Characterization of Brazilian impact structures based on interpretations of Sentinel-1 C-band dual-polarization (VV and VH) data

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ABSTRACT

The known Brazilian impact structures are characterized using C-band Synthetic Aperture Radar (SAR) images from the Sentinel-1 satellites. After acquiring the dual-polarization (VV and VH) Ground Range Detected Dataset from a public repository, we applied standard processing techniques, including calibration, speckle noise reduction, terrain correction, and conversion of backscattering values to linear dB format. RGB visualizations of the polarimetric components were then generated. Our findings indicate that most backscattering in Brazilian impact structures is seemingly influenced by soil properties or vegetation cover. However, first-order structural elements (outer rim, annular basin, or central uplift) of Brazilian impact structures could be completely, or partially, identified in SAR images, including the northern part of the outer rim of Araguainha, the outer rim of Vargeão Dome and Santa Marta, the rim and inner rings on São Miguel do Tapuio, central uplifts in Serra da Cangalha and Riachão Ring, and the annular basin in Riachão Ring. Additionally, certain features, such as silicified sandstones in the central portions of Cerro do Jarau and Serra da Cangalha, as well as structural lineaments in the Santa Marta and Vargeão Dome structures, contribute to backscattering patterns as well. Overall, our results suggest that SAR imagery can be a valuable tool for structural mapping of impact structures. As L-band radar systems (e.g., ALOS PALSAR, JERS-1) have longer wavelength and greater ability to penetrate vegetation, we recommend that the joint use of C- and L-band data could improve geological mapping of impact structures.

1. Introduction

Terrestrial impact structures form when celestial bodies collide with Earth's surface at hypervelocity, releasing immense energy and causing localized deformation (e.g., French, 1998; Osinski et al., 2022). All confirmed Brazilian impact structures are classified as complex structures, which typically feature an elevated central area (central uplift or the larger ones possibly a peak ring) surrounded by a ring syncline and an outer rim sector (e.g., Kenkmann, 2002, 2014). Secondary structural elements, such as thrust-faulting, folding, and monoclines, may also be present depending on the stratigraphy and properties of the target rock, impact scale, impact angle, and erosion level (Kenkmann et al., 2014).

Spatial imagery, particularly the Synthetic Aperture Radar (SAR), can be a useful tool in structural mapping due to its sensitivity to terrain roughness (e.g., Smith et al., 1999; McHone et al., 2002; Theilen-Willige, 2021). In the context of terrestrial impact structures, previous work has demonstrated that SAR (or derived products such as a Digital Elevation Model - DEM) images have been useful to identify first (e.g., crater-rim faults or crater-rim monocline, ring syncline, and central uplift) or second order (e.g., listric normal faults, folds and thrusts, etc) structural elements in complex impact structures, for example at Araguainha (Theilen - Willige, 1987) and Serra da Cangalha (Reimold et al., 2006), BP and Oasis (McHone et al., 2002; Koeberl et al., 2005; van Gasselt et al., 2017), Spider (McHone et al., 2002), Bosumtwi (Theilen - Willige, 2021), and Manicouagan (Smith et al., 1999). In addition, in hot desert regions, such as the Sahara Desert of Africa, depending on water content in the sands, the electromagnetic wave emitted by SAR instruments can penetrate into the ground and aid to estimate crater diameter or define associated features, like ejecta deposits or impact-induced fracture zones (e.g., Aorounga, BP, and Roter Kamm

impact structures - McHone et al., 1996, 2002). On the other hand, flat-surface trench zones (e.g., Spider impact structure) or fine-grained sediments of a post-impact crater fill (e.g., Connolly Basin crater) may decrease the backscattering on SAR images (McHone et al., 2002). Notably, by analysing the strength of backscattering on each polarimetric component, van Gasselt et al. (2017) attempted to distinguish bed rock from unconsolidated cover strata in the Oasis impact structure.

Despite the usefulness of SAR images in impact structure mapping outlined above, few studies (e.g. Crósta et al., 2012) with SAR data have focused on Brazilian impact structures so far, and Sentinel-1 dual polarimetric images have remained essentially unexplored. To close this gap, we characterize these structures using polarimetric images based on band C Sentinel-1 data, to identify structural elements and/or additional features that can improve our understanding of backscattering behaviour at Brazilian impact structures. The following sections provide an overview of the Brazilian impact structures and a description of our methodology. The main findings are then discussed in the context of existing knowledge.

