Interpretation of the aeromagnetic signatures of the Serra da Cangalha impact crater

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This paper was prepared for presentation at the 8th International Congress of The Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 14-18 September 2003.

Abstract

In this paper, the results obtained from the processing and inversion of aeromagnetic data of the Serra da Cangalha impact crater region coupled with the results of the geodynamics modeling of crater formation obtained through scaling relations are presented. An understanding of the tectonic features around the Serra da Cangalha impact crater were obtained through the interpretation of the aeromagnetic data. The most propable incident angle for the bolide that struck the region about 300 million years ago was deduced based on the pi-scaling relation to be between 25° - 30° above the horizon. Based on information obtained from the landsat image, the trajectory of the impacting bolide is suggested to be in the northwest-to-southeast direction. The development of the impact crater was controlled by the pre-impact NE – SW geoctectonic structures existing in the region. The crater boundary is well resolved from the horizontal and vertical gradient maxima maps. In addition, we obserrve that the magnetic gradient is fairly high in the impact region and adjacent areas, while it is surrounded by low magnetic gradients throughout most of the northwest and southeast portions of the crater center. The 3D analytic signal calculated produces a maximum over the source edges of the magnetic anomaly that delineate the impact crater boundary. Generally, the analysis of the aeromagnetic data suggest a predominantly shallow source with high frequency magnetic anomalies seen at the Serra da Cangalha region. The central structural uplift at the centre is estimated to be 1.2 Km relative to the surrounding basement surface while the depth to the crater floor is deduced to be 1.02 km using pi-scaling relations. A distinct uplifed basement that we suspected was due to the impact of the meteorite was delineated at about 1.2 km depth.

Introduction

Until recently, impacts by extraterrestrial bodies were regarded as, perhaps, an interesting but certainly not an important phenomenon in the spectrum of geological process affecting the Earth. It is only of recent that the study of meteorite impact craters became a subject of intensive research worldwide and ever since, the interest in studying this kind of structure has increased tremendously because it has been recognized as an important geologic process in the earth's history (Gehrels, 1994; Grieve and Pilkington 1996). The recognition that large impacts may have played an important role on the earth's climatic and biologic evolution has spurred the search for more evidence of such events (Melosh, 1989).

The Serra da Cangalha meteorite impact crater structure (Fig. 1) is located on longitude 46°52'W and latitude S 8°5'S in northeast Brazil within the intra-cratonic Parnaiba basin consisting of Upper Silurian to Cretaceous sedimentary covers. The structure is one of the eight known impact craters in Brazil (Crósta, 1987; Hachiro et al., 1996) and it is the second largest impact crater known in Brazil. It has diameter of about 13 km diameter estimated from satellite image (McHone, 1979) . The crater is characterized by a distinct high positive central magnetic anomaly having a relief of 27400 nT (total field) and a bounding low magnetic anomalies to the south, and increasing magnetic intensity to the north of the crater (Figs. 2).

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

Terrestrial impact structures with rim-rim diameters greater than ~ 4 km are predicted to contain central peak structures. The formation of central peak structures is attributed to elastic rebound of the target rocks and/or the gravitational collapse of a bowl-shaped transient cavity and crater wall (Melosh, 1989). Crawford et al (1989) reported that magnetic effects developed from macroscopic hypervelocity meteorite impacts is substantial and could generate up to 2500 nT intensity magnetic fields in low ambient field environments, and that the magnetization produced depends on the impact angle, impact velocity, strength of the target rocks and the intrinsic strength of the ambient field. Shock waves from impact crater events usually cause a new magnetization in the target rocks (Halls, 1979). Pierazzo and Melosh

(2000) showed that the volume of shock melting in target rock is a strong function of impact angle and that the amount of impact melts decreases with impact angle. Kieffer and Simonds (1980) showed that the volume of melts found in craters impacting a sedimentary targets is about two orders of magnitude less than for crystalline targets. This has been attributed to the formation and expansion of large quantities of sediment derived steam like H_2O and CO_2 that resulted in wide dispersion of the shock melted sedimentary rocks (Grieve and Cintala, 1992). The Serra da Cangalha crater was formed in Parnaiba sedimentary basin of northeaster Brazil, with a sedimentary sequence up to 3 Km; the relatively thick sedimentary sequence present at the impact site might have contributed to the dispersal of the impact melt shortly after impact.

