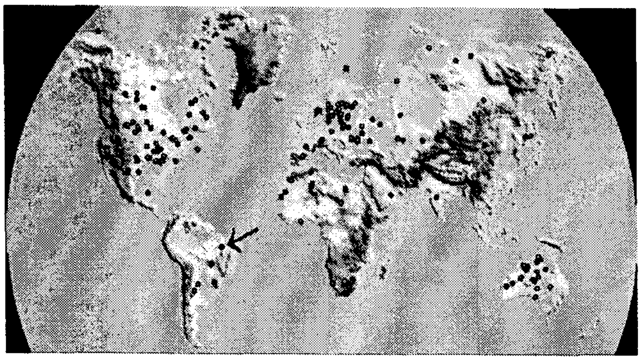

Figure 1. World craters map. The map shows the locations of all the known impact crater sites on earth. The location of Serra da Cangalha in northeastern Brazil is indicated with arrow (Culled from the Canada Geological Survey website).

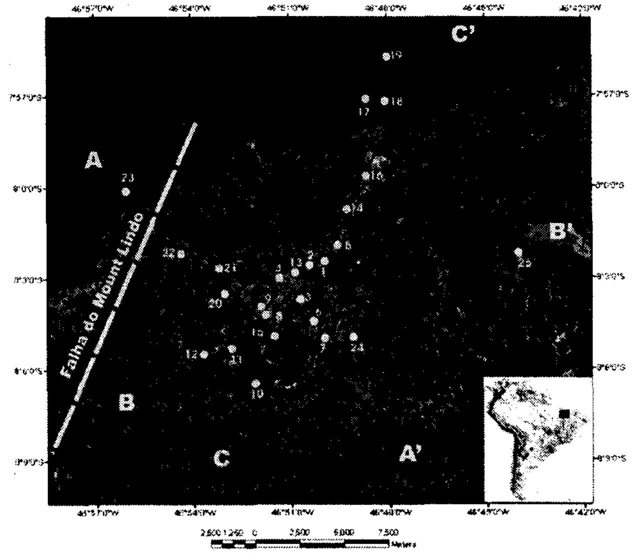

Figure 2. Landsat image of the Serra da Cangalha impact crater region. AA', BB' and CC' shows the profiles used for the magnetotelluric data acquisition. The yellow circles are the MT sounding sites

Methodology

A 3D model was constructed using the Geotools model builder, and its forward responses were calculated using the code of Mackie et al. (1994). A schematic description of the complete model used in this study is shown in Figure 3. The model is comprised of a 200 m top layer of 50 ohm-m, a second layer of 150 ohm-m lying at depths ranging from 200 m to 0.6 km, a third layer of 250 ohm-m lying between 0.6 to 1.2 km, and the fourth layer of 500 ohm-m and depth extent ranging between 1.2 to 2.0 km. At the bottom of the fourth layer lies a 1000 ohm-m homogeneous half-space. Two double ring bodies having a resistivity of 100 and 600 ohm-m respectively that represent the crater were embedded within the first three layers. For the 3D modeling, we used data for twenty frequencies ranging from 0.1 to 1000 Hz from a total of 25 MT sites. Data below 0.1Hz were neglected because we only intend to image the upper part of the crust and also because the 3D behavior is much less pronounced at lower frequencies. The central part of the model covers an area of approximately 35×35 km and involves the main geological outcrop and its adjacent area where we suspect the impact of the meteorite impact might be pronounced. The modeled region was discretized into 60 cells in the north-south direction (x-axis) and 60 cells in the east-west direction (y-axis), and 17 horizontal layers that resulted in 179537 solutions. Also, the model was graded in the horizontal and vertical direction using the geometric factors 2 in the vertical direction and factor of 3 in the horizontal direction. The *a priori* information used in constraining the 3D features have been obtained from both the results of a 1D modeling which suggest the existence of an anomalous radial 3D conductor at depth and the 2D model result shown by Adepelumi et al. 2004.

