THE ARAGUAINHA IMPACT STRUCTURE/CENTRAL BRAZIL

BARBARA THEILEN-WILLIGE*

ABSTRACT The following facts have supported the origin of the Araguainha circular structure in Central Brazil by a meteoritic impact: 1) the almost circular contour; 2) the impact-morphologic sequence including a central uplift, ring walls and a basin rim of escarpments; 3) the evidence of shock metamorphism; 4) the presence of shatter cones; 5) outcrops of suevites and mixed breccias; and 6) negative anomalies of the total intensity of the magnetic field at the center of the ring structure.

RESUMO Os seguintes fatos comprovam a gênese da estrutura circular do "Domo de Araguainha"/Brasil Central por um impacto de meteoro: 1) a forma quase circular; 2) a sequência morfológica de um astroblema, apresentando no núcleo um soergimento central, cumeadas e elevações de arranjo anelar, e uma borda de cuevas da bacia; 3) a evidência de metamorfismo de choque nas lâminas das amostras de pedra; 4) a presença de cones de estilhaçamento; 5) afloramentos de suevitas e brechas multicoloridas; e 6) anomalias negativas da intensidade magnética de campo total no centro da estrutura.

INTRODUCTION The number of well documented meteoritic impact craters on the surface of the Earth has risen astonishingly in the past twenty years, and new craters are reported annually. This report intends to give a short representation of an astrobleme in Central Brazil.

The "Domo de Araguainha" circular structure that is about 40 km in diameter is located at the border of Southwest-Goiás and Southeast-Mato Grosso (latitude: 16°30' to 17°15' south; longitude: 52°45' to 53°15' west). The ring structure is crossed by the Araguaia stream.

The "Domo de Araguainha" was firstly mentioned by Northfleet *et al.* (1969). These authors interpreted the structure to be a syenite intrusion related to the cretaceous magmatism in the Southern Paraná-Basin. A si-

milar interpretation was given by Gonçalves & Schneider (1970).

Silveira Filho & Ribeiro (1971) and Spector *et al.* (1972) supposed an ascended basement block at the center of the structure surrounded by a ring of volcanic breccias and tuffs. They considered the structure to be a cryptovolcanic intrusion. The first to mention *shatter cones* as evidence of shock metamorphism caused by a meteoritic impact were Dietz, French & Oliveira (1973). They explained the Araguainha structure as an astrobleme.

GEOMORPHOLOGIC DESCRIPTION The Araguainha structure forms a large ring-shaped basin consisting of a central elevation, annular ridges, ring depressions and valleys, arcs of isolated hills and terraced walls (Fig. 1).

Figure 1 — Schematic geomorphologic map of the multiringed basin of Araguainha

* Geologisches Institut der Technischen, Universität Clausthal, Leibnizstr. 10, 3392 Clausthal-Zellerfeld, República Federal da Alemanha

Figure 2 — Schematic geomorphologic and geologic profile of the Araguainha structure

The central elevation has an elliptical outline with a NNW-SSE-axis and consists of a basin at the center, an inner ring of hills and an outer ring of ridges and mountains that in the northern part form abruptly, nearly vertical outward slumping slopes.

This central elevation is surrounded by a ring depression. Its floor represents a slightly undulated plain with a few isolated hills. The most conspicuous aspect of the Araguainha structure is the existence of concentric multiple rings of ridges and hills and depression belts and valleys. The annular ridges have been dissected by the drainage systems. A series of step-like wall-terraces are characterizing the marginal zone of the ring basin with distinctive inward terraced wall slopes. Escarpments of the paleozoic sediments with steep inward-facing slopes and almost gently outward sloping flanks form the basin rim. Figure 2 shows a schematic geomorphologic and geologic cross section of the Araguainha structure.

A comparative study with similar ring basins of the Earth and other planets shows that the morphologic units occurring in the Araguainha structure coincide with those of ring basins which are supposed to be produced by meteoritic impacts. All larger impact structures, for which sufficient informations are available, consist according to Dence (1972) and Gumtau (1974) of similar geomorphologic units.