The principal objectives of this research is to contribute to the scientific knowledge of the Serra da Cangalha impact crater located in the State of Tocantins, northeastern Brazil and gain an insight into the crater formation mechanisms in the study through the use of aeromagnetic data supplied by Geological Survey of Bazil (CPRM). The main aim of the research is to have an insight into the geodynamics formation of the crater and the magnetic anomaly characteristics of the immedaite impact crater region; to determine the depth to the bedrock (post-impact); to determine the structural characteristics underneath the Serra da Cangalha impact zone; to estimate the amount of basement uplift in the central region of the crater; to have insights about the upper crust beneath the impact crater; to classify the Serra da Cangalha impact crater as either simple or complex crater and finally, determine determine the probable angle of impact of the meteorites.

Method

The magnetic flight lines were flown in November 1973 in the N – S direction, perpendicular to the observed regional strike. They were spaced 4 Km apart and tie lines were flown at a spacing of 27 Km in E – W direction. A constant clearance altitude of 150 m above the ground level was maintained throughout the survey. The original hardcopy aeromagnetic map provided by CPRM / DPRM was digitised and resampled to a 400 m cell grid spacing between flight lines following the suggestion of Li and Oldenburg (1996). We carried out the data processing using the OASIS montaj^{TM} data processing and analysis system (Geosoft, 2000). The total field magnetic map (Fig. 2) was subjected to IGRF 1973 correction and the main regional geomagnetic field was removed from the total field thereby leaving us with the regional residual fields only (Fig. 3). To achieve this, a second-degree regional field was calculated and subtracted from the raw magnetic data set containing the total field. Downward continuation was used to enhance the response of the magnetic basement source at depth by effectively bringing the surface of measurement closer to the source of the elongate structure seen on the magnetic map. The horizontal and second vertical derivatives of the field were calculated in order to delineate the contact locations, the minimum depths to magnetic sources and the lateral extent of the sources respectively. The second vertical derivatives method was originally applied to aeromagnetic data to sharpen and resolve anomalies of small area extent.

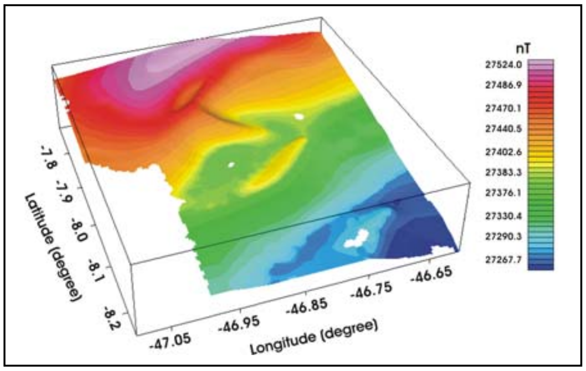

Figure 2- The total magnetic fields of the Serra da Cangalha impact crater region.

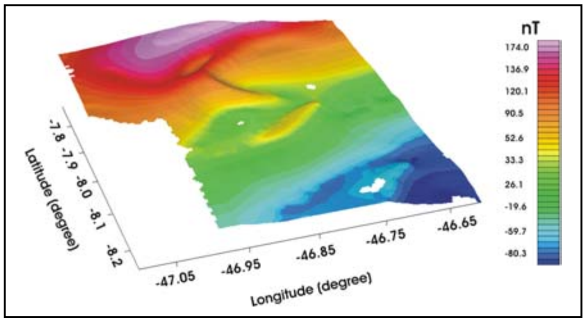

Figure 3- The residual magnetic fields of the Serra da Cangalha impact crater region.

Ravat et al. (2002), Grauch and Cordell (1987) suggested that the maximum values of the horizontal gradients would be located near the vertical sides of the anomalous body. We therefore used the horizontal gradient maxima (crater rims) to delineate to the horizontal boundaries (width) of the crater source. In addition, Nabighan (1974) and Roest et al (1992) suggested that the amplitude of the analytic signal has desirable properties for the interpretation of magnetic anomalies and that the maxima of this function overlie the source edges and are related to the source depth. Grieve and Pilkington (1996) defined the stratigraphic central uplift (SU) for craters developed in a sedimentary basin to be:

$$SU = 0.086D^{1.03} \qquad \dots\dots\dots.1$$

SU is given as the amount of uplift undergone by the deepest sedimentary horizon now exposed at the surface in an impact crater region.

