Collapse of large complex impact craters: Implications from the Araguainha impact structure, central Brazil

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ABSTRACT

The 40-km-wide Araguainha impact structure in central Brazil provides extensive outcrops to study the structural evolution of all parts of a complex crater, including the central uplift, annular trough, and crater rim. While most craters of comparable size are buried by impact-related or postimpact sedimentary deposits, Araguainha is deeply eroded and it exposes in detail outcrop-scale structural features that can be used to understand the structural evolution of large impact craters. This study explores evidence from structural features across the entire impact structure in order to provide constraints on the target rock movement during the crater collapse. Most of the structural features described here are consistent with folding and bedding-parallel shearing during several kilometers of lateral inward movement of the target rocks. Vertical movement was, in contrast, restricted to distances of less than a few hundred meters along radial and concentric fault zones around the crater rim.

Keywords: impact structure, complex crater, Araguainha, transient cavity, crater collapse, central uplift.

INTRODUCTION

Impact structures on Earth's surface provide the most accessible clues to processes associated with hypervelocity impact events and planetary evolution (e.g., French, 2004; Grieve and Therriault, 2004). However, the structural evolution of large complex craters remains relatively unknown, given the complex strain patterns associated with the excavation, expansion, and subsequent inward collapse of their transient cavity (Melosh, 1989, Melosh and Ivanov, 1999; Wunnemann and Ivanov, 2003). Although substantial geological and geophysical data have been assembled over the past decade (see review by French, 2004), field-based structural studies have focused on small (1–15 km wide) craters (e.g., Roddy, 1979; Brandt and Reimold, 1995; Reimold et al., 1998; Kriens et al., 1999; Kenkmann et al., 2005) or were limited to well-exposed parts of large complex structures (e.g., Wilshire et al., 1976; Milton et al., 1996; Lana et al., 2003). The evolution of large impact craters remains a problematic area of impact crater studies because outcrop-scale structural features, which are crucial to understanding crater collapse, are commonly buried under impact-related or postimpact sedimentary rocks or are not well preserved, owing to postimpact tectonic events.

The 40-km-wide Araguainha structure in Brazil (Fig. 1) is as a well-exposed, albeit eroded, remnant of the largest complex impact crater in South America (Dietz and French, 1973). This crater was excavated ca. 245 Ma in flat-lying sediments of the 250 Ma Paraná Basin (Hammerschmidt and Engelhardt, 1995). Erosion has not exceeded more than a few hundred meters, judging from the remnants of impact breccias in the central uplift area (e.g., Engelhardt et al., 1992). However, most of the upper parts of the impact structure, including many of the impactites of the annular trough, have been removed since the impact event (Engelhardt et al., 1992). No deformation or burial by younger sedimentary rocks has taken place since the impact event (Bischoff and Prinz, 1994). Surface exposures are thus excellent for documenting the variation of outcrop-scale structural features from the rim to the central uplift. Here we describe in detail the nature and variation of the outcrop-scale features from Araguainha to better understand the relationship between lateral and vertical movement of target rocks during collapse of large complex impact craters.

REGIONAL GEOLOGY

The Araguainha impact structure is at the border between Mato Grosso and Goias states (16°50′S; 53°00′W) in central Brazil (Engelhardt et al., 1992). Regional stratigraphic relationships, borehole core data, and geophysical interpretations indicate that the target rocks comprise an ~2-km-thick supracrustal sequence of Permian to Devonian sediments overlying a polydeformed crystalline basement of Precambrian to Ordovician age (Engelhardt et al., 1992; Masero et al., 1997). The impact structure is characterized by an ~10–12-km-wide central uplift surrounded by an 8–10-km-wide annular trough wherein most strata have been extensively folded and faulted as a result of the impact event (see dips and strikes in Fig. 1). The central uplift consists of a 4-km-wide core of crystalline basement rocks that are surrounded by a 3–4-km-wide collar of upturned fine-grained sandstones, siltstones, and shales of the Paraná Group (Fig. 1) (Bischoff and Prinz, 1994). Rocks in the annular trough and around the crater rim comprise Carboniferous sandstones of the Tubarao Group and Permian claystones of the Passa Dois Group (Fig. 1). The Carboniferous sandstones are exposed inside and outside the structure, whereas the Permian claystones are mainly preserved in concentrically arranged outliers that accentuate the crater rim. We focus our observations on structures exposed along three radial profiles from the central uplift to the crater rim (Figs. 1 and 2A–2C).

