Seismic and magnetic characterization of Vargeão Dome Astrobleme, Southern of Brazil

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Abstract

Vargeão Dome is one of the few examples of eroded impact craters (astroblemes) in the South America. This conspicuous circular depression, located at 26°49′S and 52°10′W, was formed by the collision of a meteorite against the Earth's surface and has a diameter of 12.4 km, depicting sharp topographic gradients of up to 150 meters between its outer borders and inner portions. Impact features found at Vargeão include shatter cones in sandstone and basalt, planar deformational features in minerals (quartz and plagioclase) and impact breccias. Available geophysical data for this structure comprise airborne magnetics and seismic surveys, which were processed and interpreted in combination with digital elevation model (DEM) generated by the Shuttle Radar Topographic Mission (SRTM). The results allowed the recognition of important geological and tectonic features associated with the Vargeão impact crater, such as its relationship with regional structures and its magnetic and seismic signatures. Subsurface features unveiled by geophysical data allowed an improved characterization of the crater′s configuration at depth, including extensive collapse faulting along the borders and inner portions and the ascent of underlying rocks by some hundreds of meters, combined with intense faulting, associated with the formation of the central uplift.

Introduction

There are currently only five structures in Brazil whose origin are related to the collision of extraterrestrial bodies (generically termed "meteorites", which may include either asteroids or comets), as well as another eight which may have the same origin (Crósta (2004)).

Vargeão Dome is being the focus of recent studies, due to its relatively well exposed geology and overall characteristics as a complex impact crater. Moreover, it was formed over Jurassic-Cretaceous volcanic rocks of the Serra Geral Fm., comprising basalts and rhyodacites. There are only two impact craters on Earth formed over volcanic lava flows: Lonar Lake, India, and Vargeão Dome. This implies in a relative lack of geologic and geophysical models for this type of crater on Earth. On the Moon, however, impact craters were formed over basaltic rocks.

Thus, the study of Vargeão Dome using seismic and aeromagnetic data combined with a DEM, is important not only to improve the knowledge of impact features in Brazil, both superficially and at depth, but can also serve as a model for the study of craters in other planetary bodies, such as the Moon.

Magnetic and Seismic Signature in Impact Craters

Complex impact craters are characterized by the presence of a central uplift. When magnetic data are available for this type of crater, the signature is usually marked by circular magnetic highs near the central uplift, or concentric rings of intercalated magnetic lows and highs.

Circular magnetic highs commonly found at the central uplift of several impact craters are generally attributed to the presence of melted breccias (Henkel (1992)), combined with the formation of magnetic minerals due to thermal and chemical alteration processes that occur in the early stages of deformation after an impact (Hawke (2003)). In Brazil, only Serra da Cangalha astrobleme (in Tocantins State, Brazil) was studied using the magnetic method, by Adepelumi et al. (2005) and the a signature containing a high magnetic circular anomaly bounded by a low magnetic ring anomaly was confirmed at its central uplift.

The alternation of circular highs and lows is related to following possible causes: (*i*) melted breccias lenses injected into the crater floor, (*ii*) concentration of magnetic minerals along the collapse faults by hydrotermal fluids systems, (*iii*) change in the dip of the rock's magnetic horizon by impact deformation, which truncates this horizon and produces magnetic edges, and (*iv*) pos-impact magnetic sediment deposition within the crater cavity (Hawke (2003)).

2D and 3D seismic studies of complex structures provide useful geological information for correlating observed structures at surface with their extension at depth. They may also be used for constraining mathematical models of crater formation, allowing the establishment of parameters related to crater geometry and structures, such as collapse faulting and uplifting. Subsurface characterization of impact craters goes beyond academic interest, since there are several known buried impact craters with economical potential for hydrocarbon production. Donofrio (1998) pointed out that nine out of seventeen North America impact structures located in oil-producing areas are being exploited for hydrocarbon production.

