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Investigation of Shuttle Radar Topography Mission data of the possible impact structure at Serra da Cangalha, Brazil

Wolf U. REIMOLD[1*], Gordon R. J. COOPER[1], Rafael ROMANO[2],
Duncan R. COWAN[3], and Christian KOEBERL[4]

[1]Humboldt-Universität zu Berlin, Museum für Naturkunde, Institut für Mineralogie, D-10115 Berlin, Germany
[2]Department of Geology, Federal University of Ouro Preto, Ouro Preto, Brazil
[3]Cowan Geodata Services, 12 Edna Road, Dalkeith, Western Australia, Australia
[4]Department of Geological Sciences, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria
[*]Corresponding author. E-mail: uwe.reimold@museum.hu-berlin.de

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Abstract–The Serra da Cangalha crater structure in northeast Brazil, ~13 km in diameter, has long been widely considered to be a confirmed impact structure, based on reports of shatter cone findings. Only very limited field work has been carried out at this crater structure. Landsat Thematic Mapper (TM) and Shuttle Radar Topography Mission (SRTM) data sets for the region around this crater structure are compared here with regard to their suitability to determine first-order structural detail of impact crater structures. The SRTM data provide very detailed information regarding drainage patterns and topography. A pronounced central ring of up to 300 m elevation above the surrounding area, two comparatively subdued intermediate rings of 6 and 10.5 km diameter, respectively, and the broad, complex crater rim of up to >100 m elevation can be distinguished in the Serra da Cangalha data. The maximum cratering-related regional deformation (radial and concentric features) seems to be limited to a radial distance of 16–18 km from the center of the structure. A first comparison of macrostructural information from several impact structures with that from Serra da Cangalha does not yield firm trends, but the database is still very small at this stage. The varied nature of the target geology strongly influences the development of structural features in any impact event.

INTRODUCTION AND BACKGROUND

The Serra da Cangalha structure is centered at 8°05′S and 46°52′W in the extreme northeast of Tocantins state in Brazil (Fig. 1). Based on findings of shatter cones, it is widely held that Serra da Cangalha is indeed a confirmed impact structure (Dietz and French 1973; McHone 1979; Santos and McHone 1979; Crósta 1987, 2004), although bona fide microscopic evidence of shock metamorphism has never been reported (Crósta 2004). Past authors assigned a diameter of 12–13 km to the structure, which is comprised of several ring features. Most prominent of these is a 3 km (5 km, according to De Cicco and Zucolotto 2002) inner circular ring of mountains 250–300 m high that lends this structure an appearance similar to that of the Gosses Bluff structure of Australia, which has a 4.5 km inner ring and a subdued outer rim feature at 24 km diameter (Milton et al. 1996). Similar to Gosses Bluff's inner ring structure and that of the Libyan impact crater Oasis (Koeberl et al. 2005a), the inner ring at Serra da Cangalha is thought to represent the differentially eroded remnant of a lithologically diverse central uplift feature formed from a layered sequence of target rocks.

The Serra da Cangalha structure was formed in the intracratonic Parnaíba basin (formerly known as the Maranhão basin). The basin stratigraphy involves Upper Silurian to Cretaceous sedimentary rocks. The geology of the region and the structure was reviewed by Crósta (1982, 1987, and references therein). The strata within the structure include upper Permian sandstones of the Pedra de Fogo Formation, Permian/Carboniferous sandstones of the 323–290 Ma Piauí Formation and the 354–323 Ma Poti Formation, as well as dark shales of the Upper Devonian Longá Formation. The structure is surrounded by tabular outliers (mesas) of Triassic sandstones of the Sambaíba Formation. In the center of the structure, these strata are intensely deformed and display vertical dips (Crósta 1982) (presumably on bedding surfaces). On the basis of stratigraphic drilling in the region by the Geological Survey of Brazil, the original stratigraphic depth of the strata now exposed in the center of the impact structure is estimated between 100 and 1300 m below surface, which

Fig. 1. Location of the Serra da Cangalha crater structure in the Tocantins state of north-central Brazil.

gives us an estimate on uplift gradient. According to Adepelumi et al. (2003a; Góes et al. 1993), the sedimentary rocks in the region showed a preferred NE-SW depositional direction (which we interpret to mean that there is a regional NE-SW-directed fabric).