2. Geological settings of Brazilian impact structures

Eight impact structures have been confirmed in Brazil based on the identification of bona fide shock deformation features (Fig. 1) (Crósta et al., 2019a; Reimold et al., 2022). In addition, São Miguel do Tapuio, although not officially recognized yet, has provided preliminary evidence strongly suggesting an impact origin (Crósta et al., 2019b), so that we also consider this structure to be of impact origin.

All of the confirmed Brazilian impact structures are located in two Paleozoic intracratonic sedimentary basins, namely the Paraná and Parnaíba basins (Fig. 1). The sedimentary records of these basins have been studied in terms of sedimentary

sequences (or supersequences) (Milani and Zalán, 1999). These sequences were formed by major tectono-sedimentary cycles—such as the Late Paleozoic Gondwana glaciation and the opening of the equatorial and southern Atlantic Ocean—and are separated by interregional unconformities (ibid). In summary, the stratigraphic columns of both basins predominantly comprise siliciclastic and carbonate rocks (sandstones, shales, mudstones, carbonates, etc.) deposited during Paleozoic transgressive-regressive cycles, as well as Mesozoic continental deposits with associated igneous rocks.
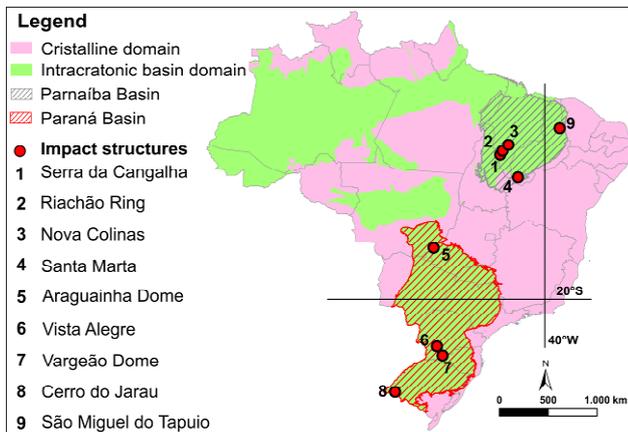

Figure 1. Locations of confirmed Brazilian impact structures 1-8) and São Miguel do Tapuio (9).

3. Materials and Methodology

The Sentinel-1 mission consists of two satellites, Sentinel-1A and 1B (since 2024, Sentinel-1B was replaced by Sentinel-1C), operating in a sun-synchronous orbit at an altitude of 693 km, phased 180° apart (ESA, 2025). Each satellite is equipped with a C-band instrument that operates at a frequency of 5.405 GHz (wavelength of 5.55 cm) in dual-polarization mode (ESA, 2025). In this study, Sentinel-1 SAR images with VV and VH polarizations were utilized, mainly due to their ready accessibility.

Sentinel-1 images capture backscattering of radiation reflected by the Earth's surface (ESA, 2025). Our images were acquired during the dry season in Interferometric Wide Swath mode and were pre-processed by ESA's Copernicus Space Component Ground Segment before having been made publicly available through the Copernicus Data Space Ecosystem. The datasets correspond to Level-1 Ground Range Detected (GRD) images, which undergo multi-look processing and are projected to ground level, resulting in a final spatial resolution of 12.5 m (ibid). Here, we used Sentinel Application Platform (SNAP) (version 11.0.0) freely available by the European Space Agency (ESA) to carry out the processing described below.

The further processing of Sentinel-1 SAR Level-1 GRD images involved: i) converting pixel values to radar backscattering through radiometric calibration; ii) reducing speckle noise (random interference caused by surface scatter) using a Refined Lee filter (Yommy et al., 2015); iii) correcting geometric distortions through terrain correction; iv) converting the radar backscattering coefficient to linear dB format to enhance visualization and analysis. Following the initial processing, additional bands were derived from the original VV and VH bands:

- Ratio Pol – calculated by dividing VV by VH components.

- Multi Pol – computed as the absolute product of VV and VH components.
- Diff Pol – determined using the absolute difference between VV and VH components.

These original and derived bands were integrated into RGB composite colour visualizations, which were then arranged into maps for further analysis.

4. Results

The RGB visualizations of impact structures in the Paraná and Parnaíba Basin are displayed in Figures 2-4. Two backscattering patterns seem to be dominant in the most figures. The first pattern (P1) shows dark blue shades and a smoothed texture (see, e.g., feature 1 in Fig. 2). The second pattern (P2) can also be characterized by a smooth texture, but is coloured in light green or cyan shades (Fig. 2). We have noted that the second pattern coincides with vegetation cover, mainly vegetation along drainage channels (e.g., Fig. 2a, 2b, 2c, 2d, and 2c). Despite the dominance of these patterns, it has been possible to identify other backscatter signatures in the SAR images with geological meaning.

