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In pursuit of causes for the greatest mass extinction: the Permo-Triassic Boundary in the Southern Hemisphere – part II

Investigating 260 million years old, meteorite-impacted sedimentary rocks in central-west Brazil

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Abstract

Various catastrophic and/or episodic events have been suggested to have caused the end-Permian mass extinction close to the Permo-Triassic Boundary (PTB). The theories and extinction-scenarios are however predominantly based on the sedimentary rock record and fossil record of the Northern Hemisphere – the Southern Hemisphere and in particular the fossil fish record worldwide being least well explored. In this second of four contributions we briefly present a little-known meteorite-impact crater relatively close to the PTB on the border of the States of Goiás and Mato Grosso in central west-Brazil. We discuss the occurrence of neighbouring Permian sedimentary rocks, a selection of accessible outcrops, fossil content and their potential to contribute to the discussion around the end-Permian extinction event.

Auf der Suche nach Ursachen für das grösste Massenaussterbe-Ereignis: die Perm-Trias-Grenze der Südhemisphäre – Teil II.

Erforschung 260 Millionen Jahre alter Meteoriteneinschlag-verformter Sedimentgesteine im zentralen Westbrasilien

Verschiedene katastrophenhafte und/oder episodische Ereignisse sind als Ursachen für das Massenaussterbe-Ereignis am Ende des Perms in der Nähe der Perm-Trias-Grenze (PTB) vorgeschlagen worden. Die Theorien und Aussterbe-Szenarien gründen allerdings mehrheitlich auf dem Sedimentgestein- und Fossilbeleg der Nordhemisphäre, während die Südhemisphäre und speziell der fossile Fisch-Beleg weltweit am wenigsten gründlich erforscht sind. In diesem zweiten von vier Beiträgen stellen wir einen wenig bekannten Meteoriten-Einschlagkrater relativ nahe der PTB an der Grenze der Staaten Goiás und Mato Grosso im zentralen West-Brasilien vor. Wir diskutieren das Auftreten benachbarter permischer Sedimentgesteine, eine Auswahl zugänglicher Aufschlüsse, Fossilinhalte und ihr Potential zur Diskussion um das Aussterbe-Ereignis am Ende des Perms beizutragen.

Key words: Brazil – fossil fishes – geochemistry – mass extinction – meteorite impact – palaeontology – Permian – Permo-Triassic Boundary – States of Goiás/Mato Grosso – stratigraphy – Southern Hemisphere

Schlagwörter: Brasilien – fossile Fische – Geochemie – Massenaussterben – Meteoriteneinschlag – Paläontologie – Perm – Perm-Trias-Grenze – Staaten Goiás/Mato Grosso – Stratigraphie – Südhemisphäre

1 INTRODUCTION

Although extensive faunal and floral turnover is known to have taken place also in the Southern Hemisphere during the Permo-Triassic over a longer geological time interval (Erwin, 2006), the question remains as to what degree the decline of biotic diversity in the Late Permian may be attributed to catastrophic global or rather more localized events. It is widely agreed that regardless of the nature of such events – catastrophic, episodic, continuous, random or stochastic – only establishing considerable interregional correlation using stratigraphy, biostratigraphy and, where possible, absolute dating, will eventually lead to relative sequencing. This is crucial for correct sequencing of events in time. 'Time control' and interpreting palaeoenvironmental changes through time are crucial components in interpreting these underlying processes. Some fossil sites and rock sections close to or across **the Permo-Triassic Boundary (PTB)** differ widely in sedimentological, geochemical and palaeontological respects (e.g., López-Gómez and Taylor, 2005; Yin et al., 2007). Even more problematic, respective sites may be condensed in time, are often discontinuous and unconformable in the Southern Hemisphere, and none of them are easily correlated (for details, see Mutter and Richter, 2007: 221–222). Nevertheless, the so-called Araguainha-impact structure in central-west Brazil is an indispensable source of information: the fossil-bearing layers provide the only accessible (terrestrial) impact structure that may be linked to the PTB, and where an impact actually caused at least a regional extinction.

The end-Cretaceous extinction event that led to the disappearance of about 75% of existing species including dinosaurs (e.g., Erwin, 2006) is more thoroughly investigated than the end-Permian mass extinction. There is an ongoing dispute about the Cretaceous-Paleogene Boundary mass extinction. Probably, the end-Cretaceous Chicxulub bolide-impact has been attributed to the mass extinction prematurely, because the diversity in many fossil groups actually dwindled some time before that particular boundary (see MacLeod et al., 1997; Keller, 2001). Recent, more detailed palaeontological and geochemical studies do not support immediate or direct links between decline in diversity, extinction, Cretaceous-Paleogene Boundary and impact rocks, and have re-opened the discussion (see, for instance Keller et al., 2003a, b, 2004; Keller, 2004; Archibald and Fastovsky, 2004).

For obvious reasons, events that happened about 180–200 million years before that boundary are more difficult to study. As outlined in Part I of this series of contributions, there have been several possible causes suggested for the end-Permian extinction event(s). Since impact craters and impact events are also increasingly more difficult to identify going back in time, there has only been recognized a vague line of evidence pointing toward a possible connection between impact(s) at the PTB and (long-term) Permo-Triassic faunal turnover (for a review, see Rohde and Muller, 2005). None of the evidence to support impact-related extinction comes from the reasonably well-known Northern Hemisphere. Instead, another major geological event, formation of the Siberian traps[1], was suggested to have been associated with the PTB in the Northern Hemisphere (see Czamanske and Fedorenko, 2004). A disadvantage in testing the latter hypothesis is that igneous[2] rocks are poor in or devoid of fossils.

