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ARTICLE

The São Jerônimo da Serra Site, Rio do Rasto Formation (Middle/Upper Permian), Paraná Basin, Brazil: faciological and taphonomic context

Karine Lohmann Azevedo[1*], Danielle Cristine Buzatto Schemiko[2], Marina Bento Soares[1,3], Cristina Silveira Vega[2], Fernando Farias Vesely[2]

ABSTRACT: *In this contribution, we present an analysis of the main faciological features of the São Jerônimo da Serra Site, related to the Morro Pelado Member of Rio do Rasto Formation (Middle/Upper Permian), from Paraná State, Brazil, integrated to its taphonomic context. The outcrop, rich in vertebrates and bivalves remains, presents a succession of red siltstones bedded with fine to medium sandstones in which three architectural elements were observed: SF (sheetflood deposits), FF (fine of flood plain) and CS (crevasse). These data, allied to the taphonomic signatures of fossils assigned to eight levels, allowed the identification of three taphofacies. The taphofacies I is characterized by preserved bones in floodplain facies, with different articulation grades and absence of any sign of transport. The taphofacies II is composed by small isolated or fragmented bones and fish scales deposited in terminal splay facies. The taphofacies III is characterized by sandy layers with bivalve shells and fish scales, preserved in crevasse-splay deposits. The obtained data shows that the studied sedimentary succession was generated on a dry trend environment, with sporadic water supply, which conditioned the fossil preservation.*

KEYWORDS: *Midle/Upper Permian; Morro Pelado Member; fossil vertebrates; bivalves; taphofacies.*

INTRODUCTION

The fossiliferous outcrops of the Rio do Rasto Formation provide some of the most important continental records of the Middle/Late Permian in South America (Langer *et al.* 2008). Among vertebrates, temnospondyl amphibians (Barberena & Daemon 1974, Barberena 1998, Barberena & Dias 1998, Dias & Barberena 2001, Dias & Kroeff 2002, Dias & Schultz 2003, Malabarba *et al.* 2003, Eltink & Langer 2008, 2010, 2014, Ramos & Vega 2011, Souza & Vega 2011, Azevedo *et al.* 2012, Strapasson *et al.* 2015, Eltink *et al.* 2016, Pacheco *et al.* 2017), a pareiasaur (Araújo 1985a, 1985b, Lee 1997, Malabarba *et al.* 2003, Cisneros *et al.* 2005), a basal anomodont (Cisneros *et al.* 2012), two dicynodonts (Barberena & Araújo 1975, Boos *et al.* 2013, Boos *et al.* 2016), carnivore and herbivores dinocephalians (Langer 1998, 2000, Cisneros *et al.* 2012, Boos *et al.* 2015) and fishes (Richter & Langer 1998, Malabarba *et al.* 2003, Pauliv *et al.* 2012, Pauliv *et al.* 2014) have been reported. Invertebrates and plants, besides ichnofossils (tetrapod tracks) and coprolites, have also been reported (Rohn 1994, Rohn & Rösler 2000, Ferreira-Oliveira 2007, Leonardi *et al.* 2002, Silva *et al.* 2012, Dentzien-Dias *et al.* 2012).

Field works in one of the fossiliferous outcrops of the Morro Pelado Member, located in São Jerônimo da Serra, Paraná State, Brazil, have been carried out by teams of the Laboratório de Paleontologia of the Universidade Federal do Paraná (UFPR) and the Laboratório de Paleontologia de Vertebrados of the Universidade Federal do Rio Grande do Sul (UFRGS). As result, many fossil remains, especially

[1]Programa de Pós-graduação em Geociências, Universidade Federal do Rio Grande do Sul – Porto Alegre (RS), Brazil. *E-mails: karine.lohmann@gmail.com, marina.soares@ufrgs.br*

[2]Departamento de Geologia, Universidade Federal do Paraná – Curitiba (PR), Brazil. *E-mails: danielleschemiko@gmail.com, cvega@ufpr.br, vesely@ufpr.br*

[3]Departamento de Paleontologia e Estratigrafia, Universidade Federal do Rio Grande do Sul – Porto Alegre (RS), Brazil. *E-mail: marina.soares@ufrgs.br*

*Corresponding author.

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vertebrates, have been recovered. Here, we present a detailed description of the outcrop São Jerônimo da Serra (Fig. 1), as well as the characterization and a discussion about the preservation patterns of the fossil assemblages and its geologic context.

