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MORPHOLOGICAL ANALYSIS OF THE SÃO MIGUEL DO TAPUIO CIRCULAR STRUCTURE, PIAUÍ – BRAZIL

ANÁLISE MORFOLÓGICA DA ESTRUTURA CIRCULAR DE SÃO MIGUEL DO TAPUIO, PIAUÍ - BRASIL

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Abstract:

The São Miguel do Tapuio Circular Structure (SMTCS) is one of the largest recognized in the Phanerozoic sedimentary rocks of the Parnaiba Basin, in Piauí (PI), Brazil. Research works on the genesis of the SMTCS consider either an endogenetic origin or meteoritic impact formation. The present study is based on bibliographic survey, fieldwork and laboratory analyses (remote sensing). The SMTCS superficial morphological features, their organization, total diameter, multi-directional pattern and high density of lineaments inside the structure were characterized by remote sensing. Also, the morphostructural units such as the outer margin, intermediate ring, annular depression and a central topographic high were defined. The fieldwork allowed identifying a variable thermal metamorphism in the sandstones that formed the SMTCS. The metamorphism grade increased clearly from the margin to the center, with the presence of highly recrystallized and consolidated metasandstones around the center of the structure. Finally, the geomorphic characterization and the geometric signature obtained for the SMTCS seem to correspond to those of complex impact structures (presence of a central uplift). Moreover, the identification of macro and microscopic deformation structures in the sandstones (while not typical of shock origin) may be more conclusive of a meteoritic origin, and the lack of evidence of igneous activity might explain the observed thermal metamorphism.

Resumo:

A estrutura circular de São Miguel do Tapuio (ECSMT) corresponde a uma das maiores do gênero registrada em rochas sedimentares fanerozoicas da Bacia do Parnaíba, Estado do Piauí, Brasil. As pesquisas considerando a gênese da ECSMT dividem-se entre uma origem endógena e uma através de impacto meteorítico. No presente estudo foram realizados trabalhos envolvendo o estágio do conhecimento atual, campo e laboratoriais (sensoriamento remoto). Os trabalhos de sensoriamento serviram para delinear a configuração morfológica superficial, o diâmetro total e compartimentos, bem como o padrão multidirecional e alta densidade dos lineamentos no interior da estrutura. Puderam ser definidas unidades morfoestruturais como a borda externa, o anel intermediário, a depressão anelar e um alto topográfico central. Os trabalhos de campo evidenciaram uma intensidade de metamorfismo termal variável observado nos arenitos interiores à ECSMT. Da borda para o centro observa-se nítido aumento no grau de metamorfismo nos arenitos, caracterizando metarenitos intensamente recristalizados e consolidados no entorno do centro da estrutura. Finalizando, a caracterização morfológica superficial e a assinatura geométrica obtida para a ECSMT são semelhantes e condizentes com várias estruturas de impacto do tipo complexa (presença de um núcleo soerguido). Somado a estes fatos temos a presença de estruturas deformacionais macro e microscópicas (mesmo que não conclusivas de choque) nos arenitos que compõem a estrutura, além da não ocorrência de registro e evidências ígneas que justificariam o metamorfismo termal observado, conferindo-lhe uma provável gênese por impacto meteorítico.

Introduction

In the last decades, remote sensing images allowed to identify many circular or semi-circular structures. Recent advances in digital image processing technology have significantly contributed to the morphological characterization of these structures, formed either by endogenous processes (structural highs, igneous intrusions, dome structures) or by meteoritic impacts.

Few circular structures in Brazil were interpreted as impact-generated: Araguainha (MT-GO), Vargeão (SC), Vista Alegre (PR), Cerro do Jarau (RS), Serra da Cangalha (TO), Santa Marta (PI) and Riachão (MA). However, other circular or semi-circular structures were formed by endogenetic processes, either by reactivation of faults or other basement structures or by intrusion of alkaline magma: Poços de Caldas alkaline massif (MG), Complexo Catalão (GO), and Caldas Novas dome (GO). A few of them correspond to dome structures in Phanerozoic sedimentary basins: Structural High of Quatiguá (PR) and Pitanga dome (SP). A small number of other structures are informally considered as astroblemes, such as those of Colônia (SP), Inajah (PA), and São Miguel do Tapuio (PI). Although they present morphological and structural similarities with impact structures, conclusive evidence of direct impact is still missing (Crosta *et al.* 2010).

The object of the present study is the São Miguel do Tapuio Circular Structure (SMTCS), located in the easternmost part of Piauí State, northeastern Brazil (Figura 1). The SMTCS reaches a diameter of ~20 km, being inset in the Phanerozoic sediments of the Parnaíba Basin. It displays a complex morphology, including margin, intermediate ring, a central topographic high (suggesting similarities with the central uplift of complex impact structures), and annular depressions. Siqueira Filho (1970), Nunes *et al.* (1973) and Lima (1978) stated that this structure was produced by endogenetic processes associated with a non-outcropping igneous intrusion (laccolith) or by reactivation of lineaments in the underlying crystalline basement. However, Torquato (1981), Crósta (1982), Castelo Branco (1994) and Martins (2011) suggested a possible meteoritic origin (astrobleme).

To address this issue, this study performed a detailed characterization of the superficial morphology and the geometry of the SMTCS. The origin of this structure is discussed from the viewpoint of previous works, the geological data obtained from fieldwork and remote sensing.

Geological context

The SMTCS is located on the eastern border of the Phanerozoic Parnaíba Basin. This large intracratonic basin (~600.000 km²) belongs to the mid-northern Brazil region. It is formed by a sedimentary series deposited between the Silurian and the Late- to Mid-Jurassic but it also presents Mesozoic volcanic rocks (Santos e Carvalho, 2009).

The stratigraphic column of the basin is approximately 3500 m thick and is divided into five depositional sequences. The first, the Siluro-Ordovician (I) corresponds to the Serra Grande Group (Ipu, Tianguá, and Jaicós Formations) and represents a complete transgressive-regressive cycle, which is the first marine manifestation within the Basin. The Devonian (II) corresponds to the Canindé Group (Pimenteiras, Cabeças, Longá, and Poti Formations) and indicates a new phase of subsidence and enlargement of the basin, resulting in a new transgressive-regressive cycle with sea-level oscillations causing the largest marine ingression into the basin. The Carboniferous-Triassic (III) corresponds to the Balsas Group (Piauí, Pedra de Fogo, Motuca, and Sambaíba Formations) and indicates strong structural and environmental changes, and the main depocentres, which were first controlled by NE to NW-trending fracture zones, have migrated towards the centre of the basin (Caputo, 1984). The Jurassic (IV) corresponds to the Mearim Group (Pastos Bons and Corda Formations) and presents reduced area and thickness reflecting a strictly continental sedimentation. Lastly, the Cretaceous (V) consists of the Grajaú, Codó, and Itapecuru Formations and corresponds to a new subsidence phase of the basin triggering a new cycle of marine sedimentation, including a rapid transgression followed by the definitive retreat of the sea, closing the sedimentary cycle.

These sequences are separated by regional unconformities correlated with tectonic events of global significance (Soares *et al.* 1978; Góes and Feijó, 1994). The SMTCS bedrock belongs to the Silurian/Devonian sedimentary sequence (Serra Grande and Canindé Groups, Pimenteiras and Cabeças Formations) according to the geological map of Piauí by CPRM at 1:1.000.000 (Correia Filho, 2006). Martins (2011) reported that ~200 Ma ages obtained through zircon fission track analysis (thermochronology) may correspond to a possible age of the circular structure (impact). These ages are perfectly correlated with the ages obtained for the rocks of the Silurian/Devonian sedimentary sequences (Serra Grande and Canindé Groups, Pimenteiras and Cabeças Formations).

The SMTCS is also located 30 km SE of the Transbrasiliano Shear Zone, a major fault zone of the underlying basement (Figura 1). However, the lineaments identified in the regional relief do not appear to be controlled by this tectonic feature.

As in large parts of the Brazilian territory, the Parnaíba Basin presents many marks of the magmatic event correlated with the Mesozoic reactivation of the South American Platform. Here, the post-Paleozoic magmatic activity gave rise to the Mosquito and Sardinha Formations (close to the study area: Figura 1). They are represented by basalt outcroppings near Aldeia Sardinha (Aguiar, 1969).

São Miguel do Tapuio Circular Structure

The SMTCS has been studied since the 70s when the pioneering works by Siqueira Filho (1970), Nunes *et al.* (1973) and Lima (1978) suggested an endogenetic formation. Later studies by Torquato (1981), Crósta (1982) and Castelo Branco (1994) suggested a formation related to a meteoritic impact.

Astroblemes are identified from indicators exclusively related to meteoritic impacts and the subsequent translation of shock waves in the bedrock (French, 1998; Koeberl, 2002). Detailed diagnostic criteria are described by various authors (*e.g.* Stöffler and Langenhorst, 1994; Grieve *et al.* 1996; French, 1998; McCall, 2009; French and Koeberl, 2010; Maziviero, 2012). Some of these features are considered as indicative, but not diagnostic, i.e. not exclusively formed by meteoritic impacts.

