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ARTICLE

Geological investigation of the central portion of the Santa Marta impact structure, Piauí State, Brazil

Investigação geológica na porção central da estrutura de impacto meteorítico Santa Marta, Estado do Piauí, Brasil

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ABSTRACT: Santa Marta is a 10 km wide, reasonably well preserved, complex impact structure located in southwestern Piauí state, northeastern Brazil, with a central uplift of 3.2 km diameter. The Santa Marta structure was recently recognized as the sixth confirmed impact structure in Brazil, based on widespread occurrence of shatter cones and the presence of shock deformation features in quartz. The latter includes planar deformation features (PDF), planar fractures (PF), and feather features (FF). The structure was formed in sedimentary strata (conglomerates, sandstones, siltstones and shales) accumulated in two distinct sedimentary basins that overlap in this region: the Paleozoic Parnaíba and the Mesozoic Sanfranciscan basins. Here, we provide an overview of the geology and stratigraphy of the sedimentary successions that occur within the structure, focusing especially on the deformation aspects of the strata from the central area. This study is aimed at advancing the knowledge about Brazilian impact structures and contributing to a better comprehension of impact cratering in sedimentary targets. The deformation in the Santa Marta structure is directly related to variations in the thickness of sedimentary strata and to lithologic diversity in the interior of the structure, which determined the complexity of the deformation, including the formation of inner rings.

KEYWORDS: Santa Marta; complex impact structure; Parnaíba Basin; Sanfranciscan Basin; shock deformation.

RESUMO: *Santa Marta é uma estrutura de impacto complexa com 10 km de diâmetro, razoavelmente bem preservada, localizada no sudoeste do estado do Piauí, nordeste do Brasil, com um núcleo central soerguido de 3,2 km de diâmetro. A estrutura de Santa Marta foi recentemente reconhecida como a sexta estrutura de impacto confirmada no Brasil, com base em ocorrências generalizadas de cones de estilhaçamento e a presença de feições planares de deformação de choque em quartzo. Estas últimas incluem feições de deformação planar (PDF) e estrutura em pena (FF). A estrutura de Santa Marta foi formada em estratos sedimentares (conglomerados, arenitos, siltitos e folhelhos) depositados em duas bacias sedimentares distintas que se superpõem nesta região: as bacias paleozoica do Parnaíba e mesozoica Sanfranciscana. Apresentamos aqui uma visão geral da geologia e estratigrafia das sucessões sedimentares que ocorrem no interior da estrutura, com foco particular nos aspectos de deformação dos estratos na sua porção central. Este estudo objetiva o avanço do conhecimento sobre as estruturas de impacto brasileiras e contribui para compreensão dos processos de impacto em alvos sedimentares. A deformação na estrutura de Santa Marta é diretamente relacionada às variações nas espessuras dos estratos sedimentares e à diversidade litológica encontrada no interior da estrutura, que determinou a complexidade da deformação, incluindo a formação de anéis internos.*

PALAVRAS-CHAVE: *Santa Marta; estrutura de impacto complexa; Bacia do Parnaíba; Bacia Sanfranciscana; deformação por choque.*

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INTRODUCTION

The Santa Marta structure is a ~10 km wide impact structure centered at 10°10'S/45°14'W (Fig. 1) in the southwestern portion of Piauí state, northeastern Brazil, located ca. 30 km north of Corrente town. The structure comprises a partially exposed raised rim, as well as a central uplift with the diameter of 3.2 km. It is located in the Parnaíba Province (Almeida 1977), in the southeastern part of the Parnaíba Basin and the northern part of the Sanfranciscan Basin, with the latter overlapping the former in this region (Lima & Leite 1978). Two other complex impact structures have, in recent years, been comprehensively investigated in the Parnaíba Province: the 13 km-diameter Serra da Cangalha and the 4.2 km-diameter Riachão structures (Kenkmann *et al.* 2011; Vasconcelos *et al.* 2013; Maziviero *et al.* 2013).

The first mention of Santa Marta as a potential impact structure was made by Master and Heymann (2000). These authors used remote sensing images to suggest the impact nature of a circular structure that they termed the "Gilbués structure", a name later revised by our group to "Santa Marta structure", according to the name of the local village. Vasconcelos *et al.* (2010) reported distinctive geophysical anomaly patterns within this structure. More recently, Oliveira *et al.* (2014) confirmed the impact origin of the Santa Marta structure by providing the first *bona fide* impact evidence: shatter cones found at several locations within the structure and different types of shock microdeformation features (planar deformation features — PDF; planar fractures — PF; feather features — FF). However, some issues related to the geology of Santa Marta remained unclear, such as the local stratigraphy and deformation aspects.

Oliveira *et al.* (2014) discussed the general geological aspects of the Santa Marta structure,without discussing in detail the stratigraphic and structural aspects. The characterization of the stratigraphy and deformation of Santa Marta is not a trivial task, mainly due to:

- The lack of regional geological maps at adequate scales for stratigraphic correlation;
- The lithological similarity of several stratigraphic units that occur within the structure, in particular the

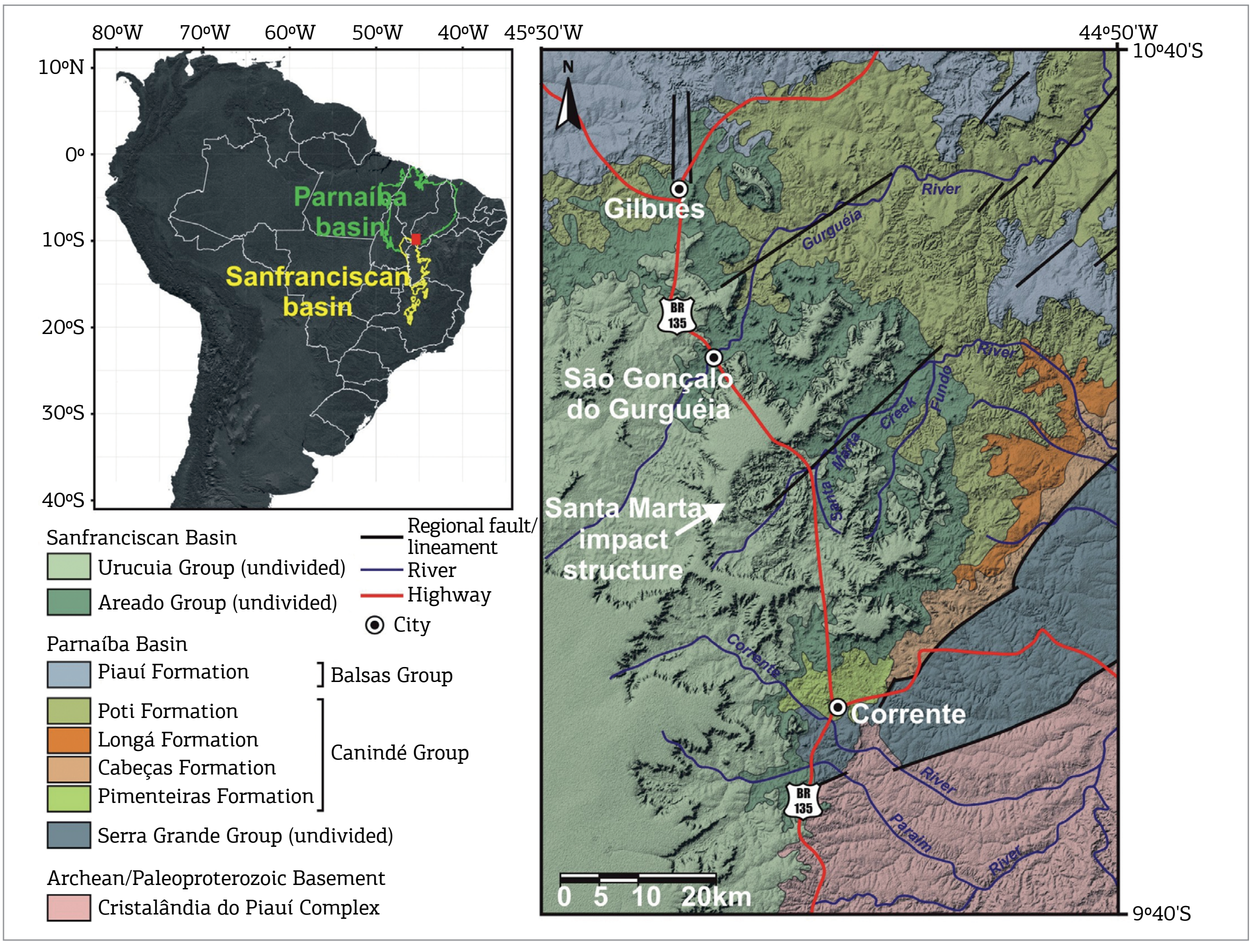


Figure 1. Geological map of the region of Corrente and Gilbués (Piauí state, Brazil), showing the location of the Santa Marta impact structure (arrow) in the context of the Parnaíba and Sanfranciscan sedimentary basins. Modified from Lima and Leite (1978) and Vasconcelos *et al.* (2004).

Paleozoic units, making it very difficult to differentiate among them;

- The highly complex deformation patterns of the strata caused by the cratering process;
- The fact that the structure is partially eroded and partially covered by younger sedimentary deposits, with only discontinuous exposures of deformed strata.

Therefore, the objective of this paper is to complement the information presented by Oliveira *et al.* (2014), by discussing in more detail the stratigraphic and structural characteristics of, particularly, the central portion of the Santa Marta structure, in which the Paleozoic units occur. Furthermore, the relationship between the polymict impact breccia described by the authors and the detrital cover of the central elevation of the structure is discussed further, resulting in the definition of two distinct morpho-structural domains, the central uplift (CU) comprising the deformed Paleozoic strata, and the central elevated plateau (CEP) comprising the undeformed Cenozoic detrital cover. The results presented here also offer a contribution to the discussion of deformation patterns in complex, medium-sized impact structures formed on previously undeformed sedimentary strata comprising a variety of lithotypes.

GEOLOGIC BACKGROUND

The Santa Marta structure is composed of sedimentary strata ranging from the Ordovician-Silurian Serra Grande Group and Devonian Canindé Group (Pimenteiras and Cabeças formations) to the Cretaceous Areado (Abaeté, Quiricó and Três Barras formations) and Urucuia (Posse Formation) groups. An undeformed detrital cover unconformably overlies these units mainly to the northwest, but also extending into the interior of the Santa Marta structure. This cover has been regionally correlated with the Chapadão Formation of Cenozoic age, comprising the unconsolidated alluvial, colluvial and elluvial sediments that cover the Late Cretaceous Urucuia Group (Fig. 2; Campos & Dardenne 1997a, 1997b).