PETROGRAPHIC DESCRIPTION The theory assuming that the Araguainha structure was produced by a meteoritic impact can definitively be proved by petrographic investigations. Within and around the ring structure have been distinguished the following main rock units.

CRYSTALLINE NUCLEUS In the area of the central basin are outcrops of hypidiomorphic and partly porphyric rocks with alkali-granitic and alkali-syenitic character. The main constituents as specified by Gonçalves & Schneider (1970) are quartz, alkali feldspar,

Figure 3 — Schematic geologic map of the Araguainha structure

diopsid, augite, biotite, muscovite, apatite, hornblende and tourmaline. The idioblastic orthoclase minerals can grow up to a diameter of more than 5 cm. In thin sections these minerals show distinct cataclasis, dislocation and rotation. In quartz grains appear planar deformation structures (isotropic lamellae). Planar elements within quartz grains are explained by Engelhardt *et al.* (1969) as optical discontinuities occurring in parallel systems oriented to crystallographic planes (Photo 1).

Photo 1 — Planar elements within quartz grains (Crossed-Nicols, 25 X)

Within these planar deformation structures appear sometimes little inclusions that represent probably the high pressure phases of quartz as coesite and stishovite. There are diaplectic quartz crystals (Engelhardt & Graup, verbal information, 1979). Planar elements within quartz crystals are unknown so far in rocks affected by tectonic stress. They have been observed, however, constantly in thin sections of samples from different impact craters of the Earth. According to Graup & Stöffler (1974) planar elements are important indicators for impact structures.

Biotite grains display in different thin sections an intensive mechanic deformation, especially kinkbands. More than three directions of kink axes can be observed in a single biotite grain. These differently oriented lenticular kinkbands are to be seen in Photo 2. Sometimes biotites are opaque.

In orthoclase grains occur twin lamellae that show small displacements, rotations, fractures and faults. The planar elements in quartz, the kinkbands in biotite, the intense mechanic deformation as well as the phase transformations of minerals are according to Offield & Pohn (1979) formed as a result of shock metamorphism. By the impact of great meteorites or comets upon the target rock with multiple sonic velocity are propagated shock waves that proceed hemispherically into the target. The peak pressure and temperature of the propaga-

Photo 2 — Kinkbands within biotite (Crossed-Nicols, 25 X)

Photo 3 — Mechanic deformation within a plagioclase grain (Crossed-Nicols, 10 X)

ting shock wave are steeply decreasing with radial distance from the point of impact. According to this pressure decay hemispherical zones of constant pressure and temperature decreasing with radial distance exist during the passage of shock wave. Within these zones of progressive shock metamorphism the most abundant rockforming minerals undergo very characteristic shock effects which are irreversible upon pressure release.

On the basis of observed shock effects in quartz and feldspar of Ries Crater samples (Southern Germany), Stöffler & Graup (1974) and v. Engelhardt (1974) classified five main stages of shock metamorphism (Table 1).

Table 1 — Stages of progressive shock metamorphism of crystalline rocks from the Ries crater according to Stoeffler & Graup (1974)

Stage	Peak pressure in kbar	Post-shock temperature in °C	Post-shock effects in quartz, feldspar or total rock	Textural properties of the rocks fragments
I	≈ 100	≈ 100	Diaplectic crystals with planar deformation structures parallel to crystallographic planes. Stishivite within quartz	Primary texture of the rock is preserved. Intense fracturing
II	≈ 350	≈ 300	Diaplectic glasses as pseudomorphs of quartz and feldspar grains. Coesite and stishovite within diaplectic quartz glass.	Primary texture preserved, but clouded appearance of the framework silicates.
III	≈ 450	≈ 900	Normal feldspar glass with vesicles and flow structures. Diaplectic quartz glass, coesite within diaplectic quartz glass.	Primary texture partially destroyed by selective melting.
IV	≈ 550 — 600	≈ 1,300 — 1,500	Total melting of all mineral phases and mixing of the melts. Remnants of isolated quartz and feldspar glasses with vesicles and flow structures.	Primary texture totally destroyed, aerodynamically shaped glassy bombs.
V	> 800	> 3,000	Silicate vapor	

In thin sections of samples from the central basin shock effects are occurring that are characteristic for shock metamorphism of stage II (verbal information, v. Engelhardt & Graup, 1979). For this reason the crystalline rocks must have layed at the moment of the impact in the deeper subsoil. Apparently the crystalline nucleus of the circular complex of Araguainha represents a basement block that was lifted by centripetal movements from all sides upwards in the central uplift area. These centripetal movements are according to David (1969) the result of relaxation after passage of the shock wave and the expansion of shock compressed material.