There are currently three crater-like structures known and placed close to the PTB (Fig. 1). The Bedout High, a disputed, impact crater-like, semi-circular morphological structure, approximately 100 km in diameter, was disco-

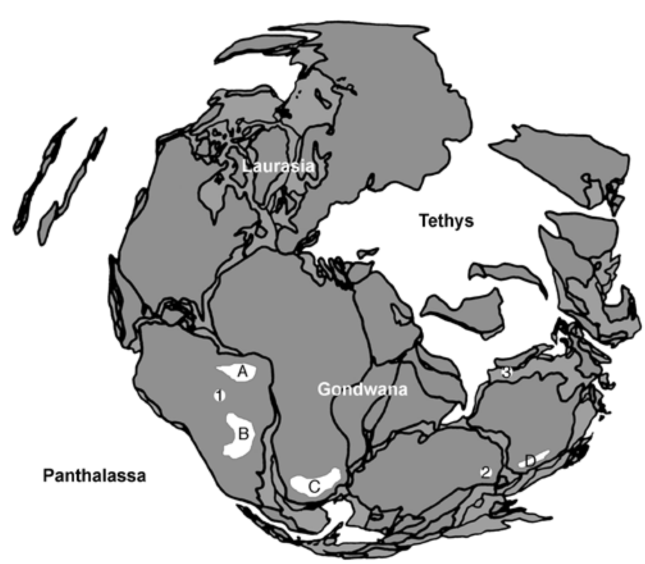

Fig. 1. Snapshot of the palaeogeography of continents around the PTB showing continents of the Northern Hemisphere (Laurasia) and the Southern Hemisphere (Gondwana) joined together in the supercontinent Pangaea. Circles indicate possible PTB impact craters (1, «Araguainha Dome» in Brazil; 2, «Wilkes Land» below Antarctica; 3, «Bedout High» off the north west coast of Australia). Irregular blank areas with letters indicate relevant Gondwana basins yielding Permian and Early Triassic fish assemblages (A, Parnaíba basin in Brazil; B, Paraná basin in Brazil; C, Karoo basin in South Africa; D, Sydney-Bowen basin in Australia).

Abb. 1. Momentaufnahme der Paläogeografie der Kontinente um die PTB, in welcher die Kontinente der Nordhemisphäre (Laurasia) und die der Südhemisphäre (Gondwana) zum Superkontinent Pangäa zusammengefügt waren. Die Kreise bezeichnen mögliche PTB-Einschlagkrater (1, «Araguainha Dome» in Brasilien; 2, «Wilkes Land» unterhalb der Antarktis; 3, «Bedout High» vor der Nordwestküste Australiens). Irreguläre weisse Flächen symbolisieren relevante Becken Gondwanas, aus denen permische und untertriassische Fossilreste geborgen werden (A, Parnaíba-Becken in Brasilien; B, Paraná-Becken in Brasilien; C, Karoo-Becken in Südafrika; D, Sydney-Bowen-Becken in Australien).

[1] Siberian traps: the largest known continental flood basalt (a large igneous province)
[2] igneous: magmatic

vered on the sea floor off the northwest coast of Australia (BECKER et al., 2004). Another controversial structure is a circular gravity-anomaly with a diameter of about 300 km, situated below the ice shield of Wilkes Land in northeast Antarctica (FRESE et al., 2006). The Araguainha impact-crater in central-west Brazil was originally interpreted as a structure resulting from a Cretaceous syenite intrusion that uplifted and deformed the Phanerozoic sediments in the shape of a dome (NORTHFLEET et al., 1969) but is now accepted to be clear evidence of a bolide-impact, which caused a crater of about 40 km in diameter (DIETZ and FRENCH, 1973; DIETZ et al., 1973; CRÓSTA, 1987, 1999).

In this paper, we explore this sole palaeontologically relevant impact structure – known as the Araguainha dome on the border of the States of Goiás and Mato Grosso. Despite the fact that the Brazilian bolide – a possible PTB meteorite – was comparatively small with an estimated diameter of not more than two kilometers, it was ‘large enough’ to cause a regional extinction – which possibly stroke near the PTB. Strangely, this crater has not yet received the scientific attention it probably deserves with respect to the end-Permian extinction event (see for instance REIMOLD, 2003), although its age (currently dated about 249–242 million years; HAMMERSCHMIDT and ENGELHARDT, 1995) could be within striking distance of the PTB, which is currently dated 251 million years or slightly older (METCALFE et al., 2001; OVTCHAROVA et al., 2006). The youngest currently known sedimentary rocks in the area are believed to be around 260 million years old. Upon improvement of dating methods in the future, these absolute dates may be further refined. The Araguainha impact crater is not only the sole accessible and indisputable impact crater near the boundary currently known, the rim of the crater also yields rare palaeontological information – and there is the potential of preservation of post-impact sedimentary rocks overlying impacted layers. These strata hence hold directly observable key evidence to addressing the question of a possible impact-related extinction event in this window in time, and at a regional scale (see also THÉRY et al., 2007; LANA et al., 2007).