The Parnaíba Basin marks the stabilization stage of the South America Platform (Almeida 1969), filled by Ordovician to Early Triassic sedimentary sequences (Góes and Feijó 1994), that reach 3,500 m maximum thickness. This filling is divided into three main sedimentary megacycles that correspond, from bottom to top, to the Serra Grande, Canindé and Balsas groups, respectively, with ages ranging from the Silurian to the Triassic (Góes 1995). These megacycles record multiple transgressive-regressive events that indicate a progressive tendency to contraction of the basin area, strong continentalization, and climatic desertification (Góes & Feijó 1994). Until the Upper Carboniferous, the depositional axes followed two major tectonic features, the Transbrasiliano Lineament and the Picos-Santa Inês Lineament (Cunha 1986). In the Permian, there was a retraction of the basin area resulting in migration of the depositional axis to the southwestern region of the state of Maranhão (Cunha 1986; Góes *et al.* 1993). Additional Mesozoic volcanosedimentary successions overlap the mentioned megacycles and represent the final stage of the Parnaíba Basin (Goés & Feijó 1994); however, these successions do not occur in the region of the Santa Marta structure. The magmatic event resulting from the break-up of the Pangea continent (Zalán 2004), represented by the Mosquito Formation (Juro-Triassic), marks the end of this intracratonic basin stage. The Cretaceous succession that occurs north of the Parnaíba Basin, correlated to the São Francisco basin (Areado and Urucuia groups), includes the Codó and Grajaú formations, together with Itapecuru Group. These deposits of the Aptian-Cenomanian interval are located in the São Luís-Grajaú Basin in the center-north portion of Maranhão State (Góes & Rossetti 2001; Rossetti 2003). According to Góes (1995) and Pedreira da Silva *et al.* (2003), these two successions, belonging to distinct basins, are separated by extensive uplift of the central area of the Parnaiba Province represented by Alto Parnaíba and the Xambioá Arches (in the sense of Almeida 1977).

The Sanfranciscan Basin represents a tectonic reactivation stage of the South America Platform (Almeida 1969). Campos and Dardenne (1997b) subdivided the Sanfranciscan Basin into the Abaeté and Urucuia sub-basins, which are separated by a structural basement high called the Alto do Paracatu. The basal sedimentary unit of this basin in the study area corresponds to the Areado Group (Early Cretaceous), which is overlain by Late Cretaceous sedimentary rocks of the Urucuia Group and Cenozoic strata of the Chapadão Formation. The Mesozoic sedimentary successions belonging to the Sanfranciscan Basin are chronocorrelated to the Cretaceous successions belongs to Parnaíba Basin and have been interpreted as an intracontinental record of the Pangea breakup, during the opening of the Atlantic Ocean. These strata unconformably overlie restricted Paleozoic glaciogenic deposits (Campos & Dardenne 1997a, 1997b), that do not occur in the region of the Santa Marta structure.

The main regional structural features are aligned along a NE-SW trend and are related to the Transbrasiliano Lineament (Schobbenhaus Filho *et al.* 1975). They may also have components trending along NNE-WSW, which are regionally less pronounced and related to the extension along the Senador Pompeu Lineament (Cordani *et al.* 1984).

The correlation of sedimentary strata that comprises the Santa Marta structure with the lithostratigraphic units that occur in the wider region is made difficult by the lack of basic mapping on an adequate scale outside the structure. Existing studies were done on a regional scale, thus lacking the necessary detail for adequate correlation, or are extrapolated from more distant regions of the basins. The Paleozoic strata recognized within the Santa Marta structure are well exposed in nearby areas, for example in the vicinity of Corrente (Fig. 1). The Mesozoic strata are better exposed in this region, near the towns of São Gonçalo do Gurgeia and Gilbués.

The different lithostratigraphic units of the Santa Marta structure occur in distinct morpho-structural domains (Fig. 3).

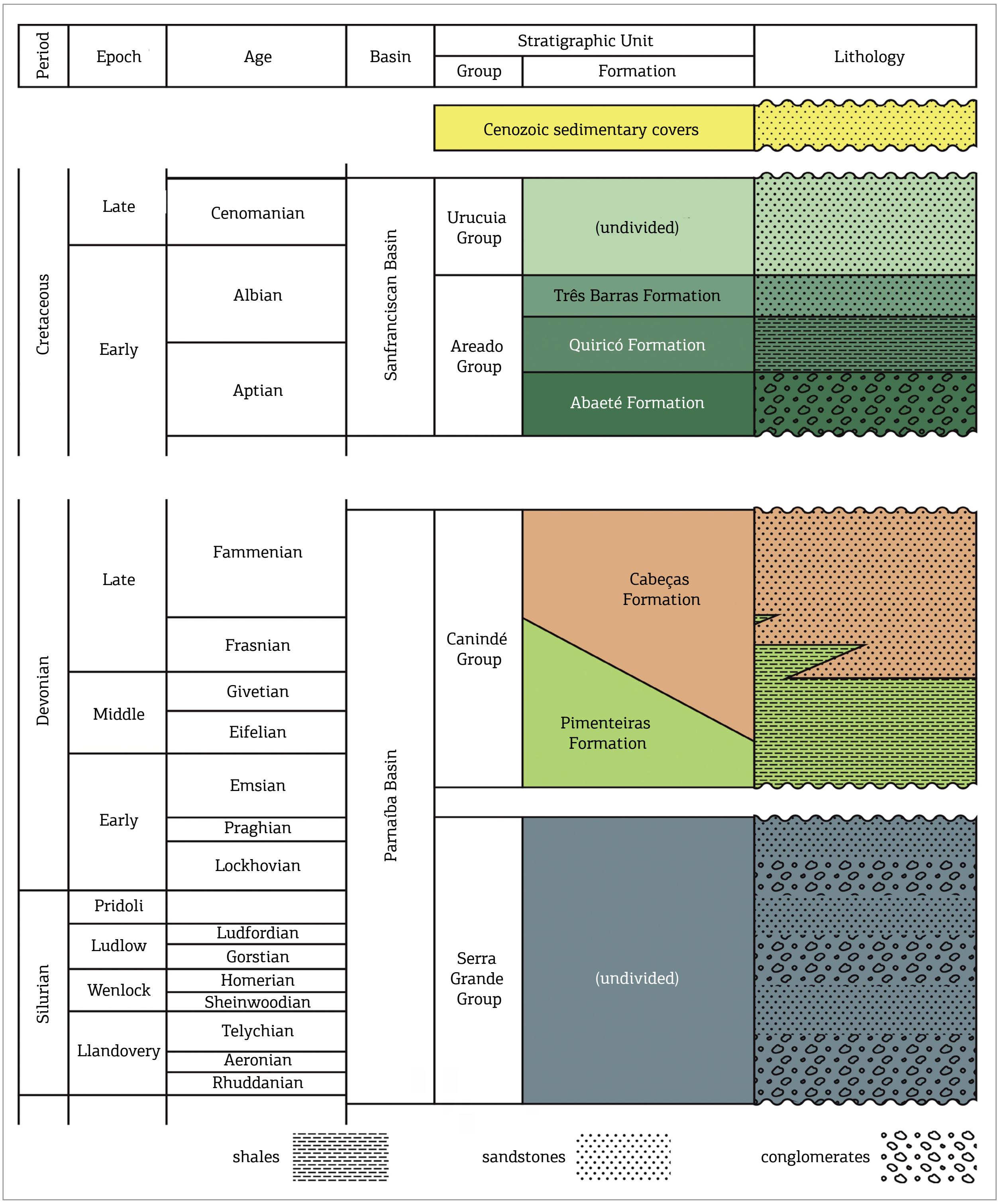
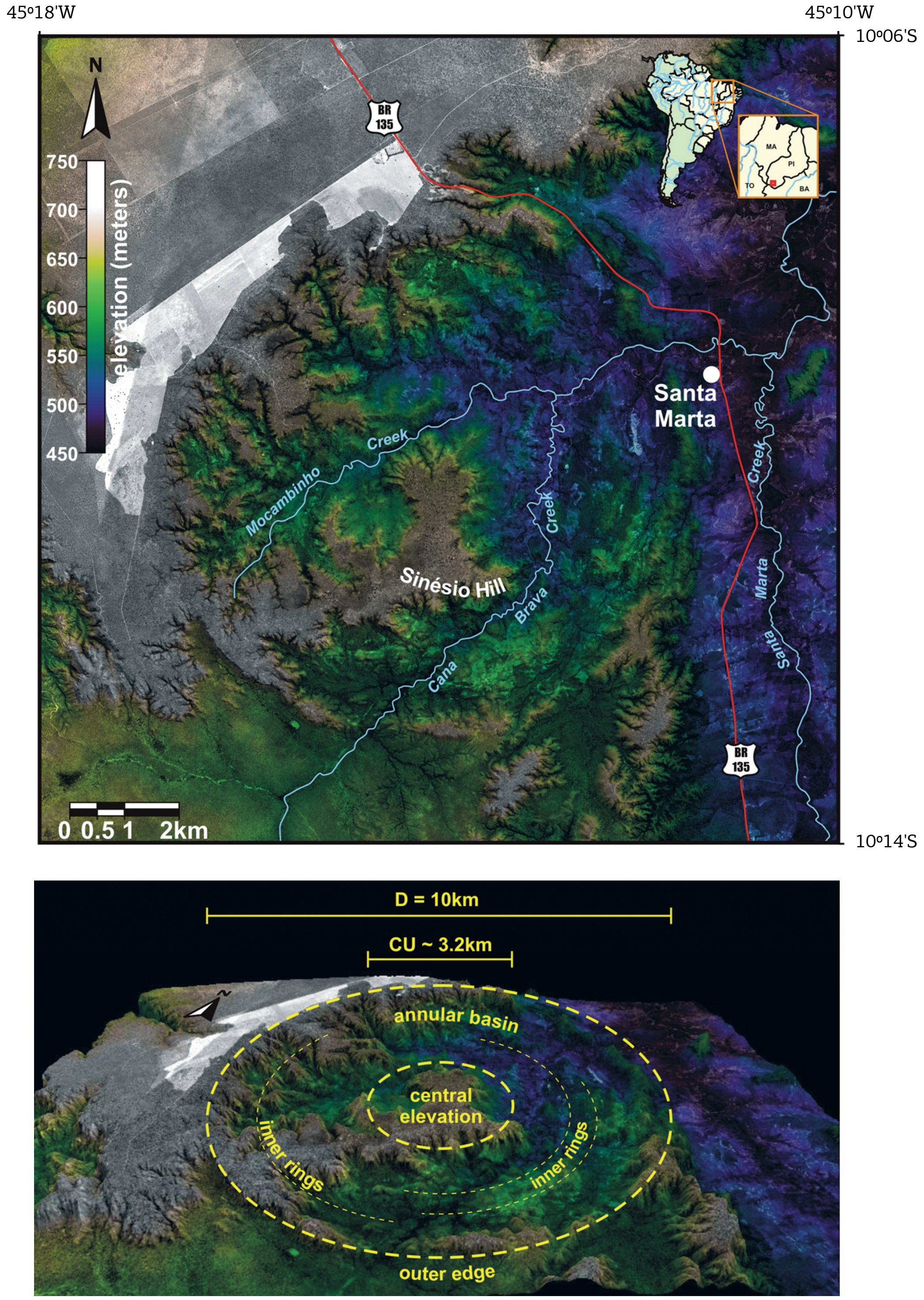


Figure 2. Schematic stratigraphic chart for the Paleozoic Parnaíba Basin and the Mesozoic Sanfranciscan Basin (compiled from Lima and Leite 1978; Campos & Dardenne 1997b; and Vaz *et al.* 2007).



