Revista Brasileira de Geofísica
RBGf
Brazilian Journal of Geophysics

Revista Brasileira de Geofísica (2015) 33(2): 319-332

ISSN 0102-261X
www.scielo.br/rbg

3D GRAVITY MODELING OF IMPACT STRUCTURES IN BASALTIC FORMATIONS IN BRAZIL: PART I – VARGEÃO, SANTA CATARINA

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ABSTRACT. In this paper, we present and discuss some geological characteristics and implications of a 3D subsurface mass density model of the Vargeão impact structure, constructed based on forward gravity modeling constrained by geological information. Vargeão is a complex structure formed by a meteorite impact in basalts of the Serra Geral Formation, with a central uplift exposing sandstones of Pirambóia/Botucatu Formations and impact breccias. There are only a few known examples of impact structures formed in basalts on the surface of the Earth, but they are common on other terrestrial planets and their satellites. Therefore, the geophysical modeling of these impact structures on Earth may also provide insights into planetary geology studies. The selected density model encompasses six geological layers that are consistent with the known regional stratigraphy. Densities were measured from rock samples from each geological unit and used as constraints in the modeling process. The model shows a large sedimentary block with the shape of a vertical truncated cone and a thickness of ∼650 m in the center of the structure. This block corresponds to the Pirambóia/Botucatu formations and it cuts the upper basalt layers. The model is consistent with sandstones outcrops located in the central uplift area of Vargeão, suggesting that the cratering process was responsible for positioning these rocks in a higher level than the surrounding basalts.

Keywords: gravity modeling, impact crater, central uplift, Serra Geral Formation.

RESUMO. Neste artigo, apresentamos e discutimos algumas características e implicações geológicas de um modelo 3D de densidade de massa da subsuperfície da estrutura de impacto Vargeão, elaborado com base em modelagem gravimétrica direta controlada por informações geológicas. Vargeão é uma estrutura complexa formada por impacto meteorítico em basaltos da Formação Serra Geral, com um núcleo central soerguido expondo arenitos das Formações Pirambóia/Botucatu, além de brechas de impacto. Existem apenas alguns poucos exemplos de estruturas de impacto formadas sobre basaltos na superfície da Terra, mas elas são comuns em outros planetas terrestres e em seus satélites. Portanto, a modelagem geofísica de estruturas de impacto na Terra pode fornecer novas perspectivas em estudos de geologia planetária. O modelo selecionado engloba seis camadas geológicas que são consistentes com a estratigrafia regional previamente conhecida. Densidades de massa foram obtidas a partir de amostras de rocha de cada camada e utilizadas como controle no processo de modelagem. O modelo apresenta um grande bloco sedimentar na forma de um cone vertical truncado com ∼650 m de espessura no centro da estrutura. Este bloco corresponde às Formações Pirambóia/Botucatu e corta as camadas superiores de basalto. O modelo é consistente com afloramentos de arenitos dessas formações, localizados na região do núcleo soerguido de Vargeão, mostrando que o processo de formação da cratera foi responsável por posicionar essas rochas em níveis superiores àqueles dos basaltos adjacentes.

Palavras-chave: modelagem gravimétrica, cratera de impacto, núcleo soerguido, Formação Serra Geral.

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INTRODUCTION

The Earth has undergone continuous and intense changes that affected its shape and size, as well as the distribution of materials. All these geological processes make our planet complex and dynamic. To understand the evolution of the Earth's surface, it is usually assumed that geologic processes occurring today also occurred in the past under the same rate of time variation. However, local and short-term catastrophic processes are also responsible for shaping the Earth and other solid planets of the solar system. Among these processes, meteoritic impacts play an important role (French & Koeberl, 2010).

Erosion, sedimentation and tectonism are among the main processes that shaped the Earth and, as a result, many of the existing impact structures on Earth were completely obliterated and modified, making it difficult to recognize impact features on the Earth's surface (Crósta, 2012). Description of their morphological characteristics, detailed geological mapping and subsurface geological modeling, as well as knowledge of their formation, are of particular relevance and allow to compare them to each other. In addition, the characteristics of impact craters in other solid bodies of the solar system can be inferred from the study of the craters on Earth (French, 1998). Particularly, impact craters formed in basalts are commonly found on terrestrial planets and their satellites, except on Earth where only a few examples are known (Kumar, 2005). Two of them are Vargeão and Vista Alegre (Crósta et al., 2010). Therefore, geophysical modeling of these structures may also provide insights into planetary geology studies.

Geophysical methods have become particularly important and are commonly used to recognize partially or completely eroded impact structures or even those that were altered by other geological processes. One of the main reasons is that they allow the construction of detailed subsurface models that may reveal the changes in the distribution of physical properties caused by meteoritic impacts (e.g. Pilkington & Grieve, 1992). In these processes, the pressure can reach hundreds of GPa, producing permanent deformation in terrestrial rocks (Melosh, 1989). In general, the density distribution and magnetization of the shocked rocks and surrounding terrain change considerably, making the gravimetric and magnetic methods appropriate to the early identification and exploration of these features (Mallick et al., 2012). These two methods have been increasingly used to determine the geometry of the crater, the variations of density/magnetization of the rocks in the region of the impact structure, and also to estimate the uplift of the basement in sedimentary targets (Vasconcelos et al., 2012).

Our work consisted in a detailed gravimetric survey of Vargeão and Vista Alegre impact structures, located around 100 km apart from each other in a similar geological context. Therefore, we have divided this paper into two parts: Part I presents (this paper) the results obtained from gravity data acquired at Vargeão impact structure; Part II brings (in a separate paper) the results obtained for Vista Alegre impact structure. Interpretation of the results for both structures has provided valuable information that allowed to answer some important issues, such as: (i) even though the two structures are relatively close to each other, are they similar in terms of subsurface geology? Has one of the two impacts affected the subsurface more than the other? Are the volume and shape of possible uplifted sandstone strata similar?

More specifically, Part I shows a selected 3D subsurface density model of the Vargeão impact structure constructed through gravity forward modeling. This model explains the observed gravimetric data within an acceptable error margin, and taking into account the available geological data. It depicts various geological characteristics such as the crater basement depth, the thickness of the rock layers and their shapes, the position of the central uplift and the location of some possible faults.

Geological Setting

The Paraná Basin is a large intra cratonic sedimentary basin region located in South America, covering an area of approximately 1,700,000 km^2. It is composed of up to 6 km thick Cretaceous to Ordovician sedimentary and volcanic rocks (Zalán et al., 1990).

Milani et al. (1998) classified the stratigraphic record of the Paraná Basin into six major super sequences, which comprise large temporal intervals in the geochronological time. They are:

(1) Rio Ivaí (Ordovician-Silurian);

(2) Paraná (Devonian);

(3) Gondwana I (Carboniferous-Early Triassic);

(4) Gondwana II (Meso-Late Triassic);

(5) Gondwana III (Late Jurassic-Early Cretaceous); and

(6) Bauru (Late Cretaceous).