4.1 Backscattering in impact structures of the Paraná Basin

The circular patterns of the Araguainha (40 km diameter), Cerro do Jarau (~13 km diameter) and Vista Alegre (~9.5 km diameter) impact structures commonly seen in optical images (e.g., Crósta et al., 2019a) are less defined in Figures 2a, 2d, and 3a. Even so, some interesting features with geological meaning are noted. In the Araguainha impact structure, such features are represented by: i) a curved feature (feature 1 in the Fig. 2b) in the northern portion of the structure. This portion of Araguainha's rim was also seen in X-band radar images (Theilen-Willige, 1987); ii) several small hill features can be seen in orange colors (feature 2 in Fig. 2b) also in the northern portion of Araguainha; iii) lineaments with NE-SW directions running in the external domain to the north of Araguainha. These lineaments seem to be interrupted by the curved feature described above, but the exact cross-cutting relationships are unclear on Fig. 2b; iv) yellow color zones with rough texture can be seen near the innermost part of Araguainha's central uplift (feature 4 in Figs. 2a and 2c), mainly in the northeastern sector; and, finally, dark brown features (feature 5 in the Fig. 2a and 2c) occur not only in the central uplift but also in its environs.

In the Cerro do Jarau impact structure (~13km diameter), light green shades with smooth textures (P2) dominate the northeastern sector of the structure (Fig. 2d and 2e). Another backscattering signature with yellowish shades (feature 1 in Fig. 2e) seemingly surrounds the outer portion of the Cerro do Jarau central uplift.

Unlike these first two impact structures, the circular pattern of the Vargeão Dome impact structure (~12.4 km diameter) is clearly seen in the Sentinel-1 C-band image (Fig. 3a). Structural features along the rim are well-defined, mainly in the western sector (feature 1 in Fig. 3a). In the eastern sector of Vargeão Dome, two NE-SW trending lineaments are evident (feature 2 in Fig. 3a).