Serra da Cangalha was first proposed as a possible impact structure by Dietz and French (1973) because of the circular shape recognized in Landsat imagery (Fig. 2), the absence of volcanic rocks in drill core from the central part of the structure, and because it appeared unlikely that diapirism could account for the geometry of the structure (no carbonate or salt layers had been recognized in the sedimentary country rock stratigraphy). Dietz and French (1973) and McHone (1979) referred to shatter cones occurring on quartzite boulders of a conglomerate from the base of the Poti Formation observed in the inner ring structure. These authors also described intricate fracturing of quartz, as well as microspherules occurring in microscopic fractures; however, neither of these constitutes proof for the existence of an impact structure. Crósta (1987) referred to occurrence of shock metamorphic features in the form of "shock lamellae" and "breccia," but did not provide further detail that could be used to confirm that these features represent bona fide shock deformation. The same author reported in 2004 that, to date, no definitive evidence of shock metamorphism has been reported for this structure (Crósta 2004). Consequently, with exception of the early reference to shatter cones, no evidence for impact has been reported from Serra da Cangalha. Consequently, we consider Serra da Cangalha as only a possible impact structure, still to be confirmed. No firm constraints for the age of the Serra da Cangalha structure have been obtained yet, either. Based only on stratigraphic considerations, a maximum age of 250 Ma can be estimated for the formation of the crater structure (i.e., the structure was formed in strata of Triassic or younger age).

Some geophysical analysis of the structure and modeling of the data has been performed in recent years (Adepelumi et al. 2003a, 2003b, 2004, 2005a, 2005b). Interpretation of aeromagnetic data (Adepelumi et al. 2003b, 2004) indicated a diameter of 12.7 km for the Serra da Cangalha structure, and the magnetotelluric investigation by Adepelumi et al. (2004) resulted in the hypothesis that the likely impact-induced structural deformation below and in the environs of the crater did not exceed a depth of 2 km. A 2-D resistivity model (Adepelumi et al. 2005a, 2005b) suggested a 4-layer model for the structure: a thin resistive layer underlain by a conductive layer, weathered basement and, ultimately, resistive crystalline basement. The depth to the basement is estimated at 1.1 km. Three-dimensional forward modeling significantly reduced the basement resistivity, the effect of which was related by the authors to impact-induced brecciation, fracturing, alteration of the shock-deformed zone, and the presence of new low-magnetic materials and fluids (see also Abraham et al. 2004).

Here, we use Shuttle Radar Topographic Mission (SRTM) data for the area of the Serra da Cangalha structure to

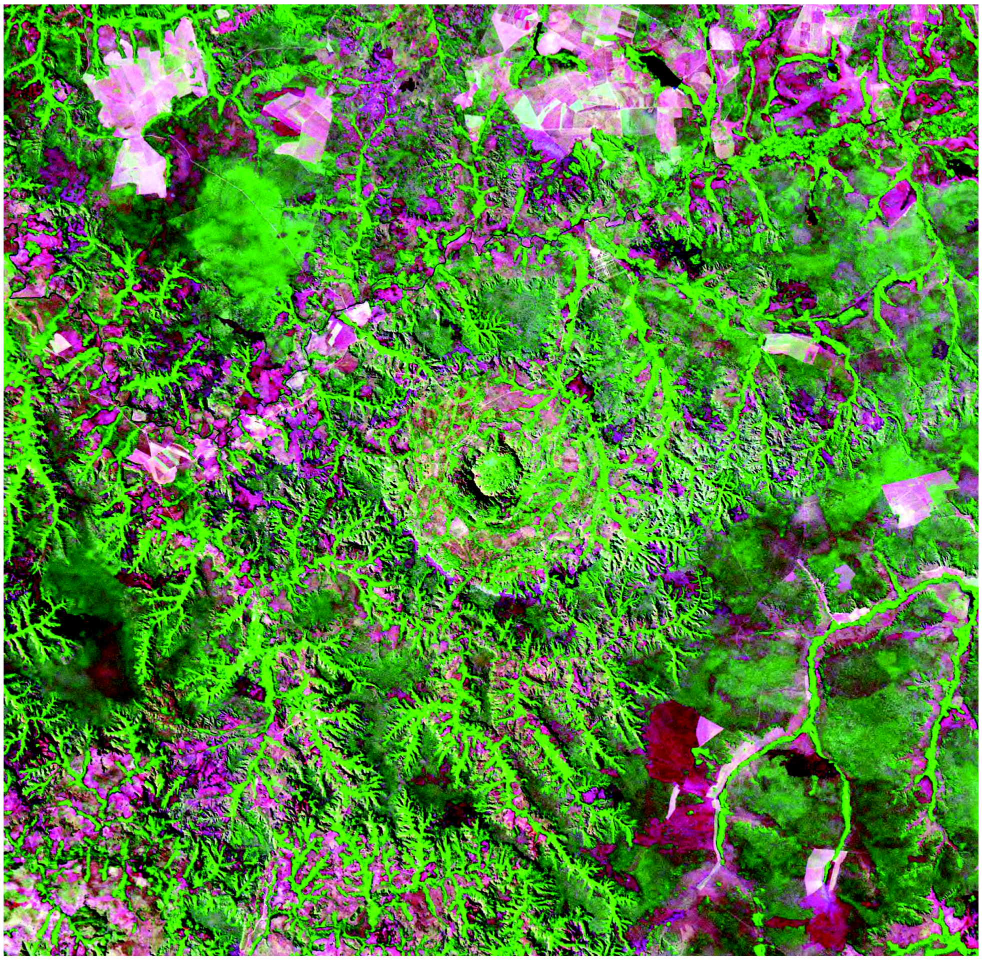

Fig. 2. Landsat image (bands 7-4-2 as RGB) over the Serra da Cangalha impact structure. The scene limits are 47°01′05″W to 46°41′50″W, and 12′21″S to 7°57′19″. In this and the following images, the top of the image is north.

