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Geology and taphonomy of the base of the Taquaral Member, Irati Formation (Permian, Paraná Basin), Brazil

ARTUR CHAHUD*AND SETEMBRINO PETRI

Universidade de São Paulo, Instituto de Geociências, Departamento de Geologia Sedimentar e Ambiental.
Rua do Lago, 562. Cidade Universitária 05508-080 - São Paulo, SP – Brazil.
*E-mail address: arturchahud@yahoo.com

ABSTRACT

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The taphonomy of Early Permian vertebrates from a sandy facies at the base of the Taquaral Member, Irati Formation, was surveyed in order to acquire data for the interpretation of the sedimentary processes and paleoenvironment of deposition. Six outcrops from the Rio Claro municipality and surrounding areas, from the Brazilian State of São Paulo, were investigated. The vertebrate groups are Chondrichthyes (Xenacanthiformes, Ctenacanthiformes and Petalodontiformes), Osteichthyes (Actinopterygii and Sarcopterygii) and Tetrapodomorpha. They occur as loose teeth, scales, spines and bone remains. The sandy facies is characterized by fining upward deposition. The coarser sandstone immediately above the underlying Tatuí Formation is rich in Chondrichthyes. However, the fine sandstone above, immediately beneath the silty shale facies, is devoid of Chondrichthyes, though Osteichthyes scales, teeth and bones were present. The taphonomy is important for inferring sedimentary processes and then the paleoenvironments. The poor sorting of the sandstone and the presence of fossils that are mostly abraded or worn are indicative of a high energy environment. In contrast, the presence of fossils in a good state of preservation, some without abrasion and breakages are indicative of only limited transport. Differences of fossil spatial density, numbers of specimens and taxa may be explained by the dynamics of deposition, from details of the palaeoenvironment can be obtained.

Keywords: Taphonomy; Permian; Actinopterygii; Sarcopterygii; Chondrichthyes.

INTRODUCTION

Ordovician to Cretaceous deposits from the southern Brazil intracratonic Paraná basin are grouped into several stratigraphic sequences. The thickest are Late Palaeozoic in age, of which the Irati Formation, Permian Cisuralian (Santos *et al.* 2006), is the most outstanding marker of changes in the tectonic behaviour of the basin (Milani and De Wit 2008). Two members of this formation were proposed by Barbosa and Gomes (1958), the Taquaral Member at the base, succeeded by the Assistência Member.

The Taquaral is represented by two facies, the sandy facies, mostly located at the base, and silty-shale. The silty shale facies is thicker (5 to 30m) more homogeneous and more widespread than the sandy facies. Crustaceans and fish remains as the only fossils recovered from this facies (Chahud and Petri 2013a, 2013b).

The sandy facies consists of fine- to coarse-grained sandstones, with beds 5–50 cm thick. These beds are

rich in fossils, teeth, scales and other vertebrates remains (Chahud and Petri 2008b, 2009, 2010a, 2012, 2014; Chahud *et al.* 2010), with different preservations, which may be caused by different types of depositional events.

The objective of this contribution is to disclose, for the first time, the taphonomies of the fossils from the sandy facies of the Taquaral Member and their contributions for a better understanding of the palaeoenvironments of the deposits.

MATERIAL AND METHODS

Most samples in the sandy facies came from six outcrops around Rio Claro municipality, State of São Paulo, Brazil (Text-figs 1−3). The fossils are Chondrichthyes scales, teeth and indeterminate bone remains.

Sedimentological and granulometric features and sedimentary structures were investigated as well as the total studied area of exposure, expressed in m².

The numbers of fossils and their spatial density in relation to the area of accumulation (N/m²) were studied herein. The fossils may be crowded or scattered, the bioclasts touching each other or separated by matrix. Three degrees of packing, after Kidwell

and Holland (1991) were considered: 1) densely packed; 2) loosely packed; 3) scattered distributed on plan observation.

The spatial position of the fossils gives clues to their dispositions along the strata (Behrensmeyer and Kidwell 1985; Behrensmeyer 1990, 1991). In plan view the fossils are either oriented or chaotic. In profile view, they are either parallel or discordant to the bedding. The fossils also may be crowded together or sparsely distributed. The orientation of the bioclasts in plan view may give clues to the depositional dynamic of the flows (palaeocurrents) (Behrensmeyer 1982, 1988, 1990, 1991; Elder and Smith 1988; Mancuso 2003, 2012; Fitzgerald *et al.* 2012)

The taphonomic study included breakages, abrasions, number of articulated pieces and size sorting. The sorting is significant for inferences of the depositional environment (Kidwell and Holland 1991; Mancuso 2003, 2012; Fitzgerald *et al.* 2012).