The landform relief contrast between the inner and outer portions of the Vista Alegre impact structure (~9.5 km diameter) is represented as different textural patterns in Figure 3b. The textural pattern in the outer portion of the impact
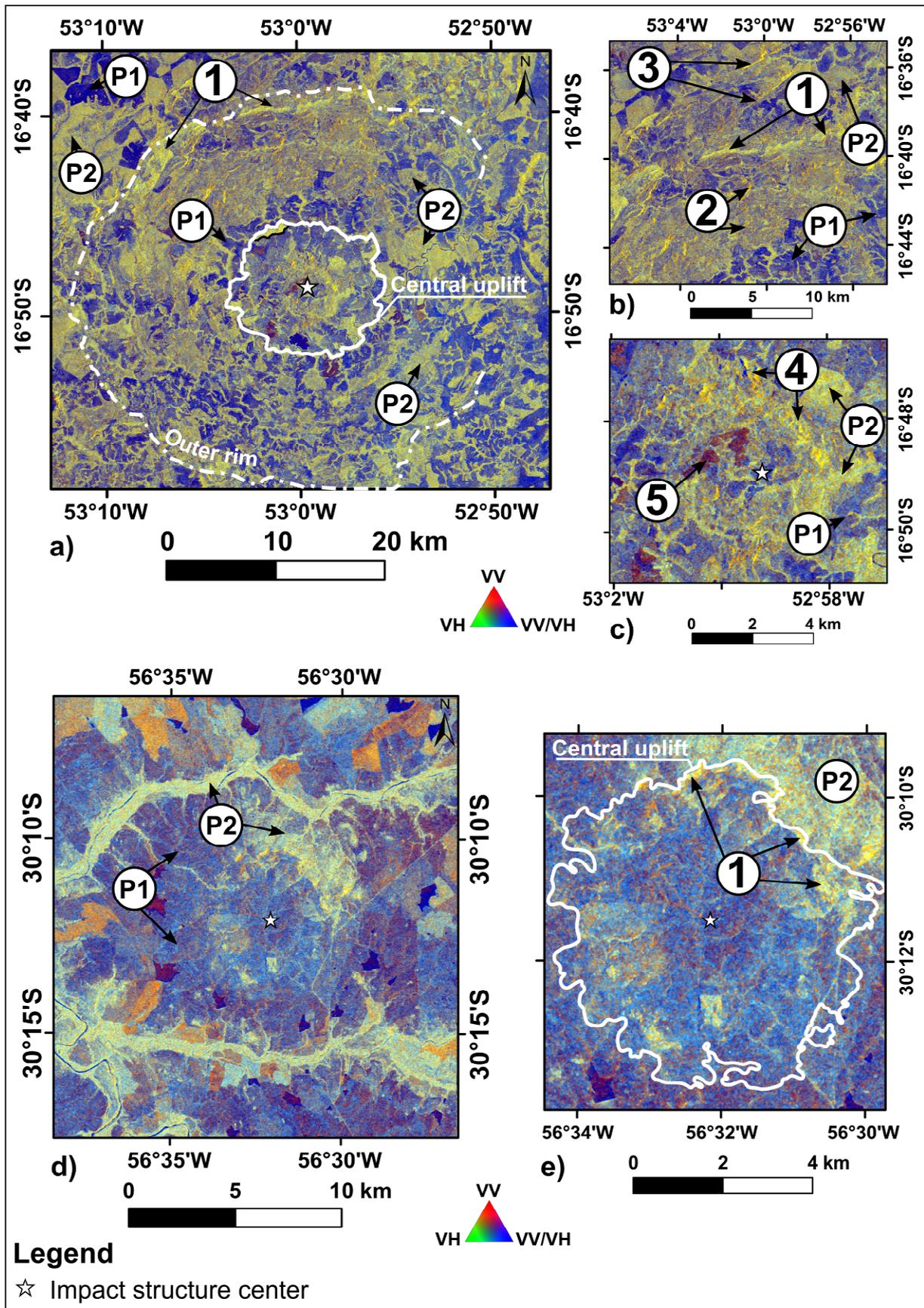
Figure 2. RGB composite colour visualizations of polarimetric components for impact structures in the Paraná Basin. a) Araguainha impact structure. b) Northern portion of Araguainha's rim. c) Araguainha's central uplift. d) Cerro do Jarau impact structure. e) Details of Cerro do Jarau's central uplift. All the numbered features are described in the text.
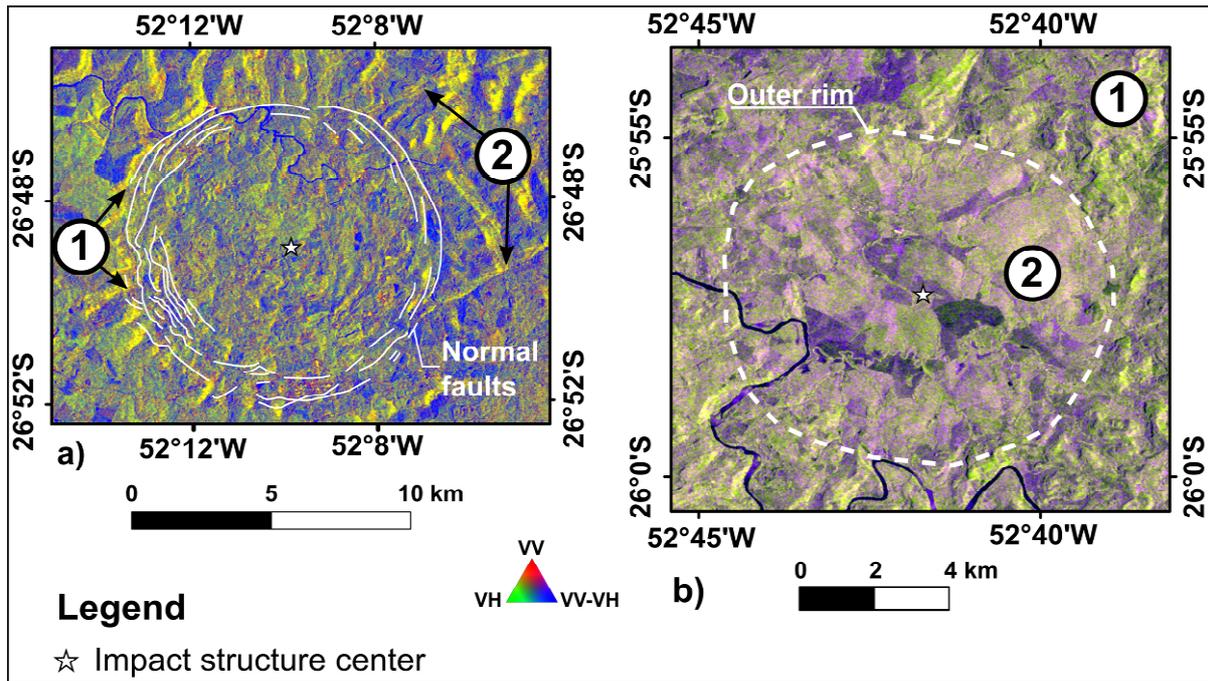
Figure 3. RGB composite colours of polarimetric components of two impact structures in the Paraná Basin. a) Vargeão Dome impact structure. b) Vista Alegre impact structure. The fractured basalt limit separates the interior of the structure from the exterior. All the numbered features are described in the text.

structure is rough (feature 1 in Fig. 3b), but inside the structure the pattern becomes smooth (feature 2 in Fig. 3b).