The impact structures of Vargeão and Vista Alegre are inserted in Super sequence Gondwana III (Serra Geral Formation; Fig. 1).

Rocks of the Serra Geral Formation were originated during the early stages of rupture of the Gondwana supercontinent, during the transition from the Jurassic to the Cretaceous, which also marked the opening of the South Atlantic Ocean (Turner et al.,

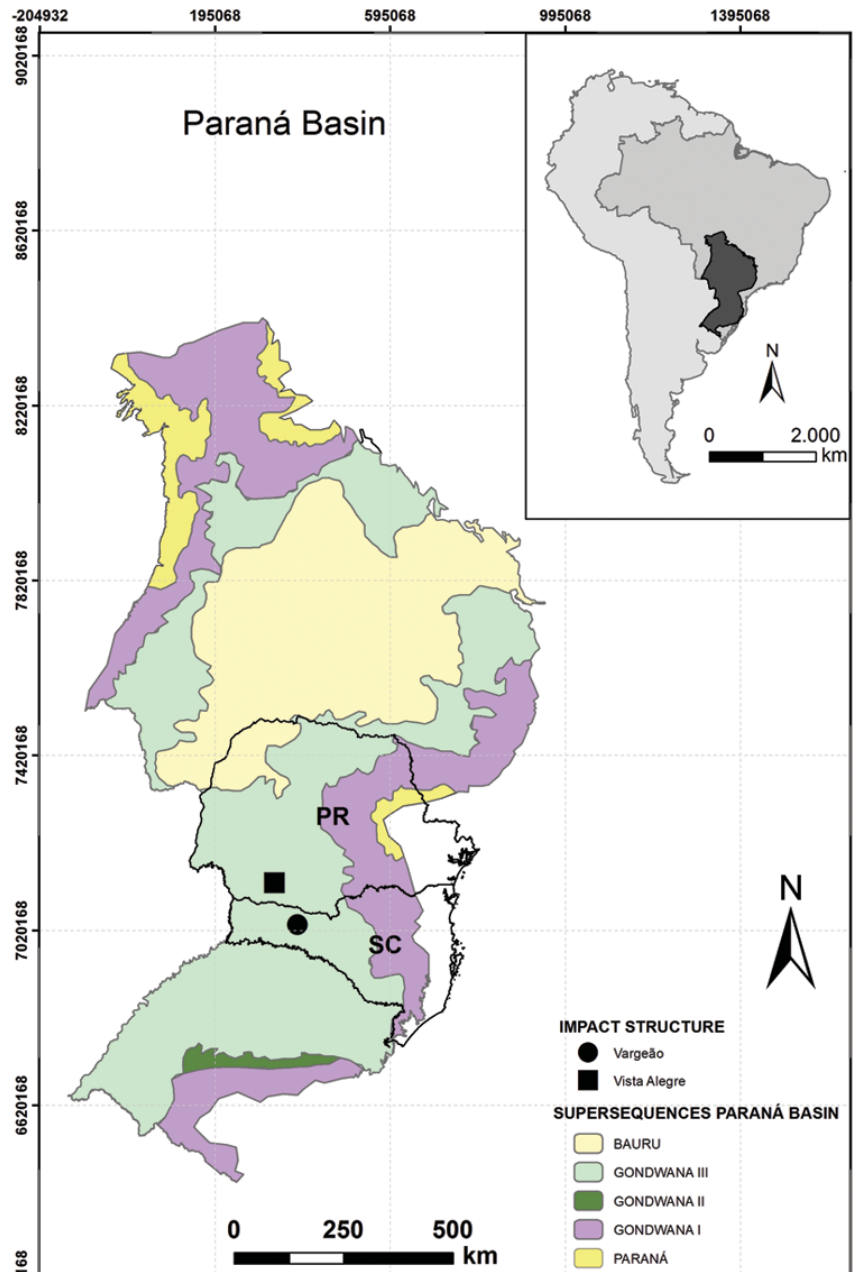

Figure 1 – Geological map of the Paraná Basin. Vargeão and Vista Alegre impact structures are located in the states of Santa Catarina and Paraná, respectively (Milani et al., 1998).

1994; Hawkesworth et al., 2000). This intense fissural volcanism of the paleocontinent resulted in a large area covered by lava flows (3/4 of the total basin area), with a thickness of up to 2000 meters (Milani et al., 2007).

The fluvial-aeolian Pirambóia Formation and aeolian sandstones that constitute the Botucatu Formation also belong to Super sequence Gondwana III. Precise positioning of the contact between these two formations is difficult to determine because of high textural similarity (Fulfaro et al., 1980).

Local Geology

Both Vargeão and Vista Alegre impact structures were formed in volcanic rocks of the same stratigraphic unit, namely the Serra Geral Formation (Fig. 1), which makes them potentially similar from a geological and geophysical point of view. Both have deformed sandstone outcrops in the central region, possibly belonging to the underlying Pirambóia/Botucatu formations, and related to their respective central uplifts (Crósta et al., 2004; Vieira, 2009). The association of those outcrops with such stratigraphic units was made through the interpretation of surrounding well log data, located approximately 22 km away from the Vargeão structure where Pirambóia/Botucatu sandstones occur below the basalts of the Serra Geral Formation, at depths between 980 to 1100 meters. Thus, the outcrops occur abnormally in these impact structures and they are also extremely deformed (Vieira, 2009), which is unusual for the otherwise undeformed strata.

Vieira (2009) published a geological map of the Vargeão impact structure, which depicts the following main observed lithologies from bottom to top: deformed sandstones of the Pirambóia/Botucatu formation, tholeiitic basalts of the Alto Uruguay unit; porphyry quartz-latite of the Chapecó acid unit; and impact polymict breccias (Fig. 2).

Impact Structures

An impact structure is created when an extraterrestrial projectile penetrates the Earth's atmosphere with low deceleration, reaching the surface at high speeds (hypervelocity) and releasing a tremendous amount of energy concentrated in a relatively small area. The impact produces shock waves that affect the structure of the target rocks (French, 1998). Impact craters can be classified based on their morphologies into two main types: simple craters and complex craters. These distinct morphologies are characterized by their size and process of formation (French, 1998). Simple craters have diameters of about 2 to 4 km on Earth, and a basin or bowl shape (Fig. 3). Complex craters generally are larger than 2-3 km for sedimentary rock targets and exceed 4 km for igneous and metamorphic rock targets (Grieve, 2005). Their relatively higher central part is known as central uplift (Fig. 3) (French, 1998; Melosh, 1989).

The formation of an impact crater can be divided into three basic and distinct steps: (a) contact and compression; (b) excavation; (c) modification. As shown in Figure 1, these stages apply to both simple and complex craters (Melosh, 1989). The first stage is when the projectile hits the target rock transferring a large amount of energy to it and generating what is called shock waves (Fig. 3a). In the second stage, shock waves propagate through the rock causing an excavation of the target ground, forming a transient crater structure (Fig. 3b). In the final stage, some modifications can occur, such as morphological changes, edge collapsing and central uplifting, causing the transient to evolve into a more stable structure (Fig. 3c-d). This modification stage has no clearly marked end, merging gradually into regular geological processes such as erosion and sedimentation (French, 1998).