D: diameter of the structure.

Figure 3. (A) The Santa Marta impact structure, showing color-coded elevation values (meters above sea level) and main topographic features; (B) perspective view of Figure 3A (3.5 × vertical exaggeration), showing the interpreted morpho-structural domains (outer edge, annular basin with inner rings, and central elevation). The central elevation is composed of the central uplift (CU) and the partially overlying central elevated plateau (CEP). Figures 3A and 3B were prepared from a GoogleEarth® grayscale mosaic draped over elevation data from the Shuttle Radar Topography Mission (SRTM), with 1 arcsec (30m) resolution.

Initially, Oliveira *et al.* (2014) subdivided the structure into three distinct domains: outer edge/outer rim, annular basin, and central elevated plateau (CEP). These authors also highlighted the existence of pronounced topographic gradients between those different morpho-structural domains. Different types of breccia that occur in the central elevation area in the Santa Marta structure were differentiated into impact breccias and those that make up the detrital cover of the central elevated plateau (CEP) and that partially cover the deformed Paleozoic units in the central uplift (CU). The term "central elevation" is therefore used as a generic term, corresponding to the Paleozoic rocks of the core of the CU and the detrital cover that comprises the CEP. Neither of them exactly coincide spatially.

In the Santa Marta structure, shatter cones occur in sandstones and clasts of monomict sandstone breccias in the central part of the structure, and within mostly well-rounded quartzite blocks that occur as large clasts in conglomerates in the annular basin near the outer edge of the structure (Uchôa *et al.* 2013; Oliveira *et al.* 2014). Shatter cones were first proposed as a diagnostic impact feature by Dietz (1947) and are the only macroscopic diagnostic feature that develops in terrestrial impact structures at relatively low to moderate shock pressures (2–30 GPa) (e.g., French *et al.* 2004; French & Koeberl 2010; Baratoux & Reimold 2016, and other contributions in that special issue). Shatter cones are curviplanar, striated fracture surfaces that can develop in all types of rocks (Dietz 1959; Baratoux & Reimold, 2016). The occurrence of shatter cones in large clasts of conglomerates was first described at Santa Marta structure by Oliveira *et al.* (2014).

These authors also described shock microdeformation, including planar deformation features (PDFs) in quartz grains in different samples from the central part of the Santa Marta structure, as well as feather features (FFs) that commonly occur associated with PDFs in quartz grains in intensely deformed sandstones — occurrences that increase in frequency towards the center of the structure.

METHODS

Geological data were collected during five field campaigns in a total of 354 GPS-referenced (using the SAD 69 zone 23S datum) locations, with detailed information about lithology, bedding plane orientations, and, where possible, structural data. Stereograms were constructed with the Open Stereo software (Grohmann *et al.* 2011) and plotted in dip-angle notation to analyze bedding orientation and to interpret the structures. The results were spatially integrated and analyzed using the ArcGIS 10.0 software, and a 1:30,000 geological map was produced. Samples were collected in the various morpho-structural domains of the crater, i.e., at the outer edge, and in the annular basin, at the CU and the CEP.

RESULTS

Geological mapping

The spatial, structural and lithostratigraphic relations of the geological units in the Santa Marta structure are shown in the geological map at the 1:30,000 scale (Fig. 4). Within the Santa Marta structure, the lithological units are highly deformed, although sedimentary structures are often preserved, which locally enables the identification of top and base of layers and, consequently, the establishment of stratigraphic correlation. Lithostratigraphy used in this article is based on Lima and Leite (1978), Góes and Feijó (1994) and Campos and Dardenne (1997a, 1997b) (Fig. 2).

Deformed Paleozoic and Mesozoic units

The CU of the Santa Marta structure is made up of strongly deformed Paleozoic strata. Considering the complex geometry of the structure, the delimitation of contacts between different rock types is not trivial. Moreover, the detrital cover of the CEP hinders a more comprehensive understanding of the stratigraphy in the core area. From the edge of the CEP outwards, there are Devonian sandstones and pelites of the Pimenteiras and Cabeças formations, respectively (Figs. 5A and 5B). The area of occurrence of these two units extends up to the concentric and discontinuous inner rings formed by Silurian conglomeratic sandstones and conglomerate of the Serra Grande Group (Fig. 5C).

The sedimentary rocks interpreted to belong to the Cabeças Formation consist mainly of poorly-sorted sandstones with occasional pebbles and erratic blocks, as well as a subordinate pelitic succession. The sandstones exhibit colors ranging from white and pink to yellow and can display levels with intense tube-shaped bioturbation that thins towards one of the tube ends, as well as plane-parallel bedding and small-scale, often tilted, cross-stratification. This unit shows intense fracturing and can display diagnostic shock features, such as shatter cones (Fig. 6) and PDFs in quartz grains. In addition to the intense brittle deformation, plastic deformation in the form of disharmonic parasitic folds was observed in finer-grained lithologies (siltstones).

Pelitic Paleozoic strata belonging to the Pimenteiras Formation includes gray-purple shales with subordinate intercalations of yellow and fine-grained conglomeratic sandstones. Fine sandy sedimentary rocks are generally poorly sorted with small-scale crossbedding. Shales may display remnants of plane-parallel lamination. Discoidal-type ferruginous concretions may occur within coarser strata. Rudaceous successions, represented by levels of up to 0.5 m-thick conglomeratic sandstone, are made up of granule-sized clasts, supported by a medium to coarse sandy matrix, and can display cross-bedding. Drag and recumbent folds frequently occur, in addition to overturned bedding.

Rudaceous sedimentary rocks, interpreted to belong to the Serra Grande Group, comprise a succession of conglomerates to conglomeratic sandstones. Clasts are moderately sorted and display variations in size, with predominance of granules, pebbles, and even blocks. There are sometimes slight imbrications and small-scale cross-bedding. Loose clasts of this unit cover the tops of knolls, giving them comparatively lighter color and facilitating their visual identification. Subordinately, levels of fine-grained sandstone may occur, with millimeter-thick layers of micaceous material that are intensely deformed and altered, with schistose appearance. Fracturing, tilting and uplift, along with overturned bedding of some strata, are the main deformation features observed in this unit.

The Mesozoic units are exposed in the annular basin and along the inner side of the outer rim of the Santa Marta structure. In the annular basin, towards the core of the structure, tectonically induced lateral juxtaposition of Paleozoic and Cretaceous rocks can be observed, with both sequences being intensely deformed: the juxtaposition occurs along shear zones, along which the sedimentary strata of the two distinct basins have been brought into contact, as evidenced by overturned top-base indicators, drag folds, and steeply-dipping fault planes. The distinction between Cretaceous rudaceous and the Silurian-Devonian pelitic strata were based on contact relations with pelitic units and on the basis of structural observations, i.e., evidence for normal or overturned bedding. Deformed eolian sandstones of the Posse Formation and the Três Barras Formation occur preferentially along the outer edge of the Santa Marta structure.

In the Abaeté Formation a succession of three different lithotypes occurs, namely conglomerate, poorly-sorted sandstone, and medium-grained, bimodal sandstone, with the latter exhibiting cross-bedding. At the outer edge of the structure, conglomeratic sandstones associated with red pelites of the Quiricó Formation were frequently observed, forming open folds with overturned limbs. Cobble-sized quartzite clasts are commonly fractured and may contain shatter cones in their interior. In the annular basin, this unit is also associated with pelites of the Quiricó Formation (Fig. 7A), with predominance of sandstones instead of conglomerates (Fig. 7B).

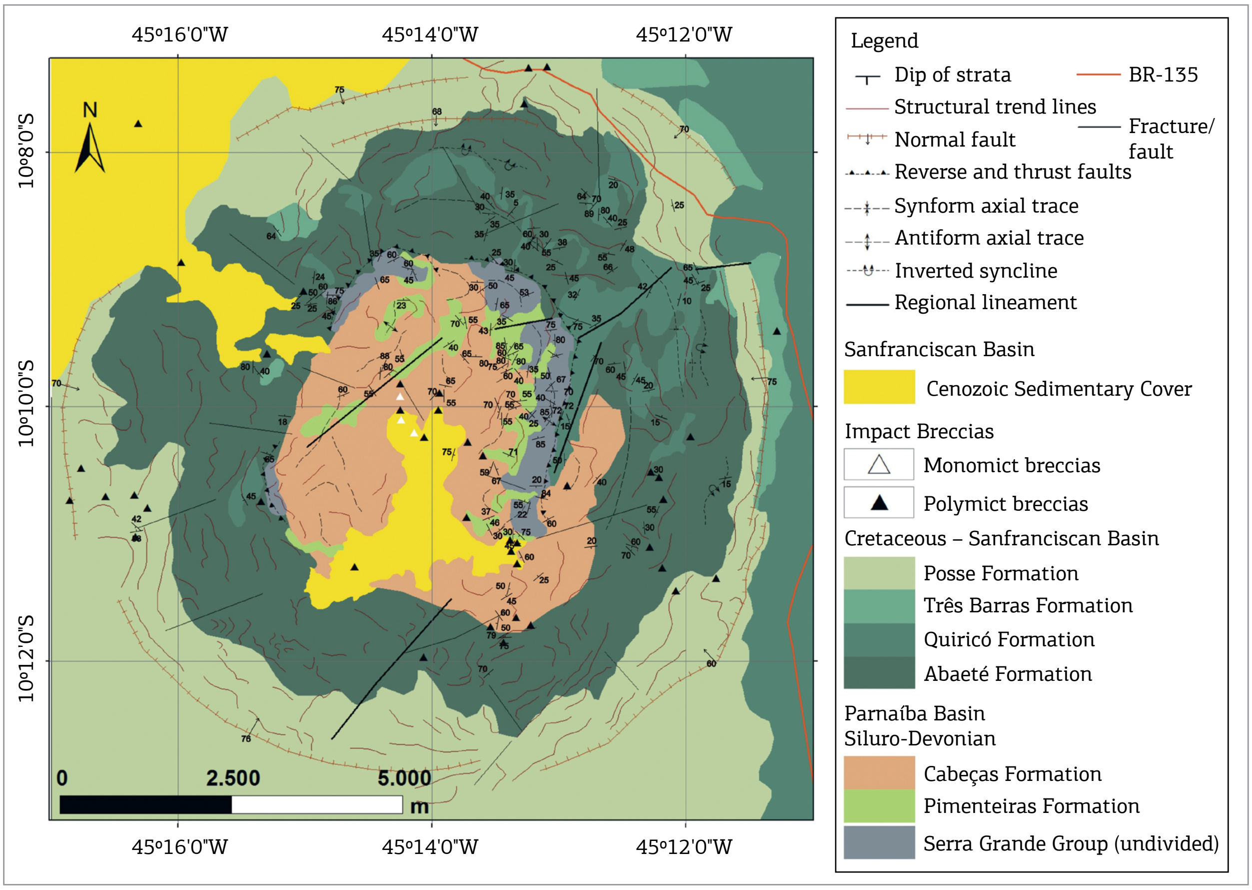


Figure 4. Geological map of the Santa Marta impact structure.

