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GEOLOGICAL RECORDS OF METEORITIC IMPACTS IN BRAZIL: EVOLUTION AND CURRENT KNOWLEDGE

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ABSTRACT

Meteoritic impacts are a rare geological process that can promote permanent transformations in crustal rocks due to the extreme pressure and temperature conditions involved. The results of such processes are the so-called “impact craters”. Over time, craters are generally modified by erosive, tectonic, and sedimentary processes characteristic of the Earth’s crustal dynamics until completely removed from its surface. Therefore, the geological record of impacts on Earth is quite incomplete, with a tendency to preserve only larger and relatively younger craters. Most known craters on Earth are just partially preserved, referred to as “astroblemes”. There are about 200 such structures currently known on Earth. Eleven confirmed impact structures exist in South America, of which nine are in Brazil. They are part of two Phanerozoic intracratonic sedimentary basins, Paraná and Parnaíba. Their estimated ages range from the Permian-Triassic transition to the Late Cretaceous. This article presents the current state of geological knowledge about these structures and their main morphological, geological, and geophysical characteristics. Some remarks are made about specific geoconservation and geoheritage actions.

Keywords: Impact structure; Impact crater; Astrobleme; Celestial bodies; Planetary geology.

RESUMO

REGISTROS GEOLÓGICOS DE IMPACTOS METEORÍTICOS NO BRASIL: EVOLUÇÃO E ESTÁGIO ATUAL. Impactos meteoríticos são um raro tipo de processo geológico que, por suas características extremas de pressão e temperatura, são capazes de promover transformações permanentes em rochas crustais. As marcas resultantes são as estruturas denominadas “crateras de impacto”. Com o passar do tempo as crateras são geralmente modificadas por processos erosivos, tectônicos e sedimentares característicos da dinâmica geológica da Terra, até serem completamente removidas da sua superfície. Por esse motivo, o registro geológico de impactos na Terra é bastante incompleto, com tendência à preservação das crateras de maior porte e relativamente mais jovens. A maioria das crateras conhecidas na Terra se encontra em um estágio parcial de preservação, recebendo a denominação de “astroblemas”. São conhecidas atualmente cerca de 200 estruturas dessa natureza na Terra. Na América do Sul há onze estruturas formadas comprovadamente por impactos meteoríticos, sendo que as nove maiores e mais antigas estão no Brasil. Elas são parte de duas bacias sedimentares intracratônicas fanerozóicas, a do Paraná e a do Parnaíba. Suas idades estimadas variam da transição Permotriássica ao Cretáceo Superior. Neste artigo é apresentada uma síntese sobre o atual estado de conhecimento geológico dessas estruturas, bem com suas principais características geológicas e geofísicas. São feitas também considerações sobre ações específicas de geoconservação e geopatrimônio.

Palavras-chave: Estrutura de impacto; Cratera de impacto; Astroblema; Corpos celestes; Geologia planetária.

1 INTRODUCTION

Impacts from celestial bodies[1] of various sizes represent a geological process of exogenous nature, present in all solid bodies of the Solar System. They form remarkable morphological features on solid planets, moons, asteroids, and comets (MELOSH 1989, FRENCH 1998). However, while in most of these objects, the resulting craters tend to remain preserved on their surfaces for long periods, this generally does not occur on Earth. The reason is that while Earth is characterized by notable crustal dynamics and a diversity of geological processes constantly transforming its surface, in the vast majority of other solid bodies in the Solar System, these processes either do not exist or, when present, act more slowly than on Earth (MCSWEEN et al. 2019).

Hence, what is observed on our planet is a rather partial record, both spatially and temporally, of meteoritic impact processes[2] that have affected Earth during its geological history. Most of the records of this nature, notably the oldest and smallest ones, have already been obliterated by processes related to the our planet´s geological dynamics, including plate tectonics and related processes, as well as erosion, transportation, and sedimentation.

As a result of impact processes on solid bodies, “impact structures” are formed. This term has been preferably used to designate any geological structures formed by the collision of a celestial body with Earth and found in any erosional stage (FRENCH 1998). The term “impact crater” is exclusively used to designate the younger structures relatively preserved from the dynamics of modification related to geological processes. For example, the craters on the Moon are generally perfectly preserved, thus applying this designation. Finally, the term “astrobleme,” originally coined by DIETZ (1960) from the Greek words “astro” for celestial body and “blema” for scar, is synonymous with impact structure, although less commonly used in the current literature.

The current number of structures formed by meteoritic impacts on our planet is relatively small compared to other planetary bodies such as the Moon and Mars. This number currently consists of around 200 structures (KENKMANN 2021). In Brazil, this number is currently nine structures that have been proven to be formed by the impact of celestial bodies.

The study of meteoritic impact processes is a relatively new field of geoscientific knowledge, having experienced significant momentum from space exploration by humanity, along with the development of Planetary Geology. Thus, starting in the 1960s, with various space missions launched by the United States and the then Soviet Union, currently Russia, and with the Apollo missions to the Moon, came the realization about the importance of studying and characterizing this type of geological process, which was until then little known and considered of secondary importance in Earth’s geological history. This conception proved to be mistaken, and it is now known that meteoritic impacts were the main process for the formation of the Solar System in its early stages of constitution and evolution and that they affected all its components, including Earth. Furthermore, impact processes provide fundamental information about planetary dynamics, the composition of planets beneath the surface, and the internal structure of planetary bodies.

In the case of Earth, impacts likely played an important role in the emergence and evolution of life on our planet, a topic that is currently the subject of intense scientific interest. The scientific view of the relationship between impacts and the emergence of life has evolved significantly in recent decades, with the current consensus focusing on impacts as a fundamental factor in providing the conditions and thermal energy necessary for the transition between prebiotic chemistry and the emergence of the first forms of life on Earth. Additionally, of the five major mass extinctions of life recorded on our planet, at least one, which occurred 66 million years ago at the Cretaceous-Paleogene boundary, is conclusively related to the event that formed the Chicxulub crater in the Gulf of Mexico (SCHULTE et al. 2010).

1.1 Meteoritic impacts: A brief history

Large-scale impacts are uncommon events when considering the human timescale, but this is

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[1] The term "celestial body" is employed here for all solid bodies coming from space, regardless of their composition and size. Therefore, the term includes meteorites, asteroids and comets.

[2] For the sake of simplification, the term “meteorite impact” is employed in this paper to mean all types of impacts of celestial bodies, regardless of the composition and size of the impacting body.

not the case in geological time. Although impacts were much more frequent in the early stages of Solar System formation and have considerably decreased in frequency over time, they continue to occur and can pose potentially serious threats and consequences to humanity.

In this regard, two relatively recent impact events are emblematic. The first was the collision between Comet D/1993 F2 (Shoemaker-Levy) and Jupiter, in July 1994. The phenomenon was monitored from Earth through ground-based telescopes, and from space through the Hubble Space Telescope and the Galileo spacecraft. The nucleus of this comet, about 4 km in diameter, had fragmented in 1992 due to Jupiter's strong gravitational forces. For six days, 21 fragments of the comet, ranging in size from a few hundred meters to ~1 km, collided with Jupiter's atmosphere, causing fireballs and plumes that reached heights of up to 3,000 km. The combined energy released by these impacts was calculated to be about 6 million megatons of TNT, equivalent to 600 times the total global nuclear arsenal (HOCKEY 1994).

The second event was the atmospheric explosion on February 15, 2013, of a meteorite 20 m in diameter at an altitude of 23 km near Chelyabinsk, a city of 1 million inhabitants in Russia (BOROVIČKA et al. 2013). The energy released was equivalent to 500 kilotons of TNT, and the resulting shockwaves caused injuries to about 1500 people, mainly due to shattered glass fragments from windows, as well as extensive material damage to thousands of buildings.

The perception of potential risks to the planet related to meteoritic impacts has reached the point where, in September 2022, NASA's DART (Double Asteroid Redirection Test) mission, specifically designed to test a method to deflect potentially hazardous asteroids to Earth, intentionally collided with the asteroid Dimorphos, 160 meters in diameter. Although this asteroid posed no risk of hitting Earth, the test results were positive (RIVKIN & CHENG 2023). They demonstrated the feasibility that, in the event of an actual collision risk being identified in the future, a mission similar to DART could prevent a disaster for the planet and humanity. Initiatives like this are part of a series of initiatives called "planetary defense" (SCHMIDT 2019), which has been rapidly developing in recent years, with strong participation from the planetary sciences community and government agencies dedicated to space exploration.

Consequently, in recent decades, meteoritic impacts have transitioned from being a geological process that did not receive much scientific attention to a natural phenomenon of fundamental importance for understanding the evolution of the entire Solar System (MELOSH 2011, REIMOLD & JOURDAN 2012, OSINSKI & PIERAZZO 2013, CRÓSTA et al. 2019a).

In Brazil, the first mentions of potential meteoritic impact structures date back to the 1960s (KOLLERT et al. 1961) and 1970s (DIETZ & FRENCH 1973). Only in the early 1980s did the first more systematic scientific studies on some specific structures of this nature in Brazil emerge (CRÓSTA et al. 1981, THEILEN-WILLIGE 1981), as well as the first list of Brazilian impact structures (CRÓSTA 1987). However, the consolidation of this area of geoscientific knowledge in our country would only occur over the last two decades, with the realization of detailed geological, geophysical, and geochemical studies synthesized by CRÓSTA et al. (2019a, b). These studies allowed establishing the meteoritic origin of nine structures in Brazil, as well as some other potential ones that still lack more solid corroborative data.

A synthesis of the current knowledge on the impact record in Brazil is presented below, with a succinct description of the main characteristics of the confirmed structures. Considerations are also made about future directions and the potential of this area of geoscientific knowledge in the country.

For those interested in the study methods of impact structures, as well as the main scientific criteria used to determine the meteoritic impact origin of a potential structure, it is recommended to consult some works that deal in detail with these themes: FRENCH (1998), FRENCH & KOEBERL (2010), REIMOLD & JOURDAN (2012), OSINSKI & PIERAZZO (2013), and CRÓSTA et al. (2019a).

2 THE BRAZILIAN RECORD OF IMPACT STRUCTURES

Brazil currently has nine meteoritic impact structures (Figure 1, Table 1) whose origin has been confirmed based on scientifically accepted criteria, as summarized by FRENCH (1998) and FRENCH & KOEBERL (2010). These structures are exclusively associated with two Phanerozoic intracratonic sedimentary basins, the Paraná Basin and the Parnaíba Basin.

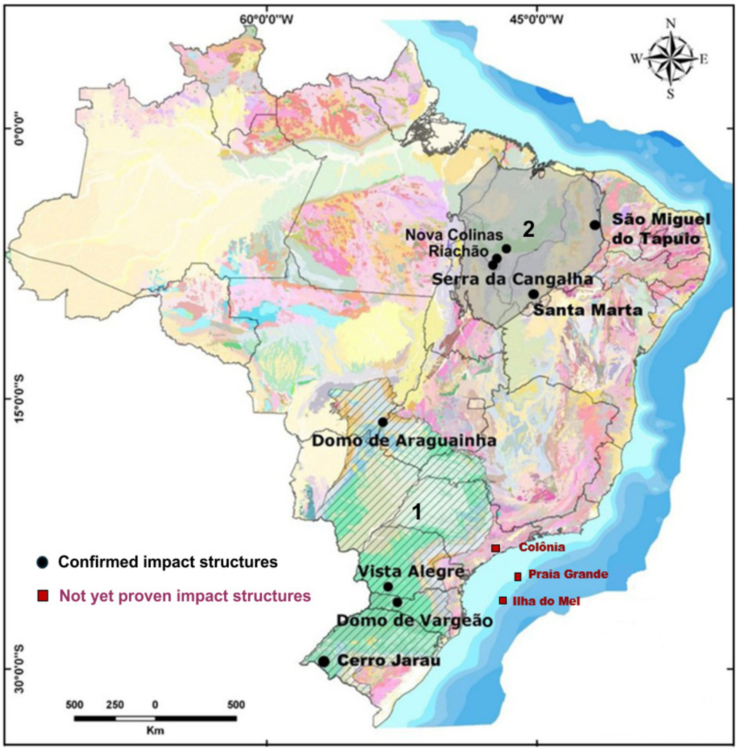

FIGURE 1 – Location map of Brazilian impact structures with the two sedimentary basins, Paraná (1) and Parnaíba (2), outlined. In the background, is Brazil´s geological chart at 1:1 million (CPRM 2004).

TABLE 1 – Confirmed impact structures in Brazil.