4.2 Backscattering in impact structures of the Parnaíba Basin

The RGB visualization of polarimetric components of impact structures in the Parnaíba Basin are shown in Figures 4a–e. Serra da Cangalha, Santa Marta, and São Miguel do Tapuio show well-defined circular patterns, whereas for Riachão Ring and Nova Colinas these patterns are subdued.

An area elevated in the inner part of the Serra da Cangalha structure (~13.4 km diameter) (Reimold et al., 2006; Kenkmann et al., 2011; Vasconcelos et al., 2013) appears as a zone of high backscatter showing a rough texture and yellow shades in Figure 4a (feature 1 in Fig. 4a). The western portion of the structure's rim is relatively well-defined (feature 2 in Fig. 4a), but the rim is not well visible in the eastern sector.

Although the circular pattern is subdued at Riachão Ring impact structure (~4 km diameter), it is possible to distinguish two zones within the structure: one area (feature 1 in the Fig. 4b) in the innermost part of the Riachão Ring impact structure characterized by high backscattering signatures, which is surrounded by another low backscatter area (feature 2 in the Fig. 4b). We have noted that this latter area coincides with the annular basin around the small central uplift area. Note that low backscattering signatures also occur outside of Riachão Ring, mainly in the western portion (feature 3 in the Fig. 4b).

Similar to Riachão Ring, a circular pattern is weakly defined at the Nova Colinas impact structure (~7 km diameter) (Fig. 4c). Strong yellow shades occur mainly in the southern portion of the structure (feature 1 in the Fig. 4c), but similar shades are also observed in the northern portion, outside of the impact structure (feature 2 in the Fig. 4c). Dark blue zones are noted near

the center of the structure (feature 3 in the Fig. 4c) but they are dominant outside of Nova Colinas, mainly to the south (feature 4 in the Fig. 4c).

In the Santa Marta impact structure (~10 km diameter), the outer rim is distinguishable in the eastern portion of SAR images (feature 1 in Fig. 4d). This rim is represented by concentric normal faults (Oliveira et al., 2014). Furthermore, brown shades appear in the northeastern sector, both inside and outside of the impact structure (feature 2 in Fig. 4d). However, this brown pattern seems to be discontinuous and heterogeneous inside of the structure (feature 3 in Fig. 4d). Dark blue shades (P1) are dominant in the northwestern part (feature 4 in Fig. 4d) of the Santa Marta impact structure.

Concentric lineaments are also observed at São Miguel do Tapuio (~23 km diameter) (Fig. 4e). Although it is not clear what the nature of these concentric lineaments is, it is likely that concentric lineaments near the outer rim of the structure are normal faults (see, e.g., feature 1 in Fig. 4e) related to inward rim collapse in the modification stage of cratering.