The most prominent feature of an impact structure is its circular shape, but merely the existence of this morphological character is not sufficient to determine whether the structure has been generated by meteorite impact or not. To confirm an impact origin, permanent shock features recorded into the target rocks, such as shatter cones, planar fractures (PF) and planar deformation features (PDF), must be identified (French & Koeberl, 2010). A shatter cone is a macroscopic geological feature that is formed in the bedrock beneath an impact crater. Shatter cones are generated only if the target rock is submitted to a shock exerting pressures in the range of 2-30 GPa. Planar fractures (PF) are microscopic parallel fractures that are formed in minerals under pressures between 5 and 8 GPa. Planar deformation features (PDFs) are characterized by sets of parallel plane strains in mineral grains, occurring at pressures in the range of 8-30 GPa (French, 1998).

There are 184 known impact structures on Earth (Earth Impact Database, 2014). Those structures are mainly concentrated in North America, Europe and Australia, with very few in South America. Brazil has six structures that have been proven to be of impact origin, namely: Araguainha, Vargeão, Serra da Cangalha, Vista Alegre, Riachão and Santa Marta (Crósta & Vasconcelos, 2013). Some other structures in Brazil may also have been formed by meteoritic impact, but they are yet to be confirmed by geological evidence: Cerro do Jarau, Colônia, Praia Grande, Piratininga, São Miguel do Tapuio and Tefé (Crósta, 2012).

The Vargeão impact structure

The Vargeão circular structure was firstly identified in 1978 from analysis of Brazilian RADAR satellite images. It appears as an anomalous circular feature on a volcanic plateau in the western portion of Santa Catarina state (Paiva Filho et al., 1978). Based on its shape, as compared to the other known impact structures at the time, Crósta (1982) formulated the hypothesis of a meteorite impact to explain the formation of the Vargeão structure. However, a complete set of evidences of meteorite impact (shatter cones, PDFs, PFs and breccias) that proved the impact origin of Vargeão was published only in 2005 (Crósta et al., 2005).

The Vargeão impact structure is located in the western portion of Santa Catarina state. It is centered on the geographical coordinates 26°49'S and 52°10'W (Fig. 1) and has an overall diameter of approximately 12.4 km (Fig. 2). It is a complex impact

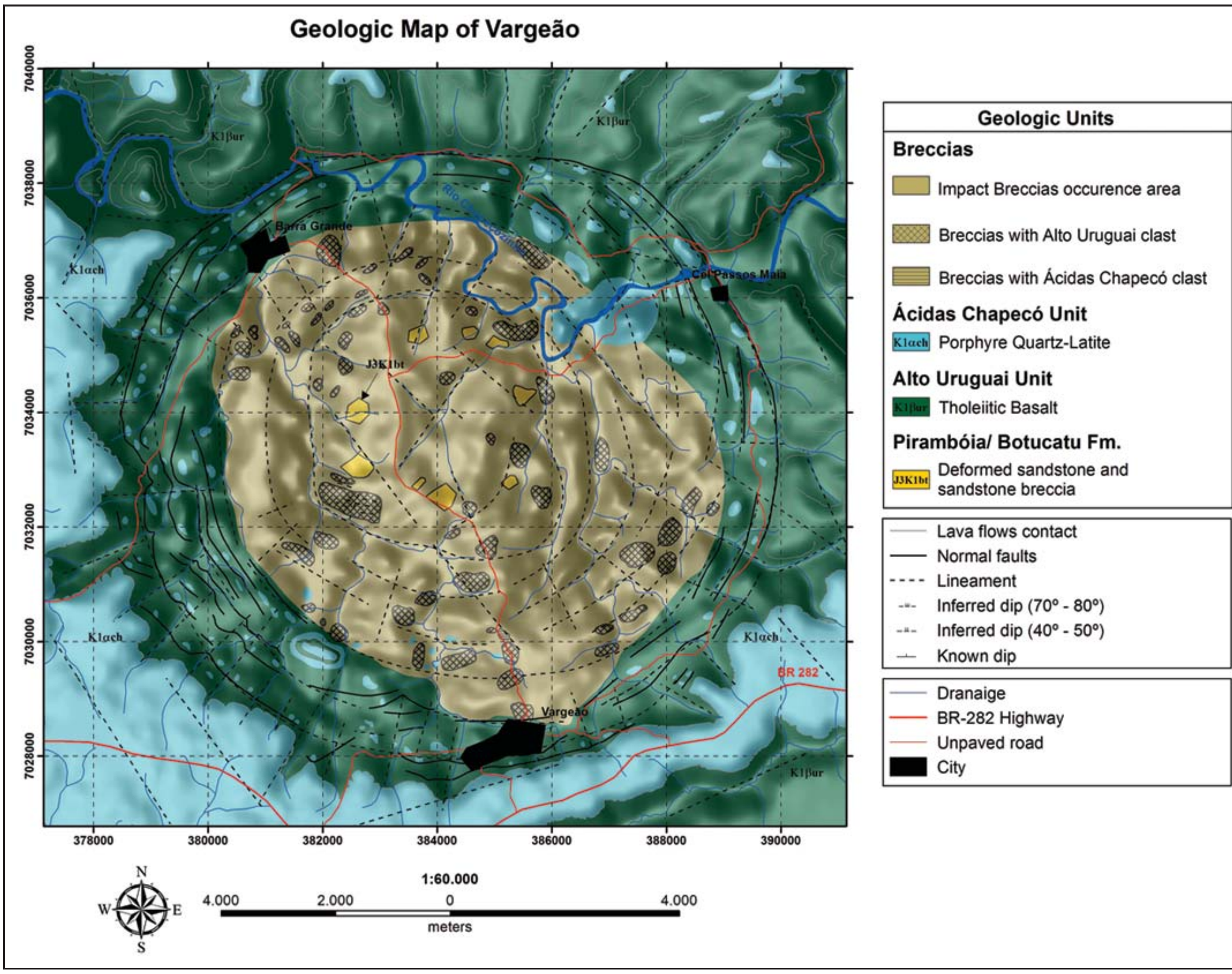

Figure 2 – Geological map of the Vargeão area (Vieira, 2009).

structure with breccias and sandstones of Pirambóia/Botucatu formations in its central uplift (Crósta et al., 2005). The sandstones within the structure have an anomalous stratigraphic position for this portion of the Paraná Basin, where regular depths of these strata may reach more than 800 m. These outcrops are bounded by faults along the contact with the volcanic rocks of the Serra Geral Formation (Barbour Jr. & Corrêa, 1981). The region was the subject of surveys related to hydrocarbon exploration and, therefore, there is a range of geophysical data available, such as: magnetic, data from an aerial survey Iguaçu River Project (PAULIPETRO); a seismic reflection line conducted by ANP – Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (National Agency of Petroleum, Natural Gas and Biofuels); remote sensing data such as SRTM digital elevation models and RADARSAT-1 and TERRA/ASTER. These data were used for a preliminary geophysical characterization of Vargeão (Kazzuo-Vieira et al., 2009). The application of regular chronostratigraphic dating methods provided a maximum age of 125 Ma for basaltic rocks of the Serra Geral Formation (Turner et al., 1994). Recent zircon dating of breccias assigned an age of 123$\pm$1.4 Ma for the same rocks (Nédélec et al., 2013).