The pelitic rocks, interpreted to belong to the Quiricó Formation, have a strong brown-red color (Figs. 7A and 7C). This unit consists mainly of strata with plane-parallel bedding, and clay siltstone intercalated with thin sandy beds, in addition to shales that are occasionally interbedded with centimeter to decimeter thick calcarenite beds with a granular texture. Sedimentary structures, such as bedding and lamination, are tilted and deformed. Locally,

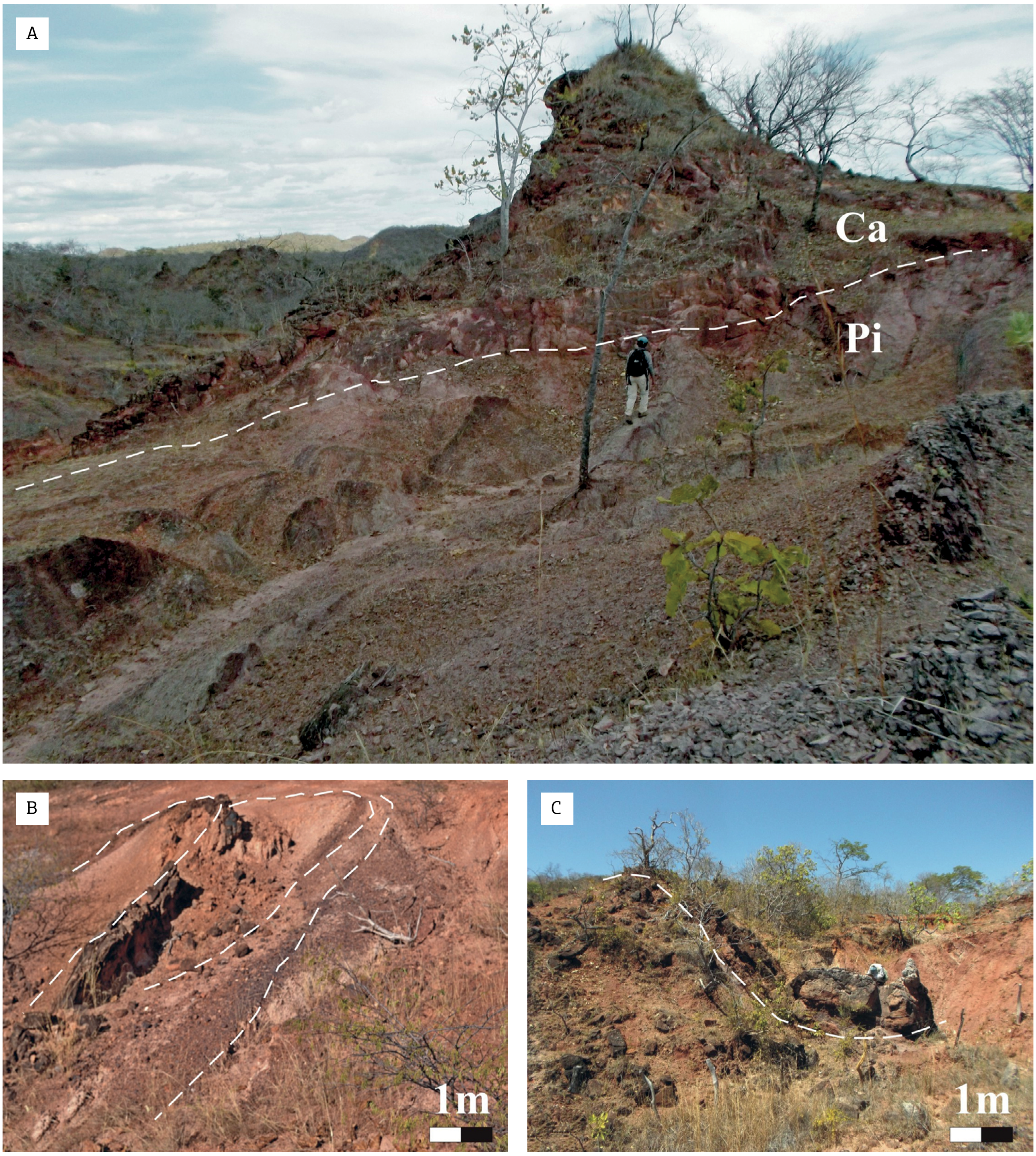


Figure 5. (A) Juxtaposition of the Devonian Cabeças (Ca) and Pimenteiras (Pi) units, verticalization of pelitic strata corresponding to the Pimenteiras Formation, and faulted sandstone megablocks of the Cabeças Formation that display different orientations of bedding are observed in the central part of the impact structure; (B) broken anticline in the central structure, showing coarser levels that stand out in the topography in relation to pelitic fractions of the Pimenteiras Formation; (C) broken radial syncline in conglomeratic sandstone of the Serra Grande Group in one of the inner rings of the structure.

different patterns of folding and fracturing occur in the outcropping strata within the synclinal annular basin of the structure. Overall, with exception of the outcrops coincident with the Senador Pompeu Lineament, the rocks of the Quiricó Formation show dominantly brittle deformation with fracturing and tilted strata and, subordinately, also show variably gentle to open folds. It is also common to observe reverse faults and drag folds. This unit was used as a stratigraphic guide to assist in the stacking of lithotypes belonging to the Sanfranciscan Basin within the structure. In this regard, structures indicating top and base of layers, such as desiccation cracks (Fig. 7C) and cross-bedding, were particularly useful.


Figure 6. Multiple shatter cones surfaces on a sample of pink sandstone in a central part of the impact structure.

The Três Barras Formation covers the second-lowest area extent among the outcropping units of the Santa Marta structure, occupying an area larger only than the occurrence of the monomict breccias. The formation consists mainly of pink-colored, fine-grained sandstones, with good sorting and high mineralogical maturity. Grains size ranges from fine to medium sand, and the sandstones have an authigenic kaolin cement. These sandstones have little resistance to weathering, being extremely friable. This feature, combined with

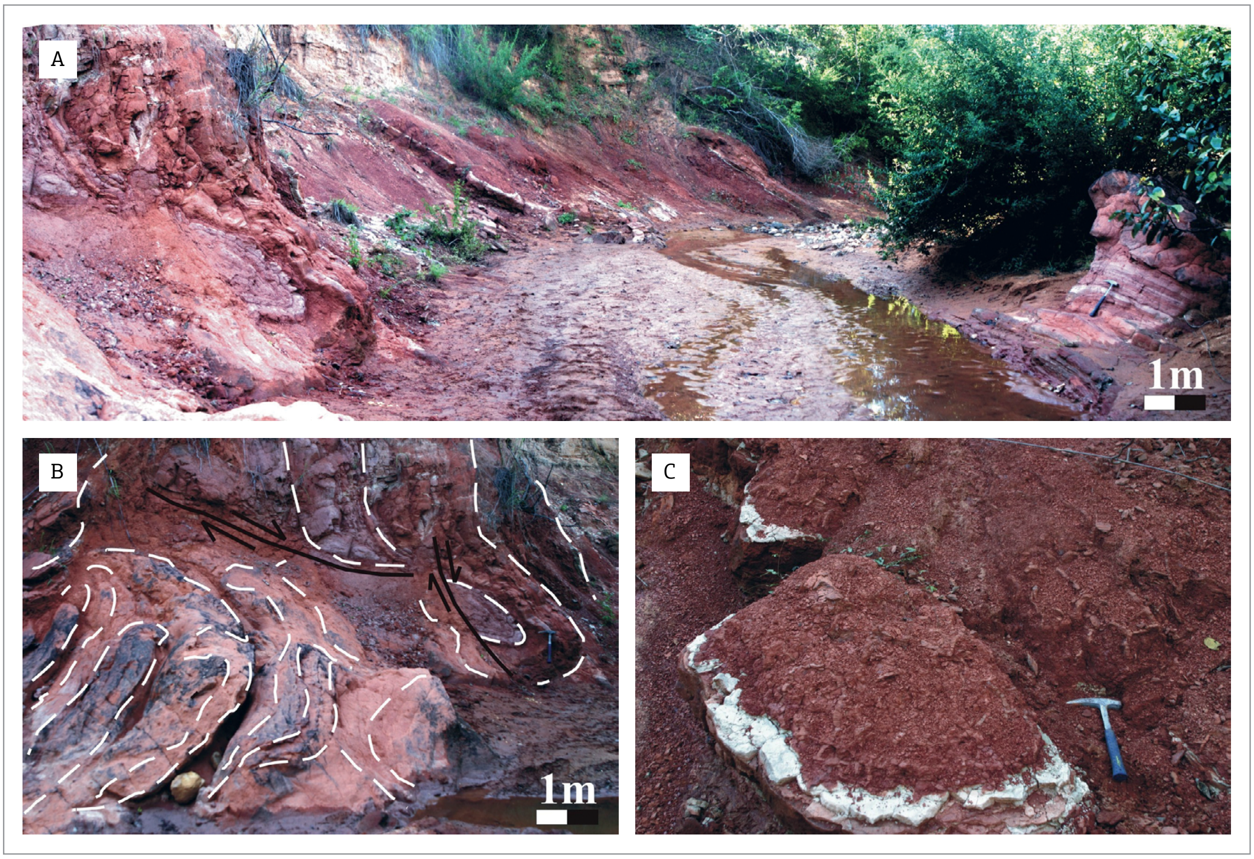


Figure 7. (A) View of the outcrop on the banks of the Canabrava creek, displaying red pelites of the deformed Quiricó Formation in tectonic contact with bimodal sandstone of the Abaeté Formation. Both strata are overlapped by young unconsolidated alluvial deposits without deformation (light colors — uppermost); (B) tectonic juxtaposition (normal fault) in the bed of the Canabrava stream between the red pelites of the Quiricó Formation (down block) and bimodal sandstone belonging to the Abaeté Formation (uplifted block). Both may be folded and/or tilted; (C) red pelites of the Quiricó Formation show desiccation cracks used as indicators of overturned strata.

the fracturing and exposure of strata to climatic agents, facilitated the preferential weathering and erosion of these rocks.

Sandy sedimentary rocks interpreted to belong to the Posse Formation of the Urucuia Group occur at higher altitudes in the outermost part of the structure. The formation consists of fine- to medium-grained sandstones that are well sorted and exhibit large-scale cross-bedding. This unit is intensely deformed within the perimeter of the impact structure and can exhibit both brittle deformation with frequent fracturing and tilting, and, less frequently, more ductile deformation in the form of flexural folds, which sometimes may have ruptured limbs. These sandstones usually occur associated with polymict impact breccias. Their deformation varies according to the sectors of the structure. Rocks along the western, northern, and northeastern outer limit show intense silicification, with recrystallization of sandstones and fluidal texture noted in places. Silicification also affects the polymict breccias. Except in the CU, the rocks of other sectors only rarely show intense silicification or ductile deformation. The deformation of the sandstone strata, in particular those outcropping in the roadcuts of the BR-135 highway (Fig. 8), resulted in intra/interstratal detachment, involving recumbent folds with vergence towards the NW and injection of interstratal breccia levels. Intra/interstratal detachment is associated with the presence of a subtle heterogeneity, for example with respect to different mineralogical composition or change of texture of the rock package at the base of large-scale sets of cross-bed, creating planes of weakness that were opened and filled with polymict impact breccia in the final, extensional stages of crater formation.