The evidence of shock metamorphism effects in the rocks excludes the origin of the ring structure by intrusion of magma of later impact initiated magmatism. Later intruded magmatic rocks could not present effects of shock metamorphism. Based on aeromagnetic and field magnetic measurements Spector *et al.* (1972) showed that in the surrounding area of the ring structure the precambrian basement lies at about 2,000 m below the present surface. Within the ring complex the basement level elevates abruptly to less than 500 m below the surface. The uplift of the basement in the nucleus of the Araguainha structure probably was not recorded because of the extensive pattern of the measurements. This elevation of the precambrian basement might have existed already before the impact event. Nevertheless the explanation of being formed by centripetal upward movement after the impact seems to be more justified.

ROCKS OF THE CONTACT ZONE Rocks within the contact area between the basement block and the paleozoic sediments are characterized by the occurrence of

shock metamorphism in different stages. At the north-western margin of the basement block are outcrops of darkgrey to greyish-green rocks with the main constituents quartz, mica feldspar and hornblende. This fine grained material shows very clearly shatter cones (Photo 4).

Photo 4 — Shatter-coned rock sample from the northwest-margin of the basementblock

Shatter cones are considered by Graup & Stöffler (1974) to be formed by shock metamorphism. Shatter cones have been discovered until now only in impact structures. For this reason they are according to Reiff (1976) the most important and relevant proof for a me-

teoritic impact. The evidence of shatter cones in the central uplift area of the Araguainha structure confirms its origin by an impact as supposed by Dietz, French & Oliveira (1973).

SUEVITE The contact zone between the basement block and the surrounding sandstones is often overlain by a blanket of ejecta and breccia material. This material is mainly exposed in the region of the inner hill-ring and sporadic outside. The ejecta blanket occurs most distinctive in the northern basin rim. The thickness of the beds range from 5 to 10 m. There a breccia with a fine grained, vesicular and porous matrix of grey to reddish-grey colour crops out that includes fragments with a size of some centimeters up to 40 centimeters. The fragments can be classified in sedimentary, crystalline and glass rocks. The sedimentary fragments are prevailing. The colour of the sandstone fragments is greenish-white, of the claystones dark-red. The few crystalline fragments normally come up to a size of 2 to 5 cm. These crystalline inclusions are strongly weathered and crumbly. Often only slack is to be observed. Porous darkgrey or black glasses show an aerodynamic formation. The other fragments are angular with numerous micro-fractures.

According to Engelhardt *et al.* (1969) polymict breccias with the above mentioned character are defined as suevites.

Suevites have been found only in impact structures. In thin sections the suevites of the Araguainha structure represent effects of different stages of shock metamorphism.

MIXED BRECCIAS Within the inner hill-ring and at the basin rim breccias are more frequently exposed than suevites. These breccias are composed of different almost weathered material. The unsorted polymict breccia consists of a matrix of finer fragments including coarse components. Fragments of sandstone, claystone and glasses are dominating. Isolated there are smaller fragments of crystalline material. Similar breccias have been described by Schneider (1971) in the Ries Crater as so called "multicoloured" breccias. Because of the resemblance of the rock material this term could be used too for the breccias of Araguainha. The constituents of the multicoloured breccias are characterized by an intense mechanic deformation like jointing, cracking, bending and rolling. The fragments of sandstone are jointed and brecciated; the claystones show partly plastic deformation. Locally a closely jointing and mortar-like texture can be observed. This mortar-like texture is according to Chao *et al.* (1978) caused by rotation and crushing of the rock components along motion zones. Overlying and overthrusting of multicoloured breccias over the surrounding sandstones are exposed at the northeast margin of the inner ring.