The concept of articulation, in the sense of Behrensmeyer (1991), includes articulated fossil, disarticulated fossil remains of the same specimen (association) and loose pieces and dispersed pieces.

The number of twenty samples per fossiliferous outcrop, collected for picking out the fossils in the laboratory, was arrived at through a test experiment, which demonstrated that 20 samples, containing more than two fossils per sample, were sufficient for calculating spatial density, the presence or absence of aggregates and the degree of sorting of the fossils.

Aliquots of each sample, 1 cm² in size, were analyzed in order to obtain fossil arrangement and spatial density data. Only fossils over 0.5 mm long were selected because smaller inorganic pieces may be hard to distinguish from similar organic pieces.

The described and illustrated specimens were registered (GP/2E and GP/2T) at the Scientific Collections of the Systematic Paleontology Laboratory (LPS) of The Institute of Geosciences of the University of São Paulo.

TAPHONOMIC CHARACTERISTICS

Santa Maria Homestead outcrops (1 and 2)

Two outcrops of the Taquaral Member are present in Santa Maria Homestead, named outcrops 1 (UTM: 23K 227055/7517325) and 2 (UTM: 23K 227050/7517669). They are 190 m apart, so they exhibit similar sedimentological and palaeontological characteristics. Fine to medium sandstones with granules and a few millimetric pebbles, angular to rounded clasts, a few centimetres in