	State	*Latitude*	*Longitude*	*Diameter*	*Age (Ma)*
Domo de Araguainha	MT/GO	16º 49’ S	52º 59’ W	40.0	254.7 ± 2.5
Vista Alegre	PR	25º 57’ S	52º 41’ W	9.5	<132
Domo de Vargeão	SC	26° 49’ S	52° 10’ W	12.4	<132
Cerro do Jarau	RS	30º 12’ S	56º 32’ W	13.5	<132
Serra da Cangalha	TO	08° 04’ S	46º 51’ W	13.7	<200
Riachão	MA	07° 43’ S	46° 39’ W	4.5	<200
Nova Colinas	MA	07º 09’ S	46º 06’ W	6.5-7.0	<200
São Miguel do Tapuio	PI	05º 38’ S	41º 24’ W	20.0	<150
Santa Marta	PI	10º 10’ S	45º 15’ W	10.0	<100

The Paraná Basin contains the structures of Araguainha Dome, located on the border between the states of Mato Grosso and Goiás, Vista Alegre in the state of Paraná, Vargeão in Santa Catarina, and Cerro do Jarau in Rio Grande do Sul.

Meanwhile, in the Parnaíba Basin, we find the structures of Serra da Cangalha in the state of Tocantins, Riachão and Nova Colinas, both in the state of Maranhão, and São Miguel do Tapuio and Santa Marta, both in the state of Piauí.

Below are the details of each of these structures within the context of the respective sedimentary basins where they are located.

3 IMPACT STRUCTURES IN THE PARANÁ BASIN

Figure 2 presents the location of the four structures of the Paraná Basin, showing the association of three of them (Vista Alegre, Vargeão Dome, and Cerro do Jarau) with the volcanic rocks of the Serra Geral Forest, on which they were formed.

3.1 Araguainha Dome (MT/GO)

The Araguainha Dome was named by NORTHFLEET et al. (1969), who attributed this large circular structural feature, measuring 40 km

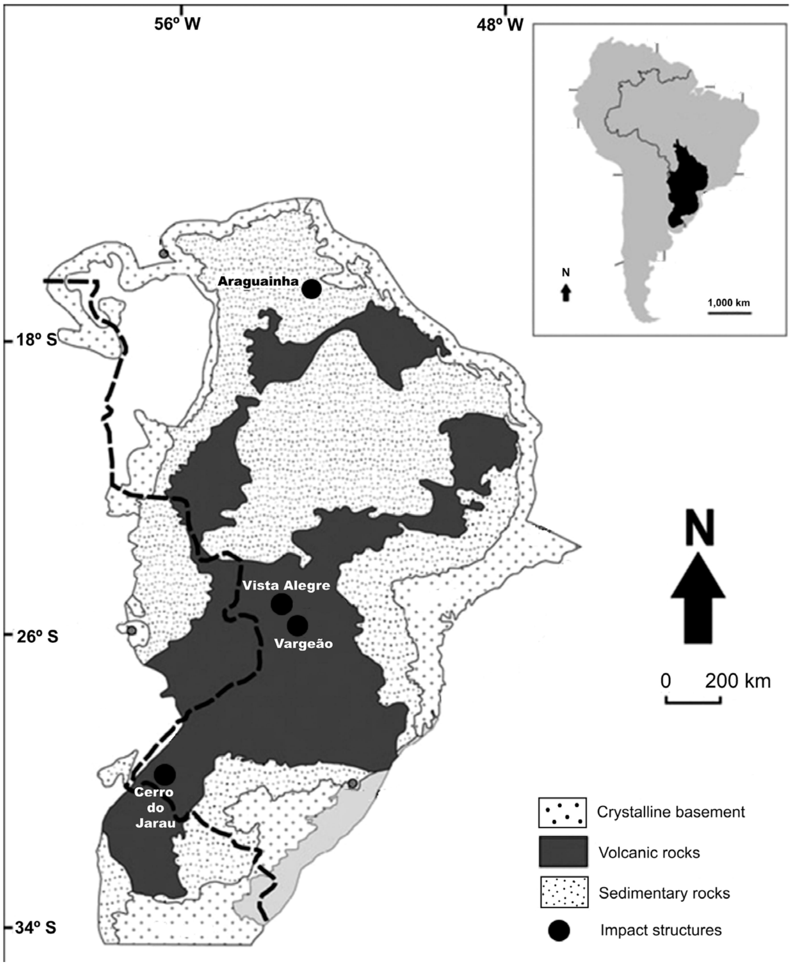

FIGURE 2 – The Paraná Basin and its meteoritic impact structures. In the upper right, the location of the Paraná Basin in relation to Brazil and South America (modified from CRÓSTA et al. 2019a).

in diameter, to an alkaline igneous intrusion that would have uplifted and deformed the Paleozoic strata, forming a dome-like structure (Figure 3). This interpretation persisted in subsequent regional mapping works conducted by the National Department of Mineral Production (DNPM) and the Geological Survey of Brazil (CPRM), particularly in the specific survey conducted by SILVEIRA FILHO & RIBEIRO (1971).

The geological interpretation regarding the nature of the Araguainha Dome began to change with the identification by DIETZ & FRENCH (1973) of possible impact structures in Brazil. These authors relied on the first orbital images from NASA´s then newly launched Landsat satellite, in which they identified two possible structures with morphological characteristics similar to those of impact structures they had been analyzing and whose origin had already been confirmed by geological studies. The two structures in Brazil were the Araguainha Dome and the Serra da Cangalha.

At that time, there were only about 40 known impact structures worldwide, and attributing this origin to the two Brazilian structures was a major novelty. However, due to the lack of detailed studies and more complete field data[3], as well as the lack of familiarity with this area of knowledge in the country, this was not widely accepted by the Brazilian

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[3] One of the authors of this innovative work, Robert S. Dietz, came to Brazil in 1973 with the aim of visiting the two structures. However, due to difficulties in accessing the respective regions, which at the time were quite remote, he was able to briefly visit only Araguainha Dome, where he collected rock samples. Back in the United States, he analyzed thin sections of these rocks, which revealed the presence of planar deformation (or shock lamellae) in quartz grains that are one of the diagnostic features of the occurrence of meteoritic impact phenomena (DIETZ & FRENCH 1973).

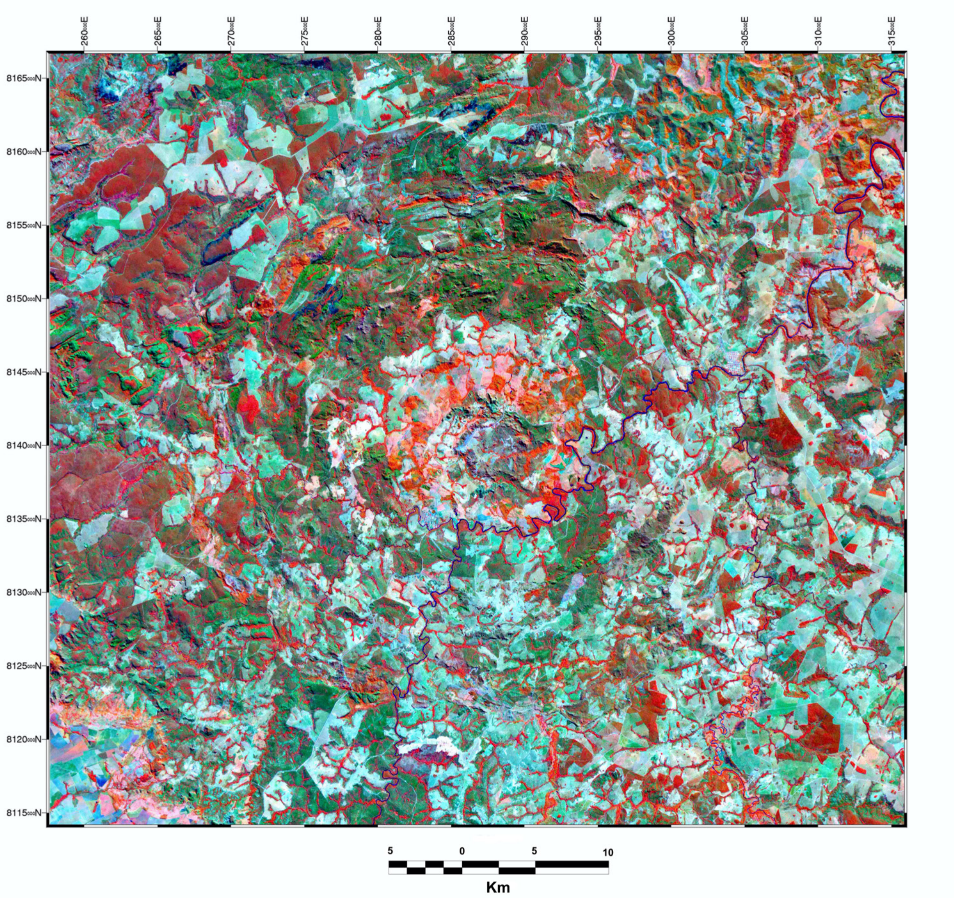

FIGURE 3 – Araguainha Dome. Image from the Landsat satellite, ETM+ sensor, bands 4, 5, and 3 represented in red, green, and blue, respectively. Coordinates are in UTM (Universal Transverse of Mercator).

geological community. Thus, the Araguainha Dome continued to be depicted in official geological maps for several years as an endogenous feature resulting from an igneous intrusion.

The evidence of the impact origin of the Araguainha Dome came from two independent works by CRÓSTA et al. (1981) and THEILEN-WILLIGE (1981), published almost simultaneously. They presented geological data demonstrating abundant shock deformation features, exclusively formed due to hypervelocity meteoritic impacts, including shatter cones and planar deformation features (PDF). These pioneering works were later complemented by detailed studies of local geology and impact deformation features conducted by VON ENGELHARDT et al. (1992), LANA et al. (2006, 2007, 2008), YOKOYAMA et al. (2012), HIPPERT et al. (2014), and HAUSER et al. (2017), among others.

With a diameter of 40 km and an area of approximately 1,300 km^2, the Araguainha Dome is the largest known impact structure in South America, as well as the 15th largest in the world. Its center is located at coordinates 16° 48′ 45” S/52° 59′ 02” W. The formation of the structure occurred about 254 million years ago (Ma) (TOHVER et al. 2012, HAUSER et al. 2017), targeting Paleozoic sedimentary strata of the Paraná Basin and underlying crystalline rocks of the basement. The structure extends over the border between the states of Mato Grosso and Goiás and is almost bisected by the Araguaia River.

The stratigraphic units affected by the impact include the crystalline basement, composed of alkaline porphyritic granite of the Serra Negra Group, phyllites and meta-sandstones of the Cuiabá Group; the Devonian Paraná Group (Furnas and Ponta Grossa formations), the Permian-Carboniferous Tubarão Group through the Aquidauana Formation, and the Permian Passa Dois Group, with the Irati and Corumbataí formations, being the youngest stratigraphic units affected by the impact event. The geological map of Araguainha is shown in figure 4. These lithostratigraphic units are arranged in