2 GEOLOGY OF THE ‘ARAGUAINHA DOME’ IMPACT SITE IN THE PARANÁ BASIN

The Chaco-Paraná basin is distributed throughout a great area of South America, it crops out in Brazil, Argentina, Uruguay and Paraguay (Fig. 2). In Brazil, the Paraná basin yields sedimentary rocks from the Ordovician up to the Quaternary[3] (MILANI and THOMAZ-FILHO, 2000) with substantial gaps in the Late Silurian, Early Carboniferous, Late Triassic and Early Cretaceous (MILANI et al., 1994). The Palaeozoic/Mesozoic stratigraphic chart of the Paraná basin is subdivided into eight groups: Rio Ivaí, Paraná, Itararé, Guatá, Passa Dois, São Bento, Caiuá and Bauru (MILANI et al., 1994).

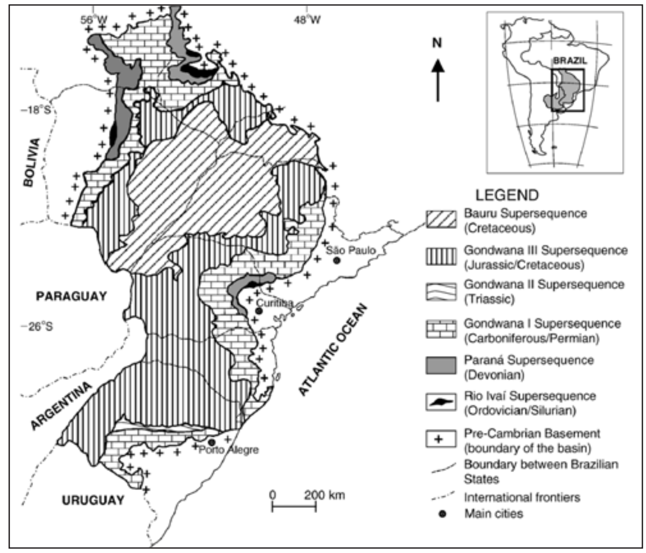

Fig. 2. Geologic map of the Paraná basin within Brazil and its borders with Uruguay, Argentina, Paraguay and Bolivia (SANTOS et al., 2006).

Abb. 2. Geologische Karte des Paraná-Beckens innerhalb von Brasilien und seine Grenzen mit Uruguay, Argentinien, Paraguay und Bolivien (SANTOS et al., 2006).

The Precambrian basement[4] and strata of Paraná, Itararé and Passa Dois groups (Fig. 3; see also Crósta, 1999) crop out outside and in the dome of Araguainha. The crater was excavated in horizontally bedded sediments of the Paraná basin (HAMMERSCHMIDT and ENGELHARDT, 1995; see also LANA et al., 2006). After the impact event, the sedimentary rocks in this area were not further deformed (ENGELHARDT et al., 1992; LANA et al., 2006), although parts of the rim collapsed and rocks were folded outside the rim immediately following the impact (see below).

Strata in the annular trough and around the crater rim comprise Carboniferous sandstones of the Itararé Group. These rocks are found inside and outside the impact structure and there are Permian claystones of the Passa Dois Group, mainly concentrically arranged inside the border of the rim of the crater (see below and LANA et al., 2006).

[3] Ordovocian to Quaternary: a time span longer than 400 million years
[4] Precambrian basement: underlying non-sedimentary rocks, at least 540 million years old