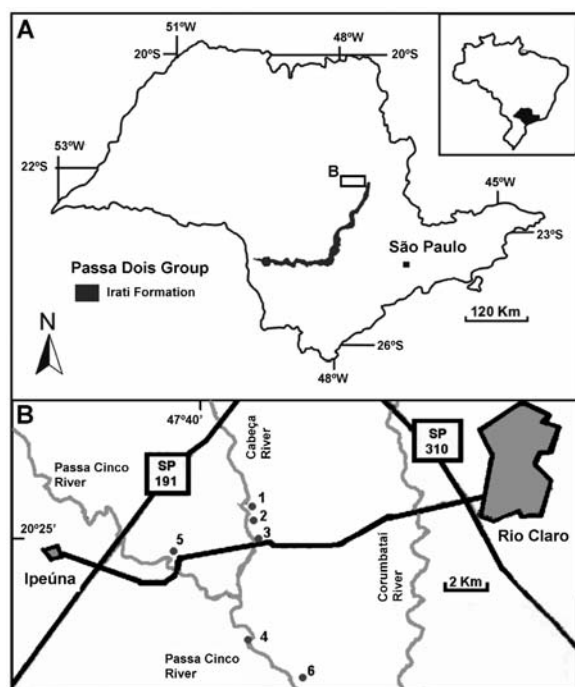
Text-fig. 1. A − Occurrence of the Irati Formation outcrops in the State of São Paulo. B − Region of Rio Claro with the locations of the outcrops studied ; 1-2) Santa Maria Homestead outcrops; 3) Cabeça River outcrop; 4) Bridge over Passa Cinco River outcrop; 5) Ponte Nova Farm outcrop; 6) outcrop near Passa Cinco River
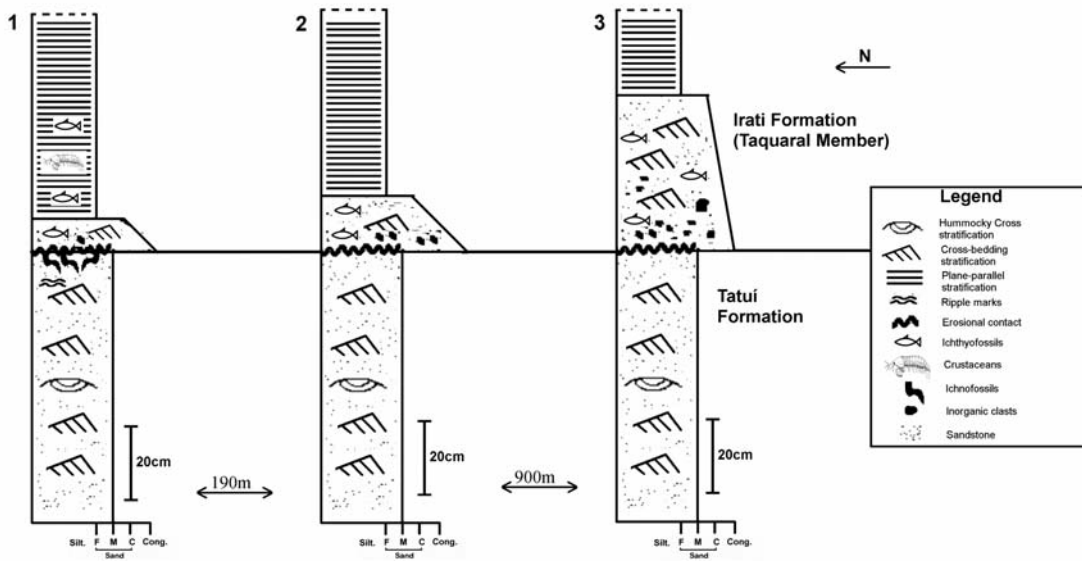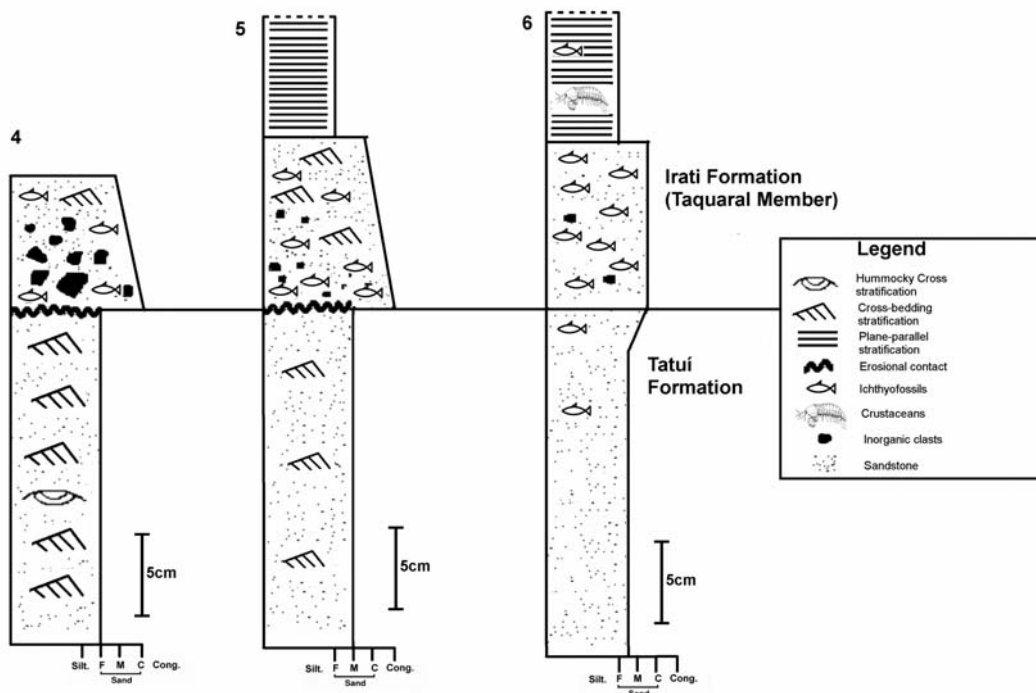
Text-fig. 2. Schematic logs. 1-2 − Santa Maria Homestead outcrops; 3 − Cabeça River outcrop

size, are present near the contact with the underlying Tatuí Formation beds.

The concentrated fossil assemblage layer of the Taquaral Member in outcrop 1 is exposed on a floor plan of 8 × 20 m and in section, along a profile, 9.5 cm thick and 20 m long. The outcrop 2, a section in steps, is 40 m long, about 0.5 m wide and 15 cm thick.

In both outcrops the fossil spatial density is rather more than 1 fossil/cm², only fossils greater than 0.5 mm were studied. Similar to the inorganic clasts, they are matrix supported. However, isolated feeble crowding of groups of fossils seldom occurs, but not exceeding 0.5 cm² per total area of the outcrop. In these cases the fossils are partially matrix supported.