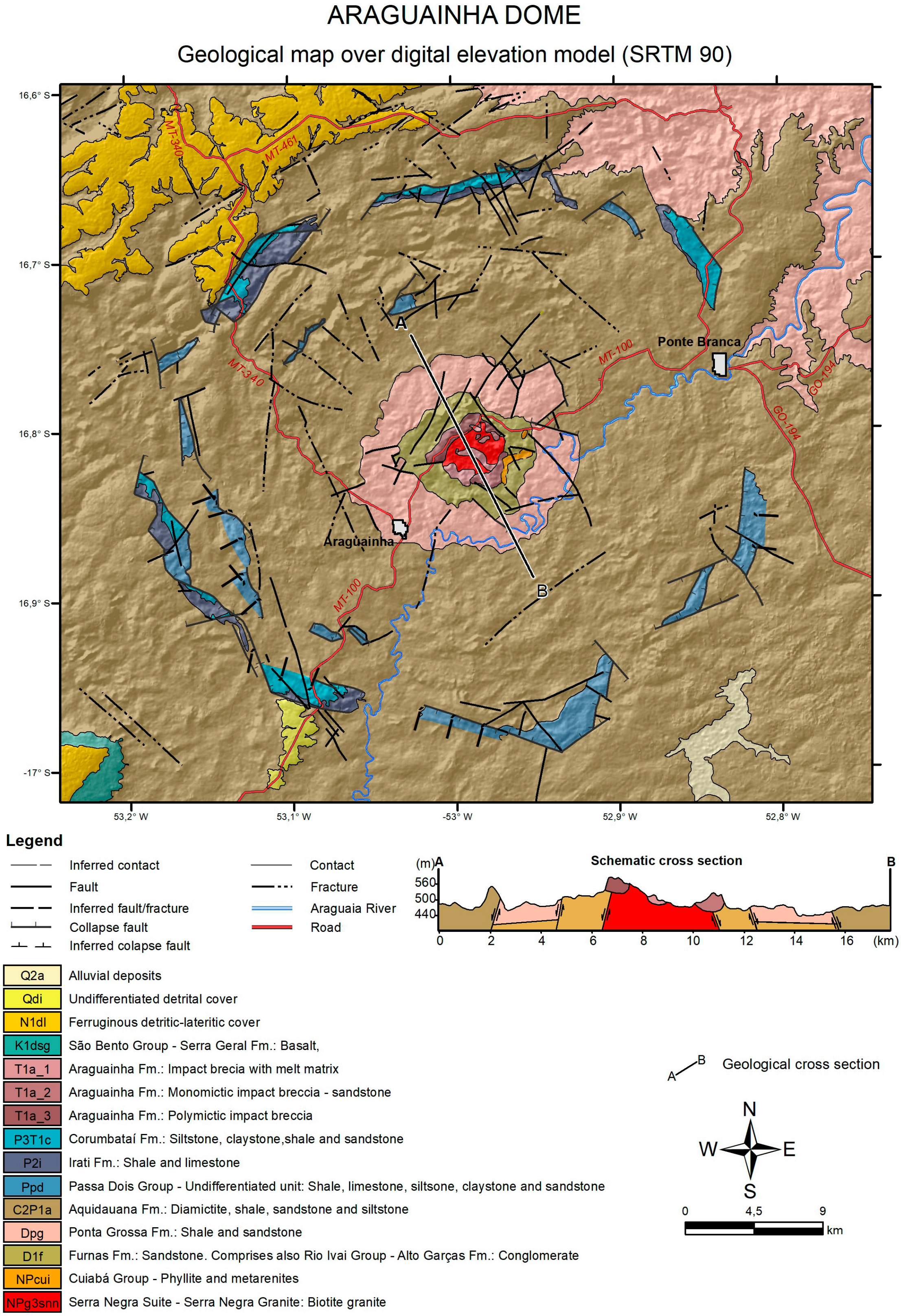

FIGURE 4 – Geological map of the Araguainha Dome and schematic geological section (THOMÉ-FILHO et al. 2012).

a circular “target” (or “bulls′ eye”) pattern, with the oldest units at the center and progressively younger units distributed around the edge of the structure. This is a typical pattern of impact structures, especially in sedimentary terrains.

The Araguainha Dome contains most of the main features of impact deformation/ metamorphism used as criteria for recognizing such events (FRENCH 1998, FRENCH and KOEBERL 2010). CRÓSTA et al. (1981) observed the occurrence of the following features:

- Shatter cones formed in phyllites of the Cuiabá Group (Figure 5).
- Planar deformation lamellae in quartz and feldspar in the granite of the Serra Negra Group, mainly planar deformation features (PDF), planar fractures (PF), and feather features (FF) (Figure 6).
- Kink-bands in mica in the granite.
- Diaplectic glass in plagioclase in the granite.

FIGURE 5 – Araguainha Dome. Shatter cones formed in phyllites of the Cuiabá Group outcropping in the central core.

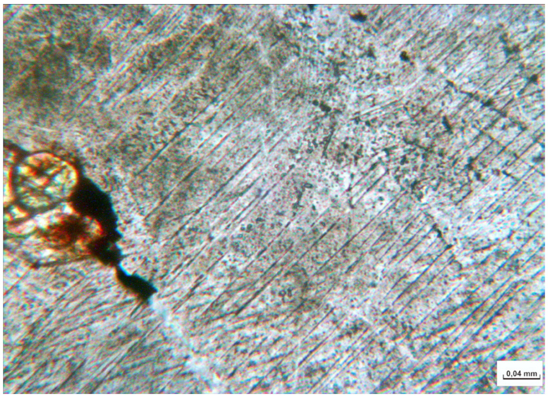

FIGURE 6 – Araguainha Dome. Shock deformation microstructures (PDF) in quartz grain of the outcropping granite in the central core.

There are also various types of impactites (rocks formed by fragmentation or melting of pre-existing rocks due to meteoritic impact). Most of them are impact breccias of various types: monomictic breccias (formed by deformation/ fragmentation of a single rock type), polymictic breccias (more than one rock type), and breccias with varying proportions of melted materials (Figure 7).

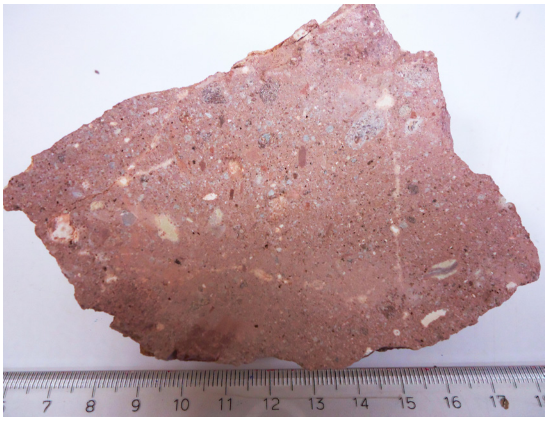

FIGURE 7 – Araguainha Dome. Impact breccias with fragments of the various lithological types present and containing a small proportion of material melted by impact.

The Araguainha Dome has also been the subject of several geophysical studies, contributing to its lithological-structural characterization, on the surface and subsurface. Among them are MASERO et al. (1994), SCHNEGG & FONTES (2002), YOKOYAMA et al. (2012), MIYAZAKI et al. (2021), and LEITE et al. (2022).

In summary, the Araguainha Dome, besides being the largest known impact structure in South America and one of the largest in the world, also exhibits the greatest diversity of geological features representative of this type of phenomenon and has been better characterized from a geological, structural, geochemical, and geophysical point of view compared to other structures of this type in Brazil. An example of this is the geochronological data, which reasonably accurately indicate the age of formation of the structure, something that other Brazilian structures do not yet have.

3.2 Vista Alegre (PR)

The identification of the Vista Alegre impact structure is relatively recent, having been initially described by CRÓSTA et al. (2004). The structure has a diameter of 9.5 km and was initially identified by the observation of orbital images. After field checking, evidence of its formation as a result of meteoritic impact was collected (Figure 8).

It is located in the Municipality of Coronel Vivida, in the western region of the state of Paraná, with its center at coordinates 25° 57′ S and 52° 41′ W. Within it lies the rural community of Vista Alegre, which gives the structure its name.

Like the structures of Vargeão and Cerro do Jarau, discussed later in this article, Vista Alegre was formed on tholeiitic basalt flows of Cretaceous age from the Serra Geral Formation. The constitution also involved older sandstones units from the Botucatu Formation and possibly the Pirambóia Formation of the São Bento Group (Upper Permian to Lower Cretaceous). These sandstones, highly deformed and recrystallized, are found in a restricted manner in the NW sector of the structure, indicating that Vista Alegre is a complex-type structure and that units below the volcanic layers were uplifted by several hundred meters as part of the formation of the central core of the structure.

FIGURE 8 – Vista Alegre. Composite image of the Sentinel-2 satellite, bands 2, 3, and 4 in RGB, superimposed on the TanDEM-X digital elevation model (GOTTWALD et al. 2020).

The geological and geochemical detailing of the Vista Alegre structure was presented by CRÓSTA et al. (2010a). The set of impactites and diagnostic impact features found in Vista Alegre comprises packages of polymictic impact breccias (Figure 9) that outcrop between the center and the edge of the structure, mainly along two streams that drain the central part of the structure and are well exposed in a disused quarry located at the entrance of the Vista Alegre community. The first examples of basaltic shatter cones known worldwide in these breccias were found (Figure 10), a diagnostic impact feature that was subsequently also found in the Vargeão Dome. Microscopic shock features, in the form

FIGURE 9 – Vista Alegre. Impact polymictic breccias composed of basalt and sandstone fragments in a fine basalt matrix. In the lower-left corner is a shatter cone fragment embedded in the breach.

FIGURA 10 – Vista Alegre. Shatter cones formed in basalt.

of planar deformation features (PDFs) and planar fractures (Figure 11), also occur in quartz grains originally from the sandstones incorporated into the polymictic breccias.

The geophysical characterization of the structure using the gravitational method was done by FERREIRA et al. (2019), while a numerical modeling of the formation of the original Vista Alegre impact crater was presented by VASCONCELOS et al. (2019).

The age of the Vista Alegre structure has not been determined, as no materials have yet been found that can be reliably dated by isotopic geochronological methods. The maximum age for its formation is 134.6 ± 0.6 Ma, the age of the Serra Geral volcanism according to THIEDE & VASCONCELOS (2010) by the ^{40}Ar-^{39}Ar method.

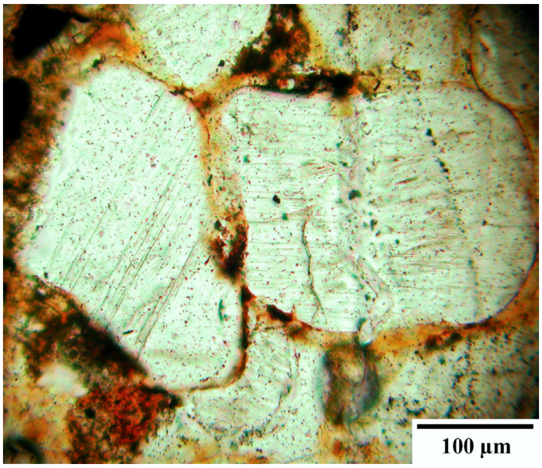

FIGURE 11 – Vista Alegre. Shock deformation microstructures (PDF) in quartz grains from sandstone fragments contained in the polymictic breccia. Two sets of features can be seen in this photomicrograph with parallel nicols.

3.3 Vargeão Dome (SC)

Vargeão Dome is located in the western region of Santa Catarina and is centered at coordinates 26° 49′ S and 52° 10′ W. It has a diameter of 12.4 km and contains the town of Vargeão in its interior (Figure 12).

The existence of an anomalous circular morphological feature was first identified in the late 1970s, based on observations of radar remote sensing images. Like many impact structures elsewhere in the world, the initial interpretations of its nature suggested the occurrence of a buried igneous intrusion as the cause for the remarkable structure (PAIVA FILHO et al. 1978).

The first evidence of the meteoritic impact nature of the Vargeão Dome was pointed out by CRÓSTA (1987) in the form of microscopic deformation features in quartz grains found in deformed sandstones, as well as the similarity of the Vargeão breccias with similar rocks from other impact structures worldwide. A series of studies developed over the last two decades have contributed to characterizing the geology, morphology, structures, and geophysical signatures of the Vargeão Dome (CRÓSTA et al. 2009; KAZZUO-VIEIRA et al. 2009; CRÓSTA 2011, 2012; FERREIRA et al. 2015). The characteristics described below are based on these works.

In this case, the target rocks of the impact event were volcanic packages of the Serra Geral Formation, as well as underlying sandstones of the Botucatu and Pirambóia formations.

One of the most prominent aspects of the Vargeão Dome is its circular morphology with multiple internal ring structures, as seen in figure 12. There is a strong structural control behind this morphology in the form of sub-vertical faults that condition the steep inner rim of the structure and its internal rings, formed in the volcanic rocks of intermediate composition (porphyritic rhyodacites) and basic (tholeiitic basalts) of the Serra Geral Formation. These structures developed during the modification

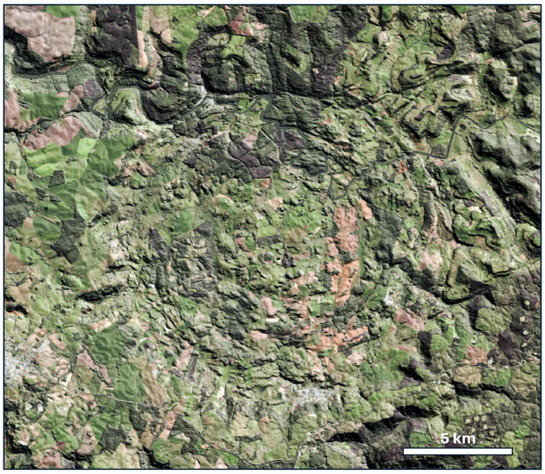

FIGURE 12 – Vargeão Dome. Composite image of the Sentinel-2 satellites, bands 2, 3, and 4 in RGB, superimposed on the TanDEM-X digital elevation model (GOTTWALD et al. 2020).

stage of the original crater, with the uplift of the central core of the structure and the collapse of the rim. In the core, partially exposed deformed and recrystallized sandstones from the Botucatu and Pirambóia formations are found, which are undivided at this location due to their intense deformation. Despite considerable modification by erosion having altered the original morphology, these structures are partially preserved and currently observable.

