

# STRUCTURAL MODELING OF THE VICHADA IMPACT STRUCTURE FROM INTERPRETED GROUND GRAVITY AND MAGNETIC ANOMALIES

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## ABSTRACT

A prominent positive free-air gravity anomaly mapped over a roughly 50-km diameter basin is consistent with a *mascon* centered on (40°30'N, -69°15'W) in the Vichada Department, Colombia, South America. Ground follow up gravity and magnetic anomalies were modeled confirming the regional free air gravity anomalies. These potential field anomalies infer a hidden complex impact basin structure filled with tertiary sedimentary rocks and recent quaternary deposits. Negative Bouguer anomalies of 8 mGals to 15 mGals amplitude are associated with a concentric sedimentary basin with a varying thickness from 100m to 500 m in the outer rings to 700m to 1000m at the center of the impact crater basin. Strong positive magnetic anomalies of 100 nT to 300 nT amplitude infer the presence of a local Precambrian crystalline basement that was affected by intensive faulting producing tectonic blocks dipping to the center of the structure, showing a typical “domino structure” of impact craters such as that of Sudbury, Ontario, Canada. Basic to intermediate mineralized veins and dikes with contrasting density and magnetic susceptibility properties could be emplaced along these faulting zones, as inferred from local gravity and magnetic highs. The geologic mapping of the area is limited by the flat topography and absence of outcrops/ geomorphologic units. Nevertheless, local normal faults along the inner ring together with radially sparse irregular blocks over flat terrains can be associated with terraced rims or collapse of the inner crater structure and ejecta blanket, respectively. A detailed airborne electromagnetic survey is recommended to confirm the gravity and magnetic anomalies together with a seismic program to evaluate the economic implications for energy and mineral exploration of the Vichada impact structure.

**Keywords:** Vichada impact structure, Gravity, Magnetic, ejecta, terraced rims.

## MODELAMIENTO ESTRUCTURAL DE LA ESTRUCTURA DE IMPACTO DEL VICHADA A PARTIR DE ANOMALIAS GRAVIMÉTRICAS Y MAGNÉTICAS TERRESTRES INTERPRETADAS

## RESUMEN

Existe una importante anomalía gravimétrica positiva de aire libre sobre una cuenca de 50 km de diámetro, la cual es coherente con un MASCON (Concentración de Masa) ubicado en (4° 30 'N, -69° 15' W-) en el departamento de Vichada, Colombia, Suramérica. Se adquirió información gravimétrica y magnética de terreno cuyo modelamiento confirma las anomalías regionales de aire libre. Estas anomalías de campos potenciales permiten inferir una estructura de impacto compuesta oculta en el subsuelo, la cual está cubierta por rocas sedimentarias terciarias y depósitos cuaternarios recientes. Las anomalías negativas de Bouguer presentan amplitudes entre 8 a 15 mGals asociadas a una cuenca sedimentaria concéntrica, cuyo espesor varía entre 100 a 500 m en los anillos más externos, hasta unos 700 a 1000m en el centro de estructura de impacto. Las anomalías magnéticas positivas presentan amplitudes entre 100 a 300 nT y permiten inferir la presencia de un basamento precámbrico cristalino que ha sido afectado por intenso fallamiento, produciendo una serie de bloques tectónicos que buzcan hacia el centro de la estructura, mostrando una típica estructura de impacto denominada “dominó” similar a que se encuentra en el cráter de impacto de Sudbury, Ontario, Canadá. Venas y diques mineralizados de carácter básico a intermedio, con propiedades de densidad y susceptibilidad magnética contrastantes pudieron haber sido emplazadas a lo largo de estas zonas de falla, lo que se deduce a partir de los anomalías magnéticas y gravimétricas positivas de alta frecuencia. La posibilidad de cartografiar geológicamente la zona de estudio se limita por ser una topografía plana y presentar escasos afloramientos o expresiones geomorfológicas. Sin embargo, se ha podido identificar la presencia de fallas locales de tipo normal a lo largo del anillo interno, y bloques irregulares dispersos radialmente sobre el terreno plano, los cuales pueden asociarse con promontorios en terraza o con el colapso de la estructura interna del cráter y el material expulsado (“eyecta”), respectivamente. Se recomienda un detallado estudio electromagnético aerotransportado para confirmar las anomalías gravimétricas y magnéticas junto con un programa sísmico para evaluar las eventuales implicaciones económicas exploratorias para minerales y energéticos que esta estructura de impacto pueda haber generado.