CRATER RIM AND ANNULAR TROUGH

Previous structural mapping established that the crater rim and the annular trough are defined by a complex pattern of radial and concentric fault zones (Correia Filho et al., 1981) visible in 1:20,000 aerial photographs and Landsat images. Along the profiles, the fault zones vary from a few centimeters to several meters in width (Fig. 3A) and are associated with conjugate sets of fractures that are orthogonal to the main fault orientation. In most places, the fault zones are vertical or steeply dipping toward the center of the structure (Figs. 2A–2C).

In the outer 5 km of the structure, radial and concentric, (near-)vertical fault zones bound kilometer-scale blocks of the Passa Dois

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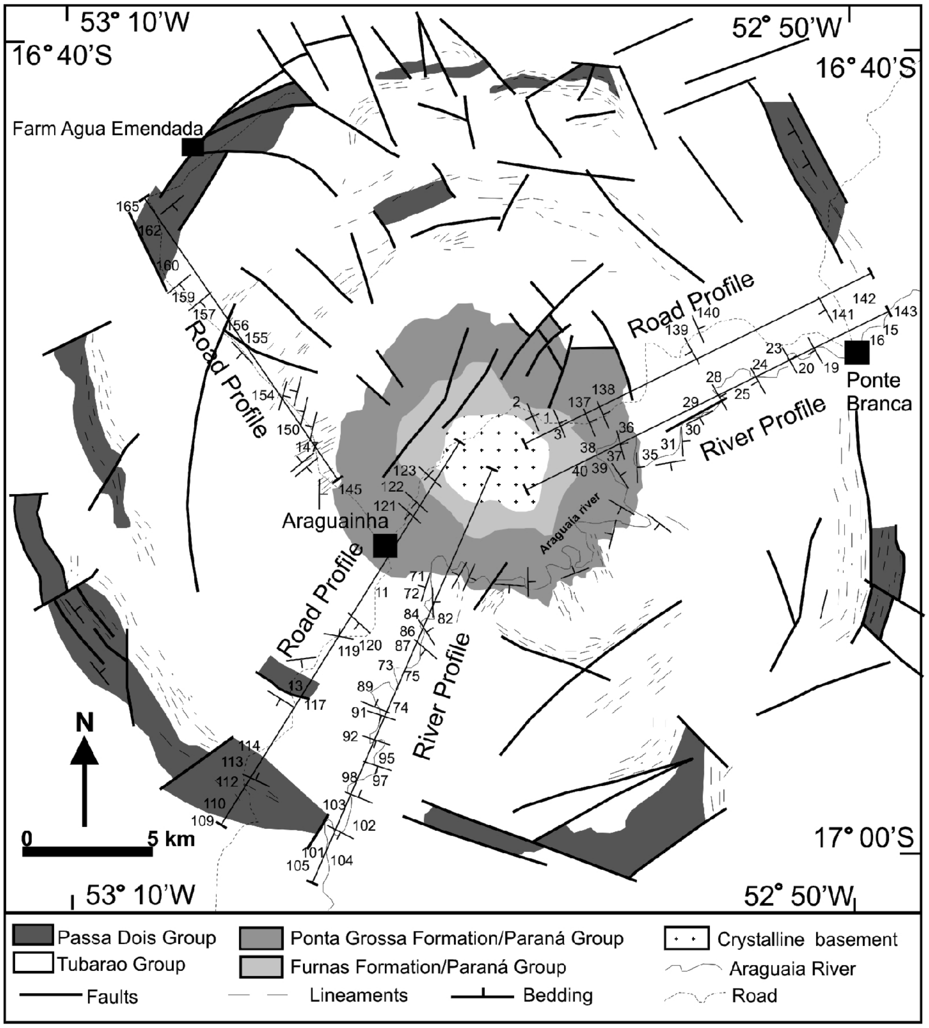

Figure 1. Simplified lithological and structural map of Araguainha impact structure, central Brazil (modified from Correia Filho et al., 1981).