All rocks occurring within the structure, both volcanic and sedimentary, exhibit some degree of deformation, ranging from brecciation to partial melting. The occurrence of different types of breccias is common, including monomictic breccias formed in the rhyodacites (Figure 13) and sandstones (Figure 14). There are also polymictic breccias with fragments of these three lithologic types amidst a fine matrix of red color composed mostly of pulverized basalt (Figure 15).

Shock deformation features identified in the Vargeão Dome include shatter cones in basalts (Figure 16) and sandstones (Figure 17), and micro-deformations in quartz grains in the deformed sandstones (Figure 18).

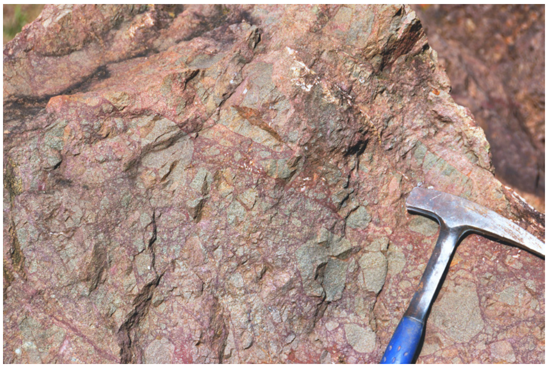
FIGURE 13 – Vargeão Dome. Monomictic basalt breccia cut by veins (pseudotachylites).

FIGURE 14 – Vargeão Dome. Monomictic breccia in sandstone.

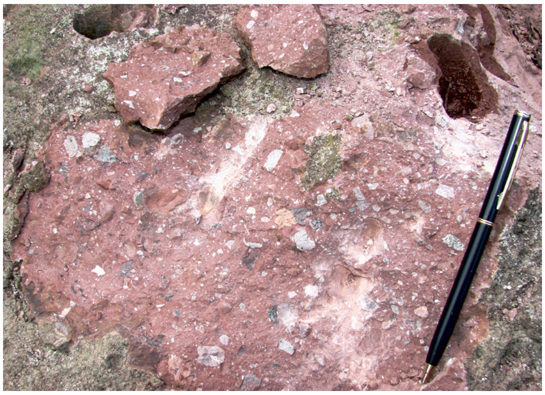
FIGURE 15 – Vargeão Dome. Polymic breccia with fragments of basalt, rhyodacite and sandstone.


FIGURE 16 – Vargeão Dome. Shatter cones in basalt.


FIGURE 17 – Vargeão Dome. Shatter cones in sandstone.

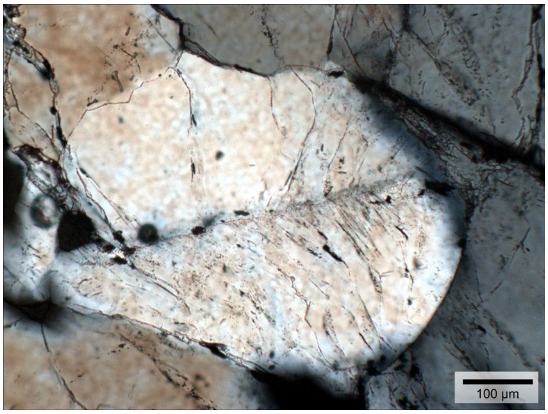

FIGURE 18 – Vargeão Dome. Shock deformation (FF) microstructures in sandstone quartz grain.

Like Vista Alegre, there is also no secure dating available for Vargeão that provides its formation age, assuming a maximum age of 134.6 ± 0.6 Ma (THIEDE & VASCONCELOS 2010) by the ^{40}Ar-^{39}Ar method, or 134.3 ± 0.8 Ma obtained by JANASI et al. (2011) using the U-Pb method in baddeleyite for the porphyritic rhyodacites of the region outside the structure. A specific LA-ICP-MS dating for a zircon grain from veins in the porphyritic rhyodacite provided an age of 123 ± 1.4 Ma (NÉDÉLEC et al. 2013). However, the dated sample came from the outer part of the structure's rim, which does not provide the necessary reliability for this age, which may be due to a volcanic or tectonic heating event independent of the impact process.

3.4 Cerro do Jarau (RS)

The third of the Brazilian impact structures formed on volcanic rocks of the Serra Geral Formation is Cerro do Jarau, whose center is located at coordinates 30° 12′ S and 56° 32′ W. It is situated in the Municipality of Quaraí, in the State of Rio Grande do Sul, and has an approximate diameter of 13 km (REIMOLD et al. 2019, CRÓSTA et al. 2019a).

Part of the central area of the structure stands out notably in the flat topography of this region of the Rio Grande do Sul, forming hills with prominent ridges of semi-circular conformation that reach up to 200 m above the surrounding plain and give the structure its name (Figure 19). These elevations are formed by intensely silicified/recrystallized sandstones/quartzites, whose nature and characteristics aroused the curiosity of researchers because they do not have similarity with lithostratigraphic units in this portion of the Paraná Basin (GREHS 1969). Analyzing the local geology, mainly consisting of these quartzose rocks and the surrounding basalt, and considering the occurrence of atypical deformation features of these rocks, LISBOA et al. (1987) suggested as a possible origin for this structure some tectonic deformation event, or a meteorite impact.

FIGURE 19 – Cerro do Jarau. Composite image from the Sentinel-2 satellite, bands 2, 3, and 4 in RGB, overlaid on the TanDEM-X digital elevation model (GOTTWALD et al. 2020).

The target rocks belong to the São Bento Group (Cretaceous), encompassing sandstones from the Botucatu and Guará formations, which outcrop in 30% of the structure area, and the tholeiitic basalts of the Serra Geral Formation, which occur in the remaining area.

The local geology comprises basalts exhibiting different degrees of deformation and breccias in addition to the aforementioned recrystallized sandstones. However, the breccias have distinct natures, with both volcanic origin (autobreccia, with fragments of basalt and sandstone) and impact origin. Visually, it is not possible to differentiate between the two breccia types. The basalt shows different levels of brecciation, forming textures similar to the brecciated basalt found in the impact structures of Vista Alegre and Vargeão. This type of deformation feature is exclusive to the basalts occurring within the structure and is not observed in the basalts of the region.

The identification of deformation features and impactites that confirmed the meteoritic origin of Cerro do Jarau is credited to CRÓSTA et al. (2010b) and REIMOLD et al. (2019). The structural detailing of the Cerro do Jarau structure was presented by SANCHEZ et al. (2014). The shock deformation features described by REIMOLD et al. (2019) include the three main types of micro-deformation in quartz grains: planar fractures (PF), feather features (FF), and planar deformation features (PDF) (Figures 20, 21, and 22). These micro deformations are typical of the ultra-high-pressure regime (between 2 and 10 GPa) and are, therefore, diagnostic of this type of event.

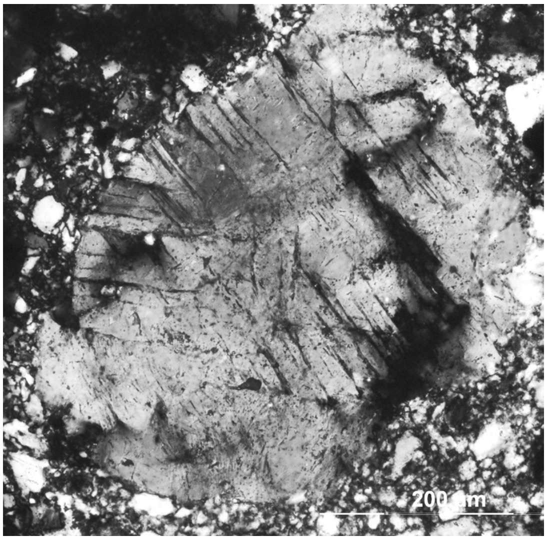

FIGURE 20 – Cerro do Jarau. Shock deformation microstructures (PF) in quartz grain from sandstone.

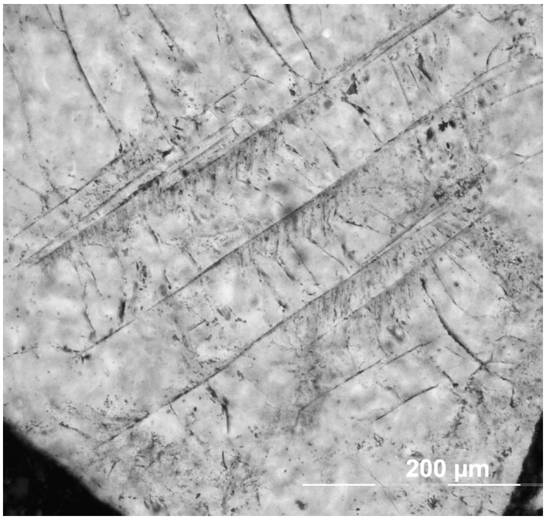

FIGURE 21 – Cerro do Jarau. Shock deformation microstructures (FF) in quartz grain from sandstone.

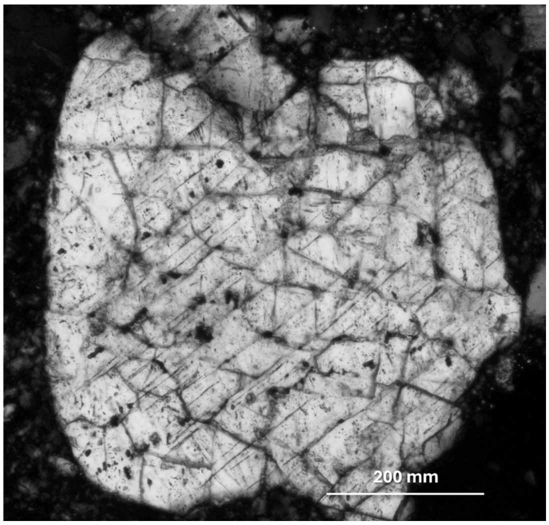

FIGURE 22 – Cerro do Jarau. Shock deformation microstructures (PDF) in quartz grain from sandstone.

The geophysical characterization by the gravimetric method of Cerro do Jarau was conducted by GIACOMINI et al. (2017) and by the gamma-spectrometric method by GARCIA et al. (2024).

4 IMPACT STRUCTURES IN THE PARNAÍBA BASIN

Figure 23 shows the locations of the five impact structures located in the Parnaíba Basin: two in the states of Maranhão (Riachão and Nova Colinas) and Piauí (Santa Marta and São Miguel do Tapuio) and one in the state of Tocantins (Serra da Cangalha).

4.1 Serra da Cangalha (TO)

From a scenic point of view, Serra da Cangalha is possibly the most spectacular among the Brazilian impact structures due to its unmistakable circular morphology, enhanced by erosion (Figure 24), with pronounced ring-shaped elevations that constitute its central part (Figure 25). These morphological features, notably of the Cerro do Jarau structure, stand out in the regional topography.

Serra da Cangalha is located in the northeastern region of the state of Tocantins, in the Municipality of Campos Lindos, with the center at coordinates 8° 04’ S, 46° 52’ W and a diameter of about 13 km.

Previously considered as a possible intrusion of igneous origin, DIETZ & FRENCH

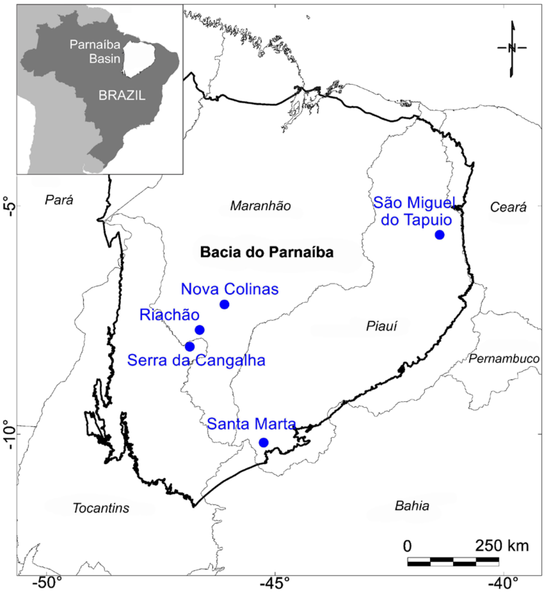

FIGURE 23 – The Parnaíba Basin and its meteoritic impact structures. In the upper left, the Parnaíba Basin´s location in relation to Brazil and South America.