Text-fig. 3. Schematic logs. 4 − Bridge over Passa Cinco River outcrop; 5 − Ponte Nova Farm outcrop; 6 − outcrop near Passa Cinco River
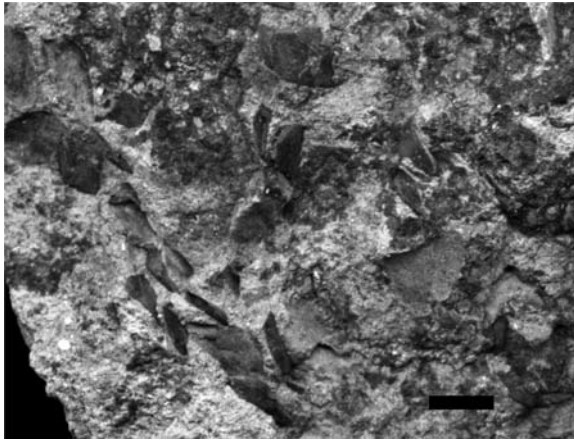
Text-fig. 4. View from above Palaeonisciformes scales. Evidence of accumulation. Santa Maria Homestead outcrop 1 (GP/2E-6383). Bar-scale: 1 cm

No Chondrichthyes were observed at the sandy facies upper contact with the silty-shale facies but bone fragments, teeth and scales of Osteichthyes are widely dispersed.

At outcrop 1, the fossils, mostly Palaeonisciformes teeth and scales, do not exhibit any orientation in plan view; however, they are oriented concordantly to the bedding, even in cross bedding structures.

Aggregates and small accumulations of fossils are rare. The bioclasts are fragmented, smaller than 0.5 cm.

Two examples of articulation are illustrated; a mandible with articulated teeth (see Chahud and Petri 2010a; figs 4, 6) and disarticulated Palaeonisciformes scales which must be from the same specimen, suddenly fallen to the bottom of the water body and immediately fossilized when disintegration started. The specimen GP/2E-6383 is specially noteworthy by the size of the scales, near 1cm. Probably they would belong to a large fish, articulated at the moment of deposition (Text-fig. 4).

The composition of the material is polytypic, consisting of scales, teeth, spines, bones and coprolites, and polyspecific, different species of Chondrichthyes and Osteichthyes. The number of taxa identified in outcrop 1 is higher than any other studied outcrop, including animals of continental origin (Tetrapoda), freshwater (Rhipidistias and Xenacanthidae) and salt water (Petalodontiformes and Diplodoselachidae).

Tetrapoda, cladodont teeth and Orodontiformes were not reported at outcrop 2; in any case, these fossils are scarce at outcrop 1. Only commoner forms of Petalodontiformes (*Itapyrodus punctatus*) and Diplodoselachidae (*Taquaralodus albuquerquei*) are present in outcrop 2.

The wide size range of bioclasts and fossils, from below 0.5 mm to more than 10mm, are neither related to taxa nor to their stratigraphic position, evidence of the total absence of sorting.

Many fossils, such as spines (Chahud *et al.* 2010) and cuspidate and ornamented Ctenacanthiformes teeth (Text-fig. 5A) are well preserved, only slightly abraded. Other fossils, such as Petalodontiformes (Text-fig. 5B), Xenacanthiformes and great Palaeonisciformes scales (Text-figs 5C−F), are strongly abraded. The degree of abrasion is related neither to the size of the fossils nor to the taxa.

Cabeça River, limit between Rio Claro and Ipeúna municipalities (outcrop 3)

This outcrop, located south of 1 and 2 (UTM: 23K 227300/7517325), is similar to them, in terms of both lithology and palaeontological content. However, the frequency of fossils is smaller, scattered along the outcrop, even though distributed along a thicker exposure. The outcrop is 5 m long and 43 cm thick. The bed strikes N45°W, dipping 10°NE, a dip greater than that of the other outcrops, which are less than 3°.

The fossil spatial density of this outcrop is about 0.5 fossil/cm². Viewed from above, no predominant fossil orientation is seen. In profile view most teeth and spines are parallel to the bedding; very few are discordant to the bedding. No aggregation were observed, compared with the previous discussed outcrops. The assemblage is polytypic with scales, teeth and bone fragments and polyspecific even though the specimens of Chondrichthyes are smaller.