FURNAS FORMATION The crystalline nucleus is surrounded by fine to medium grained sandstones with interlayers of claystones and conglomerates. The sandstones show a milky white or rosy colour and are already weathered, brittle and highly fractured. In thin sections appear within quartz grains micro-fractures and dislocations. Planar elements occur only rarely. Often they lack at all. These sandstones are described by Gonçalves

& Schneider (1970) and Silveira & Ribeiro (1971) as belonging to the lower devonian Furnas-Formation. Identifications of fossils in this area are not mentioned and probably unknown. Obviously these sediments were only distinguished by the above cited authors from the upper devonian Ponta Grossa Formation because of petrographic properties. Therefore it cannot be excluded that the so called Furnas Sandstones belong stratigraphically to the Ponta Grossa Formation that only suffered more shock metamorphism.

PONTA GROSSA FORMATION Red claystones and sandstones are exposed in the regular, up to 3 km extending ring depression around the Furnas Formation.

The above mentioned authors identified these sediments as the upper devonian Ponta Grossa Formation. The rocks show an intense fracturing and faulting.

AQUIDAUANA FORMATION A series of fine and medium grained sandstones of red colour is called by Schneider *et al.* (1969) Aquidauana Formation. It crops out in a belt with an extension of about 15 km around the Ponta Grossa sediments.

PALERMO FORMATION In a distance of 15 to 20 km from the center are occurring sediments within of a ring of 2 to 3 km breadth. The main rocks are dark grey and greyish-green claystones and fine grained sandstones. Their stratigraphic position is placed by Gonçalves & Schneider (1970) and Silveira & Ribeiro (1971) to the carboniferous Palermo Formation.

DIKES Dikes of basaltic composition have been mapped in the southeast part of the ring structure by Neto *et al.* (1974) and Leite (1975). Basaltic material crops out at the eastern border of the basement block. The basaltic magma intruded mostly into the radial and concentric fracture and fault systems of the ring structure. Neto *et al.* (1974) connect the genesis of the dikes with the cretaceous basaltic volcanism in the southern Paraná Basin. There are no age determinations of rocks in the investigation area.

CACHOEIRINHA FORMATION Within isolated circular and oval shaped shallow depressions are mapped by Leite (1975) sandy and loamy, slightly consolidated sediments. Their stratigraphic position is supposed to belong to the tertiary Cachoeirinha Formation.

QUATERNARY SEDIMENTS The youngest sediments in the area of the ring structure are quaternary unconsolidated sediments almost spread in depressions.

PROBABLE AGE OF THE IMPACT STRUCTURE Paleozoic sediments occur in concentric rings around the crystalline block at the center. The youngest sediments affected by shock metamorphism belong to the carboniferous/permian Palermo Formation. Therefore the impact must be younger than lower Permian. As basaltic dikes of probable cretaceous/tertiary age intruded into radial and concentric fracture zones of the ring structure, they must be younger than the impact event. Sediments of upper permian until jurassic age are unknown in this area. For this reason a more detailed stratigraphic determination is impossible. A cretaceous age of the ring structure seems to be probable.

STRUCTURAL FEATURES The structural features of the Araguainha impact structure can only be explained considering the events after the cosmic impact. Analogous to the knowledge about the development of other astroblemes the genesis of the Araguainha structure can be described as follows (Fig. 4). The schematic cross sections of Fig. 4 illustrate an inferred sequence of stages in the development of the Araguainha structure, a sequence which occupied a few minutes at most.

Figure 4 — Schematic cross sections showing the structural development of the Araguainha impact structure

Section *a* shows the hypervelocity impact of a cosmic bolide that propagates shock waves proceeding hemispherically into the target. In section *b* is to be seen the excavation of a crater by the high pressure shock waves and their rarefactions. At this stage the heavy shocked bolide is smeared out to line the growing cavity and the target materials are largely molten. The rarefaction waves accelerate the target material in an upward direction. The affected material is ejected into divergent, ballistic trajectories forming ejecta blankets outside the crater. Lateral movements of beds involve many small thrust folds and faults which are exposed very clearly in the Serra São João region in the northern part of the ring structure. Section *c* depicts the beginning of structural adjustments following the crater excavation phase and passage of the shock waves. The strongly shock compressed material in the central and deepest part of the target is affected by a more vertical and convergent upward motion due to the expansion of the compressed material. By these upwards motions is lifted the pre-cambrian basement block about several hundred meters. In section *d* is represented the upward motion of the pre-cambrian basement block. Ring faults form in response to the centripetal inward movements at the center. Beds

of the Ponta Grossa sediments in the ring depression around the central uplift move inwards. The synclises, graben-like ring depressions and ring faults which are mentioned by Silveira & Ribeiro (1971) too, are obviously caused by these convergent motions (Fig. 3).