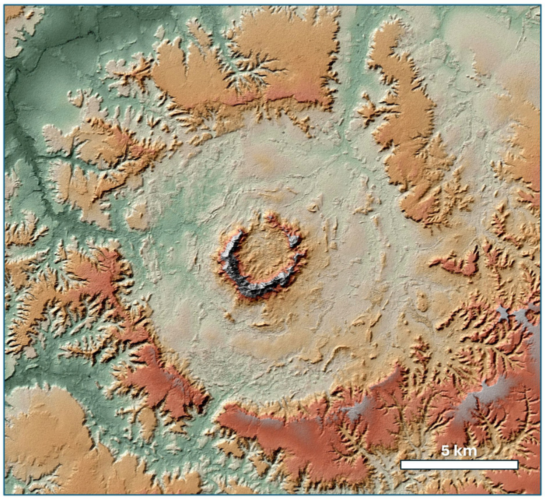

FIGURE 24 – Serra da Cangalha. TanDEM-X digital elevation model (by M.Gottwald).

FIGURE 25 – Aerial view of the central part of Serra da Cangalha (photo by A. Bartorelli).

(1973) pointed out that Serra da Cangalha, along with the Araguainha Dome, was the result of the collision of a celestial body. Their suggestions were based on the analysis of the first orbital images from the Landsat satellite and the remarkable similarity of its morphology with other similar structures then known worldwide.

Although inconclusive, MCHONE JR. (1979) pointed out the first evidence of shock features in Serra da Cangalha after field reconnaissance work with sample collection. KENKMANN et al. (2011) and VASCONCELOS et al. (2013) presented conclusive evidence of the structure´s impact origin.

Although it is in a relatively advanced erosive stage, Serra da Cangalha presents several internal morpho-structural zones that are still clearly visible (Figure 26). These zones are, from the center to the edge, (i) a prominent inner ring with a diameter of 3.2 km surrounding the central depression with a diameter of 2.2 km; (ii) an intermediate ring with approximately 6 km in diameter, followed by another incomplete intermediate ring with 11 km in diameter; and (iii) an outer ring with ~13 km in diameter, representing the outer rim of the structure.

The central collar of Serra da Cangalha, with a diameter of 5.8 km, is certainly the most prominent feature of its morphology, consisting of intensely folded and silicified sandstones with vertical ridges that rise to 350 above the terrain and surround the central depression of the structure. This feature gives the structure its name, as the sandstone strata are folded in shapes that suggest those of the saddlebags (“cangalha” in Portuguese) placed on pack animals. Interestingly, although this morphology suggests the shape of a crater itself, it is actually the result of differential erosion, where the silicified strata resulting from the circulation of fluids mobilized by the impact energy were more resistant than the surrounding strata, which were lowered by erosion, thus highlighting the central collar that stands out in the regional landscape.

According to VASCONCELOS et al. (2013), the stratigraphic units occurring in Serra da Cangalha are, from bottom to top, the Devonian Longá Formation, the Poti and Piauí formations, both from the Carboniferous and the Pedra de Fogo Formation, from the Permian (Figure 26).

The diagnostic shock features were identified by KENKMANN et al. (2011) and VASCONCELOS et al. (2013). They include shatter cones in coarse sandstones, and micro deformation features such as planar fractures (PF), feather features (FF), and planar deformation features (PDF) in quartz grains from the Longá and Poti formations, plus polymictic breccias, and shatter cones in sandstone of the Poti Formation (Figures 27 and 28).

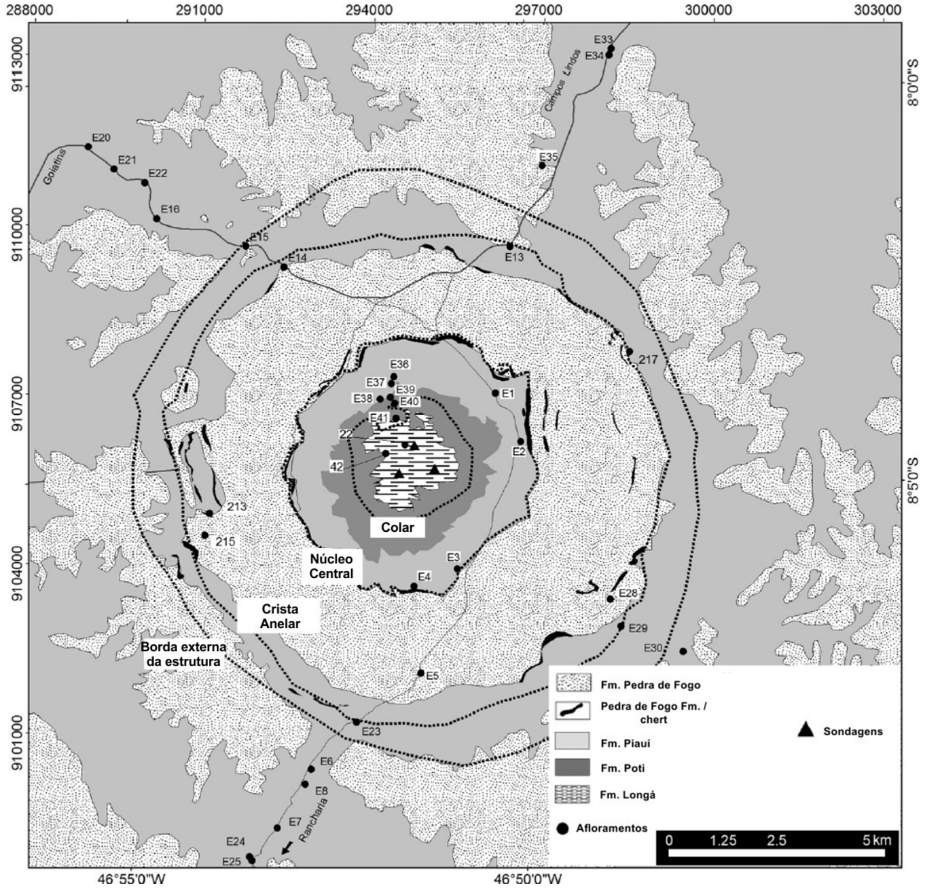

FIGURE 26 – Geological map of Serra da Cangalha with its morpho-structural zones (Vasconcelos et al. 2013).

The geophysical characterization of the Serra da Cangalha impact structure, using various methods, was carried out by ADEPELUMI et al. (2005) and by VASCONCELOS et al. (2010; 2012a, b), denoting its structural and lithological configuration on the surface and subsurface. VASCONCELOS et al. (2012b) applied numerical modeling to simulate the conditions of formation of the original impact crater, indicating that the impact occurred by a celestial body with a diameter of about 1.4 km, which released energy equivalent to approximately 2.74 × 10^{20} J and caused a structural uplift of the underlying layers by about 500 m.

FIGURE 27 – Serra da Cangalha. Shatter cones in sandstone of the Poti Formation.

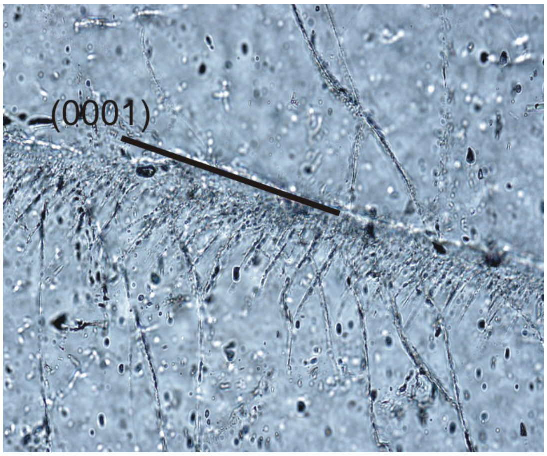

FIGURE 28 – Serra da Cangalha. Shock deformation microstructures (FF) in quartz grain from sandstone.

The structure´s formation age cannot yet be determined due to the absence of material suitable for geochronological dating. Based on stratigraphy, the maximum age can be estimated as the Middle-Lower Permian (~270 Ma), attributed to the Pedra de Fogo Formation.

4.2 Riachão (MA)

The Riachão impact structure is the smallest among the confirmed impact structures in Brazil. With a diameter of about 4 km, it is currently in an advanced erosional state. It is located in the municipality of the same name in the state of Maranhão, with its center at coordinates 7° 42' S and 46° 38' W (Figure 29).

Riachão was formed on predominantly clastic sedimentary rocks of the Parnaíba Basin, with ages ranging from the Upper Carboniferous to the Permian. The circular structural anomaly was first recognized based on regional geological reconnaissance work carried out by Petrobras in the 1960s. Its relation to a possible meteoritic impact event was suggested in the following decade, based on observations made by astronauts of the Apollo-Soyuz mission, who recorded it in orbital photographs (MCHONE JR. 1979). Field reconnaissance work by MCHONE JR. (1986) revealed the occurrence of quartz grains with sets of planar fractures, suggesting an impact

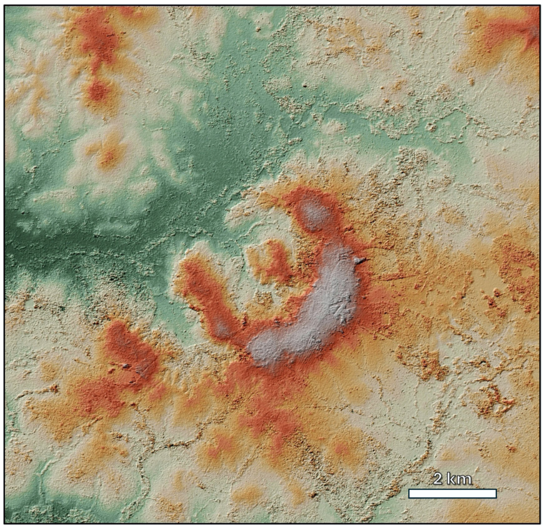

FIGURE 29 – Riachão. TanDEM-X digital elevation model (by M.Gottwald).

origin for the structure. The confirmation of this origin came from the work of MAZIVIERO et al. (2013), which provided conclusive evidence. The characteristics described below are based on this work.

The morpho-structural zones of Riachão consist of a raised central part, surrounded by an inner ring depression and externally delimited by the raised rim. They are not prominent in the local topography due to the advanced stage of erosion but are reflected by anomalous patterns of radial and concentric drainage. The exposure of the substrate rocks is also limited by the development of sandy soil cover.

The structure exhibits an overall horseshoe-shape with an opening facing NW formed by its outer rim. This opening stands out by about 50 m above the relief of the outer part. The central part, with gently raised relief, is about 30 m above the terrain of the ring basin depression.

The exposed rocks are sandstones, siltstones, and mudstones of the Piauí and Pedra de Fogo formations. The sedimentary layers inside the structure are inclined at angles ranging from 30° to 85°. Breccias of sedimentary nature related to the Pedra de Fogo Formation occur at the structure's rim. In the ring basin, there are finely laminated siltstones, calcilutites, as well as brecciated chert.

Shock deformation features found by MAZIVIERO et al. (2013) in Riachão include various types of micro deformation in quartz grains (PDF, FF, and PF) (Figure 30), all from rocks originating from the central part of the structure. However, few deformed grains were identified, reinforcing the idea that the currently exposed strata were once buried and have been exposed by erosion. No shatter cones have been recorded yet.

Similar to Serra da Cangalha, in Riachão, the formation age also cannot be established due to the absence of material suitable for geochronological dating. Thus, based on stratigraphy, the maximum age is estimated as the Middle-Lower Permian (~270 Ma), attributed to the Pedra de Fogo Formation.

Although the geographical proximity and potential overlapping age intervals between the structures of Serra da Cangalha and Riachão may suggest the possibility of them being formed simultaneously by a double impact, there is no evidence to support this hypothesis.

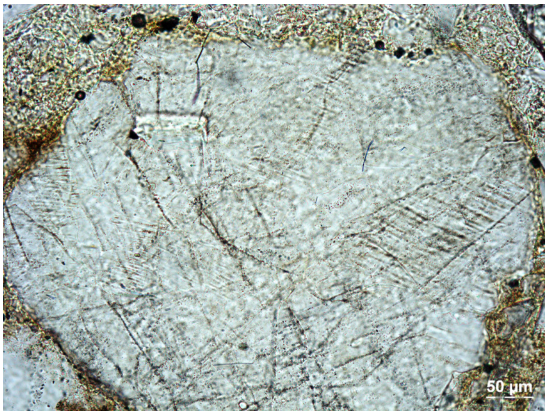

FIGURE 30 – Riachão. Shock deformation microstructures in quartz grain from sandstone.