Rocks formed by the impact

Breccias ("impact breccias") are the main rocks in terms of volume produced by impact processes (Stöffler & Grieve 2007). Impact breccias observed in the Santa Marta structure can be classified into two types: polymict breccias, which are comparatively more abundant and more widely distributed, and monomict breccias of less frequent occurrence. A brief summary of the different types of impact breccias recognized in the structure is given in Table 1. Among the different types of breccias interpreted as impact breccias, only the monomict sandstone breccia and one of the numerous samples of polymict breccias that occur at the top of Sinésio Hill present shock features, whereas the other breccias are interpreted as impact-related based on stratigraphic and structural relations observed in the field.

The monomict breccias are restricted to the center of the structure and occur in steep-slope areas along the edge of

Figure 8. Sandstones of the Posse Formation at the northern edge of the structure (BR-135) that are intensely deformed with intra/interstratal injection of polymict lithic breccia (dark brown).

Table 1. Different types of impact breccia recognized in the Santa Marta structure.

Breccia type	Short description	Location	Breccia nature
Pelitic monomict	Clasts of pelitic rocks up to a meter in size within a fine-grained matrix with cataclastic texture and flow structures.	Steep-slope areas around the perimeter of the CU.	Possible impact breccia
Sandstone monomict	Clasts of coarse-grained, poorly sorted sandstone; clasts may exhibit shatter cones, as well as PDFs in quartz fragments (grain sizes ranging from medium to coarse sand).	Top of the CU.	Impact breccia
Chert monomict	Intensely silicified breccias with clasts reaching more than 20 cm in size.	Annular basin and outer rim of the structure.	Possible impact breccia
Polymict lithic	Clasts of coarse grained, poorly sorted, different types of sedimentary rocks; some quartz grains display PDFs.	Top of the CU.	Impact breccia
Intra/inter-strata polymict lithic	Poorly sorted clasts of different types of sedimentary rocks, of different sizes and shapes, arranged in flow structures.	Occurs as injection breccias on the slopes of the central elevation and around the outer rim of the Santa Marta structure.	Possible impact breccia

CU: central uplift; PDF: planar deformation feature the CEP, at elevations around 660 m (Fig. 9A). Two distinct types of monomict breccia were recognized, both formed by *in situ* brecciation. They have different frameworks, one being constituted of pelitic rock fragments and the other one of sandstone fragments. Intensely silicified breccias occur widely distributed in the annular basin and in the outer part of the structure. They form chert blocks bearing clasts as large as 20 cm. This chert was formed by almost complete substitution of the original mineralogy of the precursor rock by silica.

The monomict pelite breccia is composed of pelitic clasts that can reach up to a meter (Fig. 9B). These clasts can occur within an injection of fine-grained matrix (impact breccia dykes, with cataclastic texture and flow structures), frequently observed among the pelitic clasts. These injections are composed of coarse-grained, poorly-sorted fragments that display intense deformation resulting from cataclasis of the original sandstone rock, with comminution of grains and displacement between the fragments. Quartz aggregates (clasts) of different sizes and shapes are surrounded by irregular and heterogeneous clusters of silicate material with cataclastic textures and flow structures. Much of the pre-existing sedimentary features have been obliterated. The monomict sandstone breccia can display clasts with shatter cones, as well as planar deformation features in quartz grains and in quartz aggregates that range in particle size from medium to coarse sand (Oliveira *et al.*, 2014).

Polymict lithic breccia (Stöffler & Grieve 2007) occurs dispersed throughout the Santa Marta structure. Different polymict lithic breccias recognized as impact products were divided into two categories: polymict lithic and intra/inter-strata polymict lithic. Polymict lithic breccia is composed of a mixture of clasts of sedimentary rocks from the different pre-impact sedimentary strata, ranging from a few to several centimeters in size, poorly-sorted, with the majority of the clasts showing angular shapes within a silty-to-sand groundmass. Most of the collected samples do not show shock features in mineral grains. Despite the wide distribution of these breccias,

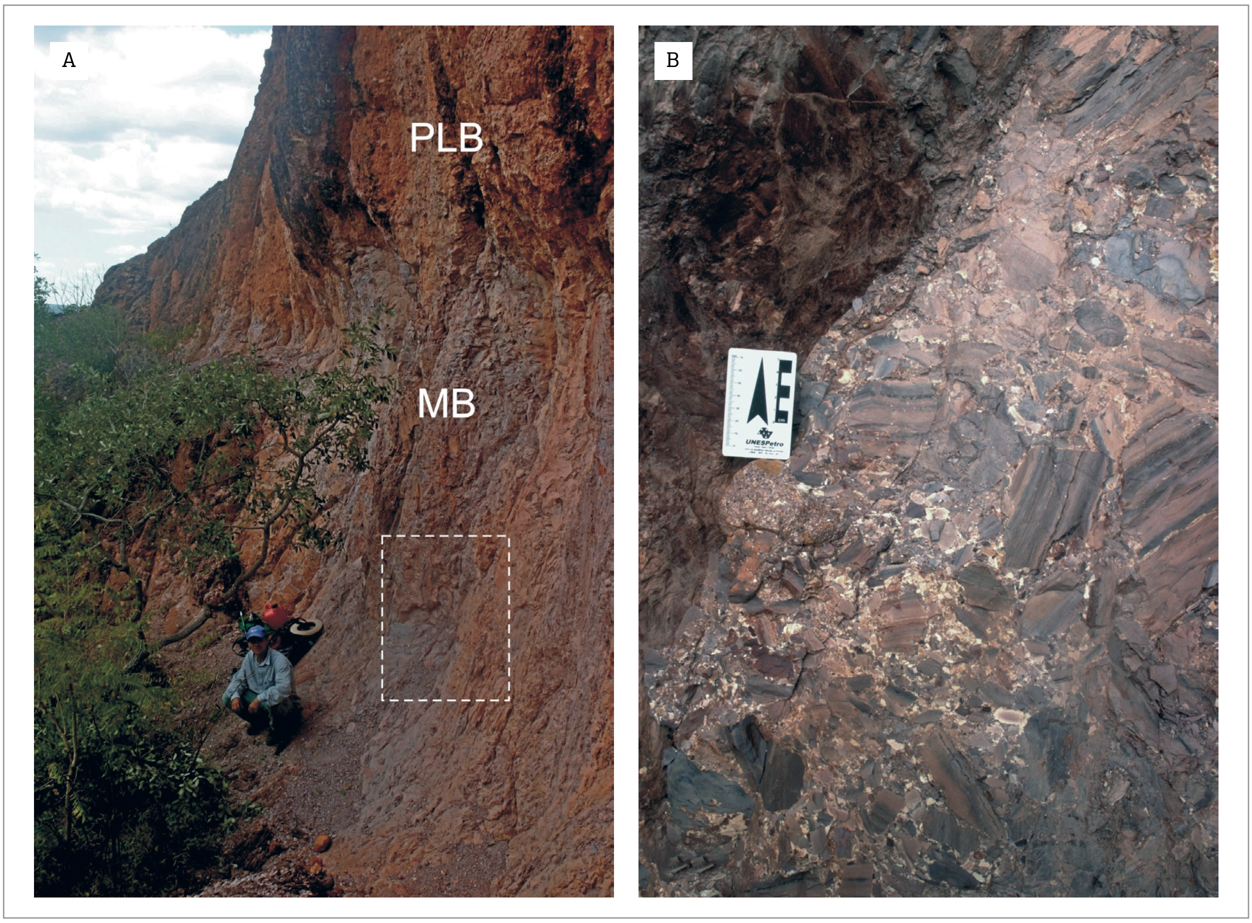


Figure 9. (A) View towards the SE of an outcrop at the center of the Santa Marta structure, at the foot of the location known as Sinésio Hill (Fig.3A), whose base consists of monomict breccia formed by pelitic rock fragments and that is overlain by polymict sedimentary breccia forming the central elevated plateau (CEP); (B) detail of the monomict breccia formed by pelitic rock fragments (MB).

only at the top of the CEP polymict breccia with clasts displaying diagnostic shock micro-deformation was observed (*GPS point and sample SM348*, Fig. 10). When the polymict breccias occur as injected breccia bodies, on the slopes of the central elevation and along the outer limit of the Santa Marta structure, they were called intra/inter-strata polymict breccia. Clasts of different sedimentary rocks, of <4 cm size and different shapes, are poorly sorted and show significant comminution of grains between the clasts. These breccias usually exhibit fluidal structure and are intensely silicified.

Post-impact sedimentary cover

A type of breccia different from those formed by the impact processes occurs at and on the CEP, partially covering the uplifted Paleozoic units in the center of the structure (CU). These breccias show a westward lateral continuity beyond the crater area (Figs. 3 and 4). The best exposures are in the Sinésio Hill area (Fig. 1), in the eastern portion of the CEP, where they have an exposed thickness of approximately 50 m (Figs. 9 and 11). It is a poorly-sorted polymict breccia with clasts ranging in size from 3 mm to 3 cm immersed in a clay matrix with a highly ferruginous component that gives it a strong red color. Clasts vary from subangular to subrounded and consist of fragments of different sedimentary rocks that are polymodal in granulometry and have different shapes (ranging from subangular to subrounded). The main clast components are quartz, pelite and sandstone fragments, and chert.

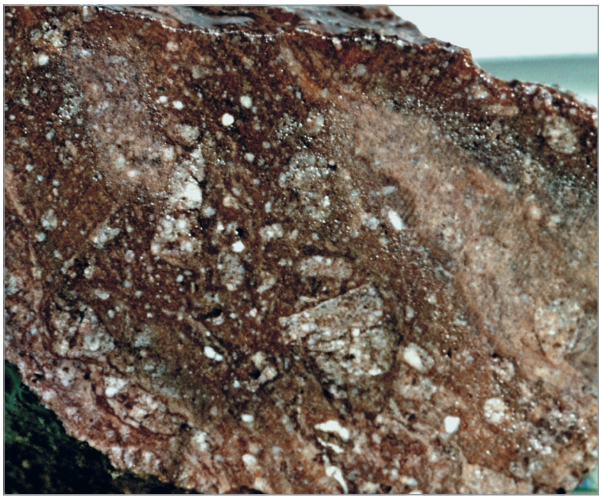


Figure 10. Polymict lithic impact breccia intensely silicified with clastic texture and aspect of fluidal texture. A sample from this exposure at the top of the central uplift, an intensely silicified sample of which gave thin sections that displayed planar deformation features (PDFs) in quartz clasts (SM348; see Fig. 16b).

Thorough analysis of this breccia under the microscope showed total absence of shock deformation features in clasts, despite the fact that, to some degree, reworked precursor material from the crater area could have been admixed if this breccia had been generated locally. The breccia forms very homogeneous packages that are massive and lack any indication of deformation. They seem to represent a unit of regional occurrence that is not restricted to the area of the Santa Marta structure.