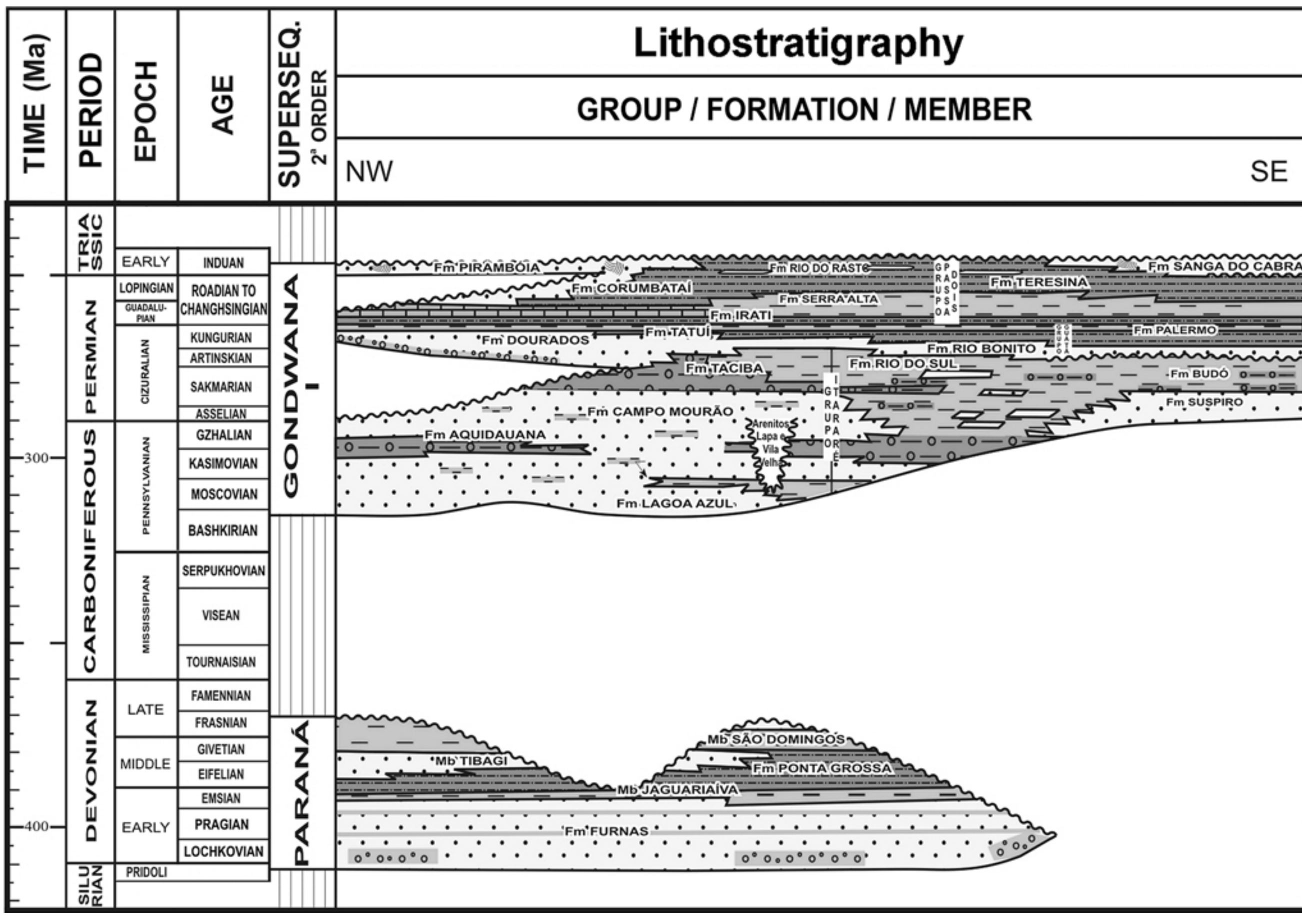

Fig. 3. Lithostratigraphic chart of the Upper Palaeozoic and the lowermost Mesozoic (Triassic) in the Paraná basin (after MILANI, 1997; absolute ages according to ICS and IUGS, 2004).

Abb. 3. Lithostratigraphie des oberen Paläozoikums und des unteren Mesozoikums (Trias) im Paraná-Becken (nach MILANI, 1997; absolute Datierung folgt ICS und IUGS, 2004).

The Paraná Group crops out in the central uplift and only in this area it is characterized by upturning and thickening, supported by recumbent folds and bedding imbrications[5]. The geometry of the structures indicate inward movement and constriction of the target rocks in the uplift area, where strata are also concentrically arranged (LANA et al., 2006). Sandstones of the Itararé Group remained relatively undeformed in the outer 5–6 km of the crater, showing evidence of bedding-parallel shearing along decimeter- to centimeter-wide breccia zones. Folding and faulting of these Carboniferous sandstones are observed in the annular trough, over a radial distance of 15 km from the central uplift. The bedding is relatively steep and it is crosscut by several meter-wide radial and concentric fault zones (LANA et al., 2006).

In the crater rim, the bedding orientation of the Permo-Triassic Passa Dois Group remained essentially horizontal. Outside the crater and on a meter scale, however, the sedimentary rocks are sometimes strongly asymetrically folded and faulted (Fig. 4). In the outer part of the sedimentary collar the Passa Dois Group follows the Itararé Group, concentrically arranged, and dips are subvertical to vertical, sometimes rotated by kilometer-scale radial fault zones (LANA et al., 2006). Outcrops of shale and limestone from the Irati Formation are preserved and show verticalized layers having collapsed after the impact (Fig. 5).

In the areas surrounding the Araguainha impact-structure, strata of the Furnas Formation (Paraná Group) comprise homogeneous, eventually conglomeratic, fluvial sandstones. These strata are overlain by usually biotur-

[5] imbrications: overlapping layers of rock

bated[6] shales, siltstones and sandstones from the Ponta Grossa Formation deposited in marine neritic[7] palaeoenvironment[8] (SCHNEIDER et al., 1974).

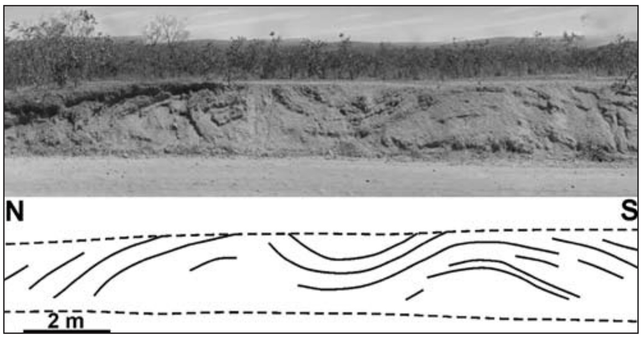

Fig. 4. Composite figure of meter-scale folding structures of Permian rocks (? Corumbataí Formation) outside the rim of the crater as a result of the impact. The roadcut section (looking west) is about 25 m wide and is approximately 20 km away from the centre of the crater.

Abb. 4. Zusammengesetzte Abbildung der durch den Einschlag verursachten meter-langen Faltungs-Strukturen in Permischen Gesteinen (? Corumbataí-Formation) ausserhalb des Kraterrandes. Die Abbildung (Blick nach Westen) zeigt einen etwa 25 m weiten Ausschnitt eines Strassen-Aufschlusses etwa 20 km vom Zentrum des Kraters entfernt.