From a geomorphic point of view, impact structures are classified as simple or complex (Dence, 1965). Simple impact structures are generally circular depressions with diameters between 3 and 6 km, depending on the host rock, with approximately parabolic cross-

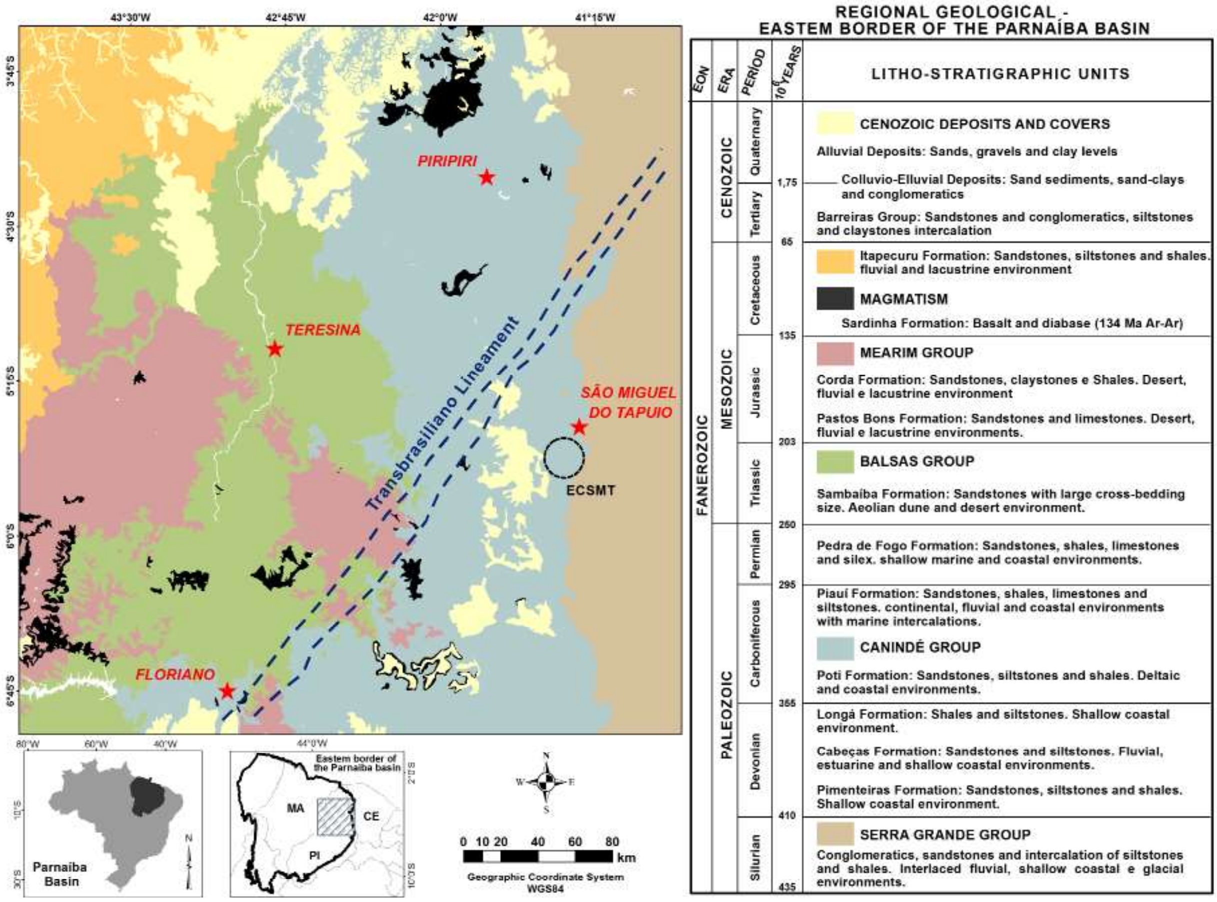

Figure 1 – Regional geology of Phanerozoic Parnaíba Basin eastern part, modified from CPRM (Bizzi et al., 2000 and Correia Filho, 2006) e ECSMT location.

-profiles and raised margins (ex: Barringer Meteor Crater, Arizona – USA). Complex structures present raised center, flat floor, annular systems of collapse faults and diameters comprised between 2 and 200 km (Grieve, 1987; French, 1998). Theoretical studies (e.g. Melosh, 1989; Melosh and Ivanov, 1999; Collins *et al.*, 2004; Collins *et al.*, 2008) state that the central high is formed in a few minutes, through complex rock displacements and deformations (during the collapse of the transient cavity), involving processes of acoustic fluidization (Melosh, 1979). Here, rocks are uplifted above their initial stratigraphical position.

The most recent works on the SMTCS were published by MacDonald *et al.* (2006), Vasconcellos *et al.* (2010) and Martins (2011). They include: i) geomorphological study, by remote sensing and digital picture interpretation; ii) identification of aerogeophysical subsurface features associated with impact structures of similar size; iii) analysis of outcrops and rock samples to identify diagnostic features that have only been inferred in previous works, so far; and iv) thermochronological dating, in order to detect the occurrence of thermal events, which cannot be related to diagenesis and possible heating by basic igneous intrusions into the sandstones.

The origin of the SMTCS remains undefined until now. Only some features suggesting a formation by impact were observed. Clear diagnostic features, formed exclusively by the passage of shock waves in the bedrock, have not yet been identified in the sedimentary rocks where the circular structure is located.

The main results of the previous works on the SMTCS are synthesized below:

1) According to Castelo Branco (1994) and Correia Filho (2006), the following stratigraphic units outcrop in the region:

- Serra Grande Group: outcrops on the eastern margin of the structure, along the road from Tapuio to Pimenteiras. This unit is made of sandstones but also includes conglomeratic layers up to 40-cm thick containing quartz pebbles less than 10 cm long.

- Pimenteiras Formation: also on the eastern rim of the SMTCS, made especially of pelitic sediments (siltites and shales) in its lower part, and of sandstones in its upper part.

- Cabeças Formation: outcrops from the central portion to the western rim of the structure. It is made of sandstones, diamictites, and sandy siltites.

2) Torquato (1981), Crosta (1987), Castelo Branco (1994) and Martins (2011) observed in the central ring of the SMTCS, the presence of highly deformed and recrystallized material in the Cabeças sandstone (quartzites), suggestive of a meteoritic impact formation.

3) Torquato (1981) suggested a pre-oceanic opening age for the SMTCS since this structure is affected by faulting related to the opening of the equatorial Atlantic Ocean. According to the same author, the Cabeças sandstone, generally light-colored, appears strongly modified in the center of the structure, replaced by fine-grained reddish quartzites. The transition between both facies is gradual but short.

4) Torquato (op cit.) also reported that the rugged landforms of the SMTCS, contrasting with the weak resistance of the strongly eroded sandstones, might suggest a shock of Tertiary-Quaternary age. However, the strong tectonic reworking observed in the region by Lima (1978), with two orthogonal fault systems (NE and NW) cutting through the radial faults in the center of the SMTCS, suggests an older age. This age might be older than the opening of the Equatorial Atlantic, which is thought to be contemporaneous with the regional fault zones.

5) Observations based upon digital processing of aerial photos and radar images show that the SMTCS is a prominent geomorphic unit, with concentric rings of positive and negative relief, and perfectly circular outlines (Castelo Branco, 1994).

All these discussions remain somewhat inconclusive. Works that are more detailed were published in the following years:

6) According to Vasconcellos *et al.* (2010), unconfirmed indications of shock deformation (planar features) were reported by Castelo Branco *et al.* (2004), including shatter cones. Analyses of conglomeratic sandstone samples collected in the center of the structure by MacDonald *et al.* (2006) failed to reveal any conclusive evidence of shock deformation; only a few weakly developed planar structures were found in quartz grains. Vasconcellos *et al.* (2010) processed low-resolution aerogeophysical data (gravimetry and magnetometry) and found incompatibilities between the characteristics of the SMTCS and those of impact structures of similar size. These results and the apparent lack of evidence from structural and metamorphic analyses lead these authors to conclude that an impact-related formation cannot be demonstrated.

7) In the meantime, Martins (2011) suggested that the SMTCS was formed by meteoritic impact and not by endogenetic processes. This interpretation is based upon the geomorphological signature, the presence of macro- and microscopic structural deformations (not strongly conclusive), the lack of identification of a sub-surface igneous intrusion from the aerogeophysical data (such an intrusion would be expected below a structure with such configuration and dimensions), and mainly the thermochronological data obtained from fission track analysis in apatites (AFTA). The latter strongly contradicts the hypothesis of SMTCS formation by endogenetic processes.