Semi-circular features are also visible in SAR images inside of São Miguel do Tapuio. Three concentric features at São Miguel do Tapuio were originally proposed by Martins et al. (2016) from digital elevation model imagery, whereas our data seemingly indicate four concentric features. Like Martins et al.'s work, our outermost circular feature (feature 1 in Fig. 4e) seems to be part of the structure's rim. The second outermost ring (feature 2 in Fig. 4e) and the innermost ring (feature 3 in Fig. 4e) can be related to the intermediate and innermost rings suggested by Martins et al. (2016). However, our data suggest a third ring (feature 4 in Fig. 4e) between the intermediate and innermost rings. The nature of this third ring is unclear, but a possible explanation will be given in the next section.
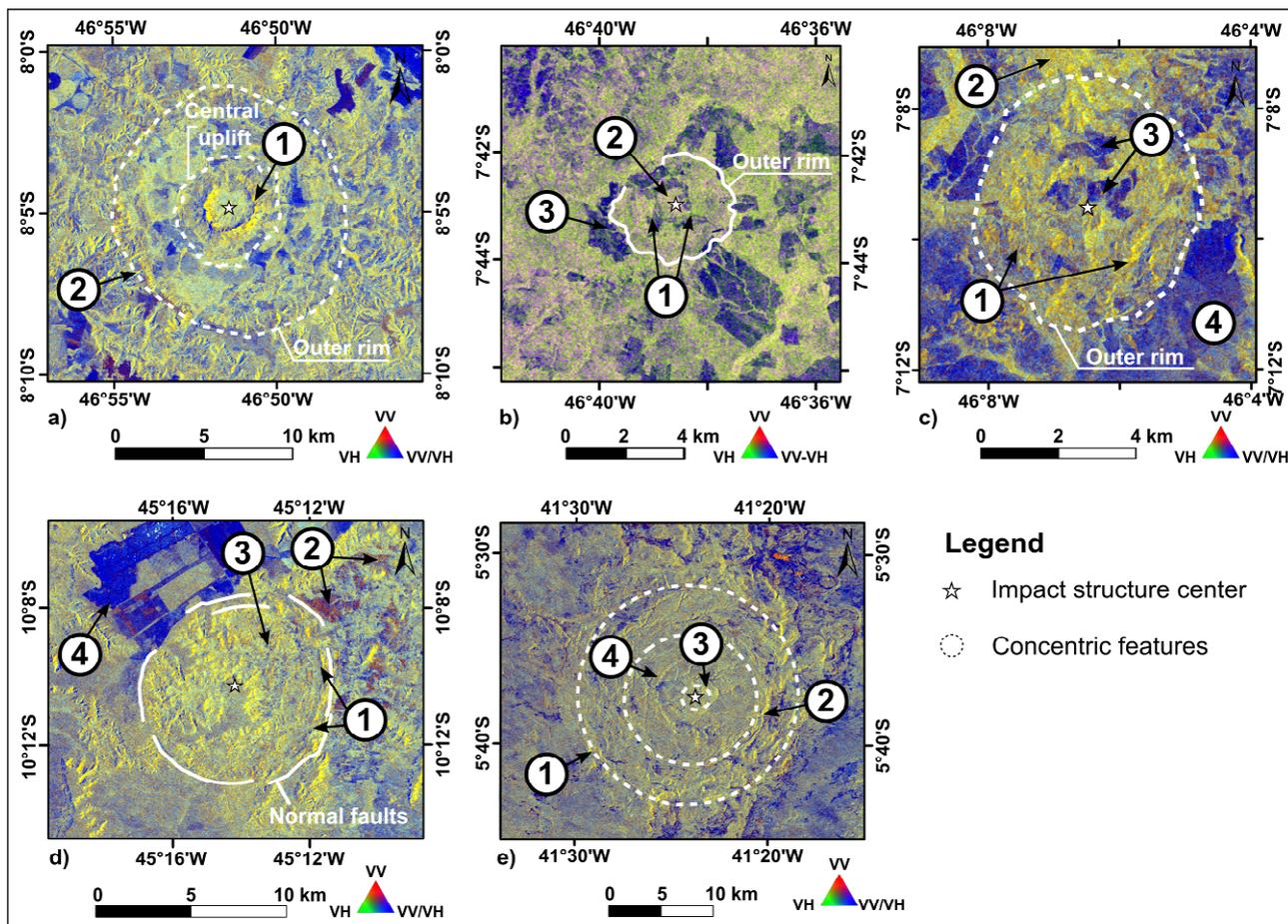
Figure 4: RGB composite colour diagrams of polarimetric components of impact structures in the Parnaíba Basin. a) Serra da Cangalha impact structure. Contour of central uplift and outer rim modified after Vasconcelos et al. (2013). b) Riachão Ring impact structure. Contour of central uplift and outer rim modified after Maziviero et al. (2013). c) Nova Colinas impact structure. Outer rim modified after Reimold et al. (2022). d) Santa Marta impact structure. Normal faults modified after Oliveira et al. (2014, 2017). e) São Miguel do Tapuio impact structure. The black arrows show parts of semi-circular features discussed in the text. Concentric features modified after Martins et al. (2016).

5. Discussion

Analysis of SAR images of Brazilian impact structure has revealed that, despite their individual peculiarities (e.g., diameter size, locality, erosion level, etc), some commocharacteristics of Brazilian impact structures can be identified in SAR images. For instance: the dark blue shades (first backscattering pattern – P1) seen in the Araguainha, Cerro do Jarau, Serra da Cangalha, Riachão Ring, Nova Colinas, northwestern Santa Marta, and the eastern portions of São Miguel do Tapuio imagery suggest the entire electromagnetic signal returned to the SAR sensor is low but the vertically transmitted/received electromagnetic wave (VV component) is relatively higher than the cross-polarized component (i.e., vertically transmitted and horizontally received—VH). We hypothesize that these signatures are primarily associated with soil properties (e.g., irrigated soil), as VH components tend to exhibit lower intensity in such materials (Guha et al., 2013). The light green or cyan shade patterns (i.e., second backscattering pattern – P2) also occur in areas covered by vegetation (e.g., along the drainage path in the north of Cerro do Jarau impact structure), so that we assume that this backscattering comes from vegetation cover.