Fig. 5. Close-up of the uppermost, nodular breaking limestone-shale succession in the Irati Formation, Passa Dois group of the Paraná basin, cropping out in vertical succession in the outer part of the sedimentary collar. The compass is 7.5 cm long.

Abb. 5. Detailaufnahme der obersten, muschelig brechenden Kalksteinschiefer-Abfolge der Irati-Formation, Passa-Dois-Gruppe des Paraná-Beckens, in vertikaler Abfolge im äusseren Teil des Sedimentgestein-Randes. Der Kompass ist 7,5 cm lang.

Within the Araguainha dome, the Itararé Group is characterized mostly by sandstones of the Aquidauana Formation (LANA et al., 2006) deposited under influence of glacial palaeoclimate and mass flux deposits and turbidites[9] (MILANI et al., 1994).

As in the northern areas of the Paraná basin, the Corumbataí Formation (uppermost Permian formation of the Passa Dois Group) possibly contains equivalents of the Permo-Triassic Boundary. In the area surrounding the impact-structure, siltstones of the Palermo Formation outcrop, and limestones and shales of the Irati Formation can be found, as well as claystones and siltstones of the Corumbataí Formation. Sections in various distances from the Araguainha dome have been logged in this area in order to evaluate sedimentological and faunal changes within this formation – some of which are discussed in more detail below (Fig. 6 and 7). Previous studies conducted in the Passa Dois Group also indicate that a regressive sedimentary sequence is recorded in the Paraná basin (MILANI et al., 1994). Taphonomic studies based on clams from Upper Permian formations (Corumbataí, Rio do Rasto and Rio Bonito formations) indicate a deposition in a mostly shallow marine palaeoenvironment dominated by events of high energy (SIMÕES and TORELLO, 2003).

3 ROCK SEQUENCES AND FOSSIL EVIDENCE

A number of rock sections of supposedly similar age along roadcuts and rivercuts were measured and logged in the vicinity of the Araguainha-impact-structure 30 km south, 50 km west and up to 135 km south-east of the Araguainha dome (Figs. 6, 7). The rock sequences are dominated by siltstone and sandstones of very variable thickness, and coloured claystone lenses or laminae are intercalated. Bioclastic levels[10], consisting of predominantly aquatic species, usually either invertebrates or vertebrates, are locally common but restricted to certain horizons and lentil-shaped layers.

Our preliminary analysis of some of these correlated profiles (Fig. 7) enables us to make interesting observations. The conspicuous, bituminous limestone sequence of the Irati Formation serves as a lithological ‘time’ marker running in section A above, in B below and in C and D within the

[6] bioturbated: sediment disturbed by organism(s)
[7] neritic: shalow sea environment down to approx. 200 meters
[8] palaeoenvironment: shallow sea environment of that time
[9] turbidite: voluminous sedimentary avalanche under water
[10] bioclastic level: a rock unit with cemented fragments and isolated fossil remains

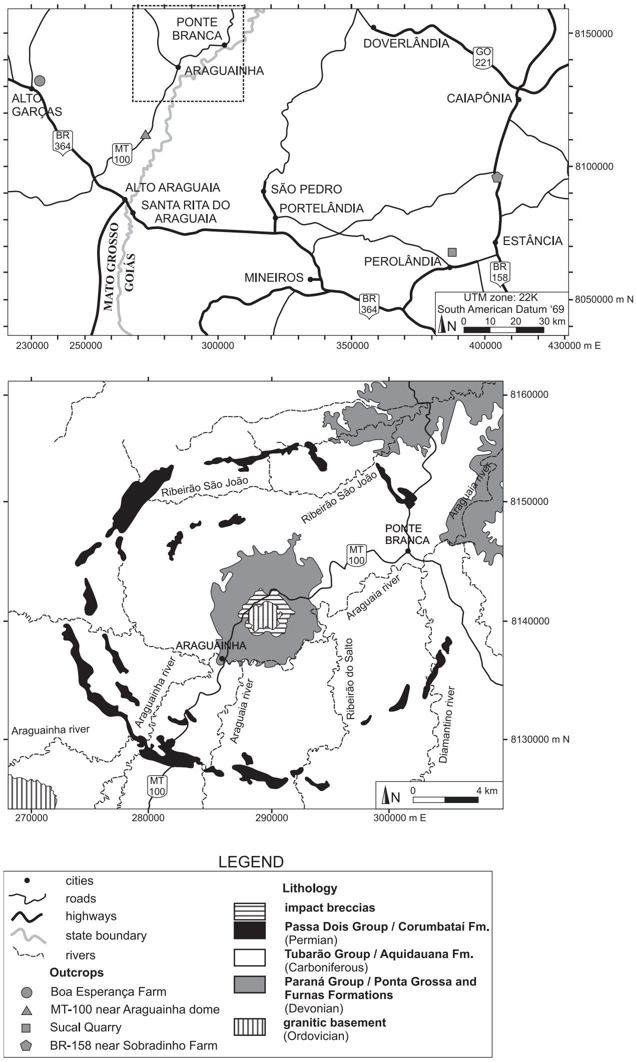

Fig. 6. A (above): geographic map of the area of the Araguainha impact-crater and its vicinity. Symbols delineate studied outcrops and sections in Fig. 7. B (below): simplified geological map of the area of the Araguainha impact-crater showing the dome in the centre, remnants of the rim, rivers and streams. Symbols delineate studied sections and sampled localities.