Material and methods

The methods used here consisted of the following stages:

i) acquisition of the data and cartographic material available for the study area; a) 1:100,000 plani-altimetric sheets (São Miguel do Tapuio, Oiticica, São João da Serra, Castelo do Piauí) (Superintendência de Desenvolvimento do Nordeste – SUDENE, 1985) and b) 1:1,000,000 geological map of Piauí (Correia Filho, 2006; CPRM - Companhia de Pesquisa e Recursos Minerais);

ii) bibliographic review (circular and semicircular structures, SMTCS);

iii) remote sensing from satellite images: data acquisition and processing, and production of thematic maps. Source material: a) Landsat scene (orbit 218, point 064, November 2004), TM-5 sensor, obtained from the website (http://www.dgi.inpe.br/CDSR); b) SRTM (Shuttle Radar Topographic Mission) data obtained in raster (HGT) format from the EROS Data Center, United States Geological Survey (USGS). Its spatial resolution is 3 arc sec (~90m); c) altimetric data from the ASTER GDEM (Global Digital Elevation Map) sensor, with images produced from stereoscopic couples with 30-m horizontal spatial resolution and 20-m vertical error at 95% confidence, obtained from the website (http://gdem.aster.ersdac.or.jp/). Primary processing was performed with ERMAPPER 6.4 and Global Mapper 11 software, assisted by the works of Crosta (1992), Castro (1997) and Drury (2004);

iv) extraction and analysis of morphostructural elements in the form of lineaments. According to O'Leary *et al.* (1976), they are mappable, simple or composite surficial linear features whose parts are aligned in rectilinear or slightly curved forms, differing from surrounding features and probably reflecting subsurface structures. More details about their analysis are given in Liu (1984, 1987), Riccomini & Crosta (1988), Oliveira *et al.* (2009), Roldan *et al.* (2010), Maziviero (2012) and Vasconcelos (2012);

v) Geographic Information System (GIS): organization of a database, integration and production of thematic maps using ARC GIS (ESRI), and assisted by the works of Boham-Carter (1994) and Barros Silva (2003), beside the ESRI manuals, available online. A lineament density map was drawn with the Line Density tool;

vi) field work in the SMTCS region to determine more precisely the petrological characteristics of the lithotypes in January 2010;

vii) integration and interpretation of the data and elaboration of the conclusions.

Results and discussion

Remote sensing

Figure 2 shows a gray tone image processed from the SRTM DEM data, representing the SMTCS region. In the eastern part of the structure, cuestas and other sharp landforms give rise to a NS stripe with mean altitudes reaching 700 m. They belong to the Serra da Ibiapaba, which extends along the border between Piauí and Ceará, forming the eastern border of the Parnaíba Basin.

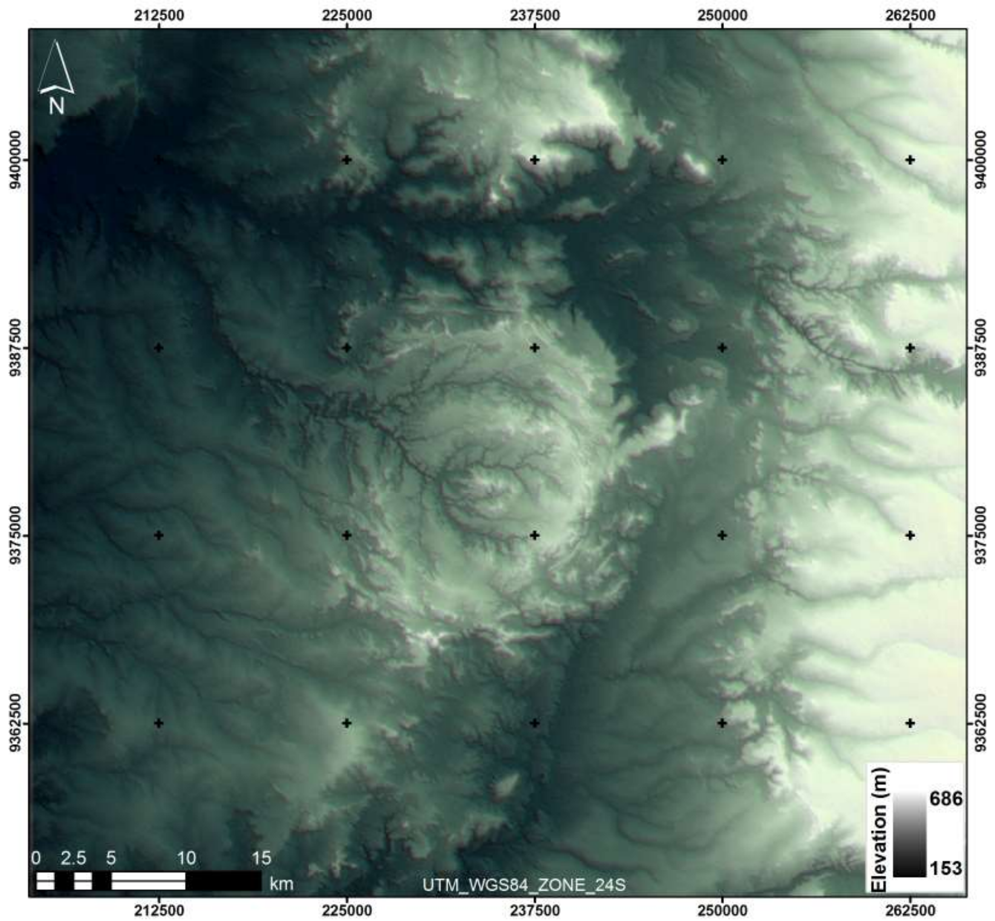

Figure 2 – The SMTCS in grey tones: Shuttle Radar Topography Mission (SRTM).

Darker tones indicate lower altitudes and correspond to depressions, valley floors, and drainage lines, e.g. in the northwest part of the scene. Except for more rugged landforms in the east and part of the northern sector, the SMTCS is the main prominent geomorphic unit in the generally flat-lying landscape of the area. A few lower zones appear structurally controlled: i) a NNE-SSW stripe located in the south down to 155 m a.s.l.; and ii) an E-W zone to the north of the SMTCS linking the catchments of the northeast and the northwest depression.

Our best results of Landsat-5/TM image processing are presented in Figura 3 A-D, with increased contrast (RGB color compositions, isolated bands, arithmetic operations, Primary Principal Component, PC1).

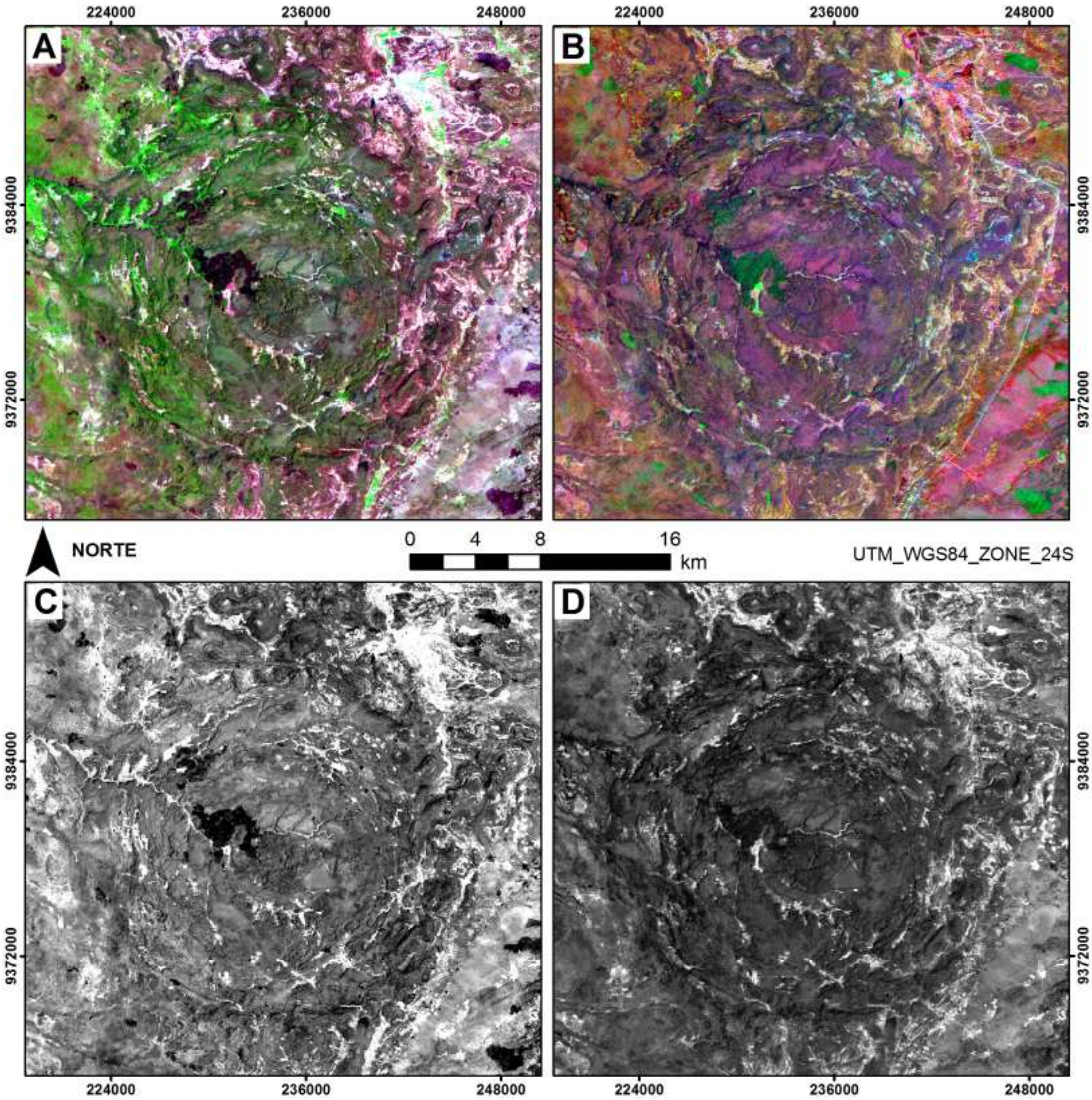

Figure 3 – SMTCS: Products obtained by processing Landsat-5/TM images. A) Colored composition R(5), G(4), B(3); B) Colored composition (band subtraction) R(5-7), G(5-1),B(3-1); C) Band 4; D) Principal Component (PC1).