Geological Setting

The occurrence of an anomalous circular feature at Vargeão (Figure 1: *Right*) was first pointed out by Paiva-Filho et al. (1978), based on observations of radar imagery from the RADAMBRASIL Project. They identified a circular depression exhibiting a ring/radial fracture pattern. They pointed out the anomalous stratigraphic position of the Botucatu/Pirambóia Fm. sandstones, suggesting the existence of a "stratigraphic window". These authors related the origin of this structure to a blind igneous intrusion.

Vargeão Dome was studied in more detail during the 1980′s, when an oil/gas exploration survey was carried out in the region. Barbur-Jr and Corrêa (1981) recognized the occurrence of sandstone outcrops and the presence of breccias within the structure. They proposed different hypotheses to explain its origin: faulting (with vertical displacements), cryptovolcanic explosion (either gas explosion or meteorite impact), volcanic explosion or igneous intrusion.

Subsequent works of Crósta (1982); Hachiro et al. (1993); Paiva-Filho (2000); Kazzuo-Vieira et al. (2004) and Crósta et al. (2005) pointed out the morphologic, lithologic and structural similarities between Vargeão Dome and others impact craters. They verified the occurrence of impact metamorphic features, such as shatter cones and planar deformation features (PDFs), found in samples of deformed sandstones and impact breccias from the structure′s interior.

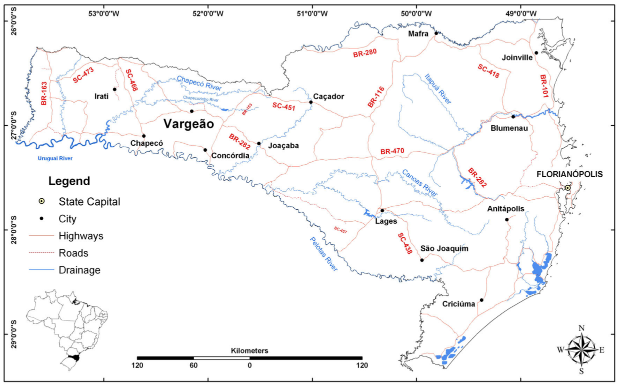
The geomorphological features seem today at Vargeão Dome are interpreted as the erosion remnants of the original crater, formed over volcanic rocks of the Serra Geral Fm. (Jurassic-Cretaceous) of Paraná Basin (Figure 1: *Left*) by the impact of an extra-terrestrial body against the Earth's surface. The regional geology is characterized by three volcanic facies of the Serra Geral Formation (Paiva-Filho (2000)). The upper (Serra Geral Upper Member) and lower (Serra Geral Lower Member) units are comprised by tholeiitic basalts, and separated by a thick lava flow of rhyodacite porphyry, termed as Goio En Member.

The eroded crater depicts steep outer borders, with topographic gradients reaching up to 150m. Internally, it shows a series of topographic elevations and depressions, arranged as concentric rings along radial lineaments. These lineaments were interpreted by Kazzuo-Vieira et al. (2004) and Crósta et al. (2005) as the superficial expression of brittle faulting associated with the crater formation process. Vargeão Dome is a complex crater, with a central uplift comprising impact breccias and sandstones from the Pirambóia/Botucatu (Triassic/Jurassic) formations (Figure 1: *Left*). These sandstone were vertically displaced by some 700 meters, in comparison with their normal stratigraphic position bellow the volcanic rocks of the Serra Geral Fm. in this portion of the Paraná Basin.

Seismic and Aeromagnetic Data Processing

Seismic and aeromagnetic data were supplied by ANP (Agência Nacional do Petróleo) and were acquired by PETROBRAS (Petróleo Brasileiro S/A) and Paulipetro in 1982 and 1980, respectively. Seismic line 0236-0078 crossed the structure close to its center, along in the ENE direction (Figure 2: *Left*). It has 1264 shots, with 15 m between shots. Each shot has 240 groups of receivers, with 30 m between receivers, in split-spread configuration (120 groups of receivers at each side of shot point). The register time was 4 sec with sample rate of 2 ms, but only 2 sec were processed. The airborne data (magnetics and gravity) were acquired using 2 km spaced NS flight lines with orthogonal tie lines flown every 20 km at 500 meters above the ground surface (Figure 2: *Left*).