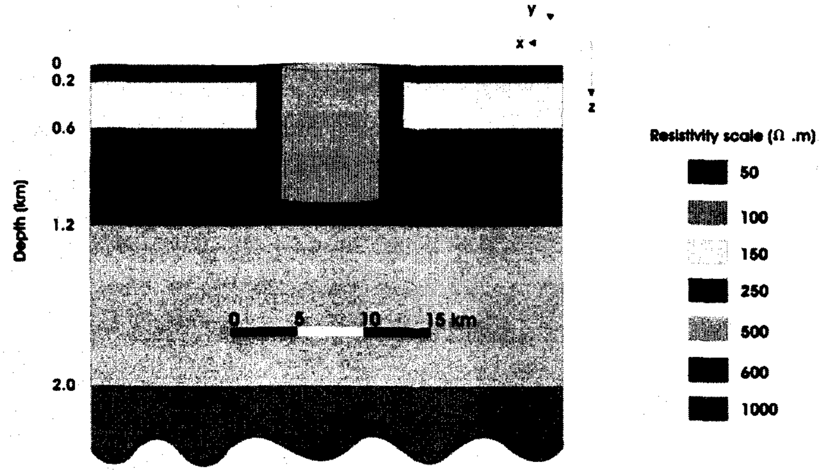

Figure 3. The conceptual 3D Model generated for the Serra the da Cangalha region and painted as vertical slice in geotool.

In order to test the validity of the 3D model shown in Figure 3, prior to estimating the final 3D responses for Serra da Cangalha impact crater region, we changed one parameter or one set of parameters, leaving all others constant and calculated the corresponding change in misfit. We have selected different models with varying crater dimensions (depth and diameter). The resistivity structure of the five layers model was same in all the models. For the model A, B and C, the depth to the base of the crater was fixed at 0.5km, 0.8 km and 1.1 km and the diameter of the crater was varied between 0.1 km and 30 km. In model D, E and F, we varied the depth to the base of the crater between 0.1 km and 3.0 km while the diameter of the crater was fixed at 8, 13, and 20 km. The misfits of the 3-D responses were computed in order to confirm the authenticity of the 3-D model that we have chosen for this region. The results are shown as Figure 4.

Discussion of results

In Figure 4 (Models A to E), we have plotted the RMS misfit of the 3D model responses as a function of the diameter and depth to the base of the Serra da Cangalha impact crater. For models A, B and C, the misfit is smallest and quite stable at a crater diameter varying between

11 and 15 km, but it increases steeply when the horizontal extension of the embedded body exceeds 15 km. On the other hand, for crater having a diameter between 5 and 10.5 km, the misfit also increases but is slightly lower than the misfit obtained for crater having a diameter greater than 15 km. This shows that the model response is not sensitive to these diameters range. This result indicates that 3D models having a crater diameter greater than 15 km are inconsistent with our data because the 3D model responses are very sensitive to changes in the diameter beyond 15 km. Whereas, 3D models having a crater diameter of between 11 and 15 km is compatible with the our data. This result suggests that the horizontal dimension of the crater is very important in constraining the 3D model responses. On comparing the misfit between models A with B, we observe that the misfit of model A is about 22% higher than the misfit of model B, as result, model B is more desirable than model A. Furthermore, a comparison of model B with C shows that the misfit in model B is 26% higher than the misfit in model C. Of all the three models A, B and C, model C have the lowest and most stable misfit. Therefore, the model C was chosen as the most adequate 3D model for Serra da Cangalha region.

Also, the results obtained due the variation of depths to the base of the crater is shown as Models D, E and F. From this figures, we observe that the 3D model responses are not very sensitive to changes in the depth to the base of the crater of between 0.1 –1.2 km. Also, the misfit of this model result is relatively stable at this depth range. However, the fit between the model responses and the observed data significantly worsens beyond 1.2 km. This result reveals that, the depth limits (for the 3D body) causing the anisotropic effects seen on some of our apparent resistivity curves maximally does not extend beyond 1.2 km depth because the lowest misfit and best fits between the modeled and observed data was obtained when the base of the 3D body causing the perturbation was fixed to this depth. On comparing the misfit obtained for models D with E, it was observed that the misfit of model D is about 44% higher than the misfit of model E, this result indicate that model E is more appropriate than model D. As a result, we chose model E instead of model D since lower misfits were obtained for this model. In-addition, a comparison of model E with F shows that the misfit in model F is 52% higher than the misfit in model E. In general, the misfit of the model increases for small crater diameter (Model D) and large crater diameter (model F). We subsequently chose model E as the most appropriate 3D model of all the models tested, because this model presents the lowest and most stable and appropriate misfits.