4.3 Nova Colinas (MA)

The Nova Colinas impact structure is the most recent discovery of a large-scale impact structure in Brazil (REIMOLD et al. 2022). It is a prominent circular structure in the regional landscape, with a diameter of around 6.5 km, located in the municipality of the same name in the southwest of the state of Maranhão, with its center at coordinates 07° 09' 33" S and 46° 06' 30" W (Figure 31).

The existence of this anomalous circular structure was first recognized by ABREU et al. (1977) during regional geological mapping, and it was named "Estrutura de Macapá" (Macapá Structure), which is the name of the river that cuts through the structure almost in half in the E-W direction.

The structure appears prominently on the aeromagnetic map produced during the regional aerogeophysical survey of the Parnaíba Basin conducted by the National Agency of Petroleum and Biofuels (ANP) (MARQUES et al. 2006). This notable geophysical signature led SILVA (2020) to interpret it as having been formed by meteorite impact without, however, presenting diagnostic evidence of this type of phenomenon. Based on field reconnaissance work and petrographic analysis of samples collected within the structure, REIMOLD et al. (2022) presented the evidence, thus proving the meteoritic origin of Nova Colinas.

The structure formed on sedimentary and igneous rocks of the Pedra de Fogo and Motuca formations (Permian), Sambaíba Formation (Triassic), and Mosquito Formation (Lower

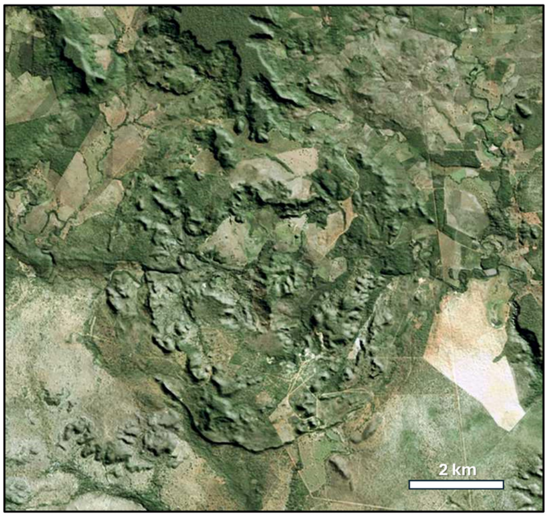

FIGURE 31 – Nova Colinas. Composite image from the Sentinel-2 satellite, bands 2, 3, and 4 in RGB, overlaid on the TanDEM-X digital elevation model (GOTTWALD et al. 2020).

Jurassic). Ongoing investigations indicate that the structure's rim is formed by basic volcanic rocks of the Mosquito Formation, while the lithologies within the structure are predominantly sandstones of the Sambaíba Formation. The circular and concentric arrangement of the lithostratigraphic units in Nova Colinas constitutes the typical target-shaped pattern of impact structures formed in sedimentary terrains.

Preliminary data presented by AVONA et al. (2023) indicate that older strata, attributed to the Motuca and Pedra de Fogo formations, occur in the central portion of the structure of Nova Colinas.

Among the evidence of meteoritic nature identified in Nova Colinas are shock deformation in quartz grains of sandstones (REIMOLD et al. 2022) (Figure 32a) and shatter cones in basalt (AVONA et al. 2023) (Figure 32b). The micro-features identified by REIMOLD et al. (2022) include all three types of planar deformations (PF, FF, and PDF). Analyses of crystallographic planes in which these deformations have developed in quartz grains indicate pressures typical of meteorite shock regimes (HÖRZ 1968). The occurrence of shatter cones in basalt from the Mosquito Formation indicates that the impact is younger than the volcanic event, dated at about 200 Ma.

An initial geophysical characterization was made by SILVA (2020) based on data from the ANP's aerogeophysical survey. This characterization was subsequently detailed by REIMOLD et al. (2022), showing a remarkable circular magnetic anomaly that coincides with the structure´s rim. It comprises a series of short wavelength anomalies, with the exact same pattern exhibited by the anomalies seen in the area of occurrence of the basic volcanic rocks of the Mosquito Fm, north of the structure (Figure 33). Analysis of seismic data for Nova Colinas is currently being performed (PEREIRA et al. 2022) and indicates the occurrence of fault and fracture systems affecting the intrusions (dikes and sills) associated with the Mosquito volcanism and the sedimentary strata within the structure.

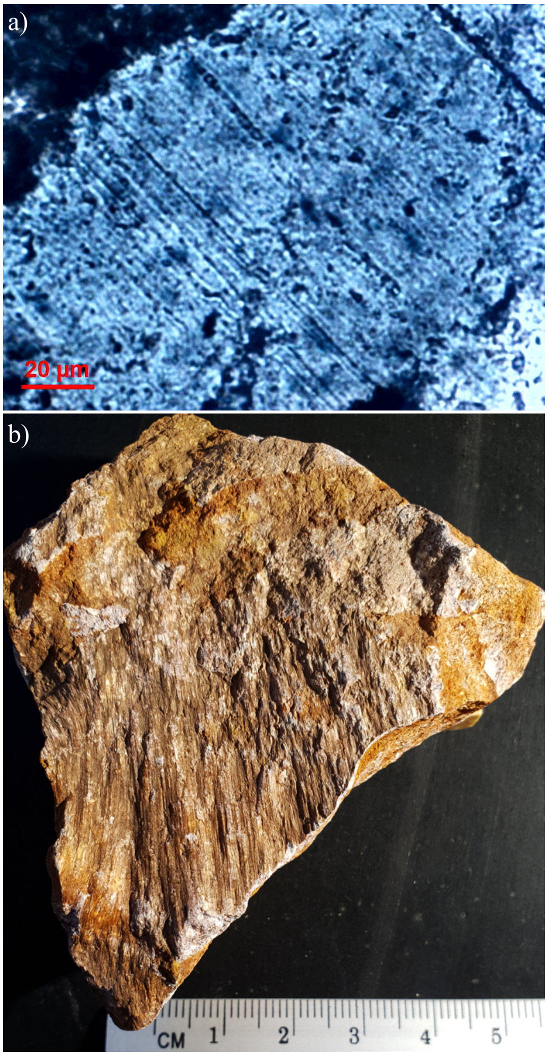

FIGURE 32 – (a) Nova Colinas. Shock deformation microstructures (PDF) in quartz grain in sandstone. (b) Shatter cones in basalt.

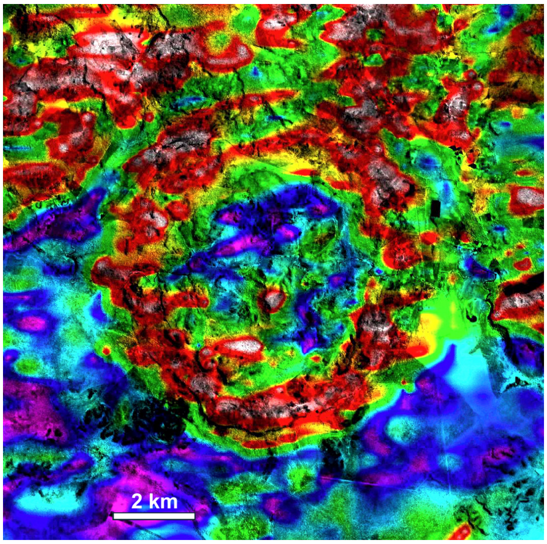

FIGURE 33 – Nova Colinas. Combination of a magnetic image (analytical signal of the tilt angle) with the Sentinel-s image. The red circular feature at the structure´s perimeter indicates the remarkable magnetic anomaly due to the occurrence of the basic volcanics of the Mosquito Formation.

Structural discontinuities were also associated with deformation that formed the central uplift.

The age of formation of the Nova Colinas structure has not yet been established, but the presence of impact-affected volcanic rocks of the Mosquito Formation, dated by MERLE et al. (2011) in the interval 197-199 Ma, points out to the Lower Jurassic as its maximum age.

4.4 São Miguel do Tapuio (PI)

This anomalous circular structure with a diameter of about 21 km has been known since the early 1980s. It is located in the Municipality of São Miguel do Tapuio, in the eastern region of the state of Piauí, with its center at coordinates 5° 37.6′ S and 41° 23.3′ W.

The attribution of the origin of the structure to a meteorite impact event was suggested by TORQUATO (1981), CRÓSTA (1987), and MARTINS et al. (2016) based on indirect aspects such as its circular morphology and concentric internal zones. They also considered that the rocks inside, predominantly sandstones, show structural deformation and recrystallization, which do not occur in the same rocks outside the structure. However, the necessary corroborative evidence had not been established until recently.

Seen in orbital remote sensing images, the São Miguel do Tapuio structure exhibits a notably rugged internal relief formed by concentric inner rings alternating between high ridges and valleys (Figure 34). This morphology contrasts with the terrain outside it, where the relief is relatively flat. These inner rings are externally delimited by the elevated edge of the structure, which is about 120 m above the external zone. At the center, it displays a raised ring with a diameter of about 5 km and rugged relief. MARTINS et al. (2016) recognized the following morpho-structural zones: outer circular rim, inner ring zones, annular depression, and alleged uplifted central core.

The local geology comprises sedimentary rocks related to the Devonian Cabeças Formation of the Parnaíba Basin, predominantly consisting of sandstones. In the southeast portion of the structure, strata from the Pimenteiras Formation, also from the Devonian, occur.

Geophysical studies on the structure were carried out by CASTELO-BRANCO et al. (2004), VASCONCELOS et al. (2010), and MARTINS et al. (2016), to determine its origin, whether by endogenic (intrusion of a igneous body) or exogenic (meteorite impact) process. The results did not indicate the presence of an underlying intrusion that could have uplifted and deformed the overlying sedimentary strata but were also inconclusive regarding the exogenic origin of the structure. The magnetic and gravimetric methods

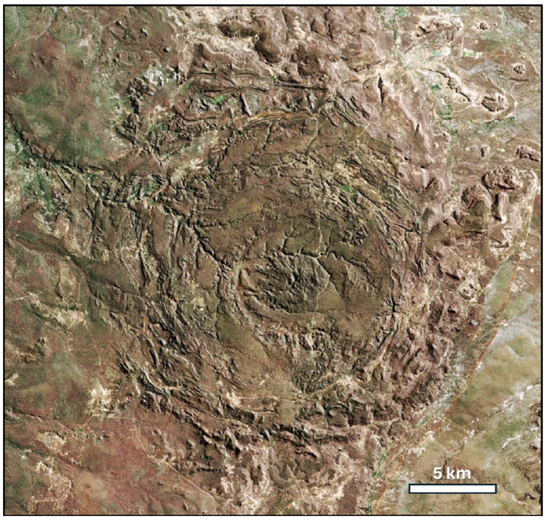

FIGURE 34 – São Miguel do Tapuio. Composite image of the Sentinel-2 satellite, bands 2, 3, and 4 in RGB, superimposed on the TanDEM-X digital elevation model (GOTTWALD et al. 2020).

indicated a conspicuous semi-circular anomaly internal to the structure, open in its NW portion, forming a “horseshoe” pattern.

Evidence of meteorite impact, in the form of shock deformation micro-features in quartz grains of sandstones and monomictic sandstone breccia collected about 1 km from the center of the structure, was reported by CRÓSTA et al. (2019c). The sandstones exhibit abundant deformation features that do not have shock characteristics, i.e., they formed under a pressure regime below the shock threshold (7 GPa), consisting of extensive and irregular planar fractures. On the other hand, the breccia contains typical shock features (≥ 7 GPa), such as planar deformation features (PDF), feather features (FF), and planar fractures (PF) (Figure 35).

A more detailed characterization of the local geology and shock deformation characteristics of the São Miguel do Tapuio structure is hindered by the great difficulty of access to the central part of the structure, characterized by very rugged topography and the presence of thorny caatinga vegetation, combined with the absence of trails or paths. In addition, the sandstones of this central zone exhibit signs of intense ferruginous laterization, which not only hinders access to local bedrock due to the thick lateritic cover but also masks the original characteristics and textures of the rock, including evidence of shock deformation.

Although evidence of São Miguel do Tapuio´s meteoritic nature is still scarce, it is the second-largest structure of its kind in Brazil and South America.

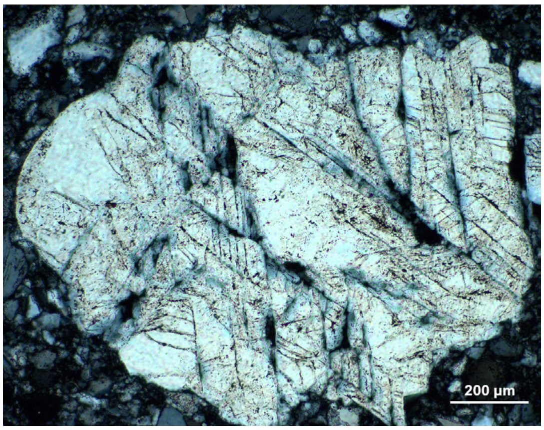

FIGURE 35 – São Miguel do Tapuio. Shock micro deformation feature (PDF and FF) in quartz sandstone grain.