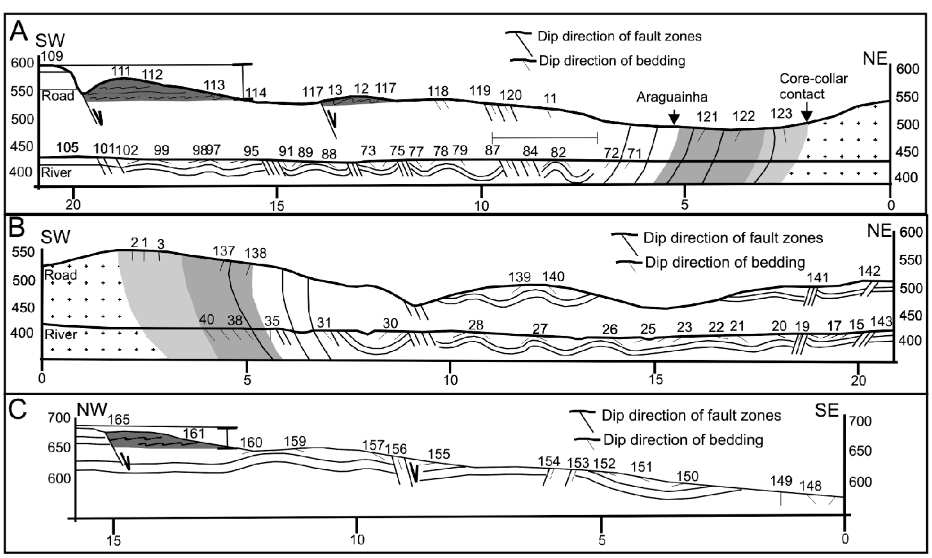

Figure 2. Structural profiles for (A) southwestern, (B) northeastern, and (C) northwestern sectors of Araguainha crater. Two main profiles (A and B) contain data from nearly 150 localities along gravel road linking Araguainha and Ponte Branca villages, and along Araguaia River. Third profile (C) presents data collected along road from Araguainha to farm Emendada on northwestern crater rim. Numbers represent structural measurement stations. Legend as in Figure 1.

Group (Fig. 1). Our structural profile in the southwestern sector indicates a minimum of 200 m of displacement between the Tubarao and the Passa Dois Groups. The displacement can be measured from the basal contact of the Passa Dois Group (station 114; Fig. 2A) and the Tubarao Group outside the crater (station 109). The same relationship seems to apply elsewhere around the crater rim (e.g., Fig. 2C), where vertical displacements were sufficiently large to exhume the Tubarao Group around the rim and preserve the sediments of the Passa Dois Group inside the structure. Bedding orientations of the Passa Dois sediments remained essentially horizontal (Figs. 2A, 2C; and Data Repository Fig. DR1[1]). On a meter scale, however, the sediments are strongly folded and faulted. The folds are strongly asymmetric and vary from recumbent to isoclinal, with NW-SE–trending horizontal hinges (Fig. 3B). The asymmetric geometry of these folds is consistent with the top sediments (the Passa Dois Group) moving toward the central uplift (Fig. 3B). Part of the inward movement was thus associated with noncoaxial deformation leading to differential slip movement between the distinct stratigraphic units (e.g., Tubarao and Passa Dois Groups). The folds are crosscut by low-angle outward-dipping fault planes that displace the bedding on a centimeter scale.

In contrast to the Passa Dois Group, the Tubarao sandstones were not folded and remained relatively undeformed in the outer 5–6 km of the crater (Figs. 2 and DR1). Bedding orientation may change from horizontal to gently dipping inward and outward, owing to small displacements and rotation of bedding along vertically dipping fault zones (Fig. 3A). Locally, the sandstones show evidence of bedding-parallel shearing along decimeter- to centimeter-wide breccia zones (Fig. 3C). The breccia zones are generally 5–10 cm thick and alternate with relatively undeformed sandstones on a centimeter scale.