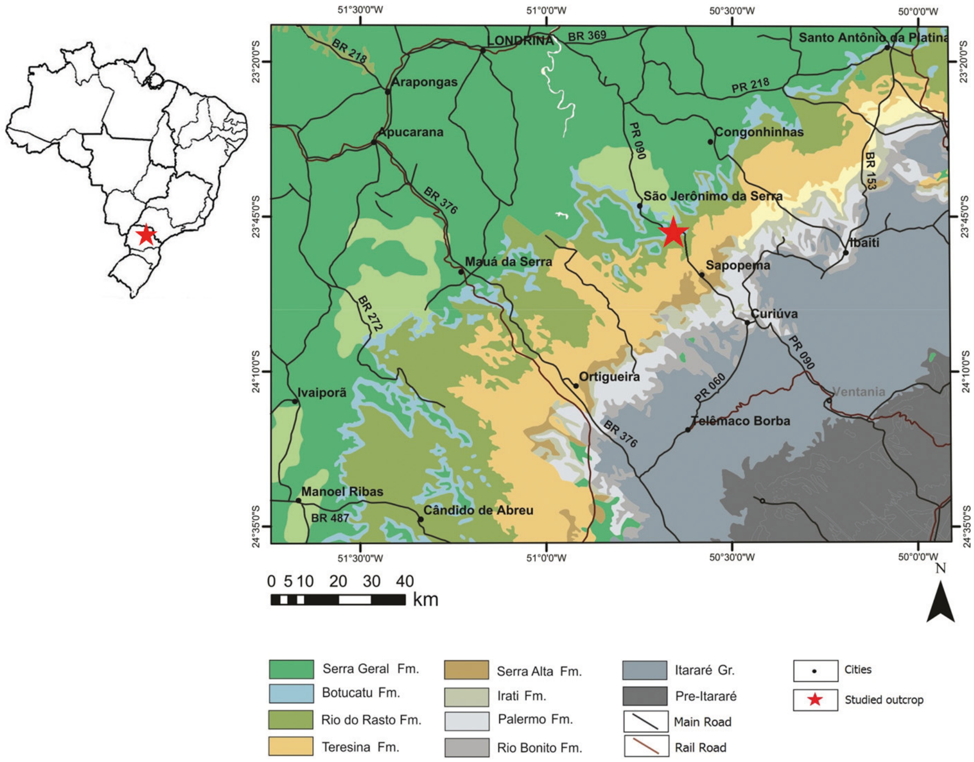
MATERIALS AND METHODS

Systematic field trips to São Jerônimo da Serra Site were done since 2007, and the vertical stratigraphic profile elaborated by Schemiko (2013) was herein improved (Fig. 2), showing a detailed identification of the lithofacies (according to Miall 1978, 1996). Ten points (numbered from 1 to 10) along the vertical exposition were selected for sampling and plotted in Figure 2. The main fossiliferous levels correspond to the points 1 to 8.

Thirteen thin sections of rocks and fossils were made from samples of the points 1, 3, 5, 6, 8 and 9 (Tab. 1). These were analyzed at the Laboratório de Análises de Minerais e Rochas (LAMIR) of the UFPR, with a petrographic microscope under both polarized and natural light (Zeiss 1024062420 2.2 / Axio imager A2m). Digital photomicrographs of the bone microstructures, as well as their surrounding minerals, were taken.

The vertebrate specimens collected were deposited at the Laboratório de Paleontologia of the UFPR, as UFPR-PV

A



B

Figure 1. (A) Map of the study area in the Paraná State, showing the São Jerônimo da Serra Site (red star) within the Rio do Rasto Formation, southern Brazil. Modified from Brasil (2004); (B) panoramic view of the São Jerônimo da Serra Site.

or UFPR-PI, and the thin sections as UFPR-PV B—*PV* means *Paleontologia de Vertebrados*, and PI, *Paleontologia de Invertebrados*. Additionally, for chemical composition investigation and improvement of the minerals identification, six x-ray diffractometry analyses with powder samples were made from the points 3, 5, 7 and 8, being two samples of fossils (UFPR 0198 PV and UFPR 0275 PV from the points 5 and 8, respectively) and four of rocks. These analyses were carried out at the Laboratório de Difratometria de Raio X of the UFRGS, with the equipment Bruker AXS D5000 (Siemens, Munich, Germany).

GEOLOGICAL AND PALEONTOLOGICAL CONTEXT

The Rio do Rasto Formation corresponds to a Middle/Late Permian unit of the Paraná Basin (Holz *et al.* 2010), included in the Gondwana I Supersequence, Passa Dois Group, that crops out in the three states of southern Brazil: Rio Grande do Sul, Santa Catarina and Paraná (Milani *et al.* 2007). This unit includes two members (Gordon Jr. 1947): Serrinha (lower) and Morro Pelado (upper). The Serrinha Member is 150–250-m-thick, formed mainly by mudstones and fine-grained sandstones, and the Morro Pelado

Table 1. Correlation between the selected points from the São Jerônimo da Serra Site, thin sections and respective materials.