In spite of scattered, badly sorted and disarticulated fossils, there are complete pieces with only small breaks. However, there are many differently sized fragmented bones.

The Petalodontiformes, even rare in this outcrop, are rounded and so strongly abraded that details of the internal dentine are revealed. In contrast, some "Palaeonisciformes" scales and teeth are well preserved, together with polished and completely worn specimens. This is a good example of different degrees of preservation of specimens deposited together.

Only uncommon forms of Xenacanthidae were found in this outcrop: two very worn and one in a better state of preservation (Chahud and Petri 2009). The Diplodoselachidae *Taquaralodus* (Chahud and Petri 2008a, 2010b) common in the other two outcrops, was not as yet found in this outcrop. This genus may be present here but the low spatial density renders it unsafe to infer its presence
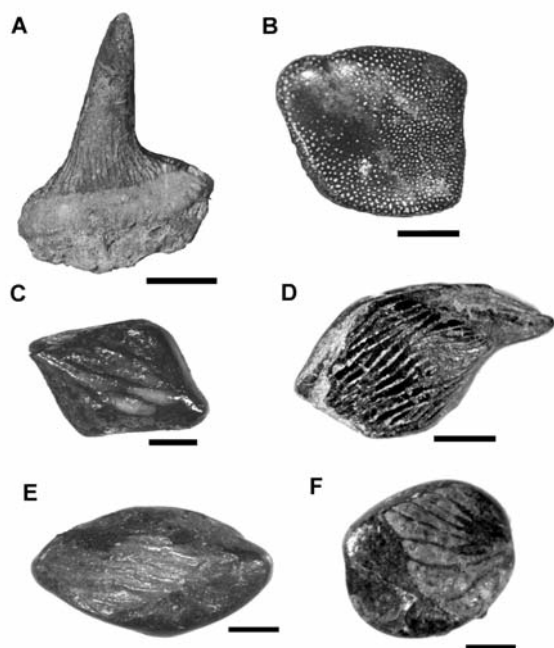
Text-fig. 5. Outcrop 1, sandy facies Taquaral Member **ichthyofossils** A − unweathered cladodont tooth (GP/2E-5919) with some matrix under it. Bar-scale 2mm. B − *Itapyrodus punctatus* tooth (GP/2T-206) with exposed dentine on the surface. Bar-scale 2mm; C-D − "Palaeonisciformes" scales (C: GP/2E-3758 and D: GP/2E-6577) with weakly abraded and ornate surfaces. Bar-scale 4 mm scale. E) Strongly abraded scale retaining some ornamentation, but loss of the original form (GP/2E-5960). Bar-scale: 2 mm. F − "Palaeonisciformes" scale (GP/2E-6463) highly abraded and worn with loss of the original shape. Bar-scale: 2 mm

Bridge over Passa Cinco River (outcrop 4)

The bed in this outcrop is 8 cm thick and is split by the Passa Cinco river (UTM: 23K 227500/751345). The sedimentary structures are the same as those of the previously analyzed outcrops, but here larger clasts are more frequent, forming a poorly sorted matrix conglomerate at the base and a conglomeratic sandstone at the top.

The fossil spatial density is $0.1/cm^2$, the smallest index of all the outcrops analysed herein. No fossil over 0.5 mm were collected, only fragmented pieces. The fossils are scattered, no association of fossils are seen, no orientation trends are perceptible, no articulated pieces are seen; therefore, the numbers of fossils and taxa were the smallest of the outcrops studied.

The percentage of abraded and fragmented fossils is higher here than in the other outcrops. The abraded Petalodontiformes teeth exposed the tubular dentine, disclosing the punctuate surface. All indeterminate scales and possible tooth fragments are angular or worn completely smooth.

Most of the fossils exhibit breakages and abrasions; however, some specimens from several taxa are intact, with no evidence of reworking, like in the other above-mentioned outcrops.

Ponte Nova Farm (outcrop 5)

The sandy base of the Taquaral Member at the Ponte Nova Farm outcrop (UTM: 23K 0224255/ 7516138) is about 12 cm thick but the erosion along the outcrop resulted in variable thicknesses, with a minimum of 6 cm.