**Palabras Clave:** Estructura de impacto del Vichada, gravimetría, magnetometría, eyecciones, montículos.

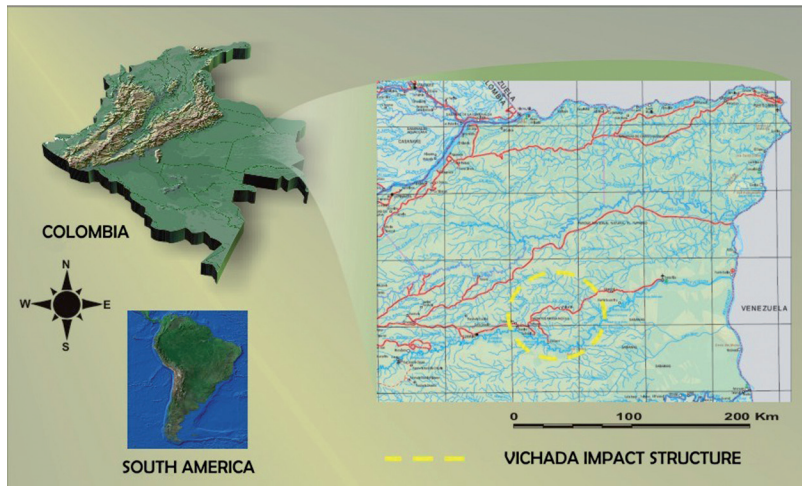
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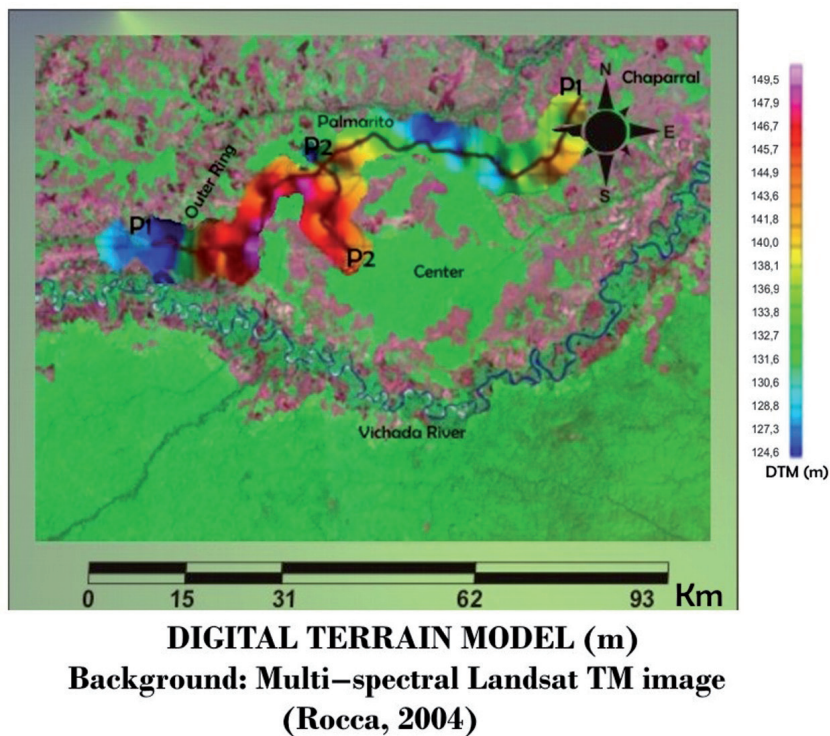
## INTRODUCCIÓN

The Vichada impact structure is located in northwestern South America, in eastern Colombia, in the Vichada Department (4°30'N – 69°15'W), having a multiple ring structure with inner and outer ring diameters of 30 km and 50 km, respectively (Spudis, 2005; FIGURE 1). The Vichada impact structure was initially proposed by

Rocca (2004) who recognized a possible large impact crater structure from an interpretation of color Landsat satellite images with a resolution of 200m obtained from the NASA's John C. Stennis Space Center, USA (FIGURE 2).



**FIGURE 1:** Geographic location of the Vichada impact structure in the Vichada Department, eastern Colombia, northwestern South America, showing the Vichada River and the Paratebueno - Palmarito - Chaparral unpaved road.



**FIGURE 2:** Digital terrain model and Multi spectral TM image of the Vichada structure showing the Vichada river, the Paratebueno – Palmarito – Chaparral road, Profiles 1 and 2, and the inner and outer ring structures with diameter of 30 km and 50 km, respectively and the elevations along the gravity and magnetic stations.

The occurrence of an impact structure is consistent with the regionally disrupted and thinned crust of the studied area between the localities of Cumaribo, Paratebueno, Palmarito and Chaparral, which includes a local 50km diameter depression beneath a well-defined EGM-96 free-air gravity maximum (Barlow, 1990; Hernandez, 2006; Hernandez *et al.*, 2007; Hernandez *et al.*, 2009; Lemoine *et al.*, 1998; Ivanov and Melosh, 2003; Khurama, 2007). The crater's terrain gravity effects accommodate an underlying roughly 30-km wide, 5-km thick mantle plug produced by crustal rebound from meteorite impact. In order to evaluate the regional free-air gravity anomalies a ground gravity and magnetic survey was carried out. Two regional acquisition profiles were designed crossing the impact structure from west to east and from the outer ring to the center of the structure. A geological reconnaissance of the impact structure was also implemented, where isolated scarp outcrops of tertiary sedimentary units and local smooth changes in the topography were observed (Melosh, 1989; 2003).

The predominance of a flat topographic of the Vichada plain, the lack of outcrops along the drainage systems and presence of thick quaternary deposits limits the geological interpretation. Nevertheless, the accumulation of erratic irregular blocks which are randomly distributed, having diameters from 20cm to 3m resting over flat terrains suggest that they correspond to ejecta blanket blocks.

Additionally, some local normal faults affecting the tertiary lithological units were observed from the outer ring to the center of the impact structure, that are interpreted as terraced rims or collapse structures that commonly occur at the center of the impact crater structures (Buczowski *et al.*, 2005; Westbroek and Stewart, 1996).

## GROUND GEOPHYSICS ACQUISITION SURVEY

A survey design was done using the only unpaved road that connects the localities of the Cumaribo - Paratebueno - Primavera - Palmarito - Chaparral road from west to east and a footpath that goes from the unpaved road to the center of the structure. Two profiles were designed (P1 and P2) along which four hundred ninety nine (499) gravity stations were acquired at 200m station spacing, with an accumulative length of 70km, approximately. A differential GPS system was used to estimate east and north coordinates, referred to a UTM Cartesian coordinate system, datum WGS84 and elevation

referred to the sea level. A digital CG3M SCINTREX gravimeter was used. A continuous magnetic survey of about 70km was carried out along profiles 1 and 2 by a rover walking G-856 Geometrics magnetometer and a standard G-856 base station magnetometer to control the diurnal variations (FIGURE 2). Gravity Reading were taken at the surface. Drift and tidal corrections were performed using the Scintrex CG3M facilities. Latitude corrections were carried out by the International Gravity Formula" of 1967 (Keary and Brooks, 1984; Telford *et al.*, 1990). The Bouguer correction used a density reduction of 2.67 gm/cm<sup>3</sup>. A terrain correction was omitted due to the prevalence of flat topography of the Vichada plain. Thematic gravity and magnetic maps were processed by Geosoft Oasis Montaj (Reeves, 1991; 2005) including Bouguer anomaly and reduced to the pole magnetic anomaly maps and their corresponding residual components. A 2D inverse modeling of gravity and magnetic anomalies was also implemented by using the GM-SYS utilities.