investigate the morphology and geometry of the structure, as well as the regional influence exerted by this possible impact event. We also test the recently developed circular sunshading method (Cooper 2003) with this application. Finally, we set out to investigate whether or not the occurrence of and spacing between specific morphological features in impact structures follow a definite relationship. Several images generated from the SRTM data over the Serra da Cangalha area were recently shown by Almeido-Filho et al. (2005), though without any geological interpretation.

DATA AND PROCESSING METHODOLOGY

Shuttle Radar Topography Mission (SRTM) data for the region around the Serra da Cangalha structure were available for this study. Global SRTM single pass radar interferometry data (Farr and Kobrick 2000) were obtained by the STS-99 space shuttle mission between 11 and 22 February 2000. SRTM digital elevation model data have a horizontal resolution of 1 arc second (equivalent to 30 m at the equator) and a vertical resolution of 10 m, for the C-band radar. The United States Geological Survey (USGS) is the responsible data archiving agency; data were made available by NASA/Jet Propulsion Laboratory. Global 3 arc second data have been released, whereas 1 arc second data are only available for North America. Initial comparison between 3 arc second SRTM and older GTOPO DEM (Global Topography 30 arc second Digital Elevation Model) of the USGS (Cowan and Cooper 2003) showed that the resolution of SRTM DEM is a significant improvement, and will be particularly valuable in areas for which limited topographic data are available.

The Thematic Mapper (TM) Landsat data available for the Serra da Cangalha region (Fig. 2) provide a means for comparison with the SRTM data. In addition, several enhancement methods were applied in this study. Sunshading techniques, such as fractional order sunshading (Cooper and Cowan 2003a, 2003b) and a technique that enhances circular anomalies (Cooper 2003) were also employed.

A standard filter used to enhance linear features in images is sunshading. It determines the reflectance from the data of a light source located at infinity. Linear features that lie parallel to the azimuth of the light source (the “sun”) are attenuated while those that lie orthogonal to it are enhanced (Horn 1982). Because sunshading is a form of high-pass filtering, it enhances both detail and noise in an image. The sunshading filter uses the first horizontal derivatives of the data, but if noise is a problem then lower-order derivatives may be used instead. These derivatives are of non-integer order and are best computed in the frequency domain (Cooper and Cowan 2003a). The results from three different sunshading operations, each of which uses derivatives of different order, may be combined to form an RGB image. High-frequency features then appear blue, while lower frequency features appear red (Cooper and Cowan 2003b). Impact structures are mostly near-circular; the sunshading filter was therefore modified to enhance features that lie either on or orthogonal to radial vectors that pass through a chosen origin position. This was achieved by making the sun azimuth a variable over the image, rather than a constant (Cooper 2003). As shown below, the circularity of this impact structure is strongly enhanced by this method. However, in the application of the circular sunshading technique to the search for further impact structures the user should be well aware that there are a range of other geological features that may have similar geometry, for example, ring structures caused by differential erosion above an intrusion, kimberlite pipes, or other volcanic features.

RESULTS

Figure 2 shows an RGB color composite image of Landsat TM bands 7-4-2. Band 7 is in the far infrared and has a strong response from hydroxyl-bearing minerals and clays, specifically carbonates, micas, chlorite, and amphiboles. Band 4 is in the near infrared and has a strong response from iron absorption and vegetation. Band 2 corresponds to green light in the visible part of the spectrum. It is useful in highlighting both chlorophyll absorption and iron features. In the figure, the Serra da Cangalha structure is comprised of a 3 km wide, near-circular central ring around a central depression.

Adepelumi et al. (2004) stated that the structure appears to be open to the northwest. An intermediate ring feature, with a diameter of ~5 km, was also indicated. The intermediate ring is surrounded by a broad and apparently low topography annulus of ~3–4 km width, which is terminated by the outer rim of the structure at 6–6.5 km from the center. The rim itself is well-defined due to the weak color shading of the interior of the structure, but not as a pronounced topographic feature.