The central uplift of the basement block destroys the initial excavation crater. Section *e* shows the final stage in the structural development of the complex ring structure of Araguainha.

No direct evidence concerning the impacting body or its direction and angle of impact was obtained in this study. Its azimuth, however, may be indicated by the elliptical outline of the central uplift with a NNW-SSE-axis, the greater thickness of the ejecta blanket and stronger deformation of the northern part. The direction of the cosmic impact probably was SSE.

INTERPRETATION OF AEROMAGNETIC DATA

Aeromagnetic maps (scale 1:50,000) are available for the Araguainha structure and depict regional structural trends in the investigation area. The maps were compiled during the "Alto Garças Project" by the Prospec S.A. (1972) (Fig. 5).

The aeromagnetic measurements were made at about 1 km intervals in N—S direction and 20 km in E—W direction (average flight level: 120 m). The aeromagnetic map does not show any larger circular anomaly. At the center of the ring complex there are three gamma-lows of small size with elliptical contours in NE—SW direction. Two of the magnetic lows are localized at the northern and southern margin of the basement block. The third is situated almost at the center of the basement block. A probable explanation for these magnetic lows might be the presence of suevite and of fractures and brecciation zones. This was suggested to be the reason for magnetic lows at various impact craters as for example by Offield & Pohn (1979) at the Decaturville structure/USA.

The general linear alignments trending NE—SW dominate the magnetic pattern of the Araguainha structure, especially in its northern part. These alignments are supposed to be caused by fracture zones. Fracture trace-maps based on the interpretation of aerial photographs (USAF, 1965), radar imagery (Folha SE.22-V-A, Projeto Radambrazil, 1976) and a satellite-frame (Landsat, 1089-13005, NASA, 1972) of the Araguainha structure show a remarkable coincidence between long distinct photolineations and the magnetic anomaly trend.

SUMMARY The results of geomorphologic, petrographic and structural investigations in the area of the Araguainha structure as well as interpretations of aeromagnetic maps have supported its origin by meteoritic impact. The suggestion of Dietz, French & Oliveira (1973) that the "Domo de Araguainha" is an impact structure is confirmed. The Araguainha ring structures shows the characteristic properties of larger complex astroblemes as the almost circular outline, the impact morphologic sequence including a central uplift, ring walls, depressions and a basin rim, indicators of shock metamorphism, exposed suevites and mixed coloured breccias and negative anomalies of the total intensity of the magnetic field at the center of the structure.

Figure 5 — Structural interpretation of the aeromagnetic map

Acknowledgements The author wishes to thank Prof. Dr. H. Quade (Geologisches Institut/Clausthal, Germany) for initiating this work and for helpful discussions. Fruitful advices from Prof. Dr. P. Kronberg (Geologisches Institut/Clausthal, Germany) are kindly acknowledge. The field study was undertaken during tenure of a fellowship by the DAAD (Deutscher Akademischer Austauschdienst). This support is gratefully acknowledged. Thanks are extended to the Nuclebrás S.A. (Empresas Nucleares Brasileiras/Goiânia, Brazil)

for the logistic and financial support and the permission to carry out the field research, especially to Dr. P. M. de Figueiredo and Dr. R. Ferreira Lopes. This study has benefited very much from the collegial help of the members of staff of the Metago (Metais de Goiás/Goiânia, Brazil) and of the Projeto Radambrazil (Goiânia). Thanks are due to Prof. Dr. W. v. Engelhardt and Dr. G. Graup (Mineralogisch-Petrographisches Institut/Tübingen, Germany) for stimulating discussions.