Landsat-5/TM image processing and analysis reveal the following characteristics: i) the presence of escarpments on the rim and in the concentric rings, following the circular contours of the structure; ii) a dense and mainly NW-trending drainage system in the central-western part of the structure; iii) higher rims and scarps in the eastern part, the most circular one; and iv) a flat area with a well-characterized depression in the outer part of the structure, to the south-east.

Figura 4 shows a 3D representation of the SMTCS prepared from a DEM and the details of its circular morphology. It allowed us to define the following morphostructural units, from the margin to the center: i) outer margin; ii) intermediate ring; iii) central topographic high; and iv) annular depressions.

i) The outer margin reaches up to 530 m and lies 300 m above the adjacent area. This prominent rim disappears to the NW and, less distinctly, in the SE, giving this unit the shape of an open amphitheater to the NW. This outer limit of the structure suggests an apparent diameter of 20.5 km;

ii) Inside the SMTCS, an elevated intermediate ring (12.6 km in diameter) is well defined. This ring is higher than the outer rim and reaches 540 m a.s.l. in the SE. It is lower in the WNW sector, where mainly fluvial erosion was particularly important;

iii) The central topographic high, 130 m above the annular depression, has a slightly elliptic shape, with ENE-WSW major axis, 3.8 km long, and the perpendicular axis 3.3 km long;

iv) The annular depressions form the lowest areas between the three elevated rings of the SMTCS. With altitudes below 390 m, the deepest parts are found in the WNW part of the structure, corresponding to the tight drainage system and the relative lowering of the other units.

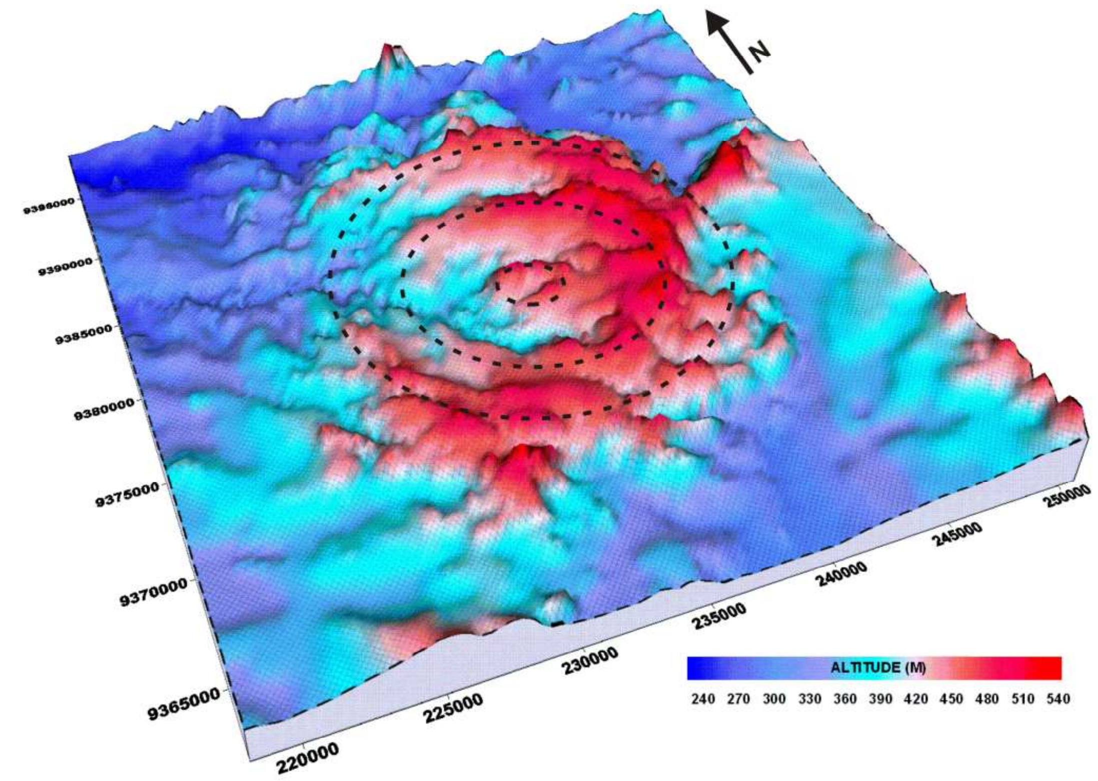

Figure 4 – *3D visualization of a Digital Elevation Model of the SMTCS.*

Figura 5 shows the shaded relief-hypsometric image obtained by processing the ASTER GDEM data. Its texture was designed to be compatible with the Landsat products. It shows perfectly the multi-ring configuration of the SMTCS, and the presence of 2 concentric rings and the central high, with approximate diameters of 20.5, 12.6 and 3.3 km, respectively.

The WNW sector appears deeply eroded, with lowering of the outer and intermediate rings. The rest of the structure is complex, with a rugged relief. Subvertical scarps and deep valleys cut the whole region between the outer rim and the intermediate ring. Annular depressions are found between the intermediate ring and the central high, with high drainage density.

Figura 6 shows three topographic profiles with the typical organization observed in various impact structures; margins and central hills (~500 m altitude) higher than the intermediate parts of the structure. Whereas a symmetrical disposition appears on the A-A' (SW-NE) and C-C' (S-N) profiles, the B-B' profile (NW-SE) shows the lower topography of the WNW sector.

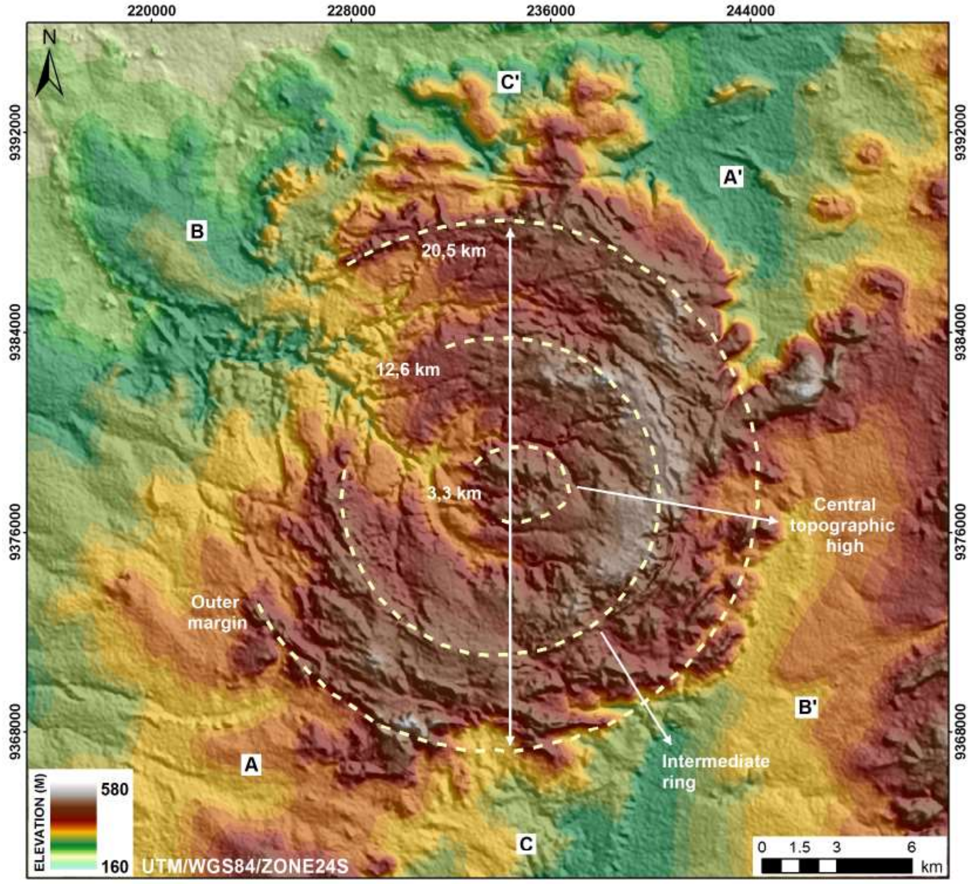

Figure 5 – Digital Elevation Model of the SMTCS (ASTER GDEM). Subdivision in outer margin (20.5 km), elevated intermediate ring (12.6 km), central topographic high (3.3 km) and annular depressions. Location of A-A', B-B' and C-C' topographic sections.