A strong radial (and in some sectors concentric) drainage pattern extends outward from the outer rim. Only a few radial drainage lines originate in the annular trough, presumably exploiting radial faults that breach the outer rim. The wider, regional drainage pattern is distinctly different from this crater-near, obviously impact-derived pattern. It appears that cratering-related structure, the underlying reason for the crater-near drainage pattern, extends to a maximum distance of 1.5–2 crater radii from the center of the Serra da Cangalha structure.

A NW-SE directed structural trend is obvious in the rather straight geometry of the NE and SW sectors of the inner ring, and in fracturing cutting across the SE sector of the outer rim.

SRTM Data

The SRTM raw data for the area of the structure are shown in Fig. 3. This provides a detailed representation of the intricate drainage pattern, providing a much clearer pattern than the Landsat imagery (Fig. 2). The regional pattern is obviously different from that at and around the Serra da Cangalha structure, with strong NW-SE and ENE-WSW components. In contrast, the crater-related pattern is dominated by radial and annular drainage. The SRTM findings confirm that this trend does not exceed the 1.5–2 crater radii limit that can also be estimated from the Landsat image.

Figure 4 gives detailed topographic information obtained from the SRTM raw data along two perpendicular profiles (N-S and E-W) across the structure. Despite some variation in the background elevation, the two intermediate rings can be readily recognized. The crater rim seems to be a broad and structurally complex annular zone. Detailed structural analysis of the crater rim zone at the 10.5 km wide Bosumtwi structure in Ghana (Reimold et al. 1998) and the very much smaller, 2 km diameter BP structure in Libya (Koeberl et al. 2005a; our group, unpublished data) also revealed broad, structurally complex crater rims, with annular, radial, and oblique faulting directions. The pronounced central ring has elevations of up to 300 m above background. The two intermediate rings are within background elevation but are obvious from their sharp, local topographic gradients. The crater rim is broad and complex, and seemingly elevated up to >100 m above the crater interior. The two elevation profiles differ significantly with regard to the definition of the crater rim, which is very pronounced on both sides of the N-S profile, but not so on the eastern side of the crater structure. The reason for this is a distinct breach of the crater rim on that side, as is evident in Figs. 2 and 3. Peculiar ENE trending features extend from the breach in the crater rim outwards. While it is not possible to provide an explanation of this from the remote sensing data alone, it is noteworthy that this feature trends parallel to the regional structural grain. In addition, the terrane in the environs of the crater structure shows significant elevation complexity, with local occurrence of mesas.

A 3-D image of the SRTM data over the Serra da Cangalha region is presented in Fig. 5. The SRTM topographic information is used to represent height, and the

Fig. 3. Shuttle Radar Topography Mission (SRTM) raw data over the Serra da Cangalha structure (90 km E-W, 87 km N-S).

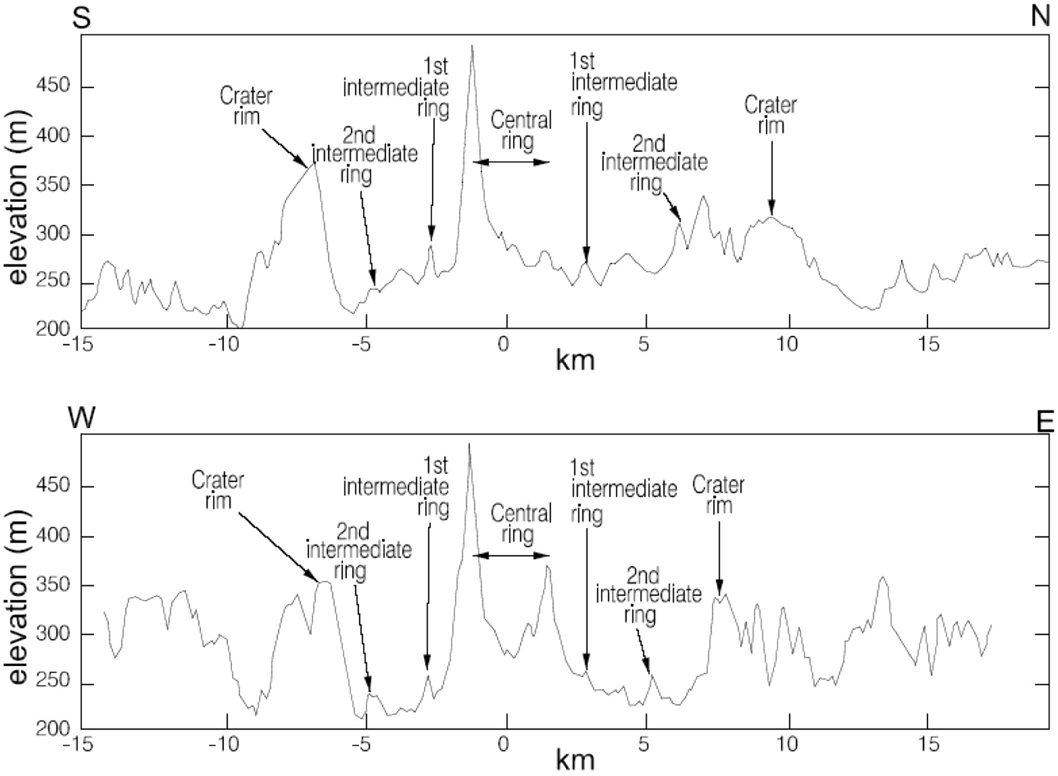

Fig. 4. N-S and E-W topographic profiles across Serra da Cangalha, taken from the SRTM raw data (as shown in Fig. 3; 90 km E-W, 87 km N-S). Annotations refer to our interpretation of the various images (see detail in text).