METHODOLOGY

All 419 ground gravimetric data were acquired in a field campaign in 2013 conducted with a CG-5 Scintrex gravity meter, along with a Trimble ProXT differential GPS for ellipsoid height measurements (see Li & Götze (2001) for a discussion about the use of ellipsoid versus geoid heights in gravity reductions). The gravity meter has a resolution of 1μGal. Accurate geometrical heights were obtained after applying differential corrections to the collected real time GPS positions at each data point location, using absolute positions from a nearby station. The final average height accuracy was $\sim$0.5 m. Accurate heights ($<$1.0 m) are crucial because gravity anomalies are obtained from topographic

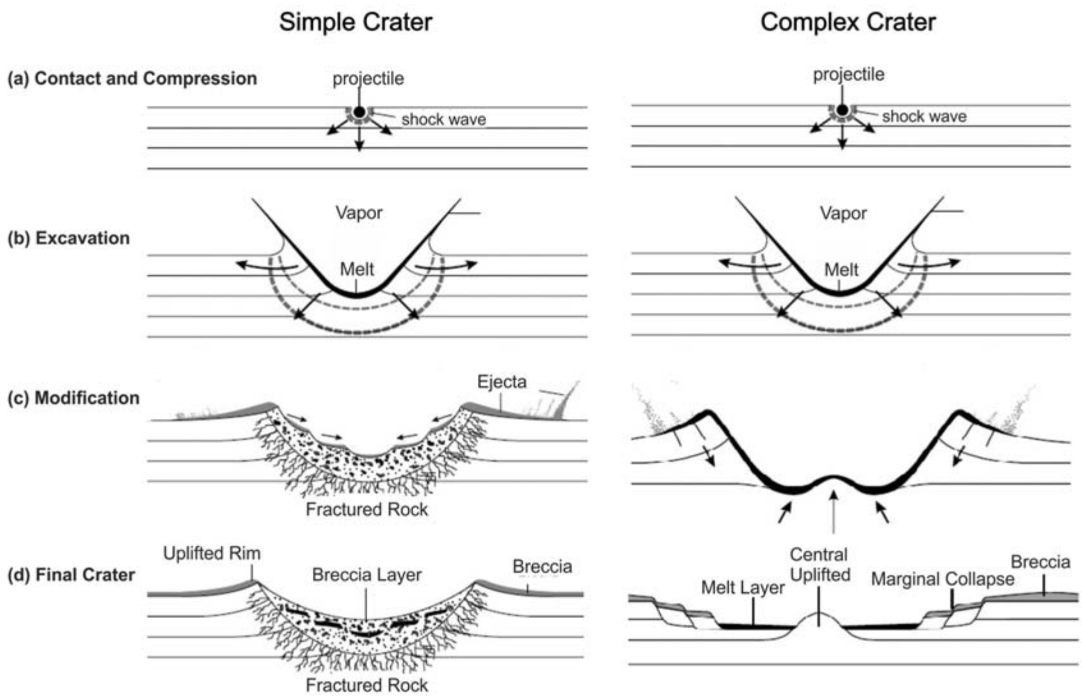

Figure 3 – Stages of simple and complex craters formation. (a) Contact and compression of the target rock; (b) Transient crater excavation and disintegration of the projectile; (c) Fracturing and central uplifting; (d) Final shape of a simple and a complex crater (French, 1998).

corrections. The distance between stations along roads was about 200 m and the spatial distribution of the data can be seen in Figure 5. Identification and removal of spurious data (i.e., gravity readings with standard deviation higher than 0.1 mGal) were carried out before the calculation of anomalies. Gravity anomaly maps and models were produced using Geosoft Oasis Montaj® software. The minimum curvature method was used for data interpolation in a regular grid with cells of 50$\times$50 m.

Data processing

As the data were collected using a differential gravity meter, which measures gravity acceleration differences, a gravimetric survey must start and end with readings on a reference absolute station. Measurements at reference stations are used to calculate absolute values on each field station within the study area, and also to estimate temporal drift. In this study, a nearby reference station was selected from the IBGE – Instituto Brasileiro de Geografia e Estatística (Brazilian Institute of Geography and Statistics) geodetic database (São Mateus do Sul/PR). This station is part of the National Network of Absolute Gravity Stations (RENEGA – Rede Nacional de Estações Gravimétricas Absolutas) and their absolute values were estimated with high precision (Gemael et al., 2002).

In order to obtain Bouguer anomalies, some temporal and spatial corrections were applied to gravity accelerations of each gravity station. Those corrections eliminate the effects that are uncorrelated with the local geology, i.e., topographic and latitude differences, static and dynamic temporal instrumental drift, and tidal effects. The Bouguer anomaly Δg_B is calculated by

$$\Delta g_B = g_{obs} - (g_0 + C_A + C_B)\,, \qquad (1)$$

where g_{obs} is the corrected observed gravity acceleration; g_0 is the theoretical gravity on the reference ellipsoid, which in this case was the World Geodetic System 1984 (WGS84); $C_A =$ 0.3086h is the free-air correction; $C_b =$ –0.04193ρh is the Bouguer correction; h is the ellipsoid height (Li & Götze, 2001); and ρ is the mean density of the topographic masses. In this work, we used the standard crustal mean value of $\rho = 2.67$ g/cm^3.

Static and dynamic drift corrections, as well as tide corrections, were computed internally by the CG-5 gravity meter. To compute dynamic drifts, surveys were started and finished at the same reference station each day. Drift errors were calculated by linear interpolation between values at the reference station, for each time corresponding to each measurement performed during the day.

Bouguer anomalies reflect mass lateral distribution of subsurface rocks along various depths. Deeper and larger bodies contribute to regional anomalies (Δg_{reg}) while smaller and shallower bodies characterize residual anomalies (Δg_{res}). Thus, the last procedure before interpretation of Bouguer anomalies is the removal of the regional field using the expression

$$\Delta g_{res} = \Delta g_B - \Delta g_{reg} \,. \tag{2}$$

As discussed, for example, in Mallick et al. (2012), there are several techniques to calculate Δg_{reg}. In this study, we fit the regional gravity field to the geographical coordinates x and y through a second-order polynomial.