## DISCUSSION OF RESULTS

The Bouguer anomaly values vary from -29.98 mGals to -10.11 mGals, with a mean value of -22.37 mGals (FIGURE 3). Local gravity highs are associated with the outer and inner rings of the Vichada impact structure. Negative gravity anomalies are located at the center of the structure and in the intermediate zone between the outer and inner rings.

Regional Bouguer anomaly gradient is recognized from east to the west. The minimum Bouguer anomaly values are located at the center of the Vichada impact structure. The residual Bouguer anomalies were estimated by obtaining the second vertical derivative of the Bouguer anomalies (FIGURE 4). The residual anomalies of high frequency are enhanced at Paratebueno, La Primavera - Palmarito and Chaparral associated with the outer and inner rings of the structure. These anomalies infer the presence of local bodies of relatively high density at shallow depths of less than 100m.

Total magnetic field data was corrected from diurnal variations (FIGURE 5). The IGRF was removed from the data. Total field magnetic anomalies were reduced to the pole (RTP). Positive RTP magnetic anomalies are located near Paratebueno and Chaparral, associated with the outer ring. Intermediate magnetic anomalies are located in Palmarito. Negative magnetic anomalies are located at the central region of the structure and east of Palmarito. RTP magnetic anomalies infer the presence of several blocks dipping to the center of the

structure, with varying magnetic susceptibilities that can be associated with a faulted crystalline basement, taking into account that the sedimentary cover is considered “non-magnetic”. Residual RTP magnetic anomalies were obtained by calculating the second

vertical derivative of the RTP magnetic anomalies. High frequency residual RTP magnetic anomalies infer the presence of hidden tabular bodies close to the surface that are interpreted as veins and dikes that could had been employed along the fracture zones (FIGURE 6).

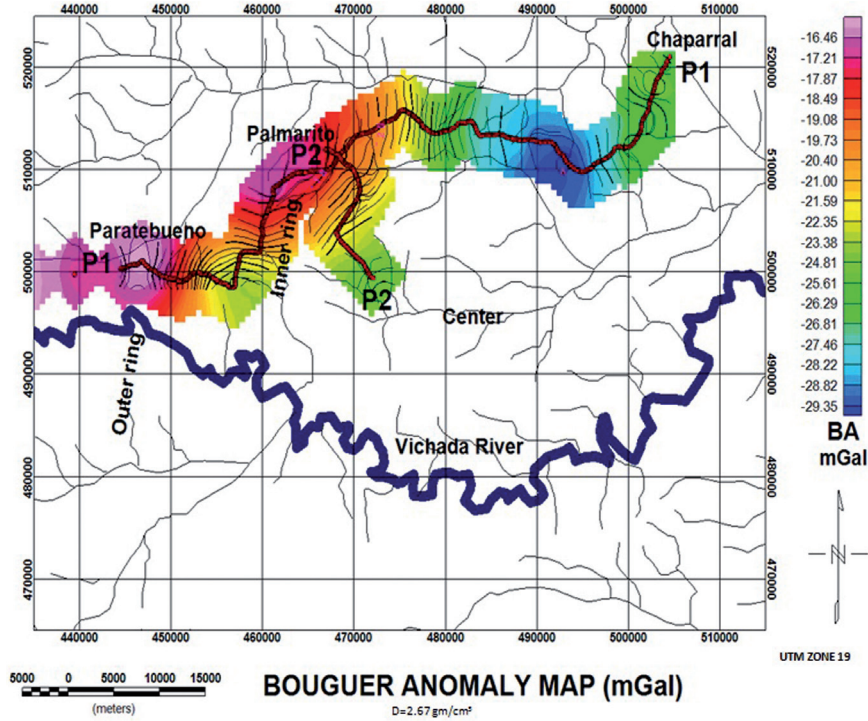


FIGURE 3: Bouguer anomaly map of the Vichada impact structure along profiles P1 and P2 showing gravity highs associated with the outer and inner rings and a gravity low at the center of the structure.

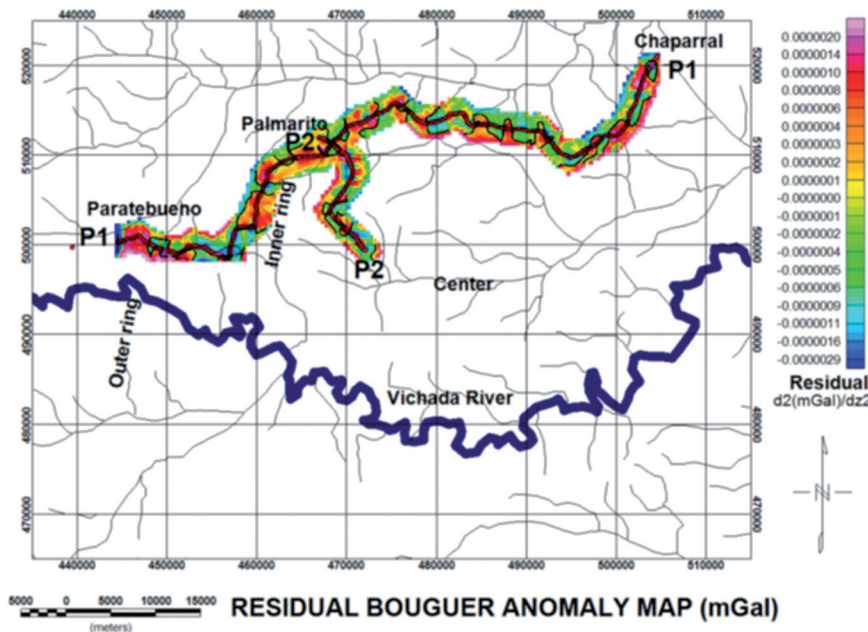


FIGURE 4: Residual Bouguer anomaly map of the Vichada impact structure along profiles P1 and P2 showing high frequency residual anomalies associated with the outer and inner rings and possible dikes and mineralized veins.