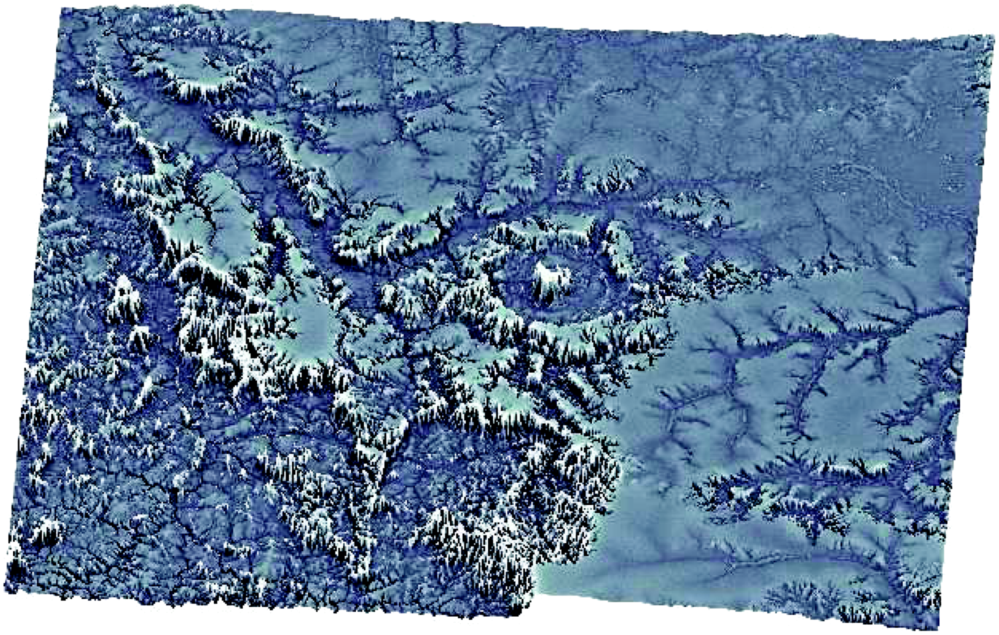

Fig. 5. SRTM data over the Serra da Cangalha impact structure in 3-D (90 km E-W, 87 km N-S). Image intensity is given by a high-pass filtered version of the same data set.

image intensity is given by a high pass filtered version of the data set. This serves to sharpen the 3-D image without adding any directional bias (as an added light source would have done). The structure stands out clearly in the DEM image, which also shows partially the detail of the regional drainage pattern. The crater rim structure resembles that in the terrain blocks (apparently plateaus) surrounding the crater structure. The crater structure is located close to the edge of a strongly dissected and blocky terrain, whereas to the east and further to the southeast of the structure another rather featureless terrain type is noted. This latter, apparently smoother terrain is identified as high elevation (compare the elevation profiling in Fig. 4), presumably relatively less eroded Sambaíba Formation, which is comprised of sandstones. The topography in this area is known to be dominated by plateaus and mesas. Nothing is known to us about the geology of the terrain to the west and southwest, and further detailed geological analysis is required in this area.

Sunshading Results

Sunshading provides a detailed image of the regional structure, where strong NW-SE and ENE-WSW fault trends are again prominent. In Fig. 6, generated after circular sunshading of the SRTM data, the crater region is extremely deformed, in contrast to larger areas (plateaus) to the SE, NW, and NE of the crater area, demonstrating the change in terrain nature already commented on in relation to Fig. 5. At most, the cratering-related annular deformation pattern does not exceed 0.7 crater radius beyond the crater rim. Figure 7 depicts the result of a calculation in which gradients of 0.75, 1.00, and 1.25 were used in the reflectance algorithm (Cooper and Cowan 2003b). The resulting RGB color image was then overlain on a 3-D surface, whose elevations were based on the original SRTM data. This resulted in a detailed DEM image, in which the various structural elements of the crater (central uplift comprising a prominent inner ring around a small, inferred topographic low; surrounded by low-lying annulus; two intermediate ring features of subdued topography; outer annulus; prominent outer rim) are clearly visible. Outside of the crater structure, several plateaus are prominent, and the opening in the eastern crater rim is clearly visible.