Abb. 6. A (oben): geografische Karte der Region um den Araguainha-Einschlagskrater. Symbole markieren die Aufschlüsse in Abb. 7. B (unten): vereinfachte geologische Karte des Araguainha-Kraters mit dem Dom im Zentrum, Reste des Kraterrandes, Flüsse und Bäche. Symbole markieren die untersuchten Aufschlüsse und beprobten Lokalitäten.

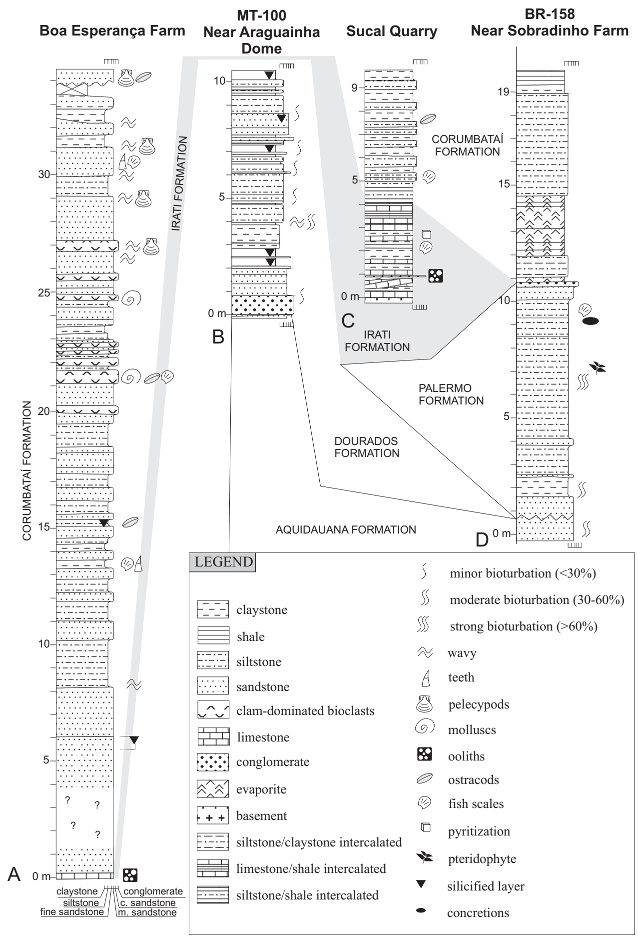

Fig. 7. Four Permian rock sequences (A, B, C, D) in Mato Grosso and Goiás correlated using the Irati Formation as a lithological marker bed. Note that the most complete section in the vicinity of the Araguainha dome (B) is stratigraphically below the remainder of the Irati Formation, pointing at a relatively older age of this particular section near the dome.

Abb. 7. Vier permische Aufschlüsse (A, B, C, D) in Mato Grosso und Goiás korreliert anhand der Irati-Formation als lithologischer Markerhorizont. Man beachte, dass sich der vollständigste Aufschluss in der Nähe des Araguainha-Domes (B) stratigraphisch unter dem erhaltenen Rest der Irati-Formation befindet, was für ein relativ höheres Alter dieses Aufschlusses in Domnähe spricht.

section. The sequences below the Irati (B and D) both near and distant from the impact site show at least moderate bioturbation. Bioturbation is characteristically absent above the Irati in all studied sections. If the correlation using the Irati Formation is correct and there is an equivalent present at the section in Fig. 7D underlying a succession of evaporitic clay layers at the base of the Corumbataí Formation, then the available data in these sequences suggests that horizons immediately overlying the Irati Formation largely lack fossils. No bioturbation has been recorded (noticeably, a section 125 km from the dome yields fragmentary fish and ostracode remains immediately above the Irati Formation; Fig. 7C). Of course, several environmental interpretations are conceivable to explain these observations and more research on many more sections is needed to place changes through layers in a larger context. In particular, the conglomeratic and oolithic[11] nature of certain horizons, but also the fish and crustacean fossil record requires more attention in order to tie-in all sequences in an over-regional environmental scenario.

The accurate dating of these layers, the impact and all events associated with this impact are indeed of great importance, because the changes of diversity in these layers may not only be linked to a 'regional' extinction but may be of importance beyond the region and greatly help our understanding of the effect of a large-scale change in the biotic system. Establishment of relative and possibly absolute ages will then be indispensable reference for evaluating the allegedly global end-Permian extinction event(s).

Among fossils provisionally identified in the field, actinopterygian scales and clams seem the most ubiquitous faunal elements. Our field studies and preliminary comparisons of rock sections show that there is yet little lithological and palaeontological evidence available to establish interregional correlation. Like elsewhere in the uppermost Lower to Upper Permian of Brazil, the facies[12] are readily interpreted as sequences deposited under classic lacustrine-fluviatile circumstances with limited lateral extent. Time-informative fossils, such as the bivalves *Pinzonella neotropica* or *Leinzia similis* may be recorded from additional sections (see Figs. 6 and 7) upon further examination and may help determining approximate ages of rock sequences. Scales of actinopterygians are ubiquitous, for instance in four bioclastic layers in one section, and might be useful for comparison of morphological features and geochemical signals.

A quite complete actinopterygian has been recovered from a quarry in Alto Garças (Mato Grosso/Goiás, Brazil) (Fig. 8), and several types of flank scales of actinopterygians have been recovered from other localities suggesting the presence of many more actinopterygian species (Plate 1A, B). Particularly brittle rock samples (Plate 1C) may only be studied by means of sections or thin sections. Scales of coelacanths have been observed in the field and collected as imprints (Plate 1D), and xenacanth[13] teeth have been recorded and collected in variable size and state of preservation (Plate 1E, F).