The age of formation of the São Miguel do Tapuio structure is not determined due to the absence of material datable by isotopic geochronological methods. The only two units affected by the impact are of Devonian age, suggesting a maximum age of ~360 Ma for this structure.

4.5 Santa Marta (PI)

The Santa Marta structure has its center at coordinates 10° 10′ S and 45° 14′ W and is located in the southern region of the state of Piauí, in the Municipality of Corrente. It was named after the district of Santa Marta, which is part of Corrente and is located near the structure´s rim. With a diameter of about 10 km, it is a complex-type structure in a relatively moderate stage of erosion, preserving its main internal morphostructural zones (Figure 36). The fact that the structure was covered by unconsolidated Cenozoic sediments, now partially eroded, seems to have contributed to its preservation. This makes it one of the best-preserved in the country, and possibly in the world, among those formed in the Mesozoic (OLIVEIRA et al. 2017).

The structure was first mentioned by MASTER & HEYMANN (2000), who identified the presence of a geomorphological anomaly of circular shape in orbital remote sensing images and suggested a relation with a meteorite impact event. OLIVEIRA et al. (2014, 2017)

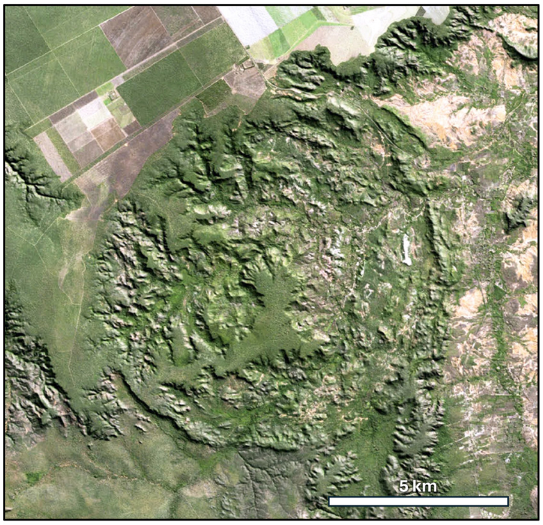

FIGURE 36 – Santa Marta. Composite image of the Sentinel-2 satellite, bands 2, 3, and 4 in RGB, superimposed on the TanDEM-X digital elevation model (GOTTWALD et al. 2020).

confirmed this relationship by identifying shock deformation features found relatively abundantly in local rocks.

Sequences from two distinct sedimentary basins are superposed in the area where the structure formed. The lower sequences affected by the impact, deposited between the Silurian and Devonian periods, are related to the Parnaíba Basin. In contrast, the upper ones, from the Cretaceous period, were deposited within the Sanfranciscana Basin. In addition to these sequences, part of the structure is covered by detrital coverings of probable Cenozoic age, which were not affected by the impact.

The morphostructural zones that make up the Santa Marta structure are, from the center to the edge, a raised core with a diameter of about 3.2 km, an annular basin, and the rim. The latter appears as a semi-circular succession of raised ridges in most of the structure´s circumference, except for the NW quadrant, where the younger and undeformed detrital covering covers it.

OLIVEIRA et al. (2014, 2017) described a variety of lithological types distributed concentrically forming the “bull’s eye” pattern, typical of craters or impact structures formed in undeformed sedimentary successions. The lithologies comprise, from bottom to top and spatially from the center to the rim of the structure, Silurian conglomerates and sandstones of the Serra Grande Group, Devonian shales and sandstones of the Pimenteira Formation, and sandstones of the same age from the Cabeças Formation, all related to the Parnaíba Basin. From the Sanfranciscana Basin, there are conglomeratic sandstones of the Abaeté Formation, pelites and calcarenites of the Quiricó Formation, sandstones and siltstones of the Três Barras Formation, and large-scale cross-stratified sandstones of the Posse Formation, all from the Cretaceous period.

These authors identified two types of impact breccias: polymictic breccias, formed by fragments of several of the mentioned lithologies and which are the most abundant and widely distributed within the structure, and monomictic breccias, formed by the fragmentation of rocks of a lithological type, which occurs more restrictively. There are also occurrences of sedimentary and detrital breccias, the latter related to fragmentation and gravitational action on the Cenozoic coverings.

Shatter cones are relatively common in Santa Marta and occur in sandstones and sandstone breccia clasts at various locations in the central part of the structure (Figure 37a). These shock macro-structures are also developed within rounded quartzite cobbles and boulders that occur as clasts in conglomerates in the annular basin (Figure 37b).

OLIVEIRA et al. (2014, 2017) identified shock deformation microstructures, which include planar deformation features (PDFs) in quartz grains found in several samples of impact breccias from the central part of the structure, as well as feather features (FFs) in intensely deformed and/or brecciated sandstones (Figure 38). The same micro deformation characteristics were observed in quartz grains of rocks bearing shatter cones.

There is no precise age determination for the Santa Marta structure due to the lack of datable materials, and its maximum age is estimated to be in the range of 93 to 100 Ma. It is based on local stratigraphy, with the Posse Formation sandstones of the Urucuia Group representing

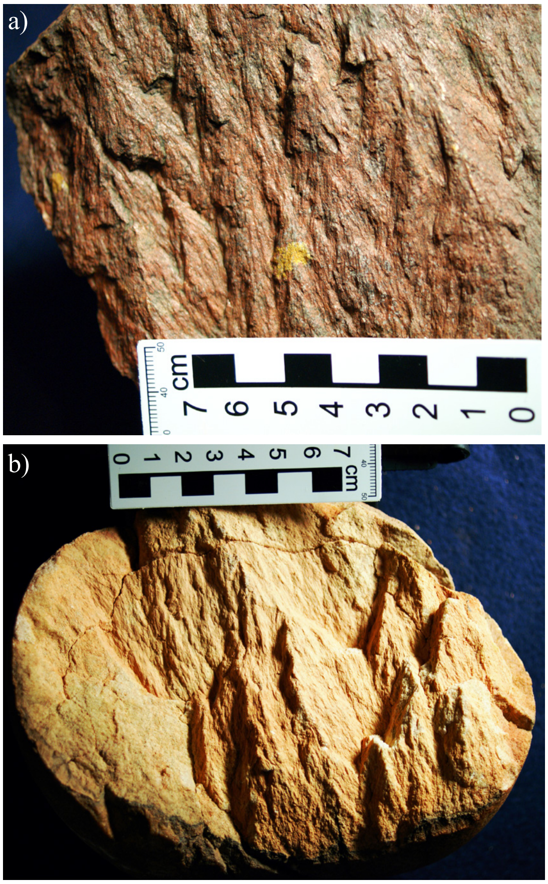

FIGURE 37 – (a) Santa Marta. Shatter cones in sandstone. (b) Shatter cones within a quartzite cobble.

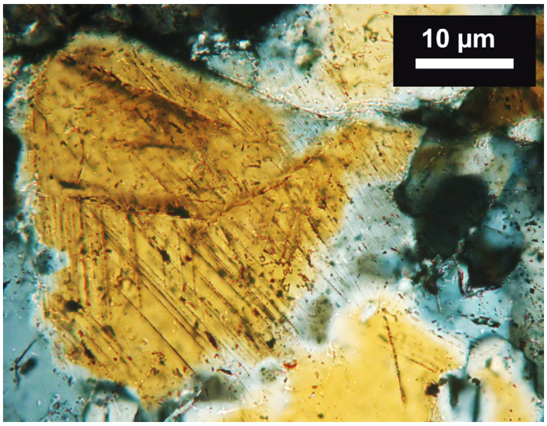

FIGURE 38 – Santa Marta. Shock deformation microstructures (PDF) in quartz grain in sandstone.

the youngest lithostratigraphic unit deformed by the impact and having their deposition age associated with this interval. A minimum age is indicated by the undeformed sedimentary cover of the Chapadão Formation (Cenozoic).

5 BRAZILIAN STRUCTURES OF POSSIBLE METEORITIC ORIGIN (NOT YET PROVEN)

In addition to the nine confirmed impact structures in Brazil, there are some others whose origin is attributed to celestial body collision processes but have not yet been proven through the unequivocal identification of shock features, a necessary and fundamental scientific criterion (FRENCH & KOEBERL 2010). Three of these structures are Colônia and Praia Grande in the state of São Paulo and Ilha do Mel in Paraná. The latter two are submarine and buried structures on the continental shelf of the Atlantic within the sedimentary context of the Santos Basin.

5.1 Colônia (SP)

Colônia, also known as the "Colônia Crater," is located in the city of São Paulo, more precisely in the Parelheiros district, with its center at coordinates 23° 52′ S and 46° 42′ 20″ W (Figure 39). The structure is 3.6 km in diameter. Its origin has been debated since the early 1960s when it was identified by KOLLERT et al. (1961) and associated with a possible meteorite impact. Since then, a series of studies have been conducted on the structure (e.g., CRÓSTA 1987; RICCOMINI et al. 1991, 2005, 2011; VELÁZQUEZ et al. 2013, 2018, 2021; LEDRU et al. 2015; PRADO et al. 2019) without conclusive evidence of its formation by meteorite impact.

The Colônia structure is a prominent circular depression with a raised rim about 125 m higher than its depressed inner portion, forming an almost closed small drainage basin with a single opening to the east, where its entire internal area is drained (Figure 39). The interior of the depression is filled with detrital sedimentary strata corresponding to the Resende Formation (Paleogene) of the São Paulo Basin and by colluvial and alluvial deposits (Neogene). The terrain surrounding the structure consists of rocks of the crystalline basement of the Ribeira Belt (Neoproterozoic), predominantly schist, gneiss, quartzite, and migmatite.

Most of the studies conducted in Colônia used various geophysical methods to estimate the shape, thickness, and other characteristics of its sedimentary filling, and investigate any endogenous phenomenon that could be responsible for its formation. The results showed the absence of an endogenous mechanism for its formation, a bowl-like or basin configuration, and a maximum depth of ~400 m to the basement in its central portion.

The sedimentary filling was analyzed in detail up to a depth of 14 m through drilling cores (LEDRU et al. 2015) and by seismic method throughout its thickness (RICCOMINI et al. 2011, PRADO et al. 2019). Combining seismic and electrical resistivity data with the profile of a

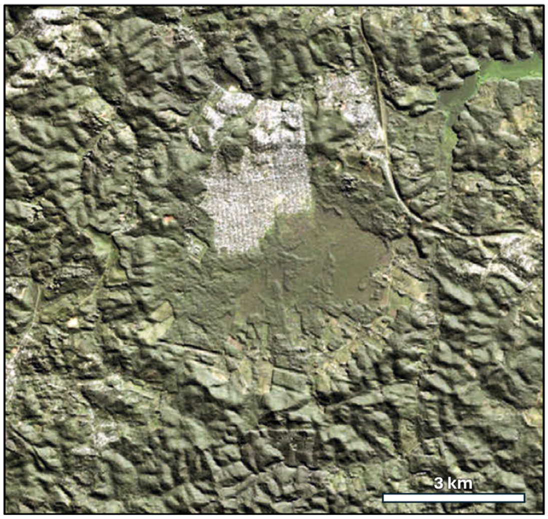

FIGURE 39 – Colônia. Composite image of the Sentinel-2 satellite, bands 2, 3, and 4 in RGB, superimposed on the TanDEM-X digital elevation model (GOTTWALD et al. 2020).

deep groundwater well drilled inside the structure up to 270 m, PRADO et al. (2019) developed a schematic sedimentary column composed of six sedimentary packages consisting of variable mixtures in thickness of four materials: (i) silt and clay rich in organic matter; (ii) sand and clay with coarse quartz grains; (iii) sand and clay with quartz pebbles; (iv) clay with pebbles and grains of quartz, feldspar, and gneiss clasts. There is a progressive increase in the grain size of the detrital materials mixed with clay with depth. Below 270 m and reaching up to ~400 m, seismic data indicate the possible presence of coarse and poorly selected material, with characteristics compatible with conglomerate levels and/or with autochthonous impact breccias (RICCOMINI et al. 2011, PRADO et al. 2019).