The preliminary model that describes the major 3D features of the impact crater is presented in this section. Figure 5 shows the horizontal depth slices of the 3D model obtained by trial and error modeling. The following inferences can be made from the 3D model: (1) the main features representing the impact crater is well delineated at the center of the model, suggesting that the impact crater is a relatively shallow tectonic structure that extends to a maximum depth of about 1.8 km. We believe that the 3D character exhibited by some MT data is due the heterogeneity of the upper crust, which was probably caused by the meteorite impact. (2) Between the depth range of 0 – 0.6 km, the outer rings of the crater is conductive while the inner ring shows a significant reduction in resistivity with depth until about 1.0km depth. This decrease in the bulk resistivity of the inner ring may be explained in terms of the influence fracturing, faulting and brecciation of the rocks in the upper crust. Another possible explanation for the moderately resistive upper crustal rocks observed around the Serra da Cangalha impact structures is given in terms of the presence of free fluids in the lower crust. This explanation seems to fit our 3-D model result because the upper crust structures in this region have undergone some sort of stress perturbations as a result of the meteorite impact. Starting from 1.0 km depth, the signature of the inner ring becomes resistive again while the outer ring becomes completely resistive as the regional basement is approached. Below this depth, the model becomes more resistive as expected for the crystalline basement. The resistivity increase with depth in the inner ring between 1.0 and 1.8 km can be explained in terms of the intrusion of the uplifted basement into the surrounding sedimentary layers. The main features of the 3-D resistivity model presented in Figure 5 are consistent with the geology of the region.