Some of these fish remains or their faunal composition may well prove useful in addition to clams and crustaceans in order to achieve a regional correlation and eventually a

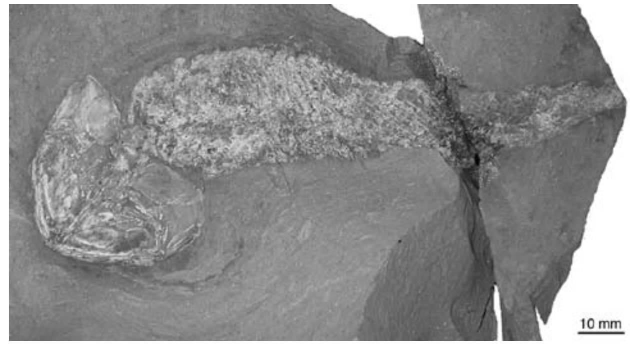

Fig. 8. A fairly well-preserved Permian actinopterygian missing only its fins. The specimen was recovered from a quarry near Alto Garças (in the State of Mato Grosso near locality 'Boa Esperança', Fig. 7 A), is dorso-ventrally flattened and preserved in dorsal view (for details, see MUTTER et al., subm.).

Abb. 8. Ein relativ gut erhaltener permischer Actinopterygier, dem nur die Flossen fehlen. Das Exemplar wurde in einem Steinbruch nahe Alto Garças (im Staat Mato Grosso, nahe der Lokalität «Boa Esperança», Abb. 7 A) gefunden, ist dorso-ventral abgeflacht und in dorsaler Ansicht erhalten (weitere Details in MUTTER et al., subm.).

relative sequencing of palaeoenvironmental events through time. Xenacanth and other chondrichthyan remains from elsewhere in the Passa Dois Group have already been studied in considerable detail (WÜRDIG-MACIEL, 1975; RICHTER, 2005 and references therein). Acanthodian remains and yet another relatively complete actinopterygian have recently been reported from southern parts of the Paraná basin (MUTTER and RICHTER, 2007; TOLEDO et al., 2007). The currently logged sequences of about 125 meters in total represent, however, only snapshots in time and space and several sections likely pre-date the impact event.

4 PRELIMINARY CONCLUSIONS

As we conclude from preliminary lithological correlation using four selected sections of the study area, the Irati Formation yields evidence of a conspicuous 'short-term' event leaving a denotative lithological signature possibly during the uppermost Lower and Middle-Upper Permian suitable for interregional correlation in central-west Brazil. However, the lateral extension of the Irati Formation may be less developed than previously thought. This formation is absent in section D (Fig. 7D) but observed stratigraphically above and only in the vicinity of section B (Fig. 7 B). There is no evidence of the bituminous limestone sequence typi-

[11] oolithic: tiny spherical grains of sedimentary rock
[12] facies: association of rock features that reflect original environment
[13] xenacanths: ancient extinct sharks

cal of the Irati Formation in section D (Fig. 7D) but a series of variably thick evaporitic horizons overlies the siltstone-dominated, bioturbated and fish scales-containing Palermo Formation. Although the Irati Formation outcrops basin-wide, we suggest here that this formation is actually absent in some localities along the basin's extreme northwest border.

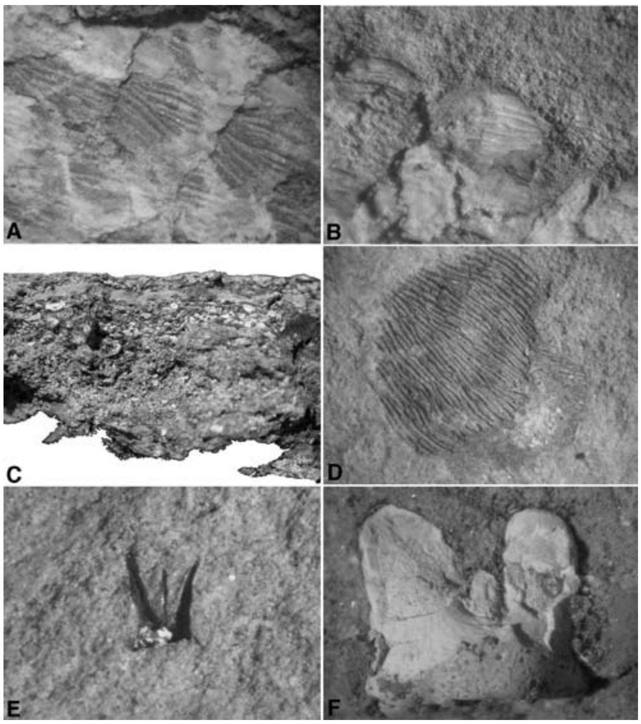

Plate 1. A: patch of actinopterygian scales (occlusal view) from the Corumbataí Formation from one of the sampled localities in central-west Brazil. Note the densely spaced and in part obliquely angled ridges in the scale surface. B: imprints of scales of the same specimen (occlusal view) from the Corumbataí Formation. Note the fairly well-spaced and running grooves. C: a bioclastic lens predominantly composed of fish teeth and fish scales. D: imprint of a sarcopterygian scale (occlusal view), showing the posterior free scale surface with longitudinal grooves and the much smaller and smooth anterior area (covered in the squamation). E: imprint of a xenacanth shark tooth with a relatively long and slender median cusp. F: weathered xenacanth shark tooth with a presumably less conspicuous median cusp than the tooth in Fig. E.