Despite the indirect evidence raised to date that points towards an exogenous origin for the Colônia structure due to a meteorite impact, there are no scientifically accepted direct evidences of this phenomenon. Based on the analysis of samples from drilling for groundwater wells inside the structure, VELÁZQUEZ et al. (2013, 2018, 2021) presented supposed evidence in this regard that does not stand up to the literature (e.g., REIMOLD et al. 2014, CRÓSTA & REIMOLD 2016, CRÓSTA et al. 2019a). The only "evidence" of shock micro-deformation presented by VELÁZQUEZ et al. (2013) is the supposed occurrence of PDFs in quartz; despite the low quality of the illustration presented for this feature, it is possible to infer that it does not correspond to true PDF and probably results from a typical tectonic deformation event of the local basement rocks and, therefore, from a pressure regime well below the shock regime. The article by VELÁZQUEZ et al. (2021), in addition to reiterating the supposed occurrence of shock features in material obtained from wells drilled for water inside the structure, a rock sampling method that is not suitable for this purpose, presents data on supposed impact-derived spherules found in the same material. Based only on the flattened shapes of the spherules (which they call "splash forms") and disregarding the fact that none of the geochemical analyses revealed any evidence of meteoritic material, they concluded that they are derived from the melting of basement rocks due to a meteorite impact event. Such a conclusion finds no support in the vast literature on spherules created by impact events (e.g., GLASS & SIMONSON 2013, and references therein).

In summary, the impact origin of the Colônia structure remains an open scientific question. It will only be elucidated through analyzing rocks recovered from strata at the transition between sedimentary filling and basement, i.e., at depths around 400 m, and/or proximal deposits resulting from the impact containing shock evidence or geochemical signatures of meteoritic material. Such deposits, still unveiled to date, may be preserved in the São Paulo Basin, whose sedimentation is partially chrono-correlated with the estimated time interval for the formation of the Colônia structure. RICCOMINI et al. (2005, 2011) estimate that it was formed at some point between 5 and 36 Ma.

5.2 Praia Grande (SP)

The Praia Grande structure is a submarine circular feature whose discovery is attributed to exploratory activities for hydrocarbons in the Santos Basin (CORREIA et al. 2005). It is located within the domains of the Atlantic continental shelf, 200 km offshore from the city of Praia Grande, with its center at coordinates 25° 38′ 50″ S and 45° 37′ 30″ W (Figure 40).

Situated beneath a water depth of 1.3 km and a column of sedimentary rocks approximately 4 km thick, Praia Grande was identified through 3D seismic surveys conducted by Petrobras. Its morphology suggests a circular structure with a diameter of 20 km, with a raised central core measuring 4.5 km in diameter.

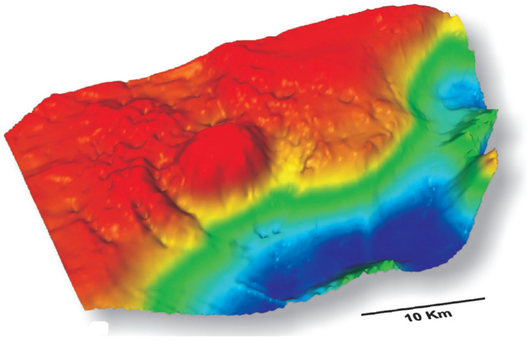

FIGURE 40 – Praia Grande. 3D projection of a Santonian seismic horizon showing the central uplifted core surrounded by the annular basin and concentric listric faults (CORREIA et al. 2005).

According to CORREIA et al. (2005), its formation occurred in the Late Cretaceous, with Albiano-Santoniano strata as the target rocks, which were later covered by younger strata from the Cretaceous (Campanian-Maastrichtian) and Tertiary. Based on local stratigraphy, these authors estimated that the Praia Grande structure formed within the interval of 83.5 to 85.8 Ma.

Currently, there is no confirmation of the meteorite impact origin of this structure. Although Petrobras did some drillings in its interior, there are no reports of shock features in the recovered local rocks, mostly carbonates.

5.3 Ilha do Mel (PR)

Similar to the Praia Grande structure, Petrobras discovered the Ilha do Mel structure as a result of hydrocarbon exploration activities in the Santos Basin (MENEZES et al. 2012). It is a submarine structure located 210 km offshore, with its center at coordinates 26° 37′ 48.3″ S, 46° 36′ 0.4″ W.

With a diameter of 6 km, the structure is characterized by 3D seismic data as it exhibits a set of concentric ring structures within it, representing possible collapse faults, with a central core and a ring basin between it and the structure’s edge. Above it lies an undeformed sedimentary package with a thickness of 400 m. The deformed sedimentary strata have Pliocene-Miocene ages, suggesting a formation age around 5 Ma.

In this case, the impact origin is not confirmed due to the absence of drilling within the Ilha do Mel structure.

6 GEOHERITAGE AND GEOCONSERVATION: BRAZILIAN INITIATIVES IN METEORITIC IMPACT STRUCTURES

Craters and impact structures are highly suitable sites for the development of actions related to the valorization and preservation of geological heritage and the conservation of geodiversity. An example of such a structure, which is already part of the UNESCO Global Geoparks Network (https://www.unesco.org/en/iggp/geoparks), is the Ries Crater in Germany (STURM et al. 2013). Another meteorite crater that receives hundreds of thousands of visitors each year is the Meteor Crater in the State of Arizona, United States (KRING 2017), a privately owned property equipped with a visitor center, museum, and attractions open to the public.

Brazil´s initiative to create geoparks is still in its early stages. At the time of the writing of this article, only six were officially registered with UNESCO, and none of the Brazilian impact structures had a geopark yet. However, some of the initiatives focus on geoconservation.

The Araguainha Dome was one of the first sites to be included in the database organized by the Brazilian Commission of Geological and Paleontological Sites (SIGEP), with sponsorship from the International Union of Geological Sciences (IUGS) (CRÓSTA 2002). The Dome was also included by CPRM/Brazilian Geological Survey (SGB) in the proposal to create Brazilian geoparks (THOMÉ-FILHO et al. 2012). The structure was the subject of an analysis of its geotouristic potential, together with other Brazilian impact structures, by SANCHEZ & BRILHA (2017). Finally, in 2022, the Araguainha Dome was selected in the list of “The First 100 IUGS Geological Heritage Sites” (IUGS 2022), being the only impact structure in the world to appear on this list (Figure 41). Despite these initiatives, the Araguainha Dome still does not have regular initiatives to promote public visitation.

The Vista Alegre structure is also part of the official geosites of SIGEP (CRÓSTA et al. 2013) and, in 2006, became part of the Geotourism Program of “Minerais do Paraná S.A.” (Mineropar), a state-owned company in Paraná, Brazil, as one of the geosites of that state. In partnership with the State University of Campinas (Unicamp) and the Municipality of Coronel Vivida, this initiative promoted the installation of bilingual informative panels in illustrative locations, in language accessible to the public. Leaflets in three languages (Portuguese, Spanish, and English) with content similar to the panels were also printed for distribution to the local population, mainly in schools, and to tourists. In 2008, the State Secretary of Culture of Paraná promoted the designation of an area of more than 10,000 m^2 with impactite occurrences containing the main evidence of the crater formation process. With the deactivation of Mineropar and the lack of interest from municipal administrations, these initiatives were discontinued for several years. In 2023, the Municipality promoted the revitalization of the designated area, installed a viewpoint on the edge of the structure, and continued to install and maintain informative panels and leaflets (Figure 42).

The Vargeão Dome is included in the list of official geosites of SIGEP (CRÓSTA et al. 2009).

THE FIRST 100 IUGS GEOLOGICAL HERITAGE SITES

IUGS

“ An IUGS Geological Heritage Site is a key place with geological elements and/or processes of international scientific relevance, used as a reference, and/or with a substantial contribution to the development of geological sciences through history „

THE INTERNATIONAL UNION OF GEOLOGICAL SCIENCES
DURING ITS 60TH ANNIVERSARY EVENT

CERTIFIES THAT

Domo de Araguainha
Impact Structure. Brazil

HAS BEEN DESIGNATED AND INCLUDED IN THE LIST OF
THE FIRST 100 IUGS GEOLOGICAL HERITAGE SITES

In Zumaia, Basque Coast UNESCO Global Geopark **28 / October / 2022**

Stanley Finney
Secretary General. International Union of Geological Sciences (IUGS)

Asier Hilario
Chair. IUGS-International Commissions on Geoheritage

FIGURE 41 – Araguainha “The First 100 IUGS Geological Heritage Sites” (IUGS 2022).

FIGURE 42 – Opening ceremony of the revitalization of the Vista Alegre quarry (July 1st, 2023). In the background, boulders of polymictic breccia and, on the left, one of the bilingual informative panels (in Portuguese and English) with information accessible to the general public. A plaque was installed by the Mayor of Coronel Vivida, Anderson M. Barreto, and by Unicamp´s professor Alvaro P. Crósta, fixed in a polymictic breccia boulder.

Despite the local population's awareness of the geological site, there have been no initiatives for geoconservation and valorization of the heritage by authorities at any level. However, at the initiative of the Public Prosecutor's Office of Santa Catarina and the Municipality of Vargeão, in collaboration with Unicamp, a set of informative panels is being implemented at various representative outcrops of rocks and impactites, also including general explanations about celestial impact geological processes and local geology. Similar to Vista Alegre, this initiative aims at scientific dissemination on the topic, targeting the general public.

The Colônia Crater, in addition to being listed as an official geosite of SIGEP (RICCOMINI et al. 2005), was designated in 2003 by the Council for the Defense of the Historical, Archaeological, Artistic, and Touristic Heritage of the State of São Paulo (CONDEPHAAT). In 2007, the Municipality of São Paulo created the Colônia Crater Municipal Natural Park, covering an area of 53 hectares, including a part still unoccupied, located inside the crater. Despite these initiatives, there are still no actions or permanent local facilities accessible to the public. Located in a district of the largest metropolis in South America, the Colônia Crater has great intrinsic potential for developing scientific, educational, and cultural activities. A fundamental step for this is the confirmation, by appropriate scientific methods, of its origin from a meteorite impact and its age, which will allow significant scientific advances in paleoenvironmental studies and the elucidation of past climates in the region since its formation.

7 CONCLUSIONS

In this article, we presented the current state of knowledge regarding confirmed impact structures in Brazil, as well as some that have the potential to be attributed to this type of geological process but still lack adequate data for detailed studies.

Cosmic collisions are the most fundamental geological process through which all planetary bodies form. They have occurred since the early days of the Solar System, during the accretion phase of these bodies, and persist to this day, albeit with a steadily decreasing frequency over time.

The geological structures that record this type of process are meteorite impact craters, the only structure on all solid bodies in the Solar System. While they are numerous on other planetary bodies, meteorite craters are relatively few and poorly distributed on Earth in time and space. The same applies to their modified versions by other processes, known as astroblemes or impact structures.

Despite just over 200 known craters and structures of this type known on Earth, of all ages and dimensions, Brazil has only nine of them. This number is considerably low, considering the country's territorial extent and the nature and age of its terrains. Other countries and regions with similar geological characteristics have dozens of impact structures despite having similar territorial areas, which suggests a potential for an increase in the number of such structures in Brazil.

The low number of meteorite structures in Brazil can be attributed to several factors. One is the limitation of geological knowledge of the Brazilian territory, with much of it being mapped only at regional scales. Additionally, the most visible structures on the surface have likely already been identified, leaving those in more advanced stages of erosion or buried beneath younger geological layers. In these cases, geophysical methods such as gravimetry, magnetometry, and reflection seismic techniques can help identify new craters and impact structures in Brazil. The virtual absence of planetary geology disciplines in Brazil´s curricula of geology courses may also contribute to the low number of identified structures.

From the perspective of methodological innovations that can contribute to new discoveries, indirect methods include remote sensing images and digital elevation models with higher spatial resolution, and aerogeophysical surveys with higher resolution (such as 3D seismic), combined with advanced processing techniques. These methods enhance the capability of unveiling subtle characteristics that differentiate the signatures of impact structures from those caused by other processes. In direct methods, significant advances have been made in characterizing shock deformation in minerals other than quartz, such as zircon and its polymorph reidite (CAVOSIE et al. 2018). Also, new high-precision analytical techniques may be applied in identifying the contribution of meteoritic material in impactites and impact deposits, typically present in very low concentrations (parts per billion) (e.g., MARTELL et al. 2024 and references cited therein). Finally, important methodological advances have been made in isotopic geochemistry, making it possible to accurately determine the ages of impact events and, consequently, reconstruct, even partially, the history of the geological record of Earth impacts. These methodological advances offer opportunities for new and exciting discoveries in the field of impact geology.

In summary, there is great potential for the discovery of new craters and impact structures in Brazil, and recent advances are opening up new opportunities to explore and better understand this important geological phenomenon.

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