3D Gravity forward modeling

Theoretically, an infinite set of models that explain the observed gravimetric data within the same accuracy level can be constructed (Saltus & Blakely, 2011). In practice, interpreters must include spatial and numerical constraints in their modeling processes, so that all accepted models are geologically plausible. To construct our gravity model, we firstly defined six subsurface layers based on the local and regional geology. From bottom to top of the model, we have:

(1) Pre-Triassic units beneath the Pirambóia Formation;

(2) Sandstones of Pirambóia and Botucatu Formations;

(3) Tholeiitic basalts of Serra Geral Formation;

(4) Fractured basalts of Serra Geral Formation;

(5) Rhyodacites of Chapecó Acid Unit; and

(6) Impact breccias.

To constrain the model numerically, we incorporated absolute density values measured from rock samples representing each one of the six layers. Those samples were also used in the work of Yokoyama (2013).

3D gravity forward modeling was carried out using the GMSYS-3D package, which is part of Geosoft Oasis Montaj® (Popowski et al., 2006). Salem et al. (2014), Gimenez et al. (2009) and Pearson & Ray (2004) show some examples of modeling using this package to various types of geological studies. The process of modeling starts by defining a set of superimposed planar surfaces that represent the vertical boundaries of parallel geological layers to which density values are attributed. The algorithm then calculates the complete gravity response of this structure at each station on the Earth's surface by applying a widely known spectral method described by Parker (1973). This method sets a relationship between the Fourier transform of the gravity data and the sum of the Fourier transforms of the powers of a model vector that describes each surface at discrete points. Its main advantage is the rapid computation of the gravity response and its main restriction is that the average depth of the interface must be known.

RESULTS AND DISCUSSIONS

Total, regional and residual Bouguer anomaly maps of the Vargeão impact structure are presented in Figure 4A-C. The boundaries of the impact structure cannot be defined based on the total or the regional Bouguer anomaly map, indicating that fractured rocks and impact breccias are confined to shallow depths. On the other hand, the residual Bouguer anomalies shown in Figure 4C produce a notable multi-circular, concentric pattern around the center of the structure. A gravity low of approximately –2.8 mGal is observed in the central portion. A ring of high gravity values of around 1.4 to 2.8 mGal encircles this gravity low. As discussed in Pilkington & Grieve (1992), this gravity anomaly pattern is typical of complex impact structures.

Regional gravity values were compared with those produced by Vidotti et al. (1998). The referred paper shows that ground gravimetric data in the Parana Basin have defined a gravity low of approximately –100 mGal on the northwestern portion of Vargeão. Regional gravity anomalies varying between –75 mGal and –95 mGal can be observed in these gravity maps. The range of gravity values and their spatial distribution are compatible with what were obtained in the present work.

3D subsurface model

Figure 5 shows the 3D subsurface model that was obtained by 3D forward gravity modeling as described in the "Methodology" section. The most notable feature of the model is that the pre-Triassic units and the sandstone layer are uplifted near the central portion of the impact structure. Maximum depths extracted from a stratigraphic chart were attributed to each layer. Additionally, density values that were directly measured from samples were set to each layer (Table 1). Our model is also supported by magnetic interpretations provided by Kazzuo-Vieira et al. (2009). Those authors have associated high magnetic values near the center to the presence of impact breccias. Low magnetic zones near the crater rim were correlated with the presence of rocks of the Chapecó Acid Units.

A comparison between observed and calculated Bouguer anomaly values is shown in Figure 6. The average difference between the two maps is equal to –0.13 mGal and the standard

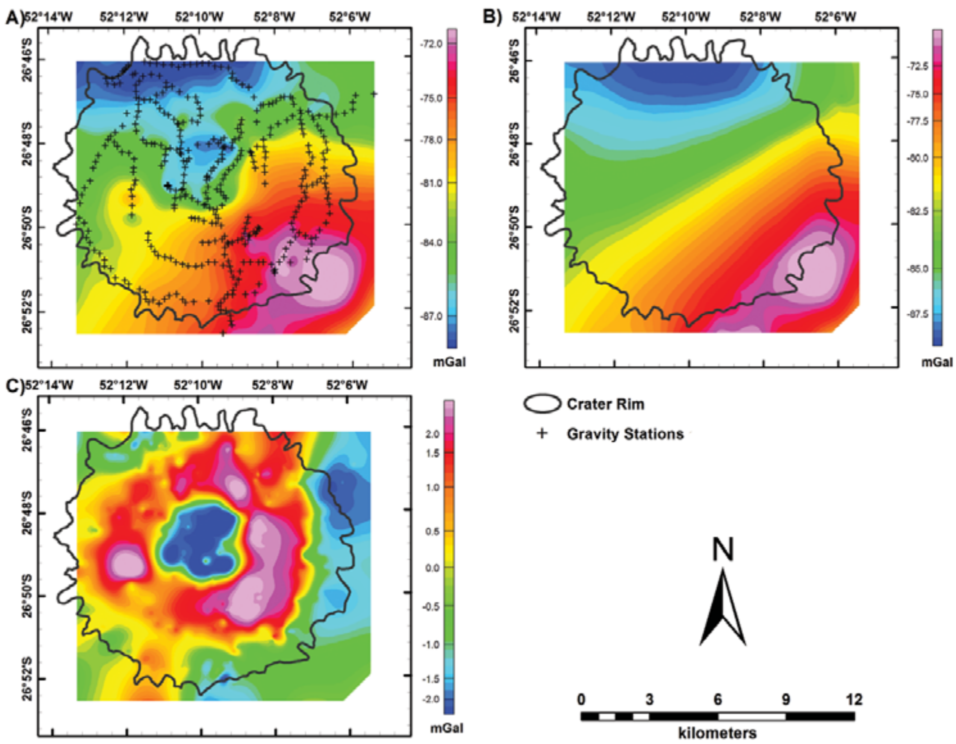

Figure 4 – Bouguer gravity maps of Vargeão. (A) Total; (B) Regional; (C) Residual. The crater rim was extracted from Kazzuo-Vieira et al. (2009).

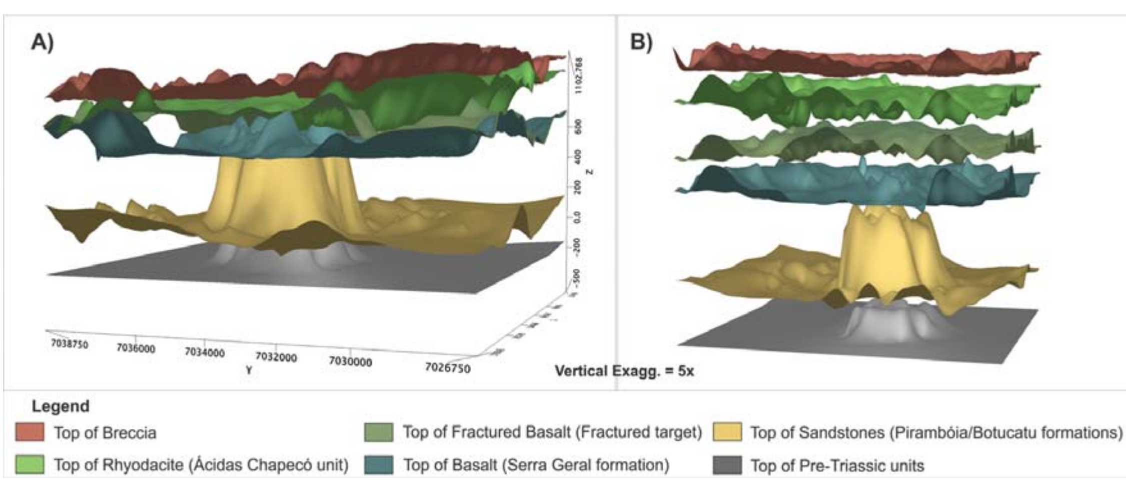

Figure 5 – 3D gravity model of Vargeão. (A) Equal vertical and horizontal scales; (B) Vertical exaggeration of 5×.