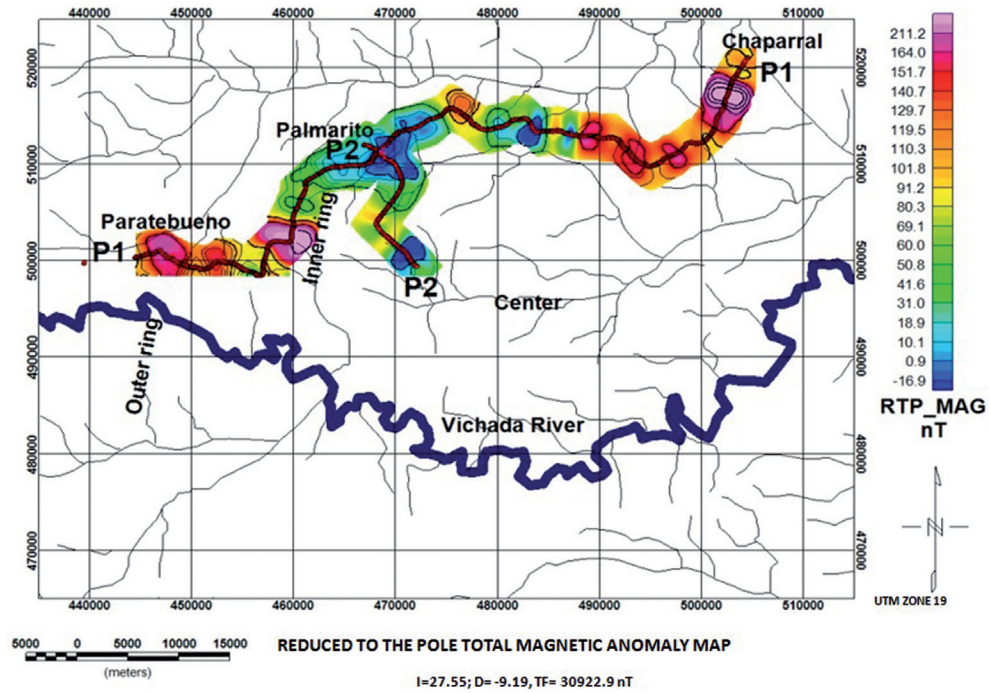


FIGURE 5: Reduced to the pole magnetic anomaly map of the Vichada impact structure along profiles P1 and P2 showing magnetic highs associated with the outer and inner rings, a magnetic lows at the center of the structure and possible dikes and mineralized veins associated with the ring crater structure.

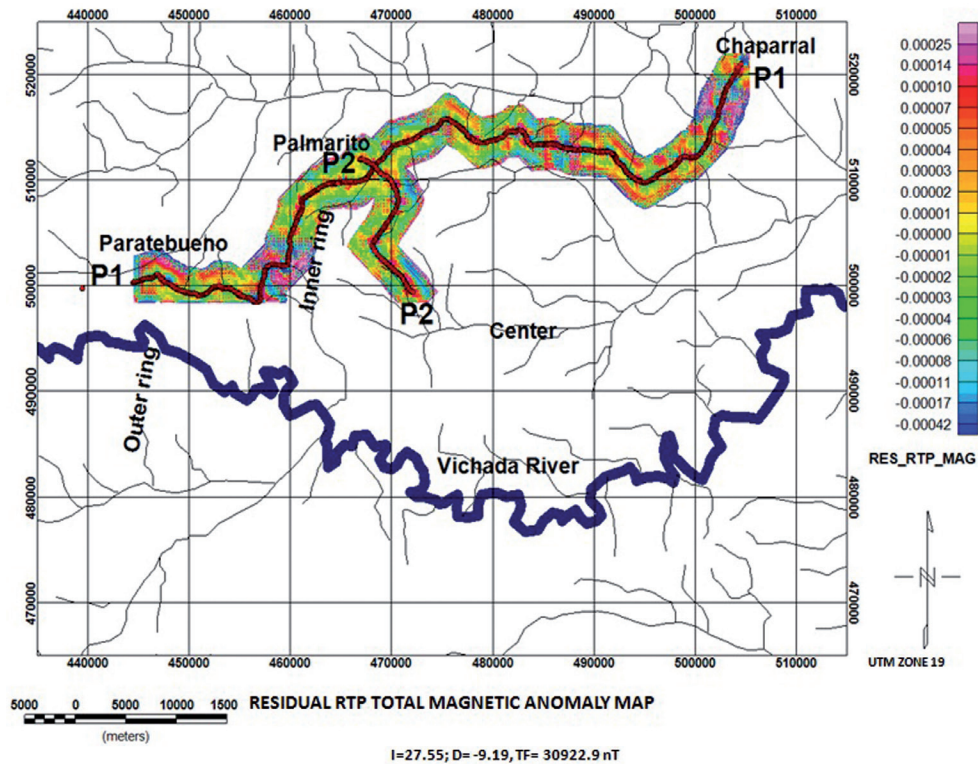


FIGURE 6: Residual reduced to the pole magnetic anomaly map of the Vichada impact structure along profiles P1 and P2 showing high frequency residual anomalies associated with the outer and inner rings and possible dikes and mineralized veins.

Radially averaged energy spectrum of the Bouguer anomalies show depth estimates of the causative bodies from 0.2km to 6km with various depth solutions in the

first 2 km depth (FIGURE 7a, 7b). This is consistent a complex impact crater structure.