Processing of seismic data was carried out using a standard sequence (Yilmaz (2000)) and $ProMAX^{TM}$ software. The processing sequence comprised: (a) segy input; (b) establish and load the geometry of the trace headers; (c) edit traces (kill and reverse polarity); (d) noise attenuation; (e) elevation and refraction statics; (f) amplitude recovery; (g) deconvolution; (h) velocity analysis and residual



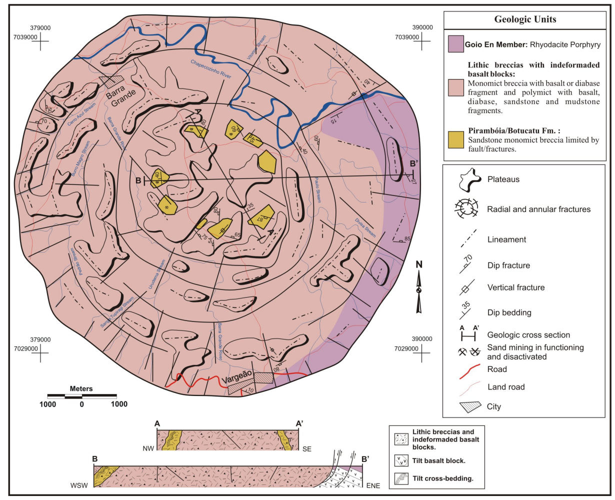


Figure 1: *Left*: localization map of the town Vargeão, which is situated within the the southern rim of the crater. *Right*: simplified geologic map of Vargeao Dome structure. Notice the occurence of the Pirambóia/Botucatu Fm. sandstones.

statics; (i) CDP domain statics application (j) stack; (k) finite difference migration. In addition, FK-filtering was used to attenuated the strong S-waves present in the data.

Aeromagnetic data processing was carried out using the $OASIS\ montaj^{TM}$. The magnetic data was expressed as the anomalous magnetic field, or in other words, as the total measured field corrected for the diurnal variation and the main geomagnetic field (IGRF). The fourth difference technique was used to track anomalous spikes in the magnetic data. The data was interpolated in a regular grid (i.e., square, 500m on a side), using the appropriate algorithms to maintain data fidelity to the original sample locations. This was followed by correction of spurious effects caused by the leveling of the original grids.

The analysis of the variation of the anomalous magnetic field was aided by its linear transformations principally that dealing with the amplitude of the analytic signal of orders 0, which are a critical products to locate the spatial distribution of magnetic sources. The upward continuation further allowed the analysis in deep. All of these steps were guided by the analysis of the radial power spectra of the anomalous magnetic field.

The main results were obtained using the analytical signal amplitude of the anomalous magnetic field (ASA-AMF) and the analytical signal of the upward continuation (ASA-UC) for 1000 m, 2000 m and 3000 m (Figure 3). In addition, the ASA-AMF results were integrated with the SRTM-DEM of the Vargeão Dome using an IHS (Intensity Hue Saturation) fusion algorithm in $ER\ Mapper^{TM}$ image processing software (Figure 2: *Right*). The IHS algorithm allows the integration of image data of different nature (magnetic and topographic relief in this case) using color and texture attributes, providing an optimal image for 2D and 3D visualization and interpretation. In particular, it allows an easier characterization of the association of magnetic anomalies and surface/subsurface structures.

Results and Discussion

The interpretation of the IHS fusion of SRTM-DEM and ASA-AMF allowed to establish some important features related to Vargeão Dome. The first one is the relationship between the impact crater and two very distinctive linear regional structures (possibly faults) which run in parallel along N60E to the northeast of the crater (Figure 2: *Right*). Previous works Paiva-Filho et al. (1978) and Barbur-Jr and Corrêa (1981) suggested a possible relationship between these two linear structures and the formation of the circular depression at Vargeão, in which the latter would be a consequence of the former. However, the analysis of the combined magnetic and topographic data clearly shows that these two linear structures are interrupted right at the NW outer border of the crater. There are therefore two possible explanations for these linear structures: (*i*) there are older than the crater and were truncated by it or; (*ii*) there were formed as a consequence of