REFERENCES

- CHAO, E. C. T., HÜTTNER, R. e SCHMIDT-KALER, H. — 1978 — Aufschlüsse im Ries-Meteoriten-Krater. Bayer. Geol. Landesamt, München.
- DAVID, E. — 1969 — Das Ries-Ereignis als physikalischer Vorgang. *Geologica Bavarica* 61: 350-378.
- DENCE, M. R. — 1972 — Meteorite Impact Craters and the Structure of the Sudbury Basin. *Geol. Ass. of Canada, Special Paper* n° 10: 7-18.
- DIETZ, R. S., FRENCH, B. e DE OLIVEIRA, M. A. M. — 1973 — Araguaiinha Dome (Goiás) and Serra de Cangalha (Mato Grosso): Probable Astroblemes?. *An. XXVII Cong. Bras. Geol.*, Resumo das Comunicações, Bol. n° 1:102, Aracaju.
- ENGELHARDT, W. v., STÖFFLER, D. e SCHNEIDER, W. — 1969 — Petrologische Untersuchungen im Ries. *Geologica Bavarica* 61: 229-295.
- ENGELHARDT, W. v. — 1974 — Ries Meteorite Crater, Germany. *Fortschr. Miner.* 52 (1): 103-122.
- GONÇALVES, A. e SCHNEIDER, R. L. — 1970 — Geologia do Centro Leste de Mato Grosso. Relatório n° 394, Petrobrás S.A., DESUL (ined.).
- GRAUP, G. e STÖFFLER, D. — 1974 — Petrologische Befunde im Nördlinger Ries. Das Nördlinger Ries, Beiträge zur Geologie und Mineralogie von Einschlagskratern, 24. Sonderschrift der Zeitschrift der aufschluss: 39-48.
- GUMTAU, M. — 1974 — Das Ringbecken Korolev in der Bildanalyse. *Münchener Geogr. Abh.* 16, Universität München.
- LEITE, G. C. — 1975 — Urânio na região do Domo de Araguaiinha-Mato Grosso. Rel. ined. da Nuclebrás S.A.
- NORTHFLEET, A. A., MEDEIROS, R. A. e MUHLMANN, H. — 1969 — Reavaliação dos dados geológicos da Bacia do Paraná. *Bol. Téc. Petrobrás*, Rio de Janeiro, 12 (3): 291-346.
- NETO, M. H. F. et al. — 1974 — Mapas Geológicos SE.22-V-C,22-V-A, escala 1:250 000, Projeto Goiânia II.
- OFFIELD, T. W. e POHN, H. A. — 1979 — Geology of the Decaturville Impact Structure, Missouri. *Geol. Survey, Prof. Paper* 1042, United States Government Printing Office, Washington.
- REIFF, W. — 1976 — Einschlagskrater kosmischer Körper auf der Erde. Stuttgarter Beiträge zur Naturkunde, Serie C, Nr. 6, Meteorite und Meteorkrater: 24-47.
- SCHNEIDER, R. L. et al. — 1974 — Revisão Estratigráfica da Bacia do Paraná. An. XXVIII Congr. Bras. Geol.: 41-65.
- SCHNEIDER, W. — 1971 — Petrologische Untersuchungen der Bunten Breccie im Nördlinger Ries. *N. Jb. Miner. Abh.* 114 (2): 136-180.
- SILVEIRA FILHO, N. C. e RIBEIRO, C. L. — 1971 — Informações geológicas preliminares sobre a estrutura vulcânica de Araguaiinha-Mato Grosso. Rel. ined., DNPM, Distrito Centro-Oeste.
- SPECTOR, A. et al. — 1972 — Levantamento gama-espectrométrico e magnetométrico na área do Projeto Alto Garças nos Estados de Goiás e Mato Grosso. Convênio CNEM/CPRM/DNPM, Prospeção S.A.
- THEILEN-WILLIGE, B. — 1980 — Fernerkundungsverfahren bei geomorphologischen und strukturellen Untersuchungen an Intrusivkörpern und der Ringstruktur von Araguaiinha in Goiás/Brasilien. Diss. TU Clausthal.

Recebido em 9 de Dezembro de 1980.