Pike (1985), Grieve and Pesonen (1992) showed that the central uplift diameter in an impact crater region could be obtain using the relation given as:

$$D_{Cu}= 0.22D \qquad \dots\dots\dots.2$$

Holsapple (1993) showed that the height of the rim above the basement surface is given by:

$$\Delta= 0.13R_r^{0.4} \qquad \text{……….3}$$

and the rim to floor basemen depth relation given a:

$$H = 0.47R_r^{0.3} \qquad \text{……….4}$$

We attempt to predict the most probable impact angle of the meteorite using the Fortran code of Melosh (1999) that is based on the pi-scaling relations contained in chapter 7 of Melosh (1989). The above relationships formed the framework within which Serra da Cangalha structures was studied.

Results

Assuming a crater having 13 km rim-rim diameter and using the relations given in equation 1, we estimated the central uplift at the Serra da Cangalha region to be about 1.2 Km relative to the surrounding basement surface. Also, by using the empirical relation given in equation 2, we derived a central uplift diameter of 2.86 km. The height of the rim was obtained to be 363 m by using the scaling factor goven in equation 3. Using the rim to floor depth relation given in equation 4, we calculated the depth of crater below the rim to be 1.02 km. The results using equations 1 – 4 were confirmed by the two-dimensional magnetotelluric models results shown by Adepelumi et al (2003). Furthermore, these results correlate with the results earlier obtained by the geologist at the Geological Survey of Brazil. From the use of the classical cscaling relations, we conclude Serra da Cangalha impact crater is a small complex crater that follows the expected trends derived from classical scaling laws.

Using the pi-scaling relations of Melosh (1999), we assume an impact velocity 25 km/sec, impactor density 3000 Kg/m^3, target density 2700 Kg/m^3, impactor diameter 535 m. We obtained the most probable angle of impact of the impactor at Serra da Cangalha area to be between 25^o - 30^o. Using the same relation, we were able to confirm the final crater to be a complex one having a rim-to-rim diameter of about 13 Km. With this diameter, we were also able to confirm the most probable impact angle using the pi-scaling relations. Melosh (1989), citing hypervelocity experiments, notes that only oblique impacts (angle greater 10 degrees) create symmetrical impact craters. Our result agrees with that of Melosh (1989). Based on this result, we conclude that the Serra da Cangalha impactor was on a northwest-to-southeast trajectory at a low angle of 25^o - 30^o above the horizon. Also, the semi-circular (open on northwest quadrant) crater shape of the Serra da Cangalha impact structure suggests oblique impact on a northwesterly - southwesterly trajectory on a compass bearing of 340^o (Fig 1). An impactor energy of 1.8 x 10^4 Megatons.

We attempt to interprete the possible causes of the Serra da Cangalha magnetic anomaly due to impact and subsequent shock metamorphism in this section. The remarkable correlation between the magnetic anomaly (Fig. 2) and the ring structure seen on the landsat image (Fig. 1) strongly suggests that this anomaly is related to an impact event, which from the regional geology must have formed in the Paleozoic. The magnitude, shape and characteristic magnetic high depicted by the Serra da Cangalha impact structure is consistent with observations of structures believed to be caused by meteorite impact developed in a sedimentary terrain around the world which generally have between tens to hundreds of nT. This anomaly is impact related and may have developed as a result of shock demagnetization, shock remagnetization (SRM) acquired at the time of impact; thermal (TRM) and chemical remanent magnetization (CRM) acquired soon after the impact effects over the target rocks and the formation of remanent magnetization of melts, breccias, footwall complex, post-impact faulting and uplifting of the basement rock (Girdler et al, 1992; Pilkington and Grieve, 1992; Grieve and Pesonen, 1992). Based on the geodynamics signature found in the study area, we infer that magnetic anomaly observed is directly related to impact structure. Also, we suspect that, the target rocks at Serra da Cangalha acquired new magnetization due to the hypervelocity impact proposed by Crawford et al (1989) which resulted in the central positive magnetic anomaly (Fig. 2 and 3).