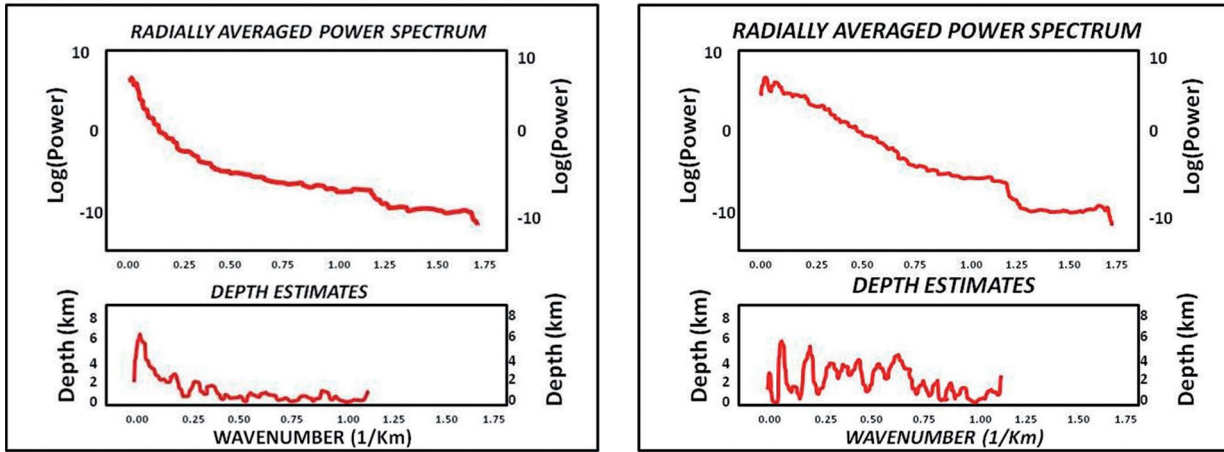


FIGURE 7: (a) Radially averaged power spectrum and depth estimates of Bouguer gravity anomalies (b) Radially averaged power spectrum and depth estimates of residual Bouguer gravity anomalies

Profiles 1 and 2 were selected for inverse modeling of the gravity and magnetic anomalies. Profile 1 was extracted along the segments A, B, C, D, E, F, G and

H, with station spacing of 200m (FIGURE 8). Profile 2 was extracted along the segments I, J, K, L at 200m station spacing (FIGURE 9).

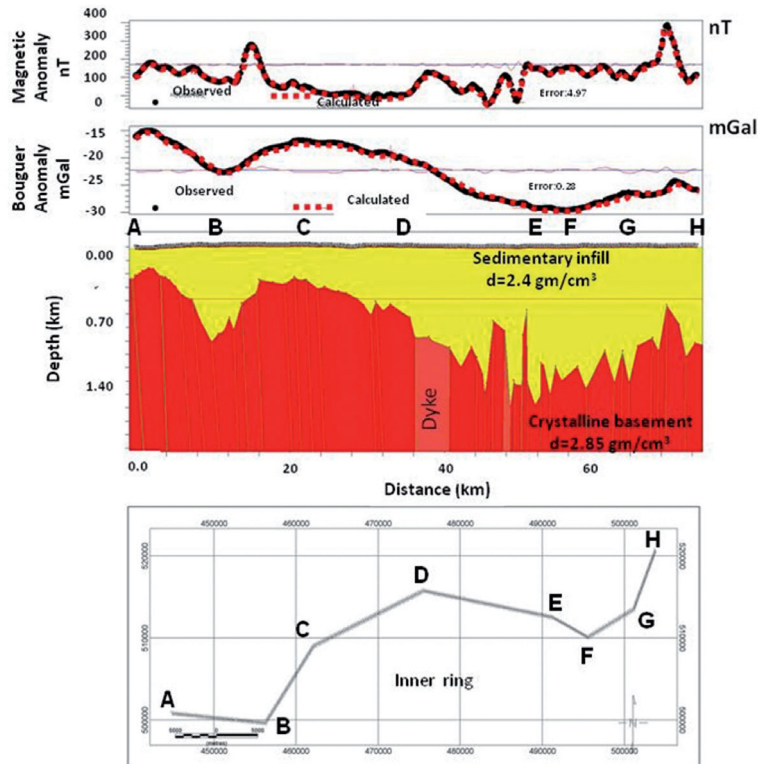
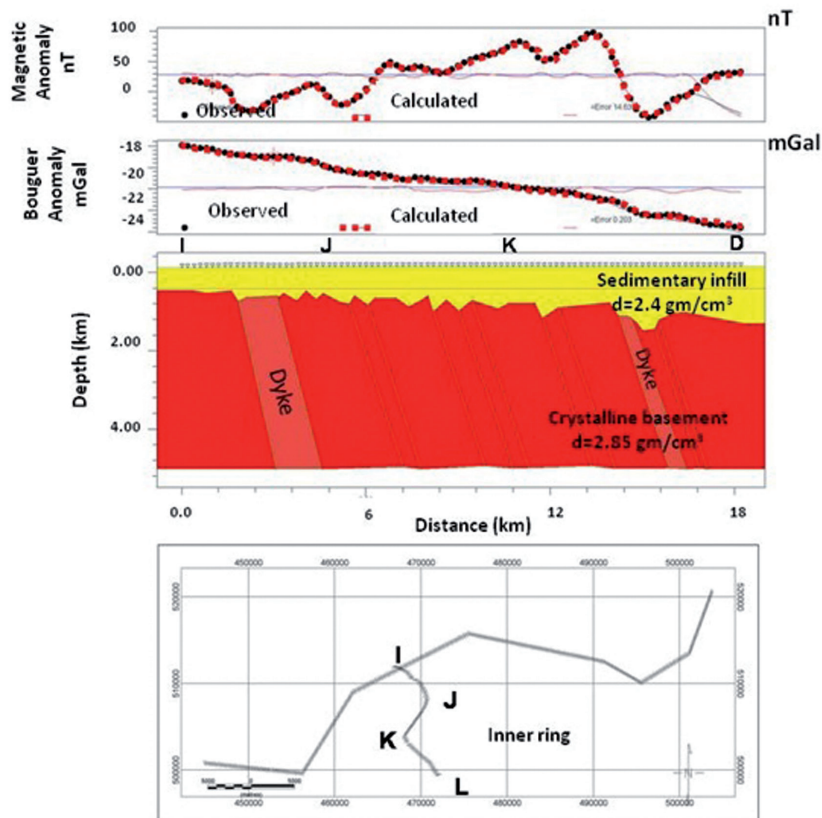


FIGURE 8: 2D inversely modeled Bouguer and RTP magnetic anomalies of profile 1 along segments A to H showing a varying basement - sedimentary infill interface. The basement highs at the left are interpreted as the outer and inner rings of the impact structure.