We have noted that the dominance of both soil properties and vegetation backscattering signatures hinders the identification of structural elements in Brazilian impact structure somewhat. For instance: Serra da Cangalha, Santa Marta, and São Miguel do Tapuio display clear structural elements, such as faults and lineaments, whereas other structures, like Araguainha, are less distinct probably due to widespread interference from soil and vegetation. To overcome these shortcomings, further studies should consider geological feature detection in Brazilian impact structures by using L-band instrument data (e.g., ALOS PALSAR 1 and 2, JERS-1, etc.) because the longer wavelength of the L-band radar can penetrate vegetation. Thus, the intermediate to coarse texture variations of surface roughness associated with various geological features (e.g. faults, folds, topographic discontinuities, bedding structures, depressions, and lithological contacts) could be revealed (Pour and Hashim, 2014).

Despite the dominance of vegetation and/or soil property backscattering patterns, this study has also found backscattering signatures that might have geological meaning. For instance: the curved feature (our feature 1 in the Fig. 2b) in the northern portion of the Araguainha impact structure likely is related to Passa Dois Group pelitic rocks that form Araguainha's rim (see Souza et al., 2024). In Vargeão Dome, the structural features

(our feature 1 in the Fig. 3a) along the western rim were already interpreted as normal (or listric) faults (Crósta et al., 2012). Similarly, the outer rims of Serra da Cangalha (our feature 2 in the Fig. 4a), Santa Marta (our feature 1 in the Fig. 4d), and São Miguel do Tapuio (our feature 1 in the Fig. 4e) are also well-defined in SAR images. In these cases, the backscattering probably reflects the morphology and structural deformation at the rim.

Beyond observations on outer rims, this work has found other backscattering signatures that could be related to first-order structural elements, such as annular basins or central uplifts. The first case is exemplified by orange colour hill features (our feature 2 in the Fig. 2b) seen in the northern portion of the Araguainha impact structure and low backscattering zones surrounding the center of the Riachão Ring structure (our feature 1 in the Fig. 4b). According to the most recent geological map of Araguainha (Souza et al., 2024), these small hill features likely correspond to prominent Aquidauana Formation sandstone outcrops. This formation is the dominant stratigraphic unit in the annular basin of the Araguainha structure. In Riachão Ring, the low backscattering zones surrounding the structure's center can be thought to arise from the flattish surfaces with fine-grained sediments from drainage channels that occur in the annular basin of the structure. Low backscattering zones related to flat surfaces with fine-grained sediments or crater fill deposits have also been observed in the annular basins of the Spider and Connolly Basin impact structures (McHone et al., 2002).

The second case is exemplified by a backscattering pattern (with yellow colors and rough texture) that was seen to the northeast of Araguainha´s central uplift (our feature 4 in the Fig. 2c), in the northeastern sector of the Cerro do Jarau central uplift (our feature 1 in the Fig. 2e), and in the inner part of the Serra da Cangalha central uplift (our feature 2 in the Fig. 4a). At Araguainha, this pattern coincides with the Serra da Arnica hills of highly deformed Devonian Furnas Formation sandstone (Souza et al., 2024), whereas silicified sandstones seem to be the source of this pattern at Cerro do Jarau and Serra da Cangalha (Vasconcelos et al., 2013, Sánchez, 2014). These findings demonstrate that the shade and texture patterns observed over silicified (or strongly deformed) sandstones on the Araguainha, Serra da Cangalha, and Cerro do Jarau central uplifts corroborate the idea that strong backscattering of cross-polarized components (here, VH components) may be useful for mapping consolidated materials and rocks exposed at surface (e.g., van Gasselt et al., 2017). Furthermore, because the backscattering patterns of silicified sandstones in the Cerro do Jarau central uplift appear more yellowish and texturally rougher than backscattering patterns from vegetation (i.e., the P2 signature), it can be suggested that both silicified sandstones and vegetation backscatter patterns can be distinguished by polarimetric decomposition analysis. It is also worth noting that the third ring between the intermediate and innermost rings in São Miguel do Tapuio could be related to the central uplift or a collapsed peak ring feature. Unfortunately, it has not been possible to find an explanation for the dark brown features seen in the Araguainha central uplift.