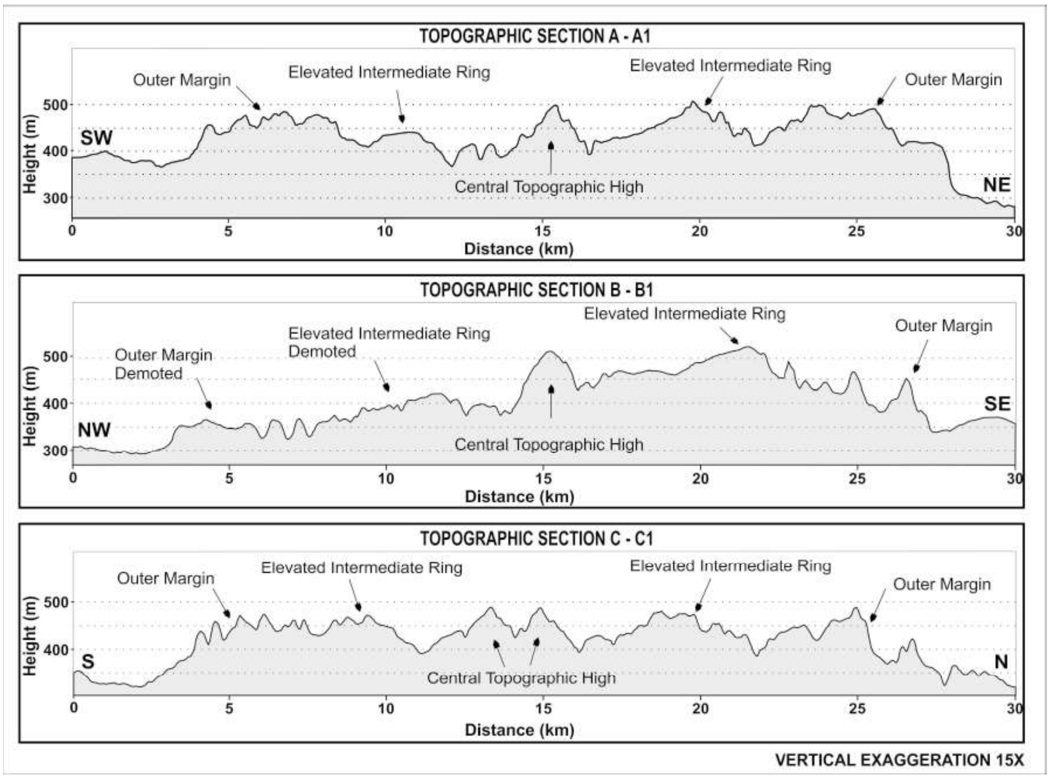

Figure 6 – Topographic sections showing the symmetry of the SMTCS rings (A-A' and C-C') and the WNW lowered portion (B-B').

A total of 3270 lineaments were extracted from the analysis of Landsat products combined with shaded relief images made in different illuminations, over a total area of 1600 km² (Figura 7). The directions' distribution was analyzed by subdividing the interior of the SMTCS in 4 quadrants: NW, NE, SW and SE. An average 300 lineaments were found in each quadrant (Figura 7E-H). Also, all the lineaments of the study site, and, separately, those inside the structure, the outer lineaments, and those found inside the intermediate ring were analyzed (Figura 7A-D).

The outlines of the lineaments also define the morphology of the circular structure. The map shows two distinct areas: i) the SMTCS, with high lineament density; and ii) the outer area, with lower density (Figura 8).

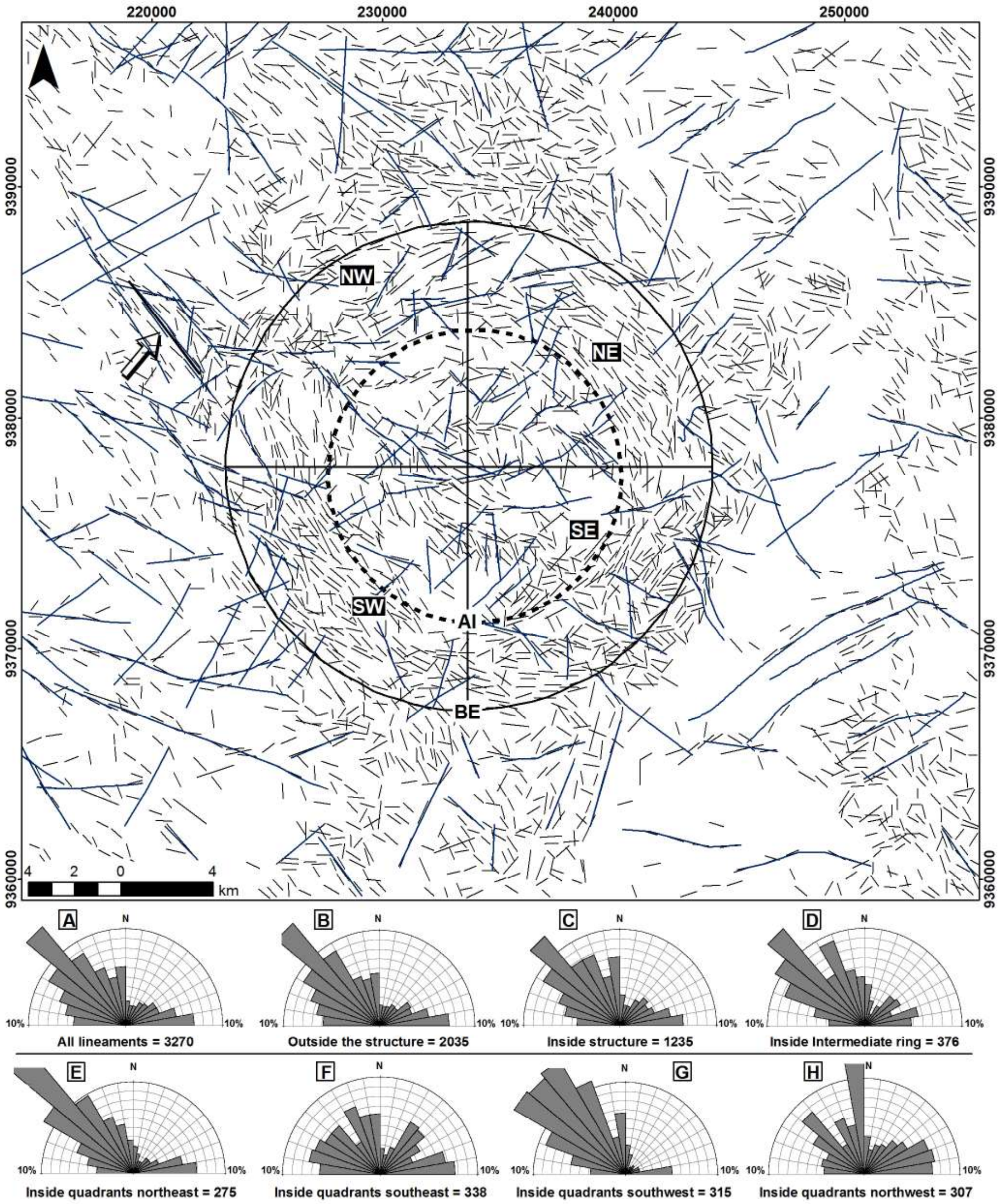

Figure 7 – Lineaments extracted by fusion of LANDSAT products and DEM of the SMTCS. The rose diagrams indicate the frequencies of their directions: (A) all the lineaments in the study area; (B) outside the structure; (C) inside the structure; (D) in the intermediate ring (dashed black line). Distribution in the quadrants inside the structure, limited by thin continuous black lines: (E) northeast; (F) southeast;