**FIGURE 9:** 2D inversely modeled Bouguer and RTP magnetic anomalies of profile 2 along segments I to L showing a varying basement - sedimentary infill interface. The sedimentary infill is thicker from the inner ring (left) to the center (right) of the impact structure. The crystalline basement is intensively faulted with tabular blocks dipping to the center of the structure in a “domino structure”.

Initially, two polygon units were modeled: a denser magnetic crystalline basement with a density value of  $2.67\text{ gm/cm}^3$  (bottom layer) and a low density non-magnetic sedimentary basin with a density value of  $2.4\text{ gm/cm}^3$  (top layer). Observed and calculated Bouguer and RTP magnetic anomalies were adjusted by using the utilities offered by GM-SYS, by dividing the subsurface in a series of polygons with varying geometry and contrasting density and magnetic susceptibility values. The geological model of profile 1 shows a crystalline basement that becomes deeper from west to east (FIGURE 8). Two highs of the basement are modeled at segments A, B and C with depths to the basement from 100m to 200m, separated by a basement low of 700m depth. These depth variations are associated with the presence of the outer and inner rings of the impact structure separated by a basement depression. From segments C - D to E the basement becomes deeper reaching depths greater than 1000m showing the basement low between the outer and inner rings. In segments F, G and H the basement becomes shallower with depths around 500m related to the Eastern region of the outer ring. The modeled magnetic data infer

the presence of a faulted crystalline basement intruded by mineralized dikes / hydrothermal veins. Profile 2 shows a crystalline basement going deeper from the inner ring zone with depths near 450 m to depths reaching 700m to the center of the structure. The modeled RTP magnetic anomalies infer a fractured crystalline basement with tabular prisms dipping at high angles to the center of the impact crater structure. In segments I and J the gravity and Magnetic anomalies are superposed (FIGURE 9).

## INTEGRATION WITH GEOLOGY

The outcropping lithological units are sparse. There are few isolated outcrops of reddish claystones and sandstones that are intensively weathered and thin layers of conglomerates. Hard Grounds with Fe enrichment are common in flat plains (Hernandez *et al.*, 2010). These rocks are correlated with the late tertiary sedimentary deposits mapped in the area (De La Espriella, *et. al.*, 1990). Quaternary deposits are composed of yellowish and reddish sands, clays and silts. The crystalline basement is not outcropping in the Vichada Structure.

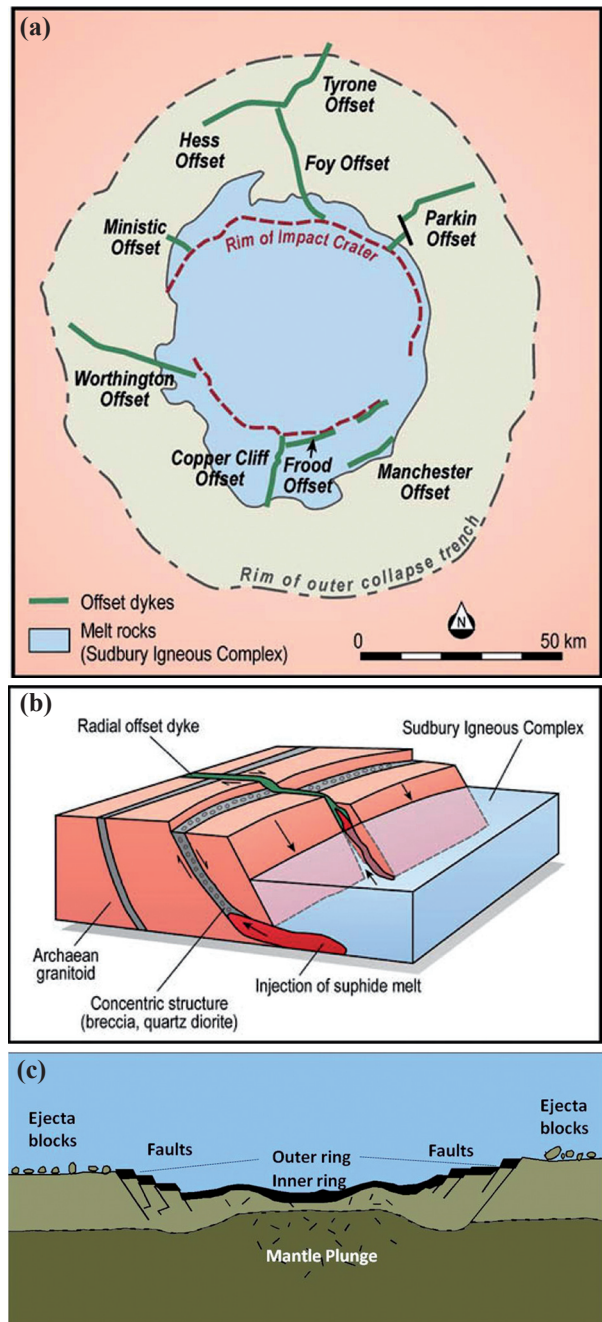
Gravity and Magnetic anomalies cannot be explained by the outcropping geological units and overburden. The local topographic highs of terraced rims are not associated with changes in lithology. Therefore, the gravity anomalies are associated with lateral variation of the sedimentary cover / crystalline basement interfase. The magnetic anomalies are associated with lateral variation in magnetic susceptibility of the faulted crystalline basement, dipping to the center of the structure in a “domino structure” typical of impact crater structures and the varying sedimentary units – crystalline basement interfase (Wrestboek and Stewart, 1996; Carporzen *et al.*, 2005, von Frese *et al.*, 1981). Local normal faults are recognized along the outer and inner rings that can be explained as “collapse structures” of the central zone of the impact crater structure.

The local gravity and Magnetic anomalies have a similar pattern than those potential field anomalies modeled at the Sudbury impact crater, Ontario, Canada, where the gravity and magnetic highs are associated with the complex multi-ring structure (Wrestboek and Stewart, 1996). Gravity and magnetic highs can be also associated with radial emplaced mineralized dikes (FIGURE 10a, b, c). The varying thickness of the sedimentary cover is related to the dislocation of the crystalline basement with contrasting density and magnetic susceptibility values due to the fractures induced by shock wave of the meteorite impact. The fracture zones could allow the emplacement of dikes and sulfur melt tabular veins that could be generated during the meteoric impact (Grieve and Masaitis, 1994).