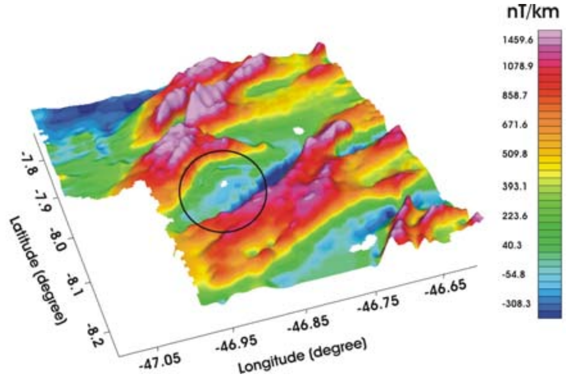

Figure 4- Horizontal gradient of the magnetic fields for the crater region. The circular ring depict the crater

The Serra da Cangalha impact crater interior shows a relatively calm pattern, this is an indication that the quantity of magnetic melt body in the Serra Cangalha impact crater area is insignificant; this has been confirmed from the three borehole logs obtained from CPRM (1972). The borehole each reached a maximum depth of 200 m and they were drilled directly on the Serra da Cangalha impact crater (inner and outer ring). Manson and Lockne impact structures (Koeberl and Anderson, 1996; Sturkell and Ormo, 1998) formed in similar environment as Serra Cangalha shows no defined melt sheets.

Figure 4 shows the horizontal magnetic gradient across the study area. Horizontal gradient maxima reveal the horizontal boundaries of the sources. Areas in which lithological contacts are located between two different geologic units of distinct magnetic contrast show evidence of high horizontal magnetic gradients around the crater rim. This magnetic contract is elongated in shape and is associated with the impact crater structure. As expected, the magnetic gradient is fairly high in the impact area and it adjacent areas, while it is surrounded by low throughout most of the northwest and southeast portions of the crater center. The evidence obtained from the horizontal magnetic gradient further supports the hypothesis that the original crater size is greater the 13 Km diameter that we presently have and that the development of the crater was controlled by the pre-impact NE – SW structures. The crater boundary is well depicted from the horizontal gradient maxima map. The high horizontal (Fig. 4) and vertical gradients (Fig. 5) seen in the magnetic field of the study area are associated with the central anomaly, thus indicating a predominantly shallow source with high frequency magnetic anomalies. The impact structure with its sedimentary fillings is well delineated in the horizontal and vertical gradient maps. A close examination of vertical magnetic gradient map (Fig. 5) indicates that the impact-induced magnetic anomalies are of similar magnitude to regional patterns shown in Figure 3 (residual fields).

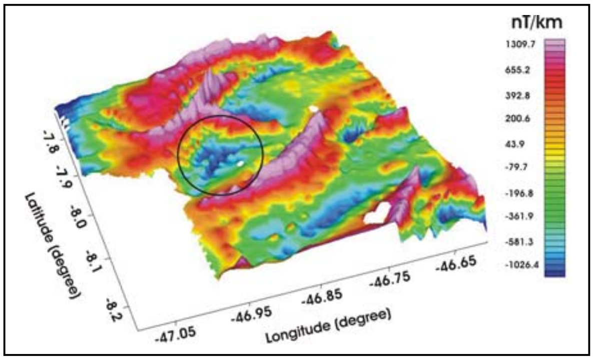

Figure 5- Vertical gradient of the magnetic fields for the crater region. The circular ring depict the crater

Figure 6 shows the 3D analytic signal calculated for total magnetic field data shown in figure 2. We observed that the analytic signal produces a maximum over the source edges of the magnetic anomaly (impact crater) regardless of the direction of magnetisation. This result agrees with the suggestions of Nabighan (1974) and Roest et al (1992). Consequently, this result enables us to accurately delineate the location of the magnetic basement in the study area. We assuming a disc-like source for the impact crater, we observe that the maxima of the analytic signal overlies the entire source and not its edges while minimum values of the analytical signals are observed at the centre of the crater. The overall pattern of the analytic signal is elongated to semi-circular; this source has a small dimension. The relative high amplitudes (1600 – 1887) of the analytic signal and the maxima over the impact source edges suggest that the depth to source is relatively shallow (Nabighian 1974; Roest et al, 1992). The pattern of the analytic signal of the Serra da Cangalha anomaly is consistent with the idea of the impact related magnetization proposed by Girdler et al (1992). Also, from figure 20, we observe that the impact induced magnetic anomaly are of similar magnitude with the regional magnetic pattern.