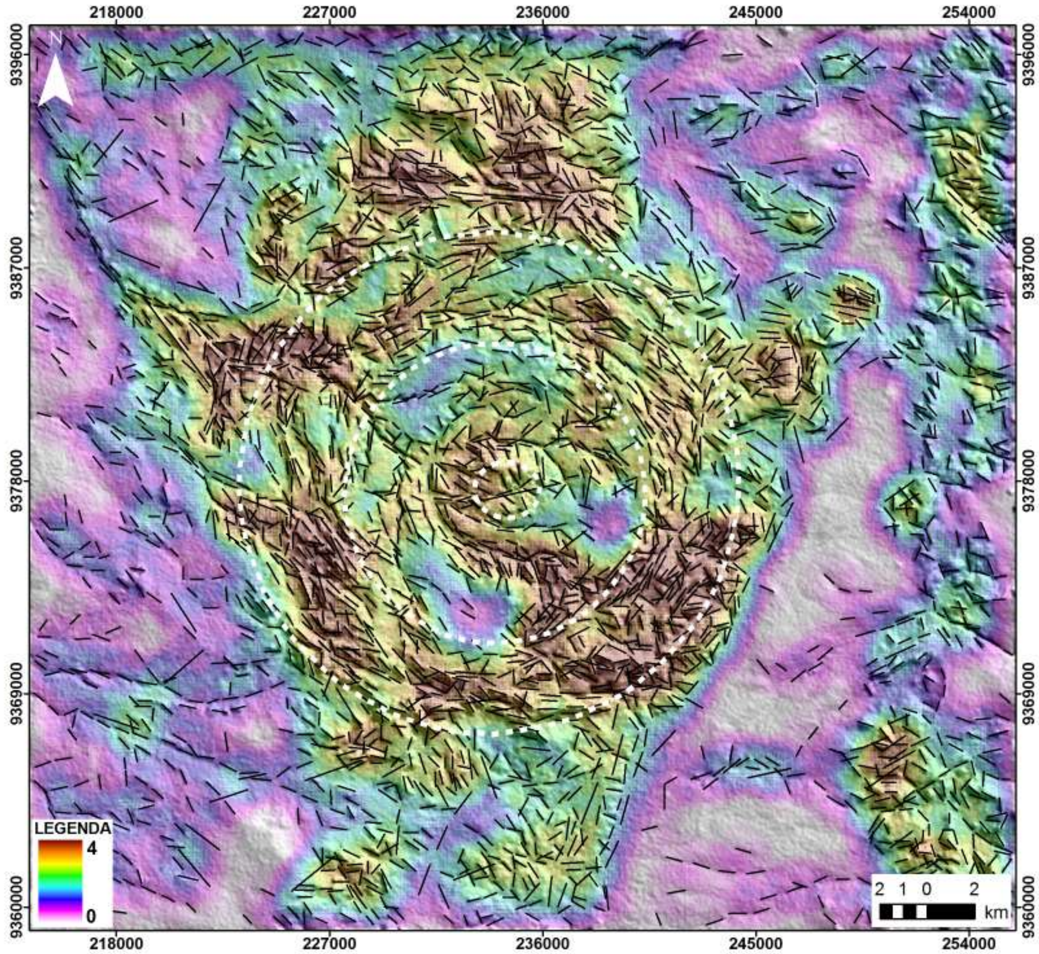

Figure 8 – Lineament density map (lineament length in km/km²) extracted in the study area and superposed upon the DEM. The white discontinuous lines correspond to the limits of the outer margin, intermediate ring and central high.

The lineament pattern inside the structure is clearly annular and radial. Some longer lineaments differ from the circular pattern and were probably formed later than the SMTCS. The main direction is NW-SE (Az 300º to 330º) in all sectors. The directions are more homogeneous in the SE and NW quadrants, with an increased proportion of NE-SW features. In the NW quadrant, the main direction is Az 350°. More generally, two preferential directions are found: N60º-30ºW (associated with a narrow silicification zone, probably along a fault line (arrows on Figura 7)), and N65º-85ºE, including a long structure that cuts through the central part of the SMTCS.

The lineament density was mapped using the ratio between the length (km) and area (km²) units. This mapping confirms the concentration of lineaments between the outer margin and the intermediate ring, particularly in the SE sector. In general, the SMTCS displays a larger density of lineaments than the surroundings, except for the north-central outer area. The units classified as inner annular depressions appear in light gray tones (low density of lineaments), mainly between the intermediate ring and the central topographic high.

The drainage system was extracted from LANDSAT, ASTER/GDEM images and correlated with the SUDENE plani-altimetric base (1985). It shows the presence of slightly sinuous valleys roughly arranged in an annular pattern superimposed on a general trend S and W (Figura 9). There is no clear difference between the SMTCS and the surroundings, but a slight tendency to a radial and/or annular organization is observed in the inner parts of the structure, associated with its system of concentric escarpments and depressions.

Geological fieldwork and petrographic studies

A geological map of the study area was produced from field observations and petrographic laboratory analyses and completed with bibliographical data (lithostratigraphic units) (Figura 10).

Three sandstone groups were defined in the SMTCS, according to their crystallization/deformation grade and distribution (morphostructural units) (Figs. 11, 12 and 13): (i) weakly or non-deformed sandstones; (ii) deformed fine-grained sandstones; and (iii) fine-grained metamorphic and intensively recrystallized sandstones.

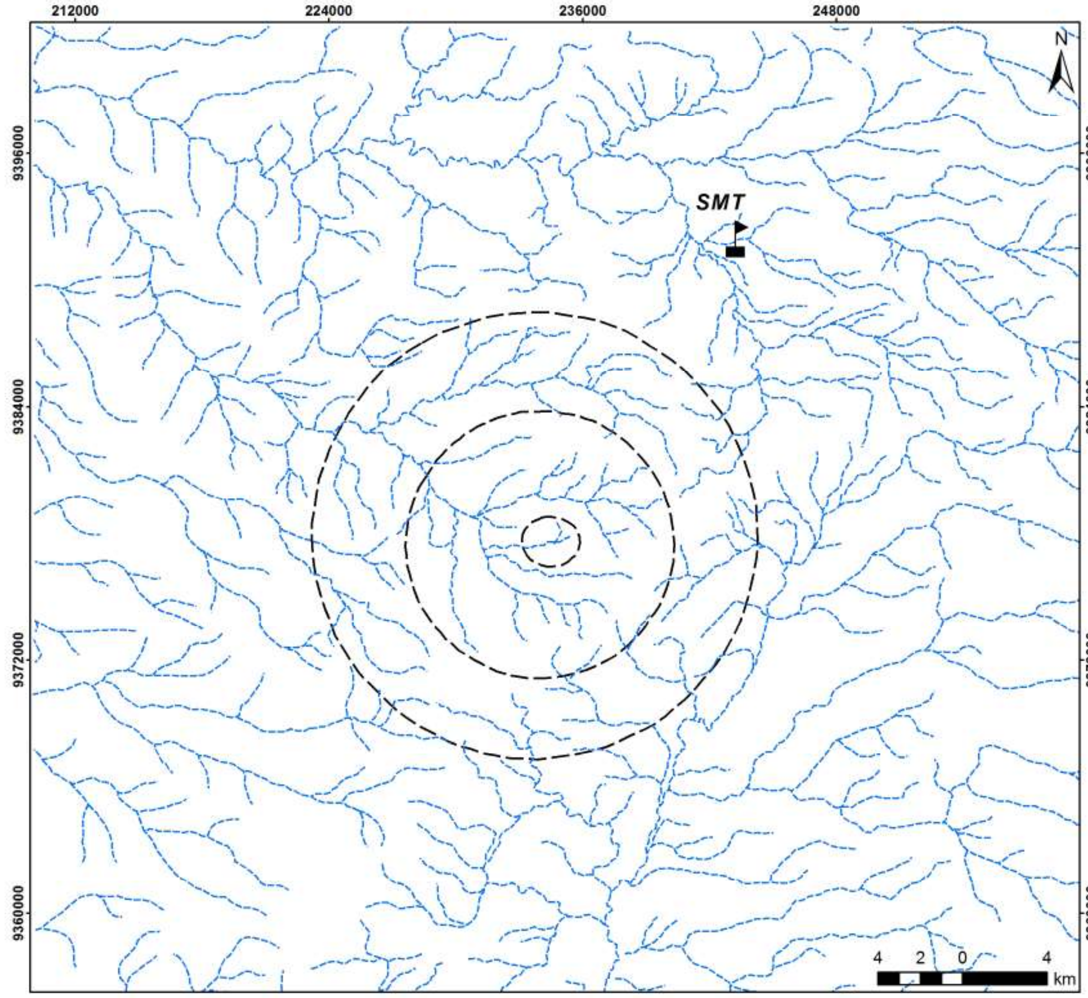

Figure 9 – *Drainage map of the SMTCS and surroundings. Drainage extracted from LANDSAT images, ASTER/GDEM and correlated with the SUDENE plani-altimetric base (1985).*

i) Weakly to non-deformed sandstones – Mainly found on the outer margin and surroundings (Figura 11, (1)), they consist of crumbly, fractured, medium- to coarse-grained reddish sandstones (Figura 11(2)). Muscovite occurs in the quartz matrix. Microscopically, they are quartz sandstones with homogenous clast-supported granular texture, including a few parts with fine-grained argillaceous matrix. The mineral composition is dominated by quartz grains (generally >90%). Subordinate minerals are opaque minerals, muscovite, plagioclase, K-feldspar, and zircon. Quartz crystals are mainly subangular to angular, medium to low rounded. In natural light, they are yellowish due to the presence of iron oxide provided by the clay fraction (Figura 11, (3a and 3b));