In addition to the backscattering signatures discussed above, the analysis of SAR images of Brazilian impact structure also revealed pre-impact features that may have been affected by the impact event. For instance: the lineaments with NE-SW direction in the northern portion of the Araguainha scene (our feature 3 in the Fig. 2b) likely are pre-impact features that may have constrained the morphology of the Araguainha structure

(Bernardes et al., in press). Similarly, the NE-SW trending lineaments in the eastern sector of Vargeão Dome (our feature 2 in the Fig. 3a) have been associated with the regional Lacinha–Cubatão fault system, a pre-impact feature that was disrupted by the impact event in the Vargeão Dome area (Kazzuo-Vieira et al., 2009).

At the Riachão Ring impact structure, flat surfaces (our feature 3 in the Fig. 4b) can account also for low backscattering outside of the structure. Here, such surfaces seem to represent alluvial deposits related to drainage that has been controlled by the presence of the impact structure. At the Santa Marta structure, soil properties derived from Quiricó Formation rocks may be the sources of the brown shaded areas outside of the impact structure (our feature 2 in the Fig. 4d). As these same brown areas are discontinuous and heterogeneous inside of the Santa Marta structure (our feature 3 in the Fig. 4d), it is assumed that this discontinuous pattern may be related to original materials (that is, the brown shades of feature 2) that were fragmented, brecciated, and mixed during the impact event.

Finally, landform relief contrast between the inner and outer portions of the Vista Alegre impact structure arises from the impact event (Crósta et al., 2010), but we interpret that the backscattering behaviour over the interior of the Vista Alegre structure is primarily due to extensive agricultural use. In the Nova Colinas impact structure, the strong yellow shades occurring mainly in the southern portion of the structure (our feature 1 in the Fig. 4c) may be related to a linear to curvilinear hill land system (see Reimold et al., 2022) which, in turn, can be considered as rotated/faulted sandstone blocks formed due to the impact. However, similar shades are probably related to vegetation developed on Corda Formation sandstones that occur in the north, outside of the impact structure (our feature 2 in the Fig. 4c). Dark blue zones near the center of the structure are probably related to a low amplitude/declivity hill land system described by Reimold et al. (2022) (our feature 3 in Fig. 4c), whereas the low backscattering zones (dark blue) in the southern portion outside the Nova Colinas impact structure may be caused by a sandstone and low declivity terrain (our feature 4 in Fig. 4c).

In summary, Brazilian impact structures can be characterized in SAR images as having a significant portion of backscatter associated with soil and/or vegetation properties. Even so, first-order structural elements can still be identified, and in some cases, the backscatter pattern of stratigraphic units affected by the impact can also be distinguished.

6. Conclusions

This study was designed to characterize the Brazilian impact structures by using polarimetric images based on band C Sentinel-1 data. From the interpretations carried out on RGB composite colour diagrams of VV and VH polarimetric components, this study was successful in identifying structural elements and additional features that improved our understanding of backscattering behaviour on Brazilian impact structures. Our findings allow us to draw the following conclusions:

- The backscattering patterns that come from soil properties, such as moisture in surface-near materials and texture, and from vegetation cover are dominant in the SAR scenes of all impact structures. Such patterns made the identifications of structural elements in Brazilian impact structure less straightforward in some cases.

- Some impact structures, such as Serra da Cangalha, Santa Marta, and São Miguel do Tapuio, display clear structural elements, such as faults and lineaments, whereas others, like Araguainha, are less distinct probably due to widespread interference from soil and vegetation. Such interferences can possibly be mitigated by using data from sensors with microwaves with better penetration capacity (L- or P-bands) and additional polarimetric components (e.g., HH and HV).

- At least one first order structural element (outer rim, annular basin, or central uplift) of Brazilian impact structures could be completely, or partially, identified in all SAR images, such that our findings demonstrate that C-band Sentinel-1 images can effectively identify structural elements in impact structures (e.g., part of outer rim of northern portion of Araguainha, outer rim of Vargeão Dome and Santa Marta structures, rim and inner rings on São Miguel do Tapuio, central uplifts in Serra da Cangalha and Riachão Ring, and annular basin in Riachão Ring).

- Vegetation and silicified sandstones exhibit similar shades, though silicified sandstones tend to appear more yellow. This suggests that these targets can be distinguished using polarimetric decomposition techniques.

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