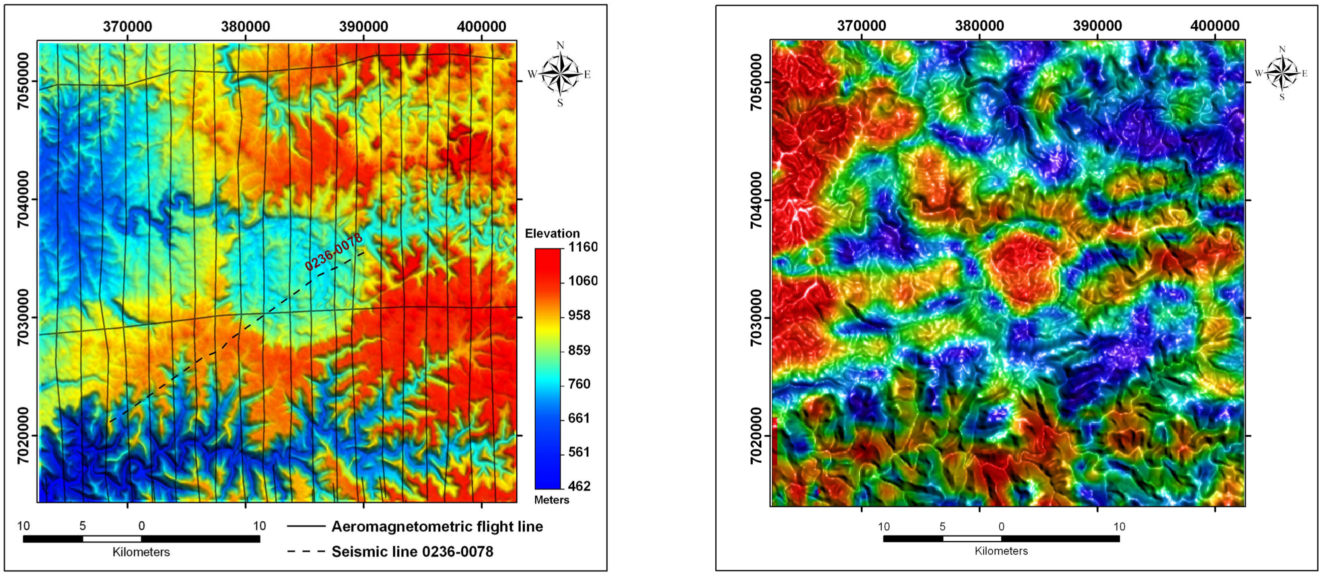


Figure 2: *Left*: localization map of the aeromagnetic flight line and seismic data over Vargeão Dome astrobleme. The crater is represented by the anomalous circular feature in the SRTM-DEM image (color image). *Right*: IHS data fusion of SRTM-DEM with ASA-AMF.