Folding and faulting in the sandstones of the Tubarao Group is observed in the annular trough, over a radial distance of 15 km from the central uplift (Figs. 2 and DR1). The bedding is relatively steep and is crosscut by several meter-wide radial and concentric fault zones, i.e., perpendicular and parallel to the structural profiles. Away from the fault zones, the Tubarao Group rocks dip inward and outward (Figs. 3D, 3E), owing to kilometer-scale upright folding. The hinges of the folds are not preserved, but the orientation of the limbs

[1]GSA Data Repository item 2006003, Figures DR1 and DR2, stereographic projections, structural profiles, and field photos, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

Figure 3. A: Vertical fault zone crosscutting (at station 101) fine-grained (f) and coarse-grained (c) layers of sandstones of Tubarao Group. Sandstone layers dip shallowly northeast (inward dipping; see Fig. 1). B: Example of recumbent fold in Passa Dois Group sandstone (station 112). Geometry of fold is consistent with top sedimentary units moving toward central uplift (to right). C: Bedding-parallel shear zone in Tubarao Group. D, E: Fold limbs of kilometer-scale folds in inner 15 km radius of crater (stations 35 and 31). Folds are upright (E), consistent with horizontal component of inward movement. Solid lines in D indicate orientation of bedding. Dashed lines in E depict fold surface. F: Upturned strata of Paraná Group in southwestern part of collar of central uplift (station 38).

indicates an upward geometry for the folds, with hinges oriented at high angles to the profile orientation. This is supported by meter-scale folds, which locally have partially preserved hinges (Fig. 3E). The geometry of these folds is consistent with a horizontal component of movement that might have been parallel to the main inward, centripetal compression.

CENTRAL UPLIFT

Bedding orientations in the collar of the central uplift are consistent with kilometer-scale upturning of the sediments of the Paraná Group (Figs. 2A, 2B, and 3F). Although borehole core information indicates that the Paraná Group is 1 km thick outside the crater (e.g., Engelhardt et al., 1992), our measurements show that the upturned Paraná Group is at least 3 km thick in the central uplift (e.g., from the collar-core contact to the base of the Tubarao Group; Fig. 2A). This fact confirms previous suggestions that thickening of target rocks (e.g., bedding duplication) may occur during collapse of complex craters (e.g., Grieve and Terriault, 2004, and references therein).

Thickening of the Paraná Group is supported by the presence of local structural features such as recumbent folds and bedding imbrication. The imbrication occurred along conjugate sets of fault planes that locally isolate lenses of highly fractured Paraná sediments (Fig. DR2A; see footnote 1). The geometry of the lenses and recumbent folds indicates inward movement and constriction of the target rocks in the uplift area. Locally some of the inward-verging folds have also been refolded (Fig. DR2B). The refolded folds verge toward the crater rim, consistent with some subsequent outward movement of the supracrustal strata.

In the outer part of the sedimentary collar, bedding orientations are highly variable on a meter scale. The variation of bedding orientation is observed within a radius of 5–7 km from the core of the central uplift, where the Tubarao and Paraná Groups are concentrically arranged and dips are subvertical to vertical. Locally, the sediments in the outer collar were rotated along several kilometer-scale radial fault zones (Fig. 1). These fault zones are in most places oriented at high angles to the main concentric geometry of the central uplift (Fig. 1) and separate several blocks of the sedimentary strata.