Table 1 – Densities of rock samples from Vargeão.

Lithology	Density (g/cm^3)			
	min	max	average	SD
Pirambóia/Botucatu Sandstone	2.41	2.44	2.43	0.01
Alto Uruguai Basalt	2.84	2.95	2.88	0.04
Fractured Basalt	2.66	2.82	2.74	0.06
Rhyodacite	2.45	2.63	2.56	0.05
Impact Breccia	2.27	2.48	2.39	0.05

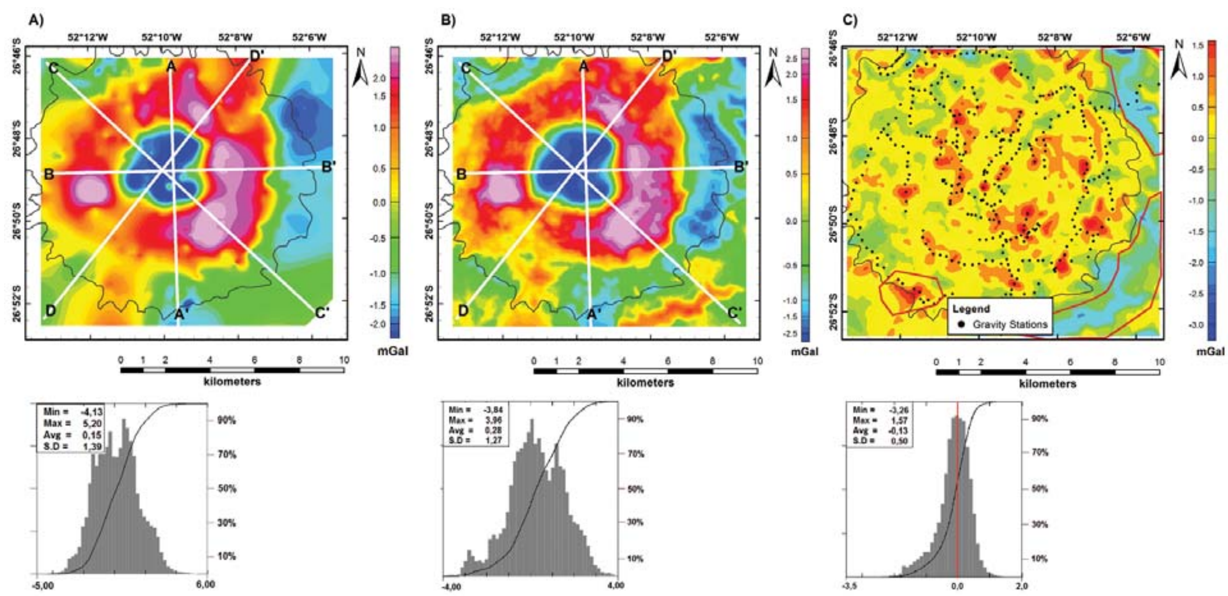

Figure 6 – Comparison between residual Bouguer anomalies. (A) Observed; (B) Calculated from the subsurface model; (C) Difference between both grids. Corresponding histograms are shown in mGal. White straight lines represent the positions along which vertical sections were extracted from the 3D model. Solid black lines on the maps represents the crater rim, extracted from Kazzuo-Vieira et al. (2009).

deviation is equal to 0.5 mGal, but the spatial distribution of the differences shows that most of them are between 0 and 0.5 mGal (Fig. 6C). High negative differences between errors are observed on the eastern portion of the map of Figure 6C, where a smaller number of gravity data points were collected. Such high errors are due to the interpolation method. The histograms of both, observed (Fig. 6A) and calculated (Fig. 6B) anomalies, are very similar and the histogram of differences between them peaks at zero mGal, as expected.

To better visualize and interpret the characteristics of the subsurface model, four 2D vertical sections along the profiles depicted in Figure 6 were extracted from the produced 3D model (Figs. 7 and 8). All profiles extends beyond the crater boundary and cut across its center.

As clearly shown in the vertical sections, the model indicates the existence of an uplifted Pirambóia/Botucatu sandstone layer from $\sim$800 m depth to $\sim$100 m depth, which explains the gravity low at the center. Thus, such deformation appears prominent below the center of the structure. However, this "sandstone uplift" hypothesis can only explain the gravimetric data if an additional uplift of the pre-Triassic units from $\sim$1200 m to $\sim$1000 m also occurs. This complementary hypothesis can be explained by an elastic response of the pre-Triassic units to the central uplifting that occurred after the impact. The average normal depth to the pre-Triassic units of our model is fairly consistent with that estimated by Kazzuo-Vieira et al. (2009) from aeromagnetic data. Therefore, the total amount of stratigraphic uplift in our model is $\sim$900 m. An empirical stratigraphic uplift formula given by Grieve et al. (1981) can be used for comparison: $SU =$ 0.06D1.1, where $D =$ 12.4 km in this case yields $SU =$ 957 m. This formula was defined based on 14 structures from 3 to 30 km in diameter and the deeply eroded Vredefort structure (Melosh & Ivanov, 1999).

Interpretation of a seismic reflection line across the structure supports our gravimetric model in that the central uplift has a conical shape and it is bounded by normal faults (Kazzuo-Vieira et al., 2009). A truncated cone with the following geometric parameters was used represent the uplifted part of the Pirambóia/Botucatu sandstones: base diameter $\cong$ 5200 m; top diameter $\cong$ 3400 m; height with respect to the surrounding depth $\cong$ 700 m. The volume of this simplified body is $\cong 1.034\times10^{10}$ m^3. Considering the measured sandstone density that was used as constraint in the gravimetric modeling (2430 kg.m^{-3}), the amount of mass that was uplifted is $\cong 2.51\times10^{13}$ kg, which represents $\sim$5% of the total mass of the rocks affected by the impact.