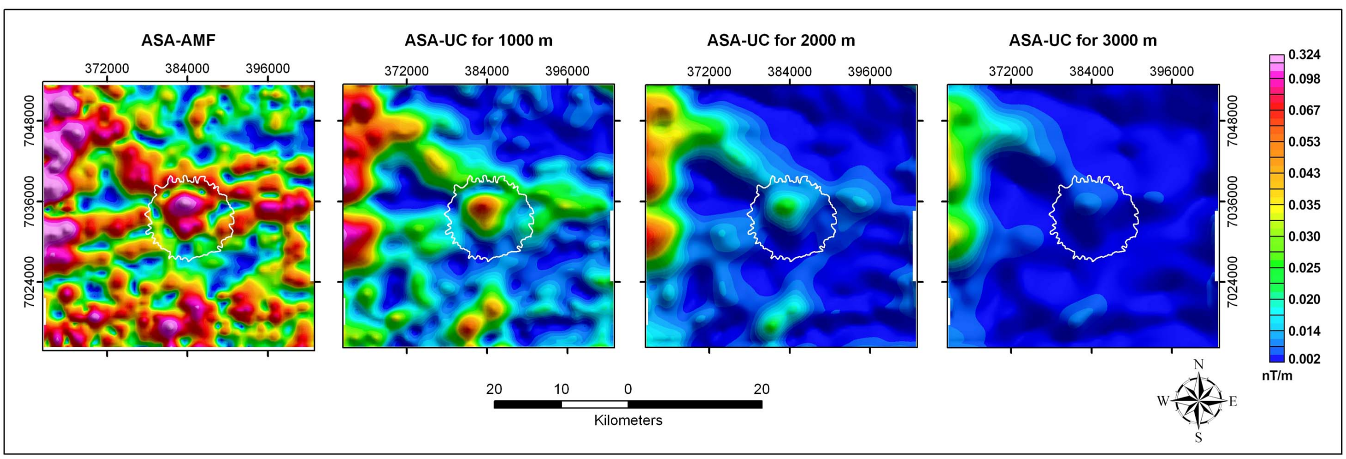


Figure 3: ASA-AMF and ASA-UC for 1000 m, 2000 m and 3000 m using a shaded relief algorithm. The white circle represents the upper limits of the structure rim. Notice the decrease of the magnetic high signature with the depth.

the crater, by directional propagation of the enormous amount of energy released by the impact, possibly along pre-existing fractures.

A second feature revealed by the analysis is the distinctive circular magnetic anomaly of 0.324 nT/m (a magnetic high) located near the central uplift, bounded by a low-medium magnetic ring zone of 0.25 to 0.002 nT/m (Figure 2: *Right* and Figure 3). ASA-UC for 1000 m, 2000 m and 3000 m also depict quite clearly this magnetic signature, characterizing it as a surface or near-surface feature. It is interpreted as the signature of melted breccias that occur at these exact locations within the crater, combined with disturbances of the crater floor by severe impact deformation (Figure 3).

Finally, areas of low magnetic values, which form a ring in the interior of the crater, close to the outer rim, are interpreted as related to the rocks of Goio En Mb

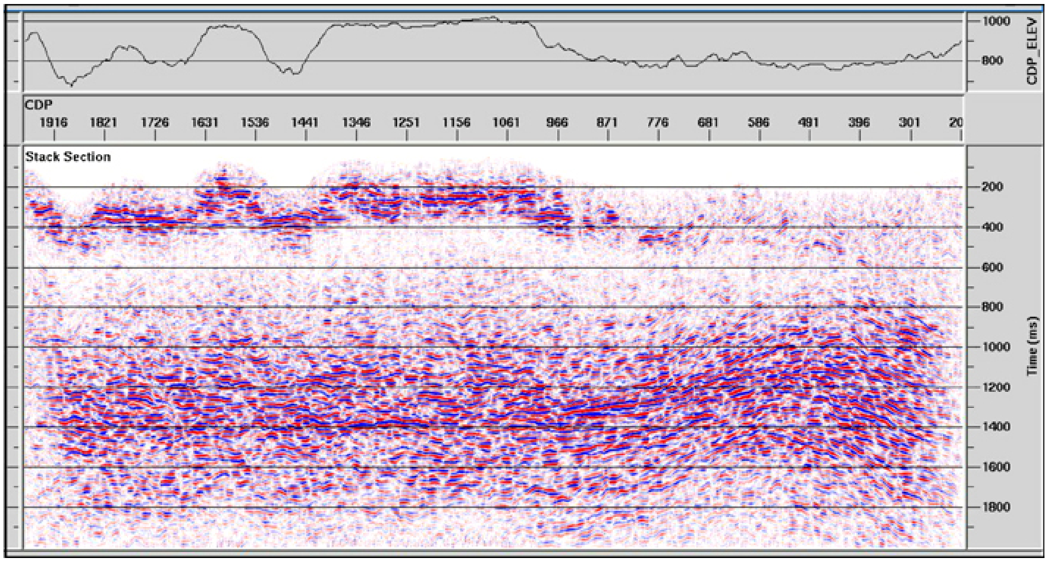


Figure 4: Stack seismic section.