DISCUSSION

The crater itself is characterized by the following elements:

1. A prominent inner ring with a central low-lying area, which is considered the collapsed central uplift of the structure. The central topographic low extends to a radius of 1.1 km, and the central ring to a distance of 1.6 km. Considering that the structure has a diameter of only 13.4 km, it is intriguing to speculate whether this central uplift feature could represent a peak ring such as one would otherwise expect to find only at much larger impact structures.
2. At ~3 km radius, the first intermediate ring is noted, followed by a somewhat more prominent though incomplete second intermediate ring structure at about 5.5 km radius.
3. The outer ring (rim) structure occurs at 6.7 km from the center.

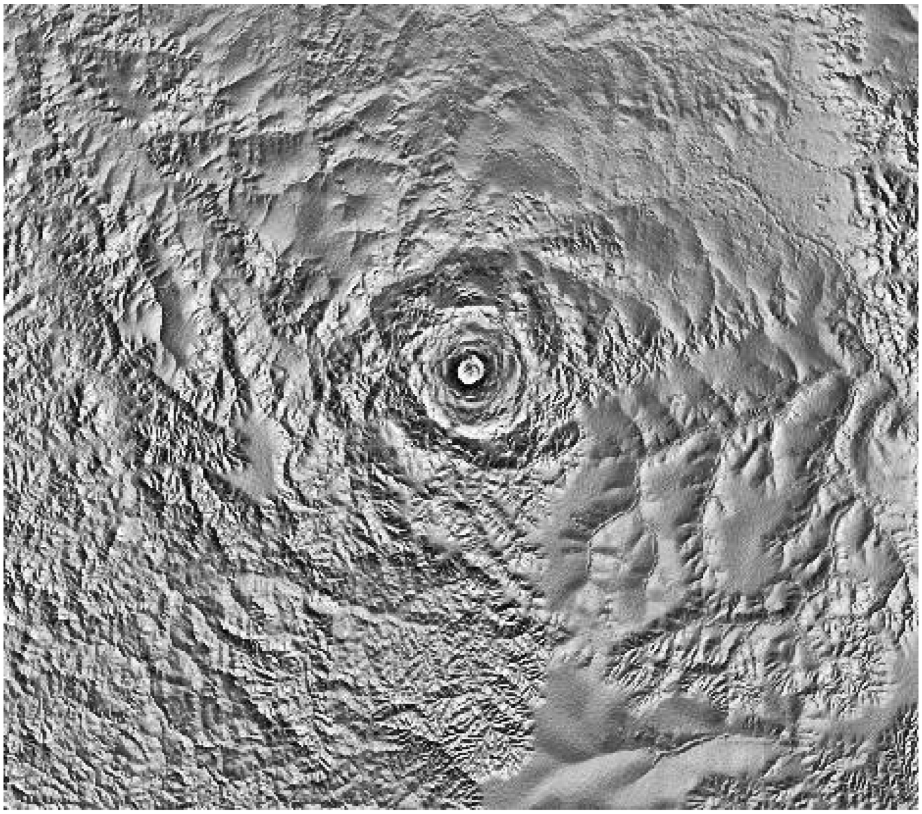

Fig. 6. Circular sunshaded SRTM data over the Serra da Cangalha region (90 km E-W, 87 km N-S).