In order to compare the Vichada Structure and the Chibxulub impact crater structure (Penfield and Camargo, 1981), an hypothetical profile with a similar path than the Cumaribo – Palmarito – Chaparral road was extracted from the Chibxulub Impact structure, keeping the 3:1 ratio taking into account the 150 km diameter and 50 km diameter of the Chicxulub impact crater and Vichada impact structure, respectively (FIGURE 11). A similar pattern behavior in the Bouguer anomaly values is recognized.

**The Vichada Impact structure in the Earth Impact Database:**

The Earth Impact Database comprises a list of confirmed impact structures from around the world. The database was conceived in its earliest form when a systematic search for impact craters was initiated in 1955 by the Dominion Observatory, Ottawa and nowadays the database is managed to the Planetary and Space Science Centre at the University of New Brunswick, Canada (<http://www.unb.ca/passc/ImpactDatabase/>).



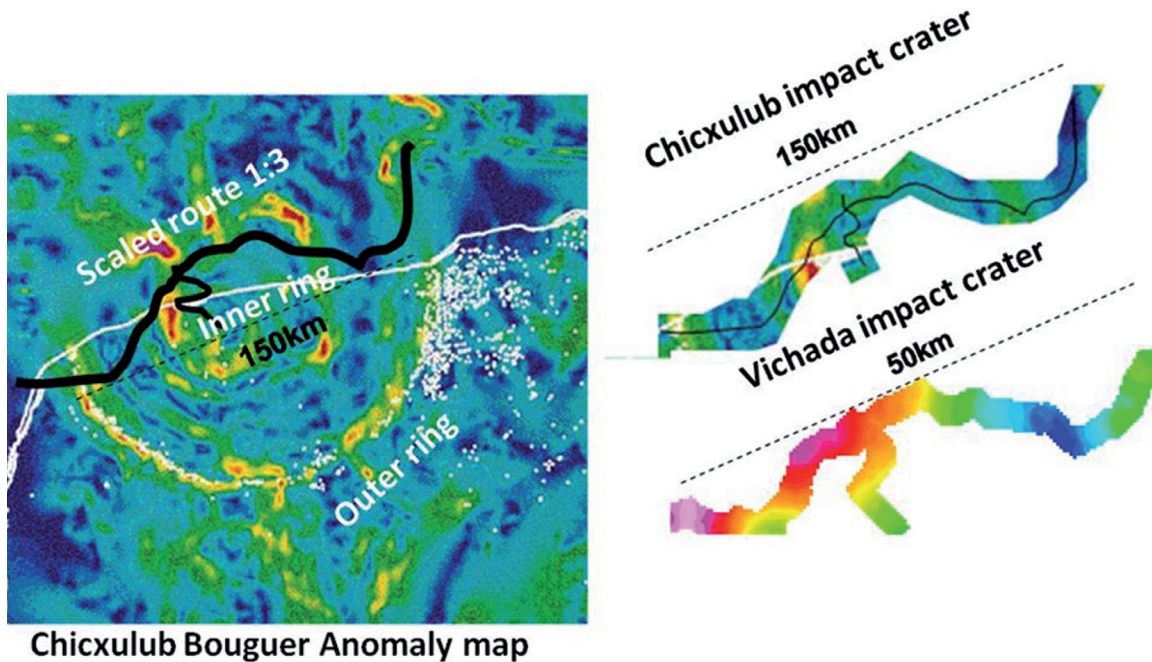
**FIGURE 10:** interpreted geological model of the Sudbury impact crater in Ontario, Canada, that could be adopted for explaining the geological and structural features of the Vichada impact structure (a) Rims of impact crater and outer collapse trench, offset dykes and melt rocks (b) Radial offset dykes, injection of sulphide melts and Precambrian basement (c) complex Impact crater section with ejecta blankets, terraced rims, outer and inner rings.

The principal criteria for determining if a geological feature is an impact structure formed by the hypervelocity impact of a meteorite or comet can be divided into megascopic (satellite scale), macroscopic



(naked eye) and microscopic features. Until now, only macroscopic criteria and geophysical evidences are supporting the Vichada Impact structure, including the presence of ejecta blocks, terraced rims, inner and outer rings and a central depression and their related satellite and ground gravity and magnetic anomalies. For buried structures, they are normally verified by drilling and sampling the material directly for

evaluation. At present, the Vichada impact crater is classified as a probable impact structure. It is officially considered “unconfirmed” because It is not listed in the Earth Impact Database. Due to strict rules or requirements regarding evidence and peer-reviewed publication, newly-discovered craters or those with difficulty collecting evidence generally are known for some time before becoming listed.