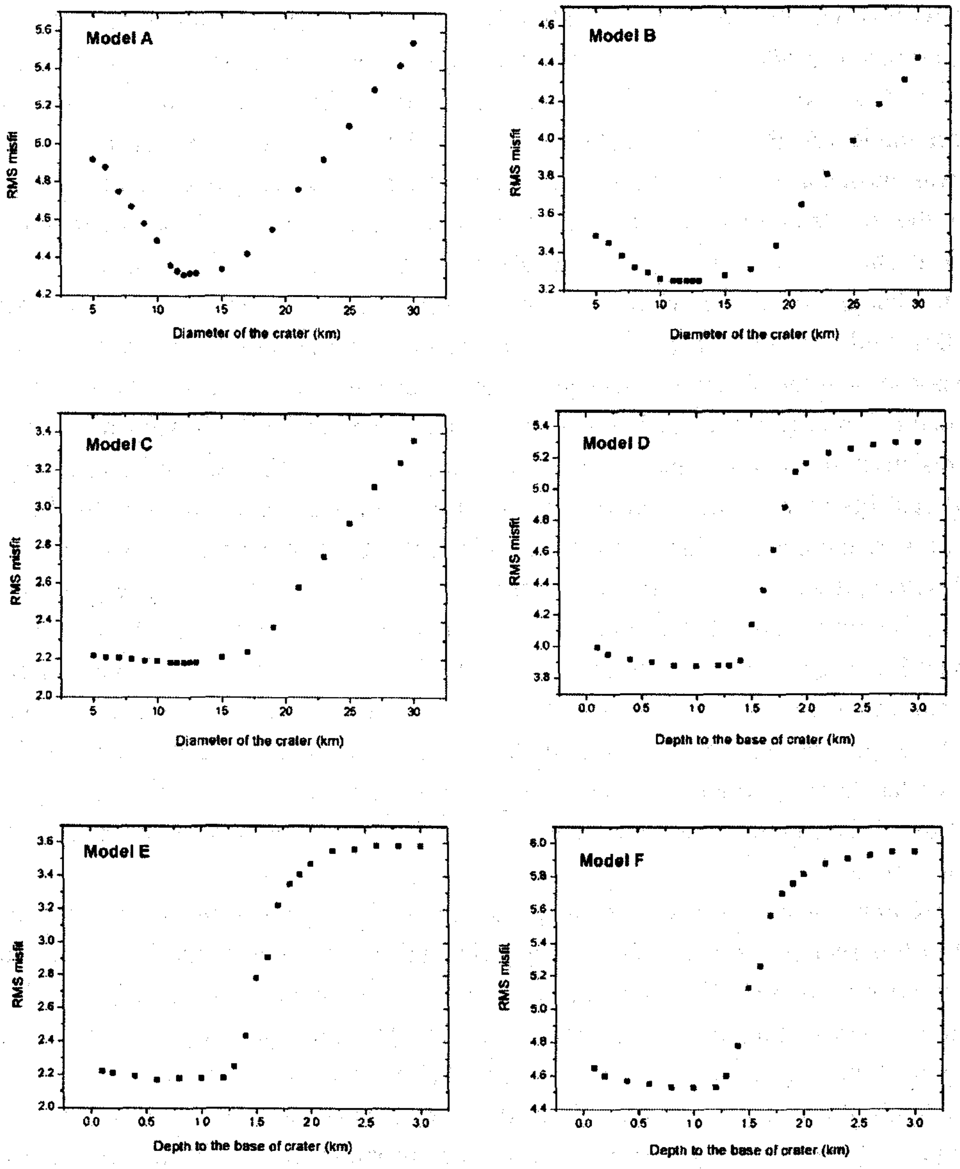

Figure 4. A plot of the results of the sensitivity tests showing the effect of variation of the diameter of the embedded impact crater on the 3-D model responses. In model A, B and C, the depth to the base of the crater was fixed at 0.5, 0.8 and 1.1 km while the diameter was varied between 0.1 km and 30 km. In model D, E and F, the diameter was fixed at 8, 13 and 20 km and the depth to the base of the crater was varied between 0.1 and 3.0 km.

Conclusions

It is interesting to note that the 3-D MT model obtained in this study has enabled us to deduce the post-impact resistivity characteristics of the upper crust that best explain our MT field data. The distinct resistivity contrast of the circular structure revealed by the 3D model may represent an inhomogeneity in the upper crust due to the impact of the meteorite. This might have been formed by considerable impact-induced fractures, microfractures with interconnected pore spaces, and brecciation within the target rocks. Similar occurrence of this low resistivity effect in the upper crust has been reported for the Araguainha crater site in Brazil and the Siljan impact region in Sweden. It was observed that in general, the small dimension of the 3D body modeled has only a small influence on the model response.

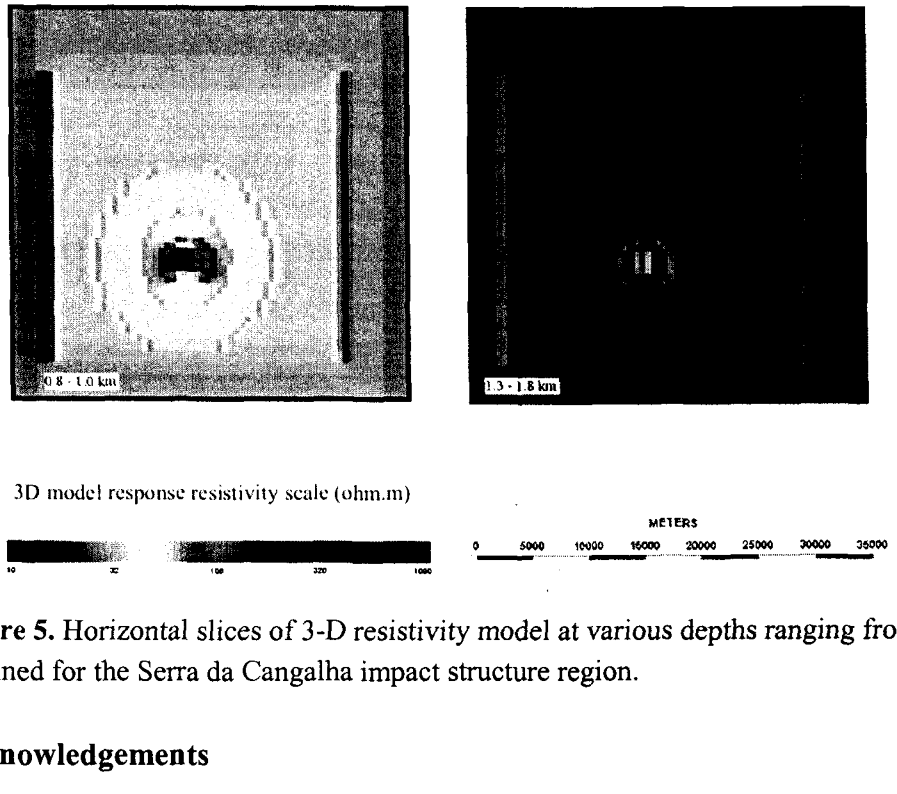

Figure 5. Horizontal slices of 3-D resistivity model at various depths ranging from 0 to 1.8 km obtained for the Serra da Cangalha impact structure region.

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