The absence of shock deformation features allows to infer that the source material for these deposits is not genetically related to the Santa Marta impact structure, but rather was supplied from outside of it. Forming the uppermost part of the local stratigraphy, this sedimentary breccia can be temporally assigned to post-impact sedimentary processes. In this study, this unit was informally called "detrital cover" (Fig. 11).

Deformation of the strata

In meteorite impact structures, deformation cannot be explained using only endogenous deformation models and

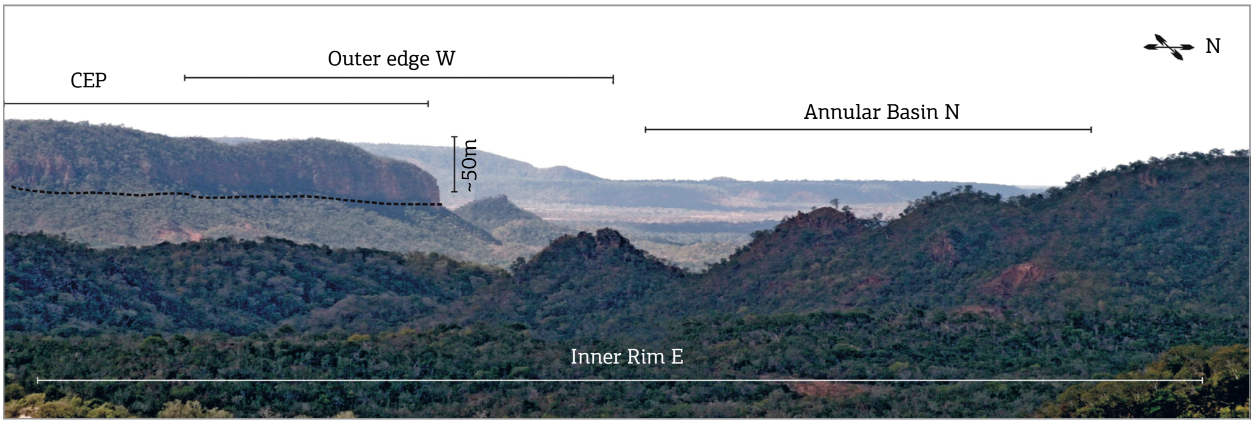


Figure 11. View of the detrital cover that partially overlies deformed Paleozoic rocks in the central structure, at Sinésio Hill, corresponding to the central elevated plateau (CEP). Note the prominent escarpment formed by this unit.

patterns (Kenkmann *et al.* 2014). Besides faulting and folding, deformation related to impact structures usually involves thickness variations, discontinuities, megablocks (Fig. 5A), and *in situ* brecciation. In addition to structural contacts between different lithotypes, up- or overturned strata commonly occur along the perimeter of the central uplift and along the rim of the structure, with frequent injections of polymict breccia of different compositions and origin, often exhibiting fluidal texture.

Deformation caused by large bolide impact is generally heterogeneous and tends to be complex and chaotic — with increasing intensity and complexity towards the center of an impact structure, sometimes mixing brittle and plastic deformation features, with the latter being more restricted in spatial extent.

Brittle deformation in the Santa Marta structure occurs in all observed units, with the exception of the detrital cover (Fig. 11). The brittle deformation is heterogeneous and irregular, and is of wide scope, occurring in all morpho-structural domains and affecting all lithotypes, albeit with varied intensity. Commonly observed evidence involves different degrees of fracturing and *in situ* brecciation. Ductile deformation is of restricted occurrence and is conditioned by lithology and spatial location, being commonly observed in fine-grained rocks near the slopes of the central uplift and in intra/interstratal polymict lithic breccia occurring on the slopes of the central elevation and along the rim of the structure.

The sedimentary rocks of the Parnaíba and Sanfranciscan basins in the neighborhood of the Santa Marta structure show no evidence of ductile deformation prior to the impact. Structures related to soft-sediment deformation are restricted to the Três Barras Formation/Areado Group, and are specifically represented by sand injectites. These structures are probably associated with seismic events contemporaneous to the deposition of this unit (Chamani 2015), and are not observed within the crater. Therefore, all the ductile deformation observed in the Santa Marta structure was seemingly generated by the impact event.

Given its complexity, the deformation associated with the Santa Marta impact structure was analyzed separately for each of the morpho-structural domains (Fig. 3). The block diagram in Figure 12 presents the main structural features

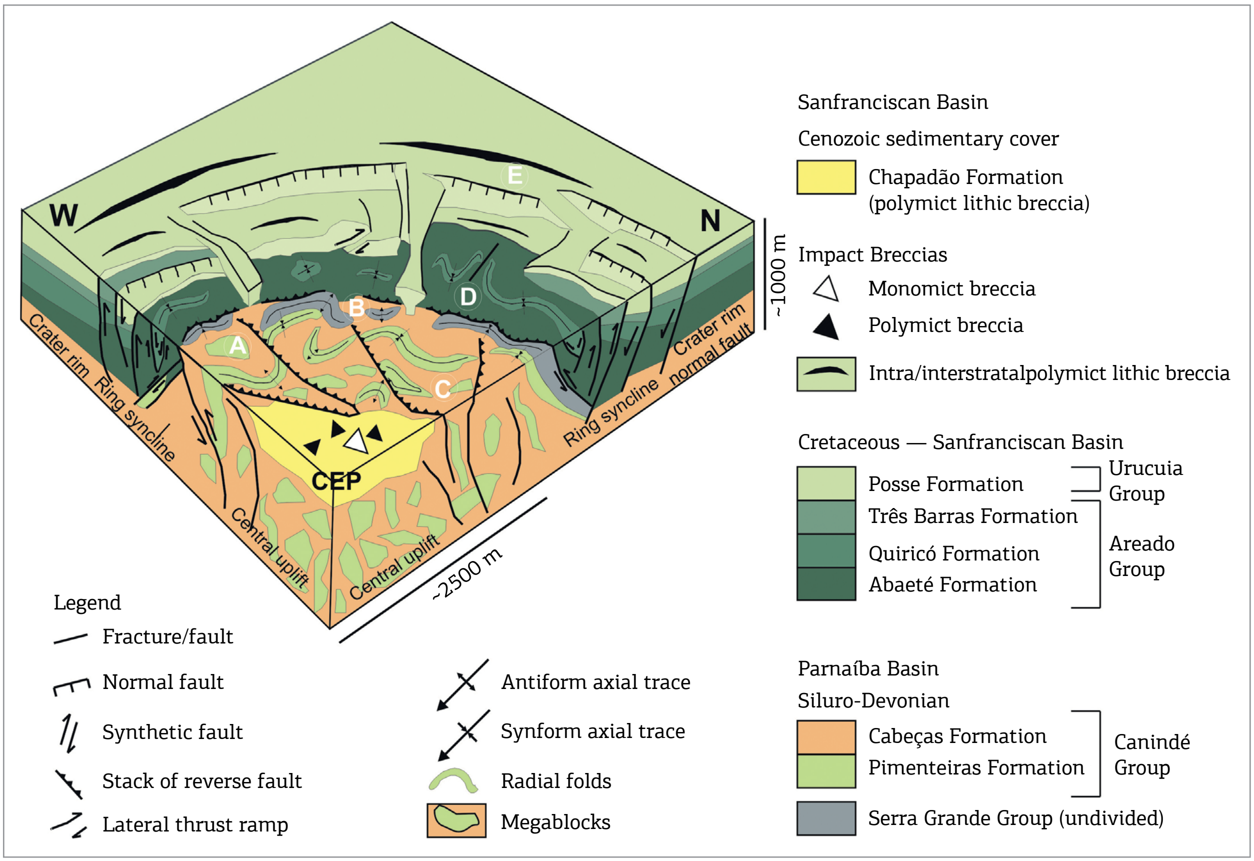


Figure 12. Schematic block diagram showing the main geological and structural characteristics of the Santa Marta impact structure. A to E refer to: central uplift (A, B and C), annular basin (D) and outer edge (E). The central elevated plateau (CEP) (in yellow) partially covers deformed Paleozoic units in the center of the structure, but it is undeformed itself.

for each domain (CU and CEP, annular basin, and outer zone) of the Santa Marta structure. This representation is simplified and schematic, as the actual deformation occurring at the meter-to decameter-scale is much more complex than what can be reasonably shown in such a sketch.

In the Paleozoic units of the central uplift (Figs. 12A-12C), the intense deformation is chaotic. Disruptive features such as fractures and faults are prevalent, and *in situ* fracturing and brecciation of rocks are common. They are more intense in the center of the structure, where they are associated with the development of the monomict breccias previously described (See "Rocks formed by the impact" section). More rarely, plastic deformation features occur in fine-grained sandstone of the central structure. Megablocks of various sizes and arrangements are common in the central area (Fig. 12A). Among the different megablocks, those made up of pelites and sandstones, interpreted to belong to the Devonian Pimenteiras and Cabeças formations (Fig. 5A), are dominant.

Discontinuous exposures of radial anticlines and synclines (Figs. 12B and 12C) are common along the periphery of the central uplift, especially where the topography is sustained by rudaceous strata of the Serra Grande Group (Figs. 5C and 12B). The rudaceous strata of the Serra Grande Group are variably shallow- to steeply-dipping. These rocks exhibit a concentric and radial distribution of open asymmetric folds. Where there is alternation between pelitic sedimentary successions and centimeter-thick layers of sandy conglomerates of the Pimenteiras Formation, isolated recumbent folds are common, as a result of rupture and detachment of the radial anticlinal and synclinal folds (Figs. 5B and 12C). Reverse faults and drag folds are abundant. Attitudes of the Paleozoic strata in the CU exhibit fairly dispersed patterns, with remarkable concentrations of bedding planes showing shallow to steep dips toward NE (Fig. 13).

The contact between the Paleozoic units of the CU and the Mesozoic units of the annular basin is marked by faults dipping towards the outer rim of the structure. Asymmetric overturned folds with vergence towards the center of the structure and extensive inverted flanks are associated with these faults, affecting both, the Mesozoic units in the inner limit of the annular basin and the Paleozoic units on the border of the CU. Movements along these faults are associated with both, the formation of the CU and the compressive stresses generated during the final stages of crater formation, thus resulting in a complex kinematic history. The compressive stresses responsible for this deformation are likely generated by outward flows associated with gravitational collapse of the CU, interacting with simultaneous inward flows of material moving from the cavity ring (Kenkmann *et al.* 2014).

The annular basin, or ring syncline, corresponds to the topographically depressed area between the rim and CU. It contains several concentric but discontinuous inner rings formed by rudaceous strata that may belong to the Serra Grande Group (Fig. 12D). The ring syncline is not a simple synform. Thus, in order to analyze the deformation, the annular basin was subdivided into segments. Between the crater rim and the axis of the ring syncline there are a number of concentric normal faults trending along NE-SW and NW-SE. The strata are often inclined or vertical. Overturned bedding is common closer to the outer rim, with frequent overlap of reddish pelites of the Quiricó Formation onto conglomeratic sandstones of the Abaeté Formation. Bedding plane dip angles tend to be low near the center of the structure, whereas near the rim they mainly exhibit high angles.