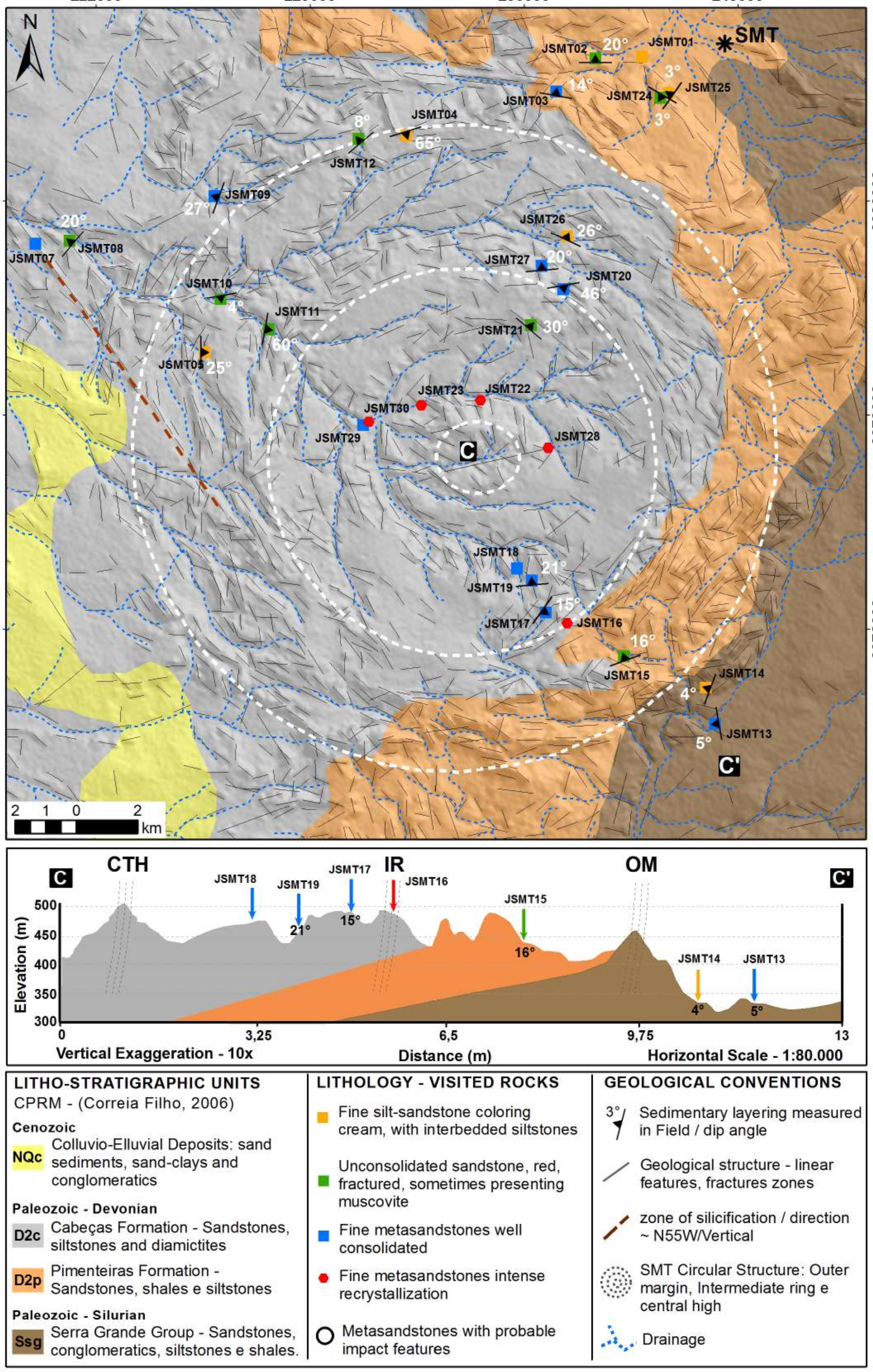

Figure 10 – Geological map drawn from field work data and satellite image interpretation superposed upon a DEM and on the CPRM geological map (Correia Filho, 2006). CTH – Central Topographic High; IR – Intermediate Ring; e OM – Outer Margin.

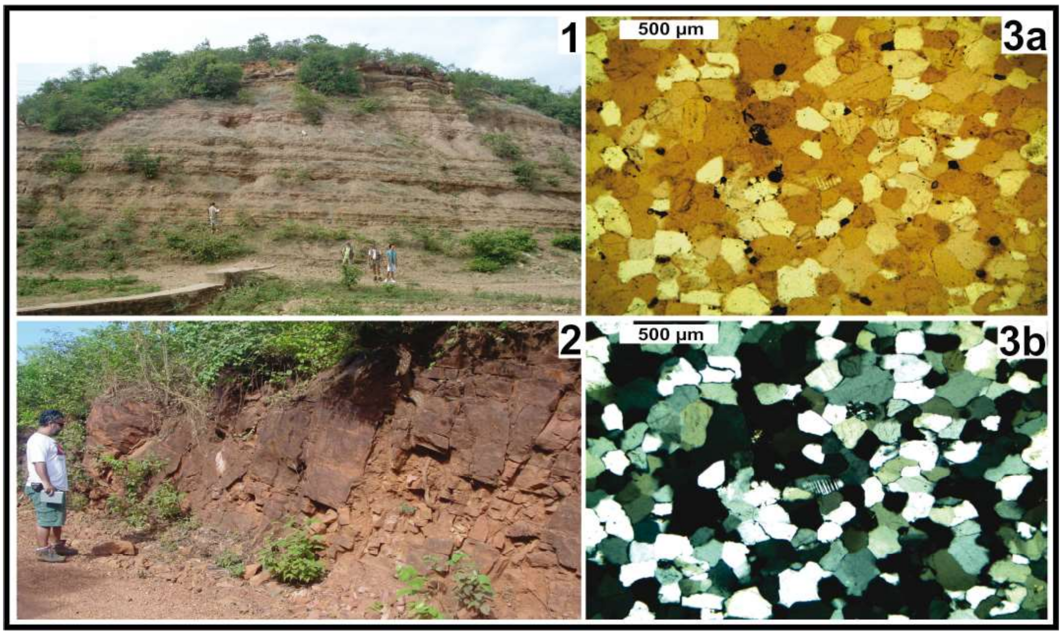

Figure 11 – Details of the sandstones in horizontal layers at the outer margin and petrographic characteristics.

The analysis of thin sections of sandstones showed lack of or weak deformation. The deformation features (microfractures) and intense recrystallization observed in other groups were not identified here. Hence, this type of sandstone must represent units that, in spite of more or less intense tilting, were not submitted to the thermal and/or deformation episodes that were identified in the other units.

ii) Deformed sandstones – Outcrop in the inner parts of the structure (intermediate ring). These sandstones are fine--grained, well-consolidated, forming locally true metasan-dstones. They present typical deformation structures, such as convergent fracture planes forming flattened triangular structures. These features have a pervasive character and dimensions varying from 1 mm up to ~10 cm (Figura 12 (1, 2 and 3)). Microscopically, they are defined by intersecting oblique planes containing clay material, oxides, and some comminuted quartz grains (Figura 12, (4a and 4b);

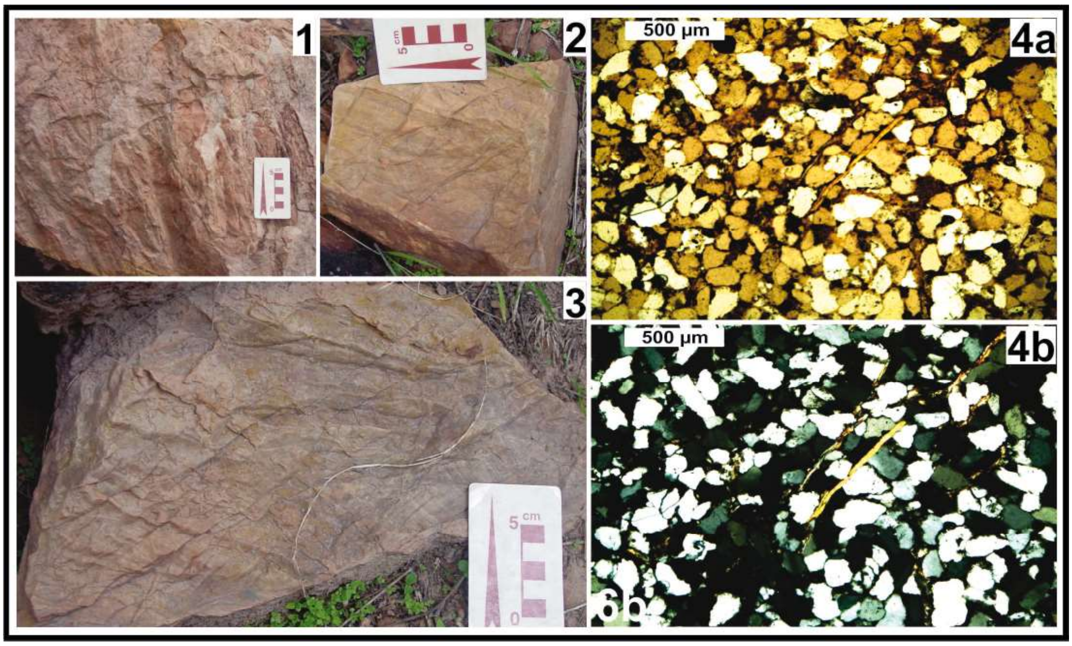

Figure 12 – Details of the fine-grained, well consolidated and highly fractured, sandstones, with typical deformation structures and petrographic characteristics, close to the elevated intermediate ring.

iii) Fine-grained, metamorphic and strongly recrystallized metasandstones – Specifically found in the center of the structure and the immediate surroundings, these metasandstones present an intense recrystallization of the quartz grains. They are medium- to fine-grained, and whitish to cream in color (Figura 13 (1, 2 and 3)). The microscopic characteristics relevant in terms of recrystallization and deformation are the following: 1) reduced grain size in comparison with other sandstone groups, presence of parts with quartz grain comminution and significant reduction of clay matrix volume (up to 100%) (Figura 13, (4a and 4b)); 2) presence of microfractures in quartz grains: a) irregular, slightly curved, disposed in groups of two distinct oblique planes in a few grains (Figura 13, (7a and 7b)); b) regular, in systems of simple planes, restricted to a few grains and filled with dark material (oxides?) (Figura 13, (6a and 6b)).