The lithologies are badly sorted sandstones and conglomeratic sandstones, similar to the Santa Maria Homestead sandstones. However, close to the contact with the Tatuí Formation deposits, the sandstones are coarse to very coarse and the clasts and bioclasts become larger.

The fossil spatial density is similar to that at outcrop 1, approximately $1/cm^2$ fossil, but the fossil distribution is different. They are not uniformly scattered but found together as small accumulations. The fossils are concentrated at the base, just above the Tatuí Formation.

Like other outcrops viewed from above, no fossil orientation is seen, whereas in profile view most of them are concordant with the bedding. Also, as in other outcrops, the taxonomic composition is polytypic, composed of scales, spines, bones, and polyspecific, with several Chondrichthyes, *Taquaralodus albuquerquei*, *Itapyrodus punctatus* and *Amelacanthus* sp. (Chahud *et al.* 2012; Chahud and Petri 2014) (Text-fig. 6A–G) and Osteichthyes.

Chondrichthyes and Osteichthyes are reported together in aggregates, resulting from accumulations of transported material.

No size sorting of the fossils is observed. The bioclasts range from 0.5mm long to over 50mm. Many fossils, among them Palaeonisciformes scales, were strongly abraded and polished.

Outcrop near Passa Cinco River (outcrop 6)

This outcrop typically exposes fine sandstones with sparse 0.5 mm to 1 mm clasts, on both sides of a road to the Passa Cinco river (UTM: 23K 228537/7512610).

In contrast to the other outcrops studied, the fossils here are either scattered or more closely packed, with a density of over $10/cm^2$, so this outcrop is placed in the last column of Table 1. Viewed from above no fossil orientation is observed. In profile view many of the fossils are concordant with the bedding.. Some scales, teeth and bones are fragmented or comminuted.

In spite of the high density of the fossils, neither taxon associations nor fossil articulations were observed. In contrast to the other outcrops, the fossils are well sorted, mostly similar in size.

Most fossils must have been destroyed by breakage as many of the bioclasts are angular and weakly polished.

TAPHONOMIC RESULTS

The lithologies and fossil associations of the outcrops 1 to 5 have the following common features: badly sorted lithologies; badly sorted fossil associations; bioclast fragmentation; very rare articulated fossils, intensive abrasion of scales and teeth and chaotic fossil disposition in plan view. These common characteristics indicate a common origin, a high energy environment.

Besides the reworked and fragmented fossils, others occur in a good state of preservation, such as teeth with no or very little abrasion or small breakages. These rare examples of fossils in a good state of preservation indicate little transport, small reworking or only a short residence in the Taphonomically Active Zone (TAZ) (Davies *et al.* 1989). The conjunction of evidence excludes the hypothesis of reworked ancient deposits.

The fossil spatial densities are larger at outcrops 1 and 2 and smaller at outcrop 4, the deposits of which are coarser. From outcrops 1 to 3, the thicknesses increase from 9.5 cm to 43 cm and the spatial densities decrease from $1/cm^2$ to $0.5/cm^2$.

These differences might be explained by an increase in distance from the sources of the sediments which were located to the south in the present day geography. Holz and Simões (2002) suggested that a long time of exposure results in a high spatial density and time averaging.

This southward transgression caused the fining-upward deposits, the fossil spatial density decrease from 1 to 4 and larger clasts at outcrop 4.

Increase in water volume by transgression, together with reworking events during deposition, caused remobilization of the fine material, while the very coarse material, with granules and pebbles, remained, retaining the most resistant fossil pieces. This high energy paleoenvironment would be responsible for the small thicknesses, seldom reaching 1 m (Walker and James 1992; Holz and Simões 2002). A high degree of reworking mean that the fossils were submitted to extended activities of reworking and transportation.