Figure 9 shows a map of the uplifted sandstone layer. Outcrops mapped by Vieira (2009) are delimited by red polygons and the whole set of outcrops forms a ring-shaped feature. Regions of our gravimetric model that are near the surface are

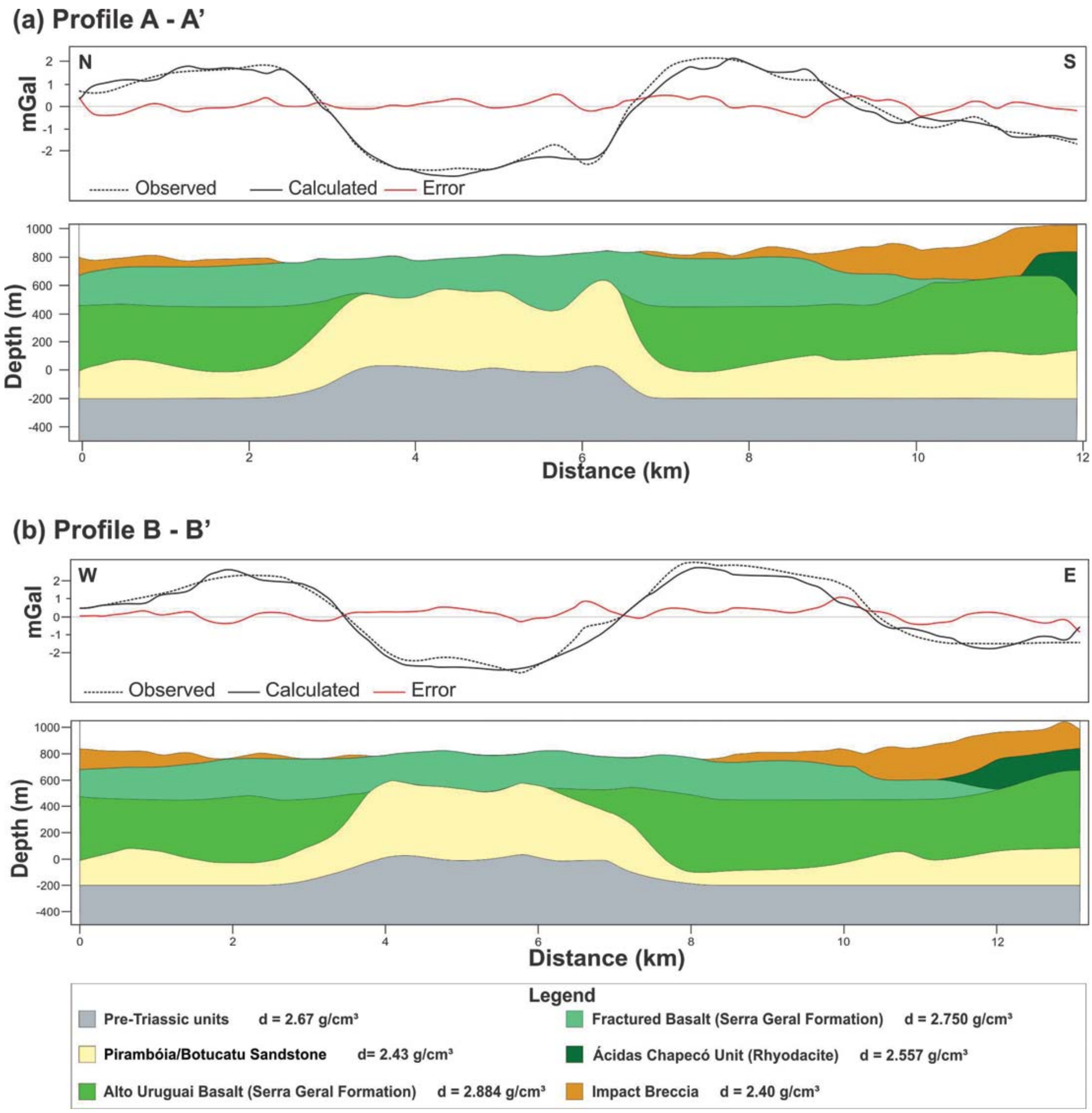

Figure 7 – Vertical sections extracted from the 3D gravimetric subsurface model of the Vargeão impact structure. Vertical exaggeration is 2×. (A) Profile A-A' in Figure 6. (B) Profile B-B' in Figure 6.

strongly correlated with those previously mapped sandstone outcrops (see e.g. Fig. 8), which reinforces the hypothesis of inversion of layers, taking into account that these strata belong to the Pirambóia/Botucatu Formation, which originally lie underneath the Serra Geral basalt layer. Satellite images shows that the central uplift has an area ≅ 20 km^2 (Crósta, 2012). In our model, this area is estimated to be ≅ 21.4 km^2 because of a slight NW shift as depicted by the dashed line in Figure 9.

The two uppermost layers of our model are: (i) impact breccias with average thickness ≅ 100 m; and (ii) fractured basalt with variable thickness up to ≅ 400 m. These two layers were the last to be affected by erosive processes that were responsible for modifications in the original structure. Topographical variations from the center to the boundaries of the structure are defined by both layers. There is a topographic gradient of up to 200 m from the center to its steep rims that mark the boundaries of