Figure 7 shows the map of the magnetic basement derived from the downward continuation residual magnetic fields. A distinct uplifed basement due to the impact of the meteorite was encountered. Depth of magnetic basement obtained from the map is about 1.2 km below the sea level. The magnetic basement is relatively shallow at the center of the crater and relatively deep at the rim. This shallow basement is considered to be the source of the high magnetic anomalies observed at the center of the crater. The abrupt uplift of the basement and the subsequent re-magnetization might have resulted in the high magnetic anomaly seen extending in a northeast-southwest direction. The depth of 1200 m obtained from the downward continuation shows a good correlation with the depth obtained from the 2D magnetotelluric interpretation shown by Adepelumi et al (2003). Furthermore, this method clearly delineated the uplifted basement structures seen at the center of the impact crater.

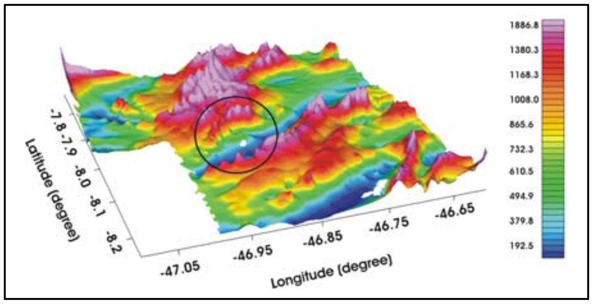

Figure 6- Analytical signal of the magnetic fields for the crater region. The circular ring depict the crater

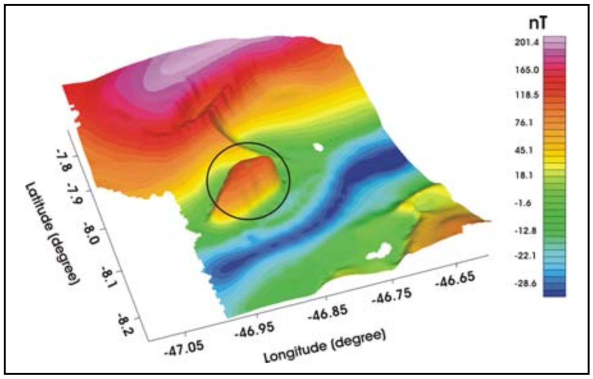

Figure 7- Aeromagnetic data downward continued to 1.2 Km. Note the uplifted basement at the centre of the crater. The circular ring depict the crater centre

Conclusions

The following conclusions are drawn from the present study. First, the study suggests that the morphology of the Serra da Cangalha impact structure appears to fit that of a complex impact crater based on all the major geomagentic features delineated from the aeromagnetic data, The impact-induced magnetic anomalies observed in the study area are of similar magnitude to regional patterns of the residual magnetic fields. The relatively high amplitudes of the horizontal magnetic field, veritcal magnetic field analytic signal and the maxima over the impact source edges suggest that the depth to basement source is relatively shallow. This was confirmed from the basement depth of about 1.2 km derived from the downward continued map of the region. We attribute the occurrence of various types of remanent magnetizations at the Serra da Cangalha impact as the main source of the total magnetic intensity observed in the study area as was earlier discussed by Wasilewski (1973). The processed aeromagnetic data of the study area helped in delineating the upper-crust magnetic characteristics of the region beneath the impact crater region; also, we were able to obtain the post-impact geomagnetic signatures of the Serra da Cangalha impact crater region.

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Acknowledgments

I deeply appreciate the unflinching supports and encouragements of my Ph.D supervisors (Drs. Jean Marie Flexor and Sergio. L. Fontes) that made it possible for me to complete my Ph.D in record time. Also, The financial support of CAPES/CNPq Brazil in terms of Ph.D scholarship to the first author is well appreciated.