Tafel 1. A: im Verband erhaltene Actinopterygier-Schuppen (Aufsicht) aus der Corumbataí-Formation aus einer der beprobten Lokalitäten im westlichen Zentral-Brasilien. Man beachte die dicht stehenden und zum Teil schräg verlaufenden Rippen in der Schuppenoberfläche. B: Abdruck von Schuppen desselben Aktinopterygier-Exemplares (Aufsicht) aus der Corumbataí-Formation. Man beachte die relativ weit auseinanderliegenden und fast parallel verlaufenden Furchen. C: eine bioklastische Linse, die zur Hauptsache aus Fischzähnen und -schuppen besteht. D: Abdruck einer Sarkopterygier-Schuppe (Aufsicht) mit länglichen Furchen im hinteren (unbedeckten) Teil und einer glatten, viel kleineren vorderen (im Verband überlappten) Schuppenoberfläche. E: Abdruck eines xenacanthiden Haifischzahnes mit einer relativ langen und schlanken Mittelspitze. F: angewitterter xenacanthider Haifischzahn mit einer vermutlich weniger ausgeprägten Mittelspitze als der Zahn in Abb. E.

Hence, based on evidence from section B (in Fig. 7 and field observation in collapsed ring-structures), the oldest possible age for the Araguainha impact is stratigraphically above the Irati Formation, possibly even after deposition of the Corumbataí Formation, following consolidation of the sediments of that formation (see Fig. 4 and Fig. 7). There are several possible absolute ages currently available for the Irati Formation, bracketing a time interval of over 17 million years (approx. 280–263 my), equivalent to the late Early to Middle Permian (see Mutter and Richter, 2007 for discussion). The currently youngest possible age for the impact event is Early Triassic with 245 my based on $^{40}Ar/^{39}Ar$-dating (Crostá, 1999), allowing for a time bracket of about 35 million years for the impact to have taken place. Considering the fact that the bolide struck unconsolidated sediments of a shallow sea at the time, we may, actually not, expect preservation of any sedimentary rocks immediately prior to the impact, in the impact zone: the collapsed ring structures – uppermost Lower Permian containing the Irati Formation – must be clearly older than the actual impact event.

It will be highly rewarding for future studies to systematically collect and study in detail rock and fossil samples from as many localities as possible in the Paraná basin close to and far from the impact crater in order to understand and reconstruct changes through time and space in this crucial end-Permian timeframe. Although the Araguainha bolide-impact was likely large enough to cause a regional extinction, it is currently unclear whether it predated, coincided, overlapped with or postdated other possible biotic extinction events.

5 EPILOGUE: IS THE PERMO-TRIASSIC TRANSITION A UNIQUE EVENT IN TIME?

As detailed in part I (Mutter et al., 2007, pp. 72–73), there have been other exceptional, global or large-scale geological events suggested to be associated with the PTB such as the Siberian traps and sea level fall. In trying to assess changing biotic diversity during the Phanerozoic – during several hundred million years – it may also be advisable to remember the Earth in our solar system as a celestial object, which was initially (in geological terms 'shortly'

– within 1.5 billion years after its own formation) heavily bombarded by extraterrestrial impacts (Hörz et al., 1991). Impact rate then decreased rapidly beginning about 4 billion years before present but it is concluded from both, theoretical consideration and actual dating of terrestrial craters that an unusually high number of impacts on Earth (so-called 'terrestrial craters') fall within the 300–200 million years time window before present (see original data in Soderblom and Lebofsky, 1972; also Grieve, 1982; Hörz et al., 1991; French, 1998). Hence, it is this time window (and not the end-Cretaceous featuring the popular dinosaur extinction) that is unique in terms of both greatest decline in biotic diversity and greatest extraterrestrial impact rate during the Phanerozoic. Interestingly, the biotic diversity (as inferred from the fossil record) during the Phanerozoic has furthermore been suggested to have undergone a cyclic decline-recovery phase every 62 million years (Rohde and Muller, 2005). However, even for the greatest Phanerozoic extinction event, there is no clear evidence for a causal relationship between decline in diversity and extraterrestrial impact(s).

Considering the severity of the Araguainha (and currently only accepted) impact alone (equivalent to or greater than the Earth's total annual energy release, or over 15 million Hiroshima bombs; French, 1998: table 2.1) in this time frame, serious concerns may arise as to whether currently applied palaeontological and geochemical techniques are capable of capturing and re-constructing catastrophic biotic and abiotic events that took place about 250–260 million years ago.

In this context, it is noteworthy that a major gap in preservation of the sedimentary rock record (2 km in thickness) is reported east of the 24° E longitude in southern Africa, where the most complete rock record is exposed in the Karoo basin. Therefore, Brazilian sedimentary rocks younger than Early Permian are notoriously difficult to date (see Wanke et al., 2000; Rubidge, 2005; Mutter and Richter, 2007 and references therein). There may be far greater information value than previously thought in gaps of the rock record, in 'mutual boundaries' and in disentangling time-averaged fossils from within sedimentary rocks, if we assume the working hypothesis that the Permo-Triassic transition was a difficult time for life on Earth.

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