IMPLICATIONS FOR CRATER COLLAPSE STUDIES

Structural observations have previously been reported from a number of small, <10 km impact craters (Roddy, 1979; Brandt and Reimold, 1995; Reimold et al., 1998; Kenkmann et al., 2005). In all these cases, detailed structural observations were limited to exposures either in the central uplift or at the crater rim. Araguainha is one of a few examples of craters of its size, i.e., 30–50 km diameter, where sedimentary target rocks are preserved

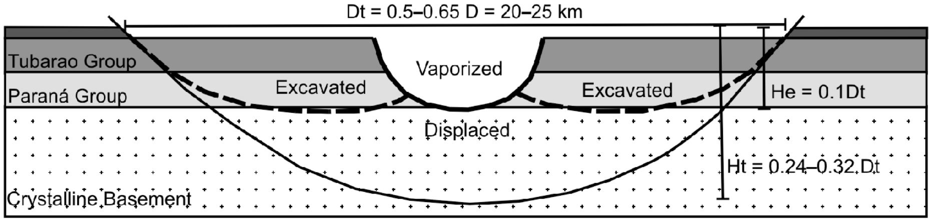

Figure 4. Diagram illustrating diameter (Dt) of transient crater of 40-km-diameter impact crater (Dt = 0.5–0.65, D = 20–25 km). Note that originally 2.0–2.5-km-thick sedimentary cover (Tubarao, Paraná, and Passa Dois Groups) is completely excavated (He) during formation of transient cavity (He = 0.1, Dt = 2.0–2.5 km). Remaining sediments and crystalline basement are displaced downward and outward during expansion of cavity. This geometric relationship is consistent with most of thickened Paraná Group (now exposed in central uplift) being displaced from transient cavity walls toward central part of crater. Diagram and transient crater dimensions are based on Melosh (1989, p. 78, 138).

and continuously exposed from the central uplift to the crater rim. These sedimentary target rocks provide an excellent opportunity to determine the variability of outcrop-scale features across a large complex impact structure (Figs. 2A, 2B). Our observations indicate that the dominant structural features are all consistent with lateral inward-directed displacement of the target rocks during transient cavity collapse. The lateral displacement in the outer 5–6 km (close to the crater rim) was achieved by differential slip movements between the stratigraphic units, which are characterized by different mechanical properties. Deformation associated with the movement was accommodated by folding of the relatively weak clay layers of the Passa Dois Group and bedding-parallel shearing in the Tubarao Group (Figs. 2A, 3B, and 3C). Upright folding and imbrication of the strata in the central uplift and the annular trough were mainly achieved by a substantial amount of horizontal constriction of target rocks into the central uplift area (see also Kenkmann and Dalwigk, 2000). This process might have contributed to the considerable thickening of the originally 1-km-thick Paraná Group by ~2–3 km during formation of the 3–4-km-wide collar of the central uplift (Fig. 1B).

The sedimentary target rocks at Araguainha can also be used to understand the relationship between vertical and lateral movement occurring during transient cavity collapse. The 40-km-diameter (D) of the crater requires a depth of excavation (He) between 2 and 2.5 km and a transient cavity diameter (Dt) of 20–25 km (Fig. 4). As shown in Figure 4, these estimates require that a substantial part of the originally 2–2.5-km-thick target strata was either vaporized or ejected from the transient cavity. Most of the sediments composing the 3-km-wide Paraná Group in the collar of the central uplift were thus displaced from the transient cavity walls and moved inward by several kilometers. The vertical movements around the crater rim were, in contrast, restricted to several hundred meters along vertical, radial, and concentric fault zones (Fig. 2). The largest vertical displacements led to the concentric arrangement of kilometer-scale fault-bounded blocks and preserved the upper sedimentary strata in the outer 5–10 km of the crater (Fig. 1).

CONCLUSIONS

Our study provided for the first time field-based observations that constrain the relationship between lateral and vertical movements of the target rocks during collapse of a large transient crater. Evidence from Araguainha indicates several kilometers of lateral movement of the supracrustal sequence from the crater wall toward the central uplift area and relatively small (by hundreds of meters) vertical displacements at the crater rim. The horizontal movement was accompanied by differential slip between the stratigraphic units and bedding-parallel shearing. Constriction of the sediments in the central part of the crater led to kilometer-scale folding of the target rocks in the inner 15 km radius of the crater floor and thickening of the sedimentary strata in the collar of the central uplift.

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Notes

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