In the western part of the SMTCS, a narrow vertical structure oriented N55°W (Figura 10) is made of yellowish to pink and intensively silicified sandstones, probably formed by remobilization of SiO_2 along a fault zone. Samples of these rocks bear significant volumes of cavities filled with up to 1-cm crystals of hyaline quartz.

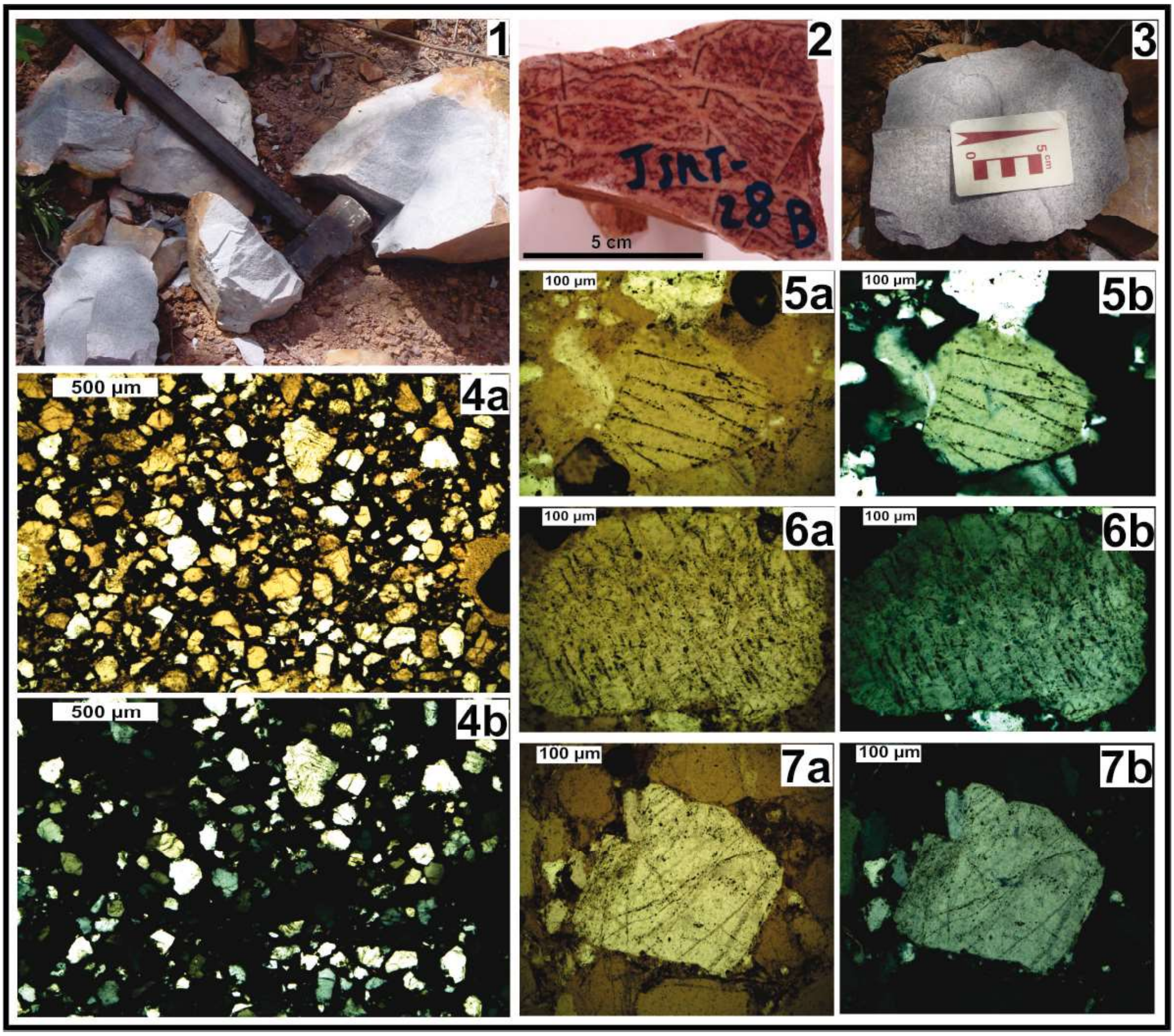

Figure 13 - Details of the metamorphic sandstones, intensely recrystallized and consolidated and petrographic characteristics, close to the central topographic high.

Summary and conclusion

The products obtained by digital processing of LANDSAT, SRTM, and ASTER/GDEM) data helped to define the geomorphic configuration of the SMTCS. The main results are: i) identification of morphostructural units correlated with the geological features; ii) an almost perfect symmetry of the concentric rings and the multi-ring character of the structure, which is very distinct from the surroundings; iii) the presence of discontinuities (lowering) in the elevated rings, mainly in the western part of the structure; iv) the preferential lineament directions, extracted and analyzed using rose diagrams and density maps; and v) a slight tendency of the drainage pattern to follow an annular/radial pattern in the inner part of the SMTCS.

The morphostructural units (compartments) identified in our study are: i) an elevated outer margin (500 m a.s.l.) representing the total diameter of the structure (20.5 km); ii) an elevated intermediate ring (530 m a.s.l.), with an approximate diameter of 15.6 km; iii) lower annular rings (360 m), mainly between the intermediate ring and the central high; and iv) a slightly elliptic central high (520 m a.s.l.), with an approximate diameter of 3.8 km (major axis).

The intensity of the thermal metamorphism observed in the SMTCS sandstones is variable. The metamorphism grade increases from the margin to the center, with the presence of intensely recrystallized and consolidated metasandstones in the central parts of the SMTCS. These sandstones bear atypical deformation structures and textures, sometimes similar to those observed in less deformed and recrystallized sandstones. However, these structures are strongly obliterated by the intense recrystallization. A petrographic analysis of these sandstones from the margin to the center revealed apparent complete elimination of the matrix, decrease and comminution of quartz grains, and the presence of fracture planes in these grains.

The rocks observed in the silicification zone of the western part of the structure should be further investigated since their deformations are not compatible with those of the circular structure. They must have been formed by a later recrystallization process.

The topographic profiles indicate the almost perfect symmetry of the concentric rings forming the structure. Assuming an exogenetic origin for the SMTCS, discontinuities in the western portion might be explained by oblique impact. In studies of lunar impact structures with different diameters, Forsberg *et al.* (1998) stated that those formed by impacts with angles between 15° and 45° exhibit a discontinuous rim portion on the opposite side toward the direction of impact. The ejecta would be deposited in an asymmetric way in the same direction. However, the ejecta blanket is rarely preserved on Earth, and only geomorphic, structural and/or geophysical criteria may help identify the impact obliquity (Scherler *et al.*, 2006).

The lineaments are preferentially NW-SE oriented inside and outside the structure. A secondary NE--SW direction is mainly identified within the NW and SE quadrants of the SMTCS (see Figura 7). Hence, the results of lineament analysis, combined with the definition of morph-structural zones, suggest that the NE-SW lineament system was formed consecutively to the impact. The NW-SE lineaments may be related to a tectonic event of regional extent. Dips measured in the sedimentary layers follow the same preferential directions (Figura 10).

Based on the geomorphic and structural criteria discussed by Scherler *et al.* (2006) and Kenkmann & Poelchau (2009), the elliptic morphology of the SMTCS central high, the NW position of the hiatus in the raised ring, and the direction of the lineaments within this ring, perpendicular to this NW-SE axis, suggest an impact at an angle ≤15º, from NW to SE (if this interpretation is confirmed).

The analysis of aeromagnetic data (Martins 2011) showed lack of any underlying anomaly indicative of basic and/or alkaline igneous intrusion, which might be associated with a circular structure of this size. The lack of superficial or sub-superficial igneous rocks, confirmed by fieldwork and airborne geophysical investigations, also indicates that an endogenetic origin may be discarded.

Finally, several geomorphic and geometric characteristics of the SMTCS are similar to those of various complex impact structures (rings, presence of a central high). Moreover, the fact that macro and micro-deformation structures (even non-conclusive) were identified in the sandstones affected by the SMTCS, together with the lack of evidence of any igneous intrusion that might explain the observed thermal metamorphism, strongly suggest an impact-related origin. However, uncertainties reported in the literature about the origin of the SMTCS, such as the lack of conclusive evidence of shock deformation (MacDonald *et al.*, 2006; Vasconcellos *et al.*, 2010), suggest that a more superficial explosion, such as the airblast of a big impactor (ice?) close to the surface, sending a shock- and heat-wave without direct impact, such as proposed for the origin of "splotches" or halos on Venus (Schaber *et al.*, 1992), should also be considered. Although not entirely comparable because of the difference in atmospheric densities which control the maximal size of such impactors, the diameter and the structural features of the SMTCS (rings, fractured surface of the radar-bright splotches, among others) have similarities to those observed on Venus. A confirmation of one of these interpretations, also taking into account the role of erosion in the blast- or impact-modified rocks and structures, might be obtained by more detailed morphostructural (e.g. identification – or not - of a former transient cavity and a central uplift: Degeai and Peulvast, 2006) and deep geophysical investigations, possibly including electromagnetic methods, and detailed geological work, mainly on the central high.

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