According to Assine *et al.* (2003) the sandy facies was laid down under a lag process, which would mean
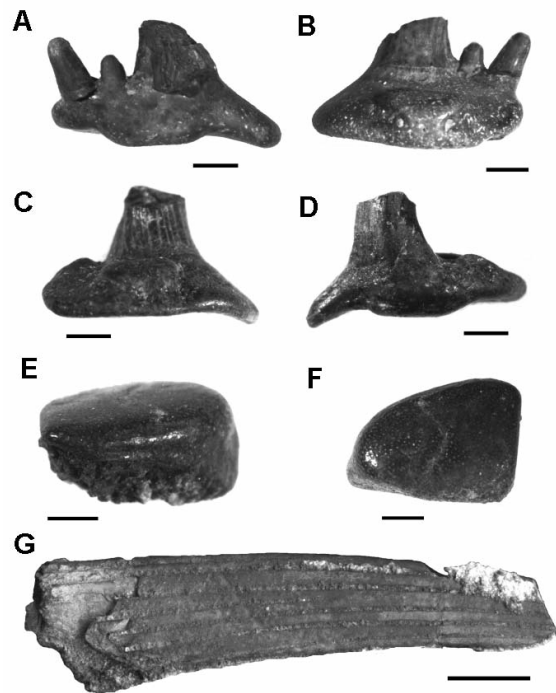
Text-fig. 6. Chondrichthyes from the Taquaral Member sandy facies at Ponte Nova Farm outcrop. A–D − *Taquaralodus albuquerquei* little worn teeth, but with broken cusps (A-B: GP/2E-6580 and C-D: GP/2E-6581). E-F − *Itapyrodus punctatus* (GP/2E-6589) little worn teeth. A–F Bar-scales 2 mm. G − *Amelacanthus* sp. (GP/2E-6579) Spine with well preserved ribs. Bar-scale: 10 mm

a continuous winnowing of fine deposits and coarser deposition. In this scenario good preservation of fragile fossils was not possible. The presence of thin laminae of siltstone interbedded with coarse sandy deposits and fragile fossils are better explained by short episodes of higher energy events.

The sharp contrast of good and bad preservations may be explained by two hypothesis (A and B). Both hypotheses could be true, depending on the outcrop studied. A) Swift episodic changes of energy of the palaeoenvironment increase wave reworking, transporting coarser material toward the larger water body. B) Rainy seasons caused the river to overflow into the large water body, increasing the bedload. So, increasing the bedload of the larger water body is the result of both hypotheses, favouring the preservation of fragile fossils.

Occasional fine sandstones and silty laminations are interbedded with coarser deposits. They occur mainly in Santa Maria Homestead outcrop 1; short intervals of low energy favoured fine laminations.

The increasing thicknesses of the outcrops 1 to 3 (Text-fig. 2) furnish important clues for understanding the episodes of the dynamics of sedimentation. These

Data obtained / Outcrops	Santa Maria Homestead outcrops 1 and 2	Cabeça River Outcrop 3	Bridge over Passa Cinco River Outcrop 4	Ponte Nova Farm Outcrop 5	Outcrop near Passa Cinco River Outcrop 6
Sedimentological characteristics	Fine to medium sandstone or conglomeratic. Some centimetric clasts in basal contact of the unit.	Fine to medium sandstone or conglomeratic. Some centimetric clasts in basal contact of the unit.	Conglomerate with little matrix. Some larger clasts more abundant	Fine- to medium-grained sandstone or conglomerates. Some centimetric clasts in basal contact of the unit.	fine sandstones with rare clasts
Bed thickness	9.5 cm at Outcrop 1 15.0 cm at Outcrop 2	43.0 cm	8.0 cm	12.0 cm	10.0 cm
Spatial density Fossil/cm²	~ 1.0/cm²	~ 0.5/cm²	~ 0.1/cm²	~ 1.0/cm²	Varies from weak to strongly packaged ~10/cm²
Spatial arrangement in plan view	Random	Random	Random	Random	Random
Spatial arrangement in profile view	Generally concordant	Generally concordant	Generally concordant	Generally concordant	Random
Accumulations and aggregates	Rare (few occasional accumulations)	Absent	Absent	Present in fossils of various sizes	Occasional dense concentrations
Chondrichthyes rate number (based on orders and subclass)	5 Petalodontiformes, Ctenacanthiformes, cladodonts, Xenacanthidae and Diplodoselachidae	2 Petalodontiformes and Xenacanthidae	1 Petalodontiformes	3 Petalodontiformes, Ctenacanthiformes and Diplodoselachidae	Absent
Osteichthyes rate number (based on orders and subclass)	4 Palaeonisciformes, Coelacanthimorpha, Osteolepimorpha and Tetrapoda	2 Palaeonisciformes, and Sarcopterygii indeterminate	2 Palaeonisciformes, and Sarcopterygii indeterminate	4 Palaeonisciformes, Coelacanthimorpha, Osteolepimorpha and Tetrapoda	2 Palaeonisciformes and Sarcopterygii indeterminate
Articulation	Generally absent (Only few articulated teeth or associated bones)	Absent	Absent	Absent	Absent
Bone parts selection (general context)	Bad (many fossils of different sizes)	Bad (many fossils of different sizes)	Bad (many fossils of different sizes)	Bad (many fossils of different sizes)	Bad (many fossils of different sizes)