The outer rim is characterized by frequent normal faults and accentuated topographic roughness (Fig. 12E); the northwestern portion of the rim is partially covered by the younger detrital cover. The sandstones of the upper sequence of the Sanfranciscan Basin (Três Barras and Posse formations) are limited to the rim of the structure and show low outward-directed dips. These sandstones are occasionally steeply upturned along the inner rim, and separated by abundant normal faults. Normal faults tend to dip towards the center of the structure, with dip angles between 60 and 80°. Sandstone outcrops belonging to the Três Barras Formation are discontinuous and show an advanced stage of weathering and erosion. The eolian sandstones belonging to the Posse Formation show intense brittle and ductile deformation and are sometimes associated with intense silicification.

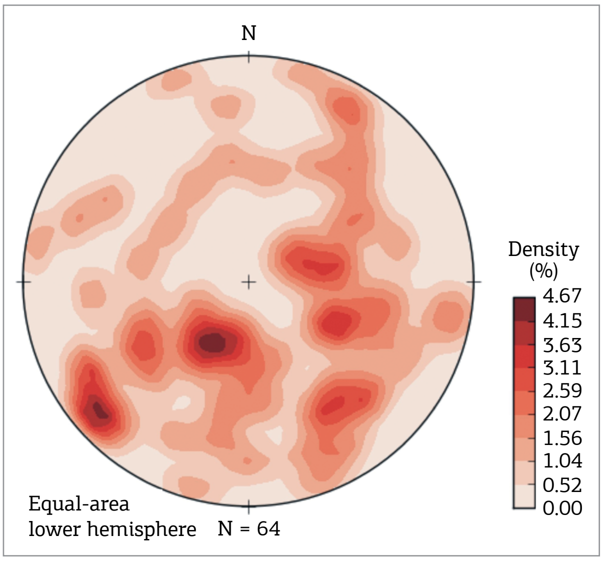


Figure 13. Stereogram with density (%) of poles to bedding planes for the Paleozoic units of the Parnaíba Basin, measured in the central portion of the Santa Marta structure (Schmidt diagram, lower hemisphere projection).

Injections of intra/interstrata polymict breccias, as observed in a section of the BR-135 highway (Fig. 8), are also common among the discontinuities of this unit (especially among large-scale sets of cross-beds).

Attitude measurements of the bedding of the Mesozoic units in the annular basin and outer rim are less numerous in the western and southern portion of the structure. It is because the access to these sectors of the Santa Marta structure is difficult and outcrops are scarce due to the widespread occurrence of the detrital cover. Bedding planes are predominantly shallow-dipping and EW trending, with subordinate orientations in NE-SW and NW-SE directions and then showing comparatively steeper dips (Fig. 14). The distribution of the highest concentrations of poles reflects the influence of concentric synforms in the SE and NE portions of the structure.

The ductile deformation exhibited by intensely deformed sandstones, monomict sandstone breccia, and, to a lesser extent, by polymict lithic impact breccias (Fig. 10), records the deformation mechanisms active during the formation of the CU. Observations made in thin sections of monomict and polymict impact breccias suggest that there was almost complete loss of internal consistency during deformation (Fig. 15A). The loss is mainly due to grain crushing and collapse of pore space. The fluidal aspect is commonly associated with intense silicification, which may or may not be associated with ferruginous cement around the grains of the framework. The fragments locally remained close together, with some displacement between them after cataclasis, but still retaining impressions of the original grain contours. However, sometimes they have become completely separated, obliterating the original shapes of the grains. Rotated and even stretched grains and rock fragments also occur. At the top of the central elevation, monomict breccia and intensely silicified sandstone of "cooked" appearance and increased cohesion and strength were found. In thin sections, these rocks exhibit shock microdeformation including PDF, PF and FF, as well as sutured contacts between quartz grains of the framework. Micaceous minerals were squeezed between the stronger grains of the framework (Fig. 15B).

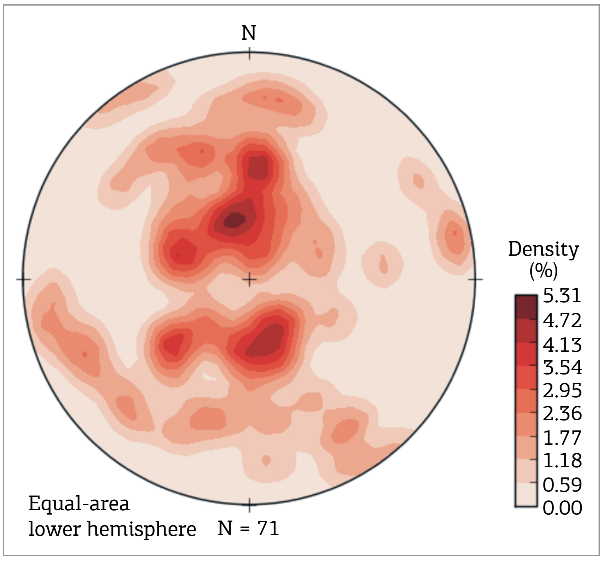
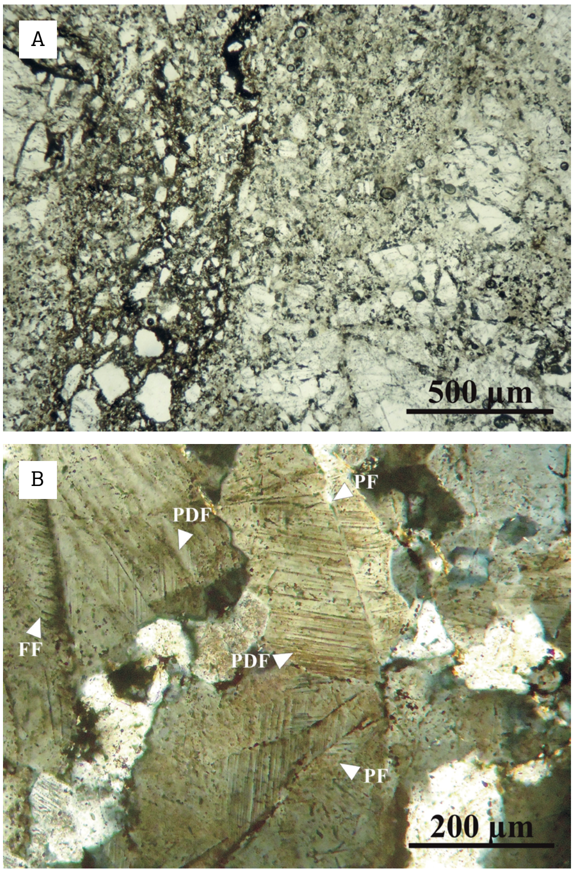


Figure 14. Stereogram with density (%) of poles to bedding planes of strata of the Mesozoic units of the Sanfranciscan Basin in the annular basin and along the inner outer rim of the Santa Marta structure (Schmidt diagram, lower hemisphere projection).



PDF: planar deformation feature; FF: feather feature; PF: planar fracture.

Figure 15. (A) Photomicrograph of monomict sandstone breccia from the central uplift (CU) (sample SM17b), in plane polarized light, displaying intense fracturing of the framework grains, and collapse of the pore space that is also associated with intense silicification and that, to a lesser extent, is filled with ferruginous cement. The clastic groundmass locally yields a fluidal aspect (plane polarized light); (B) photomicrograph of polymict lithic impact breccia (sample SM348; Fig. 10) from the top of the CU, displaying coarse sandstone clasts and quartz grains displaying sutured contacts and intense deformation, with frequent shock microdeformation (PDF, FF, PF).

The main drainage channels within the Santa Marta structure, the Mocambinho and Canabrava creeks, are controlled by a linear feature with ENE-WSW orientation. This is likely related to the Senador Pompeu Lineament, an important regional tectonic feature (Cordani *et al.* 1984). Outcrops coincident with this linear feature exhibit ductile deformation and intense silicification (Figs. 16A and 16B). Kinematic indicators, like asymmetric folds and clasts with asymmetrical or rolled tails in conglomeratic sandstone of the Abaeté Formation, suggest sinistral strike-slip movement and localized reactivation of this tectonic feature, which may have been caused by the impact event. Alongside of the Canabrava creek recent alluvial deposits with thicknesses in the range from 0.5 m to little more than 10 m in the central area of the Santa Marta structure are currently excavated by the drainage, indicating recent tectonic reactivation causing erosion.

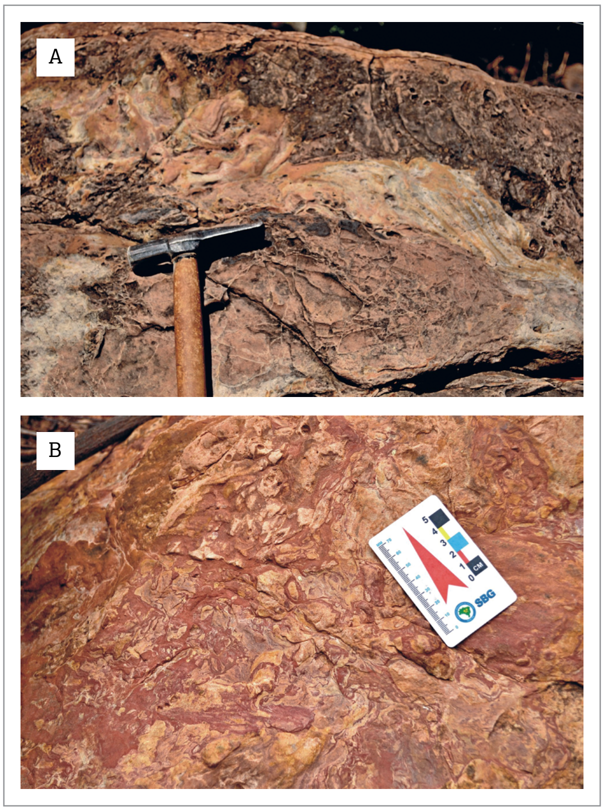


Figure 16. Outcrops at the northeastern edge of the Santa Marta structure coincident with the extension of the Senador Pompeu Lineament inside the structure. (A) Conglomeratic sandstone of the Abaeté Formation, exhibiting intense deformation and silicification; (B) intensely deformed red pelite of the Quiricó Formation. Note that ductile deformation is not common among Mesozoic lithotypes at the outer edge of the structure. This deformation is equally intense both in the pelites of the Quiricó Formation and in the conglomeratic sandstones of the Abaeté Formation.

DISCUSSION

The lithostratigraphic classification of the Paleozoic sedimentary strata that occurs within the Santa Marta structure, and that is thought to belong to the Serra Grande and Canindé groups (Pimenteiras and Cabeças formations), was hampered by the absence of geological mapping at an adequate scale in the region outside the structure, as well as by the deformation of rocks, which is more intense and complex in the center of the structure. Levels with ferruginous ooids, nodules and concretions are typical of the Pimenteiras Formation (Lima & Leite 1978; Kegel 1953). Thus, the occurrence of levels of ferruginous discoidal concretions, as well as structural and stratigraphic field relationships (such as overturned top-base indicators and sedimentary features like cross-stratification that are associated with the conglomeratic sandstones), allowed the association of Paleozoic pelitic facies with this unit. The less deformed Mesozoic sedimentary deposits that occur within the structure correspond to Cretaceous and Cenozoic rocks belonging to the Abaeté, Quiricó and Três Barras formations of the Areado Group, to the Posse Formation of the Urucuia Group, and to the Chapadão Formation of the Sanfranciscan Basin, respectively.