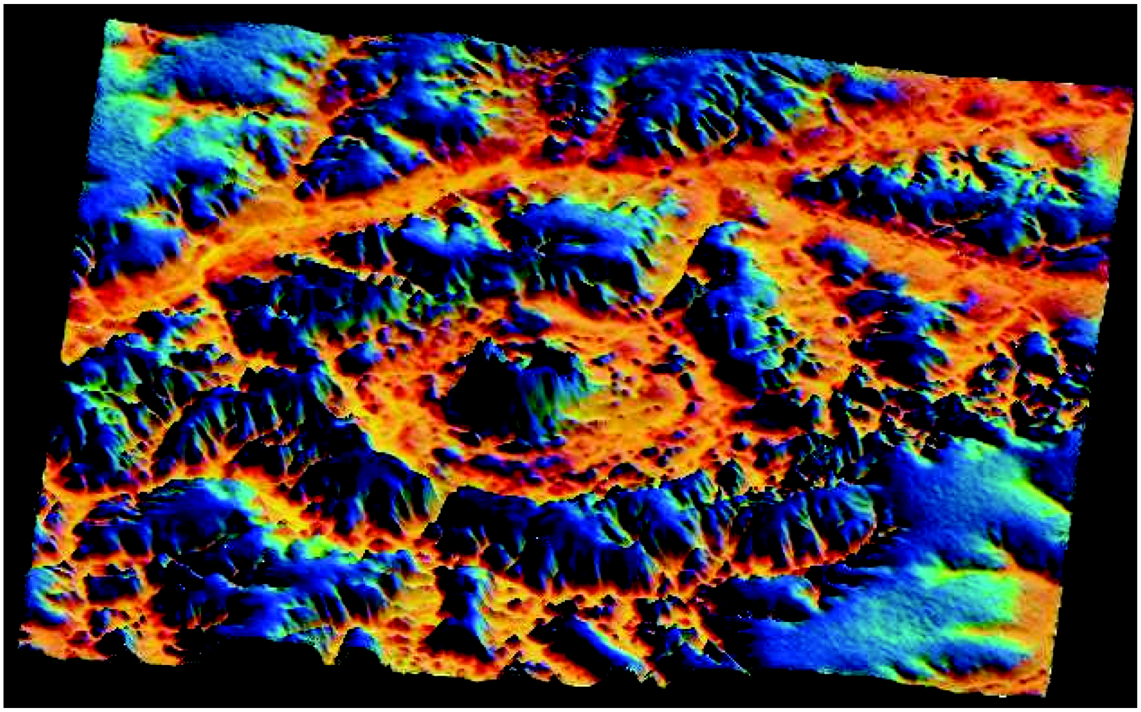

Fig. 7. Fractional order horizontal derivative sunshaded SRTM data over the Serra da Cangalha impact structure overlain on the SRTM data itself (in 3-D). The sun inclination used was 30° from the horizontal and the sun azimuth was northwest. Image measures 31.7 km E-W and 34.6 km N-S. Exact vertical exaggeration unknown: as determined by software.

Table 1. Apparent diameters of structural features of several eroded impact structures.

Crater	BP	Steinheim[a]	SdC[a]	Oasis[b]	Bosumtwi	Gweni-Fada	Aorounga	Goss. Bluff	Ries crater	Chicxulub crater
Crater diameter[c]	2[d]	3.4	13.4	11.5 [18?]	10.5	13 [18?[e]]	13 [24?][e]	24	24	~180
Central ring/uplift	0.5	1	3.2	5–6	1.8	5	4 [6?]	4.5	4[f]	80
First intermediate ring	–	–	6		–	8?	6?	7[g]	10	–
Second intermediate ring	–	–	10.5	–	–	–	11–16	–	–	–
Crater rim	2	3.4	13.4	11.5 [18?]	10.5	13 [18?]	13 [24?]	24	24	180
Outer ring feature (detachment fault?)[h]	2.8			18	18–20					240

[a] SdC = Serra da Cangalha; Steinheim = Steinheim Basin (data from Ivanov and Stöffler [2005]).

[b] The remote sensing observations are not conclusive and ground truth is scarce; there are two alternatives regarding the actual crater diameter: 11.5 km, as favored by Koeberl et al. (2005a), and 18 km, as favored by McHone et al. (2002).

[c] Estimate of apparent (eroded) crater diameter.

[d] A further low-topography feature outside of this rim was interpreted by Koeberl et al. (2005a) as a detachment fault dipping at low angle toward the crater interior.

[e] Larger estimate based on SRTM topographic data (Koeberl et al. 2005b).

[f] Ries data from Wünnemann et al. (2005 and references therein): central uplift is considered “incipient.” Chicxulub data after Morgan et al. (1997, 2002).

[g] Our interpretation of Fig. 2 of Milton et al. (1996).

[h] See Wagner et al. (2002) and Koeberl et al. (2005a).

Very intricate structural detail in the form of inferred faults of radial to oblique (with regard to the center) orientation is imaged outside of the outer rim, but these structures do not extend into the plateau regions further out. Thus, the impact-macrodeformed zone is limited to a maximum radial distance of 10–11 km from the center. Several radial faults do extend further to a maximum distance of 16–18 km from the center, about 1.5 times as far as the extent of the crater-related drainage pattern. This interpretation is further supported by the two elevation profiles shown in Fig. 4. They also demonstrate that the crater has a high degree of symmetry. The complex structural terrane indicated in these data strongly suggests Serra da Cangalha as a prominent target for detailed ground-based structural geological analysis, to supplement the limited structural data base for impact craters of such moderate (10–20 km) diameter.

The SRTM data provide a powerful tool for the detailed structural investigation of geological features, including likely impact structures. In comparison to the Landsat TM data, impact-related deformation can be imaged and interpreted in greater detail from the SRTM data. This allowed us to better define the various structural elements of the crater and their respective diameters. While it can be argued that some of the information had been obtained from Landsat imagery already, the SRTM data provide a new means to investigate crater morphology at a very good resolution.