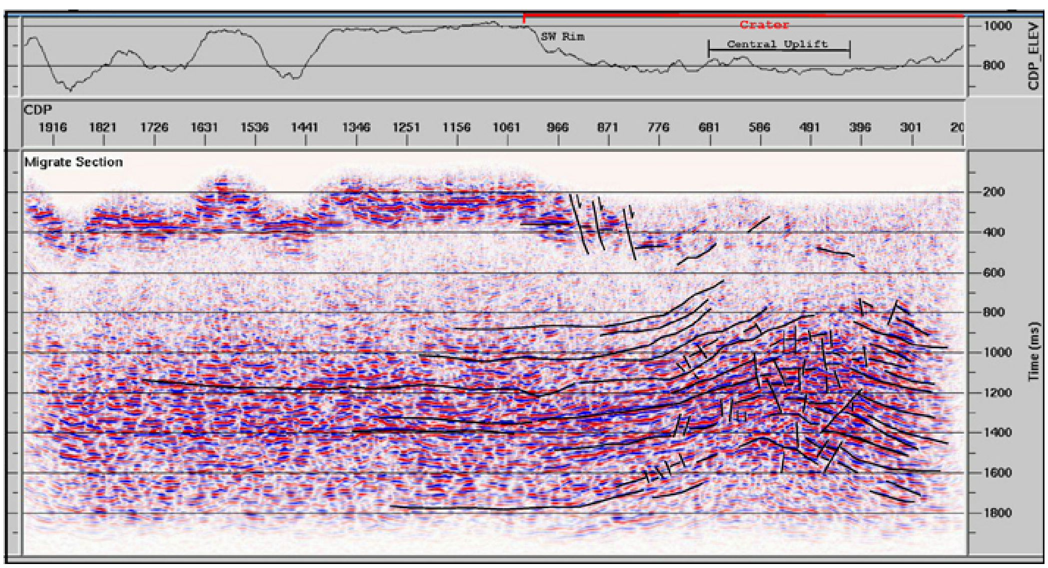


Figure 5: A simplified interpretation of the time migrate seismic section. Notice the colapse faults near SW crater rims and the faulted/fractured cone or dome-shaped structure bellow the crater center, with strata increasing their dips towards the center of the crater.

(rhyodacites) (Figure 2: *Right* and Figure 3). These rocks were displaced downwards some 200 m bellow their normal topographic by collapse faulting during the modification stage of the crater formation.

The stack (Figure 4) and the interpreted migrate (Figure 5) seismic section 0236-0078 allowed the confirmation of collapse faults near the crater rim, predicted by Crósta et al. (2005). Moreover, the section shows the subsurface configuration of the crater floor and its central uplift. This latter is expressed by a cone or dome-shaped structure at the center of the crater, depicting the ascent of the lower volcanic units of the Serra Geral Fm. (Serra Geral Lower Member), together with the sandstones of the Botucatu/Pirambóia. This vertical displacement of some 700 meters is associated with strong deformation by faulting/fracturing, as shown in the seismic section. As in other complex impact craters, the central uplift of Vargeão Dome was formed by ground isostatic response, during the excavation stage of the crater formation process.

Conclusions

The integrated geophysical study with seismic and magnetic data helped to improve the knowledge about the morphology of Vargeão Dome astrobleme. The subsurface analysis of the crater based on seismic data shows an underlying cone or dome-shaped structure representing the central uplift commonly found in complex impact craters. This structure explains how the sandstones of the Botucatu/Pirambóia Fm. cropped out at the center of the crater, vertically displaced by several hundreds of meters in relation to their normal stratigraphic position in this portion of the Paraná Basin. This is the first time that the subsurface features of an impact crater have been characterized in Brazil using seismic data.

Finally, it should be pointed out that the information obtained from seismic and magnetic data is in complete agreement with geologic data collected at outcrops and with petrographic characterization of shocked material. These results further strengthen the crater formation model proposed by Crósta et al. (2005) and the impact origin of Vargeão Dome.

Acknowledgments

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