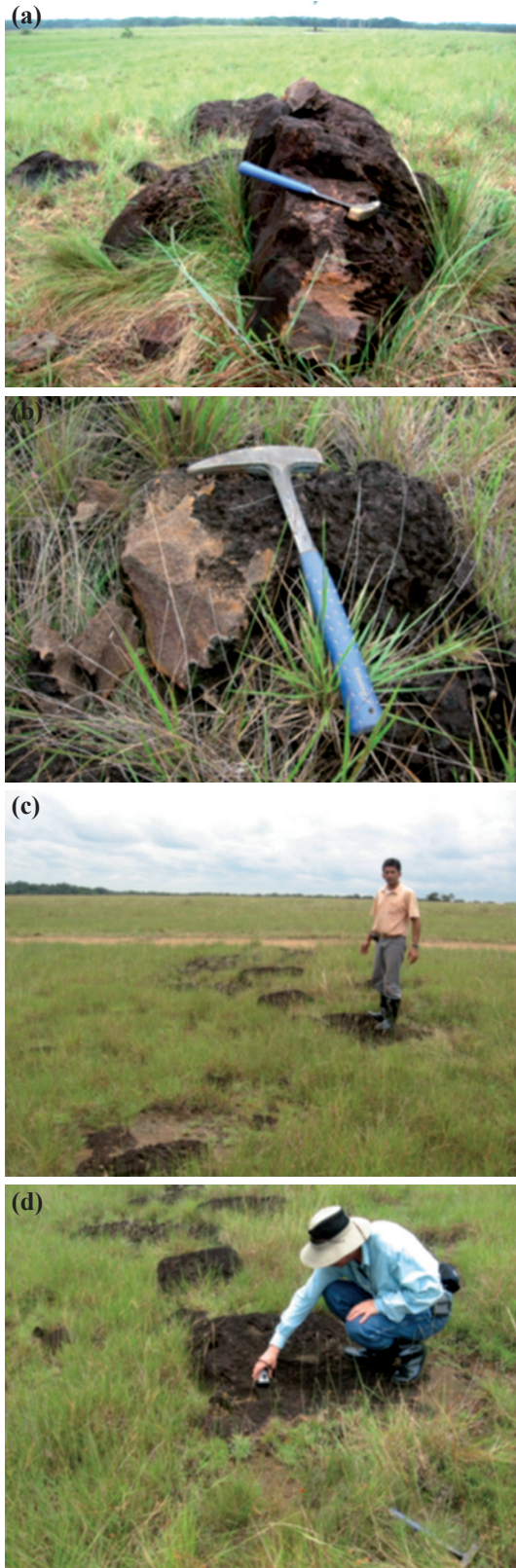


**FIGURE 11:** Comparison of the Bouguer gravity anomalies of the Chicxulub impact crater, Yucatan, Mexico, and the Vichada Impact structure, with a 3:1 proportional diameter of 150km and 50km, respectively. The gravity highs and lows pattern is similar.

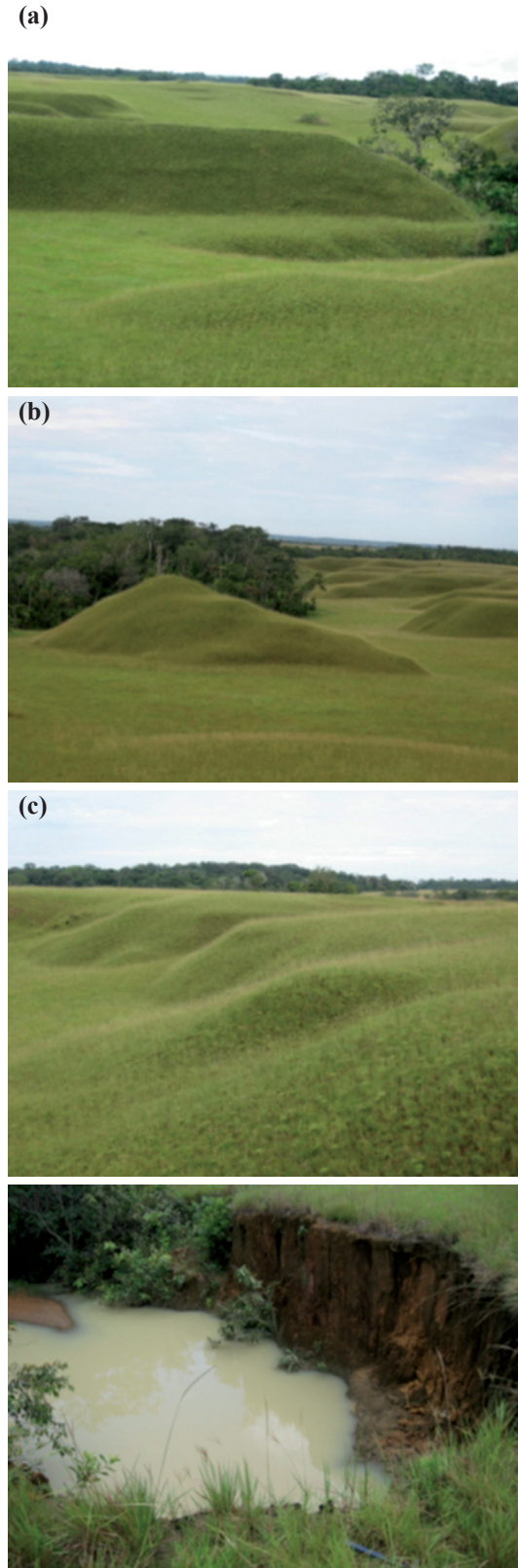
## CONCLUSIONS

Ground gravity and magnetic anomalies support the Vichada impact crater interpretation. Local positive Bouguer and positive reduced to the pole magnetic anomalies are associated with the outer and inner rings of the structure. Local negative Bouguer anomalies and Negative magnetic anomalies are associated with the central area of the structure and the area between the outer and inner rings. The modeled magnetic data infer the presence of a crystalline basement with contrasting magnetic susceptibility values related to a group of faulted blocks dipping to the center, typically of impact crater structures. These interpretations are also supported from the presence of erratic blocks associated with ejecta material (FIGURE 12 a, b, c y d) and local normal faults observed at the ring zones of the structure related to terraced rims (FIGURE 13 a, b, c).

The inner zone also shows iron enrichment, intensively weathered soils, repressed circular drainage patterns and local trenches. The geological and geomorphologic evidences suggest that the impact structure is quite young, being younger than the affected late tertiary sedimentary rocks. Craters between 25 km and 130 km in diameter usually have a central peak and in proportion to diameter, the excavation zone is much shallower than smaller simple craters. Instead of excavating a proportional amount of material as in smaller craters, here some of the impact force has been absorbed. The Bouguer and RTP magnetic anomalies do not support the presence of a central uplift of the Impact Vichada structure. Until now, the Vichada impact crater is classified as an unconfirmed in the Earth impact database. Further research is required to search for rock evidence that had undergone shock-metamorphic effects, such as shatter cones, melted rocks, and crystal deformations.



**FIGURE 12:** (a, b, c, d) Erratic blocks of reddish sandstones that are observed along the Cumaribo –Paratebueno road that are interpreted as ejecta block material.



**FIGURE 13** (a, b, c) Normal faults associated with the terraced rims or collapse structures of the inner ring of the Vichada impact structure. (d) Trench of the outer ring impact structure.

## ACKNOWLEDGEMENTS

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