Table 1. Comparison of outcrops studied to taphonomy

observations reinforce a scenario of river overflows, carrying great amount of detritus, including freshwater organisms, which were transported to a water body of variable salinity. The euryhaline fossils (Petalodontiformes, Diplodoselachidae) increase the fossil richness in deeper water palaeoenvironments.

Outcrop 3 (Cabeça River) is noteworthy because of its greatest thickness and low fossil density. The frequency of petalodonts is low, Diplodoselachidae *Taquaralodus* and spines are absent so far. Rare Xenacanthidae, which were probable inhabitants of freshwater palaeoenvironments, were also found (Table 1).

Better preserved larger fossils are always found in the coarser lithologies. These deposits might be laid down at the beginning of the transgressive event. Ragonha (1978) similarly observed it in the Assistência municipality (near Rio Claro), where these fossils were present only in coarser and badly sorted lithologies.

The Santa Maria Homestead outcrop 1 site would be the area of higher energy episode caused either by overflows or storms. The Cabeça River outcrop 3 site would be nearer the source area, and hence exhibiting higher thickness and smaller spatial density.

Outcrop 6 (Near Passa Cinco River) is unique in the studied region by the presence of millimetric, very fine sandstones and siltistones, interbedded with fine sandstone. The small clasts and millimetre-sized fossil fragments were dropped by decantation. The increased spatial density is caused by lightweight bioclasts as compared to heavier clasts. However, as the fossil fragments are small and reworked, their preservations are not good.

Table 1 synthesizes the similarities and the differences of the outcrop deposits and fossils. Their common char-

acteristic is the intense abrasion and fragmentation of the fossils, which reinforce the palaeoenvironmental interpretation of a generalized high energy body of water.

CONCLUSIONS

Several sedimentological and palaeontological characteristics are common to the six outcrops: small thicknesses from 8 cm to 43 cm, fining-upward deposition and poorly sorted conglomeratic sandstones and conglomerates. Only fine sandstone is present in outcrop 6.

From a palaeontological point of view, the fossil spatial densities at the outcrops 1 to 5 vary from 1/cm² to 0.5/cm², seldom greater when locally the fossils are aggregated. There is no orientation of the fossils when observed from above but the fossils are concordant with the bedding in profile view. In outcrop 6 orientation of the fossils cannot be clearly seen because the fossils are completely comminuted.

The fossil contents are always vertebrates belonging to the following taxonomic groups: Chondrichthyes (Petalodontiformes, Ctenacanthiformes, cladodonts, Diplodoselachidae and Xenacanthidae), Actinopterygii (Palaeonisciformes) and Sarcopterygii (Coelacanthimorpha and Indeterminate Sarcopterygii) and tetrapods.

The Santa Maria Homestead Outcrop 1 is unique in that it shows an aggregate of bone remains packed together from a single specimen, which were disarticulated a short time before deposition, with the mandible still retaining articulated teeth (Chahud and Petri 2010a) and well preserved spines. The small degree or complete absence of breakage of the fossils and the association of fragments from a single specimen are suggestive of sudden death by overflows and storms with rather short transport.

The association, at several outcrops, of more frequent fragmented fossil remains and rare well preserved fossils without abrasions or breakages not related to specific taxa, is a highly significant relationship, suggesting different organisms episodically transported downstream during different overflow phases, with the possible addition of some storm episodes.

The Chondrichthyes are reported from the basal beds of the sandy facies, immediately above the Tatuí Formation deposits. They are absent in the fining-upward deposits. Furthermore, it is important to remember the absence of stenohaline fossils in the entire Taquaral Member (Mussa *et al.* 1980; Chahud and Petri 2013b). These observations enable the inference that no typical marine palaeoenvironments are represented in the sediments of the Taquaral Member with the exception of the most basal beds of the sandy facies being of a transitional nature.

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