In Table 1, the first-order structural features of Serra da Cangalha are compared against those for Gosses Bluff (Australia), after Milton et al. (1996); the BP and Oasis structures in Libya, after Koeberl et al. (2005a); Steinheim Basin (Ivanov and Stöffler 2005); Aorounga and Gweni-Fada in Chad (Koeberl et al. 2005b); Ries (Wünnemann et al. 2005); and Chicxulub (Morgan et al. 1997, 2002). Note the uncertainties on many of these data, as shown in the table and discussed in associated footnotes. In several cases, hardly any ground-based geological information is available to confirm these estimates based on interpretation of remote sensing information. It is obvious that this first compilation of such data does not yield any obvious trends; the existing values for apparent crater rim diameters and the ratios of crater rim diameter/central uplift diameter give a weak indication of positive correlation, as does plotting of crater rim diameter versus ratio of crater rim diameter/inner intermediate ring diameter for the craters up to 24 km apparent diameter, but with much scatter. Clearly, more data of this nature are required to test the validity of such spurious correlations.

It must also be cautioned that any such comparison of data for terrestrial impact structures must be subject to careful consideration of a number of factors, such as target stratigraphy and, particularly, variation in relative levels of erosion. The values compiled are generally apparent diameters (cf. Turtle et al. [2005] for a detailed discussion of this problem). In addition, the nature of outer ring features is still a subject of debate, as, for example, discussed by Wagner et al. (2002).

Comparison of the crater structures of very similar, small size (BP and Steinheim Basin) suggests similarity of crater geometry within the limitations of topographic analysis. Bosumtwi, Serra da Cangalha, Oasis, Gweni-Fada, and Aorounga are all traditionally listed with similar size (10.5 to 17 km diameters), but have different diameters of central uplifts and first intermediate rings. These differences could be caused by uncertainty in where to take the actual diameter of a collapsed uplift. Using the recently derived (Koeberl et al. 2005b) larger crater diameters of 22 and 17 km for Gweni-Fada and Aorounga, respectively, yields better agreement in a comparison of these craters with the Ries and Gosses Bluff in terms of crater diameter, central uplift/ring, and intermediate ring spacing. Whether or not this is a possible indication that the diameters of both Gweni-Fada and Aorounga have originally been underestimated (as suggested by Koeberl et al. 2005b) remains to be tested.

Naturally, studies like the present one are important with regard to further identification of impact structures on Earth through remote sensing and regarding their differentiation from volcanic crater structures. As described in some detail by, for example, Greeley (1994), volcanic structures can be of a wide range of morphologies, from simple bowl-shaped structures to large, complex caldera collapse structures. In particular, collapsed crater walls may be extensively faulted, resembling the complex deformation of impact crater rims. Small, maar-type volcanic craters are very similar in appearance to simple, bowl-shaped impact craters. Similarly, drainage and fault patterns around volcanic structures may resemble the annular and radial patterns formed around impact structures. To date, however, we have not found any evidence of multiple ring structures or distinct central uplift features in volcanic crater structures, with the exception of volcanic craters characterized by repeated eruptions resulting in a further cone or crater form in the central part. Where volcanic craters display raised rims, this would be the result of accumulation of ejecta, and in a fresh case, such a rim appears rather continuous and comparatively smooth, as compared with the heavily faulted and folded upturned rims of impact structures. Erosion of such volcanic landforms may, of course, result in more complex structural morphologies. Crater collapse structures (calderas and caldera structures) are, for example, reviewed by Cole et al. (2005).

Distinguishing volcanic features from impact structures is not easy, as both types have circular outlines and a rim and central structure. Digital elevation models, possibly generated from SRTM or other SAR data, can help to discriminate between the two types of features, as impact structures generally have steeper slopes and larger rim to surroundings height, as was observed in tests of automatic crater recognition programs (e.g., Earl et al. 2005; J. Earl and C. Koeberl, unpublished observations). Thus, high-resolution remote sensing data that allow to recognize central peak forms and multiple ring structures and their morphological nature will be extremely useful for further recognition of impact structures.

CONCLUSIONS

The SRTM data have been shown to be superior to the older Landsat TM data with regard to detail that can be discerned in drainage patterns and structural analysis of crater structures. The following macro-structural division of the Serra da Cangalha impact structure in NE Brazil was characterized: a central ring (diameter = 3.2 km), two intermediate rings of limited elevation (diameters = 6 and 10.5 km, respectively), and a structurally complex crater rim (diameter = ~13.4 km). It appears that impact-produced macrostructural deformation in the environs of the crater is limited to a maximum of about 9.5 km (~0.8 crater radii) from the crater rim. Serra da Cangalha would be a rewarding target for detailed structural geological investigation. A first comparison of structural data for impact structures of a wide range of apparent crater diameters suggests that some of these data may have been estimated wrongly in the past. Further detailed remote-sensing studies, in particular based on the now accessible global SRTM data, together with comparative field-based analysis as well as numerical modeling, are required to provide a more extensive data set on crater morphological features for other complex terrestrial impact structures.

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