Meteorite impact structures exhibit a wide range of deformation features, formed under different conditions of pressure and temperature, and during extremely reduced time intervals (i.e., at very high strain rates). Maximum pressures and relatively higher deformation rates are achieved early in the impact process, when shock waves pass through the target rocks at hypervelocity. The deformation phases range in time from microseconds to minutes, occurring at all stages of crater formation (French 1998; French *et al.* 2004; French & Koeberl 2010; Kenkmann *et al.* 2014). Thus, understanding and interpreting the different deformation patterns in impact structures are a challenge (Kenkmann *et al.* 2014).

The main structural characteristics of the different morpho-structural domains of the Santa Marta structure show variations in deformation resulting from both the stress to which the rock material was exposed and to heterogeneity of the sedimentary strata that occurs within the structure (Fig. 12). The main heterogeneity is a direct consequence of the lithologic variation between the different stratigraphic units and their thicknesses in the area of the Santa Marta structure. However, other discontinuities, such as set limits in the cross-bedding of eolian sandstones and the alternation between coarse-grained and fine-grained sedimentary rocks within a lithostratigraphic unit (Fig. 8), are reflected in the deformation complexity in the Santa Marta structure. Under high stress conditions, the set limits of eolian sandstone cross-bedding can create space that afterwards may be occupied by polymict breccias. Heterogeneity of grain size and different thicknesses of strata can produce parasitic and disharmonic folds within thin strata, mainly in pelites and thin sandstones.

Different lithologies exhibit different behavior under the stresses to which they were exposed. In general, rudaceous and coarse-grained psammitic facies behave as rocks of greater competence, resulting in erosion resistant rocks that often sustain elevations higher than the surroundings inside the structure. Rudaceous facies of the Serra Grande Group sustains the tops of elevations corresponding to the inner rings demarcating the Paleozoic units in the central area of the structure. Conglomeratic sandstones of the Abaeté Formation can occur on both the tops of inner rings in the annular basin and overturned beds near the outer rim of the structure. Thicknesses of sedimentary strata and lithologic variations have been considered as determining factors in the face of significant structural differences between terrestrial impact structures of complex type and moderate size, and formed in sedimentary targets. The existence or absence of inner rings is one of the differences observed by Kenkmann *et al.* (2013) in such structures. The inner rings of the Santa Marta structure are not only related to sedimentary thickness, but also to the recurrent rheological contrast between sedimentary strata in the structure.

The CU region is the area where Paleozoic strata of the Parnaíba Basin are exposed. Considering the structure's 10 km diameter and the estimated depth to the basement in the Santa Marta area, as determined by evaluation of geophysical data (Vasconcelos *et al.* 2010), it is possible that the stratigraphic units in the central part of the structure have been subjected to an uplift of around 1,000 m, as suggested by Oliveira *et al.* (2014). This estimate is consistent with the ~920 m uplift by the equation proposed by Grieve and Pilkington (1996). The rocks currently exposed in the CU region were subjected to peak shock pressures of around 20–25 GPa, as indicated by the crystallographic orientations of PDFs in quartz grains (Oliveira *et al.* 2014).

The increase in complexity of the deformation towards the center of the structure is interpreted as a response to increased constriction by the movements of the rock material towards the center, and it is possibly also associated with the outward flows generated by gravitational collapse of the CU (Kenkmann *et al.* 2014). The ring syncline in Santa Marta, as well as in other terrestrial impact structures of the complex type, cannot be considered as a simple synform. The deformation tends to be complex and heterogeneous, increasing in intensity and complexity towards the center of the structure. From the syncline axis towards the rim, faults are frequently observed along non-planar surfaces which, according to Kenkmann *et al.* (2013), are often associated with antithetic or synthetic rotation of basement blocks.

The outer rim of the structure is delimited by annular normal faults, with frequent injections of intra/interstrata polymict breccia, which occurs generally when there is a discontinuity in the deformed rock, enabling the detachment and opening of spaces between layers and faults/fractures (Fig. 8). On the western edge of the structure, sharp breaks in the relief and narrow valleys that form the drainage network are common, forming morphological grooves ("gullies") in the relief, which may be associated with the partial degradation of the outer rim. Just as in the annular basin, there are also occurrences of shatter cones on the outer rim of the structure, as well as PFs in quartz grains from these rocks, although not as frequent as in the inner parts of the structure. The shatter cones are mostly restricted to the interior of quartzite blocks in conglomerates. Lack of PDFs suggests maximum shock pressure for this outermost zone of 8–10 GPa (Huffman and Reimold 1996).

Breccias are, in terms of volume, the main product of the impact (Figs. 9 and 10). Shock microdeformation features in quartz grains of clasts from a polymict breccia sample collected at the center of the structure confirm their origin by impact, allowing their characterization and differentiation from sedimentary breccias that form the detrital cover in the central area of the structure (Figs. 10, 15A and 15B).

At Santa Marta, the polymict breccias exhibit different patterns of occurrence. They occur intensely silicified at the top of the CEP (Figs. 10 and 15A), recording the deformation during the formation of the CU. They are easily distinguished from the injection breccias, which are associated with the opening of intra/interstrata spaces, enabling material accommodation during excavation and collapse of the transient crater (Fig. 8). They also occur as chert breccias (Oliveira *et al.* 2014) that would be related to the final phase of the crater formation, with intense silicification associated with hydrothermal processes, which likely remained active for some time after the formation of the structure. In turn, these different breccias allow to establish a temporal scheme for their formation.

The ductile appearance displayed by different lithotypes, including sandstone of the Cabeças Formation, monomict sandstone breccias, and polymict breccias of the CU, differs from that one shown by intra/interstrata polymict breccias, both in the central elevation and in the outer rim. Flow textures observed in the layers of the Cabeças Formation were formed by crushing of framework grains, followed by the collapse of pore space, and setting off cataclastic flow in the first seconds of the crater formation process. On the other hand, the flow aspect exhibited by intra/interstrata breccias is the result of the detachment of strata and the accommodation of the fractured and remobilized material during the opening of the transient crater and/or during the final collapse of the crater.

Microstructural analysis revealed that the macroscopically observed ductile appearance is the result of cataclastic flow (Fig. 15A). The intense silicification affecting sandstones and breccias of the CU, as well as the breccias of the outer rim of the structure, such as the chert breccias, may be related to chemical dissolution of quartz grains of sandstones of the Cabeças Formation in the center of the structure. These have sutured contacts between the quartz grains of the framework, and along grain boundaries, and at quartz aggregates (Fig. 15B), which macroscopically corresponds to the "cooked" texture of the rocks of the core. These features have not been found in other thin sections of the same unit or other units, suggesting that the chemical dissolution evidenced by the sutured contact between quartz grains would be the primary source of silica and could be related to pressure and temperature conditions arising from hydrothermal processes concurrent and/or subsequent to crater formation, and not to diagenetic processes.

Regarding the age of the Santa Marta structure, Oliveira *et al.* (2014), in the absence of melt material that could provide more accurate isotopic ages, suggested the range from 66 to 100 Ma, based on stratigraphic constraints. They used the age of the youngest strata affected by impact deformation, namely the Posse Formation of the Urucuia Group and its age range as suggested by Campos and Dardenne (1997b). However, this chronostratigraphic positioning of the Urucuia Group is not well constrained, and the late Cretaceous age is presumably based on its contemporaneity with alkaline volcanic and epiclastic rocks of the Mata da Corda Group, which occur only in the southern part of the Sanfranciscan Basin (Sgarbi *et al.* 1991). A review of the regional stratigraphic information indicates that the age range suggested by Lima and Leite (1978) for the Urucuia Group, which is a somewhat older than the age given by Campos and Dardenne (1997b), may be more accurate. This idea is corroborated by the suggestion of Chang *et al.* (1992) that the deposition of sediments of the Urucuia Group occurred in a subsidence area, associated with a change in the regional stress field during the Aptian-Albian. Thus, the maximum age range for the Santa Marta impact proposed here is 93–100 Ma (according to the age range proposed by International Chronostratigraphic Chart, Cohen *et al.* 2013), which corresponds to the deposition of the Urucuia Group (Lima & Leite 1978). Additionally, it is important to consider that the age range adopted by Lima and Leite (1978) is also based on field relations and regional correlations, as no index fossils have been found by the authors in the Urucuia sedimentary strata. Note that it has a direct implication on the dating of the Santa Marta impact structure. The recent detrital cover shows characteristics of an elluvial-colluvial nature and is stratigraphically correlated to the Chapadão Formation. This cover lies on top of the strongly deformed Paleozoic strata of the CU and shows no evidence of deformation. Therefore, our interpretation is that this cover is younger than the Santa Marta impact structure. Consequently, the age of the Chapadão Formation, which according to Campos and Dardenne (1997a) is Cenozoic, can be used to constrain the youngest age for the impact event.

FINAL REMARKS

This study contributes to the lithostratigraphic definition of Paleozoic and Mesozoic sedimentary strata that occurs within the Santa Marta impact structure. We identified the presence of rocks of the Serra Grande Group and of the Canindé Group (Pimenteiras and Cabeças formations) belonging to the Parnaíba Basin, in addition to the Abaeté, Quiricó, Três Barras and Posse formations of the Sanfranciscan Basin. A variety of lithotypes of these stratigraphic units that occur in the interior of the structure is responsible for the different responses to impact-generated stress and results in different deformation zones from the center to the crater rim, conditioned not only by their respective shock-pressure zones, but also by the respective lithotypes. The occurrence of inner rings in the Santa Marta impact structure is here interpreted as a direct consequence of variation in lithology. The thickness of sedimentary strata and lithologic variations are important factors determining the complexity of the deformation and the existence of inner rings. The analysis of shock macro- and microdeformation features has allowed to estimate pressure ranges for the different morpho-structural domains of the Santa Marta structure, with peak pressures of 20 to 25 GPa for the currently exposed rocks of the CU, and ca. 10 GPa for the rocks of the ring syncline and along the outer rim of the structure. Estimates made from stratigraphic relationships, and geophysical modeling suggest an uplift of approximately 1,000 m in the central region of the structure, exposing Paleozoic units of the Serra Grande Group in the innermost parts.

The maximum age range for the crater forming impact event is estimated between 93–100 Ma, based on the age proposed for sandstones of the Posse Formation of the Urucuia Group that occur at the rim of the structure and represent the youngest unit affected by the impact event. Regarding the youngest age, the undeformed sedimentary cover correlated to the Chapadão Formation of Cenozoic age can be used as a constraint. This cover has likely been a key factor that contributed to the preservation of the structure from more intense erosion, making the Santa Marta structure one of the best preserved impact structures in Brazil and, despite its considerable age, a still very well preserved impact structure in the global context.

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