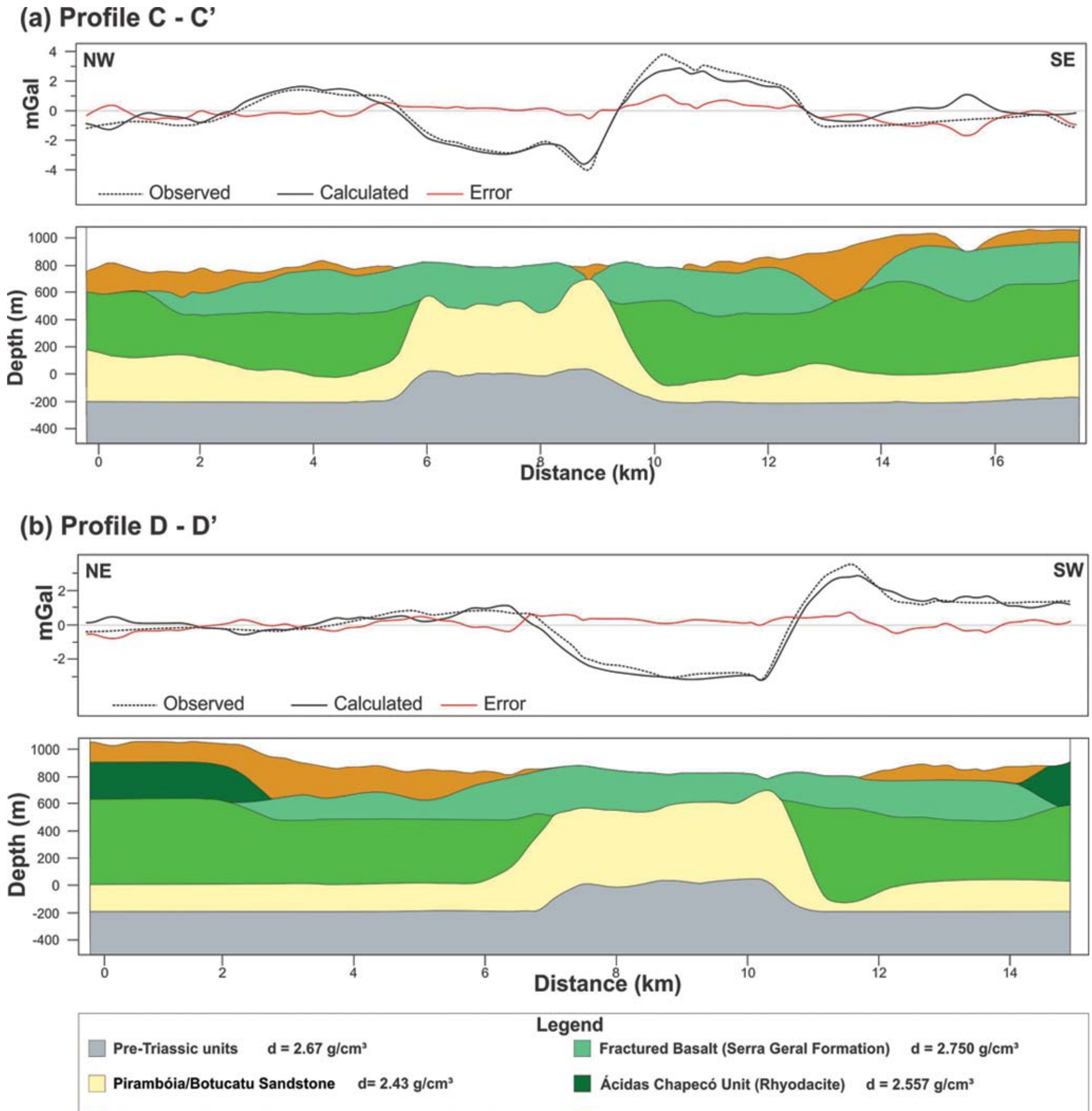

Figure 8 – Vertical sections extracted from the 3D gravimetric subsurface model of the Vargeão impact structure. Vertical exaggeration is 2×. (A) Profile C-C' in Figure 6. (B) Profile D-D' in Figure 6.

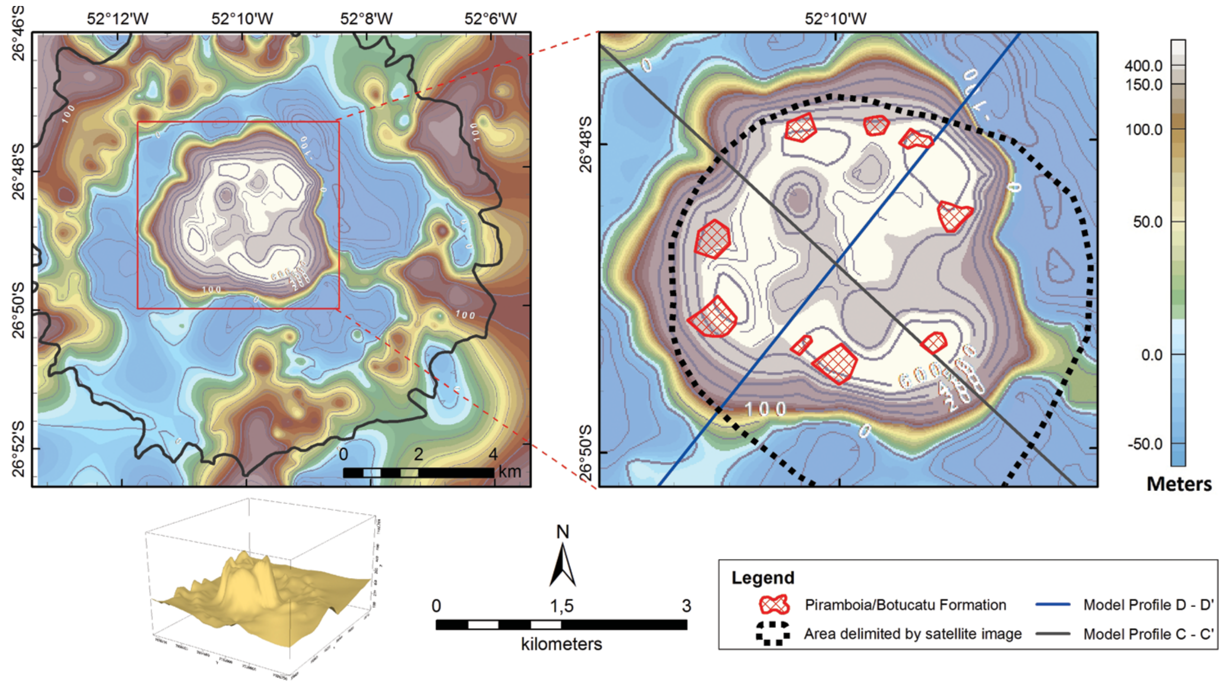

Figure 9 – Depth map of the sandstone layer with respect to the topographic surface. A zoomed view of this uplifted layer is shown with the sandstone outcrops and the boundary of the central uplift delimited in previous studies.

the structure that are bounded by normal faults (Kazzuo-Vieira et al., 2009). Those faults could not be resolved by our gravimetric modeling, probably because of: (i) most of fault scarps are eroded and obliterated rapidly by erosive processes (Wicander & Monroe, 2005); and (ii) there are not sufficient gravity observations near the boundaries of the structure.

CONCLUSIONS

We have produced a 3D subsurface model of the Vargeão impact structure that explains a set of Bouguer anomalies obtained from ground gravimetric data. This model is consistent with measured densities, geological information, and previous geophysical and remote sensing interpretations. An uplifted part of a sandstone layer is hypothesized to exist below the center of the structure. The geometry of this uplifted mass can be approximated by a truncated cone with the following approximated parameters: base diameter $\cong$ 5200 m; top diameter $\cong$ 3400 m; height $\cong$ 700 m; and mass $\cong 2.51\times10^{13}$ kg. This hypothesis is consistent with the location of sandstone outcrops of the Pirambóia/Botucatu Formations, which would come up to the surface through fractures opened in the basalt layer with the impact process. To keep the model consistent with the observed gravity Bouguer anomalies, the top of the pre-Triassic units layer has to be uplifted from $\sim$1.2 km to $\sim$1.0 km depth. The total stratigraphic uplift ($\sim$900 m) is compatible with that calculated from a well-known empirical formula.

ACKNOWLEDGMENTS

The authors are especially thankful to: FAPESP (Process n. 2011/08014-5) for the financial support; IG/UNICAMP for providing the geophysical equipment; IAG/USP for providing the equipment to measure densities; Prof. Elder Yokoyama for kindly providing rock samples; A.P. Crósta acknowledges his research grant from CNPq (305911/2013-9).

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Recebido em 13 novembro, 2014 / Aceito em 8 julho, 2015
Received on November 13, 2014 / Accepted on July 8, 2015

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