Point	Thin section	Identification
1	UFPR 0097 PV B	Rock and adjacent to the Temnospondyli jaw
3	UFPR 0208 PV B	Rock adjacent to a paleonisciforma scale ans a non identified bone frament
5	UFPR 0198 PV B 1, UFPR 0198 PV B2	Temonospondyli jaw fragment
	UFPR 0199 PV B 1, UFPR 0199 PV B 2	Temonospondyli skull fragment
	UFPR 0199 PV B 3	Temnospondyli tooth and adjacent rock
6	UFPR 0169PV B	Bivalves shells, fish scales and adjacent rock
8	UFPR 0275 PV B 1	Temnospondyli post-cranial fragment
	UFPR 027PV B 2	Temnospondyli scale
	UFPR 0275 PV B 3	Temnospondyli femur
	UFPR 0275 PV B 5	Rock adjacent to a Temnospondyli post-cranium
9	P 09	Rock

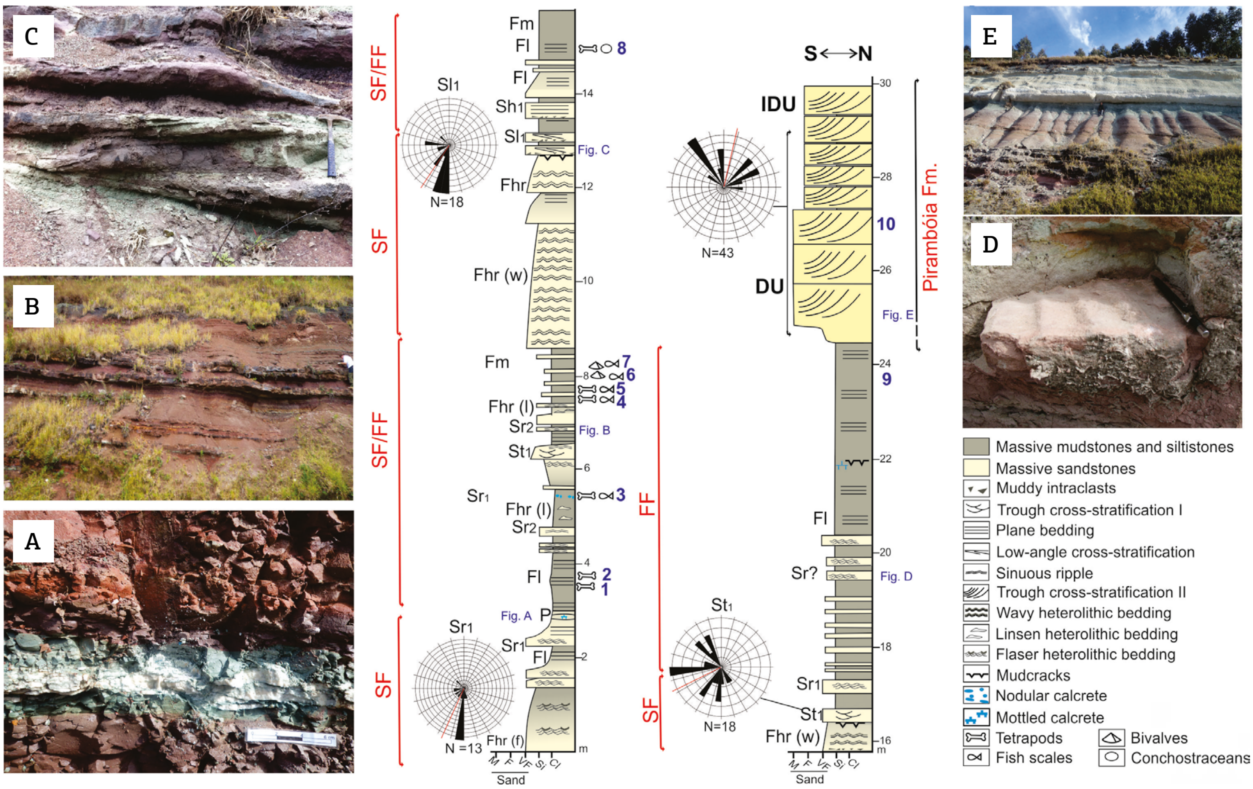


Figure 2. Lithological profile of the São Jerônimo da Serra Site, Morro Pelado Member, Rio do Rasto Formation. Modified from Schemiko (2013). The rosette diagram indicates the water flow. The analyzed points correspond to numbers 1 to 10. The identification of the sedimentary lithofacies is shown in Table 2.

Member is 250–300-m-thick, composed mostly of fine to medium-grained sandstones (Holz *et al.* 2010).

Rohn (1994) argues that the Serrinha Member represents a lacustrine environment associated to humid climate conditions. The Morro Pelado Member, on the other hand, represents the most severe phase of aridization recorded in the Rio do Rasto Formation, and the range of paleoenvironmental interpretations encompasses meandering fluvial to mixed lacustrine, deltaic and aeolian systems (Lavina 1991, Rohn 1994, Warren *et al.* 2008, Schemiko *et al.* 2014). According to the interpretation of Rohn *et al.* (2005), which is followed herein, the deposits of this member indicate distal alluvial fans connected with fluvial plains and, occasionally, with crevasses and channels.

The São Jerônimo da Serra Site comprises the top of the Morro Pelado Member and is located in the northeastern Paraná State, about 15 km from São Jerônimo da Serra municipality, on PR-090 road, at km 277 (UTM 22K 0538201 / 7368276). It is about of 30 m height (Fig. 1). The outcrop described shows the contact between the Rio do Rasto Formation and the subsequent sandstones of the Piramboia Formation *sensu* Sanford & Lange (1960).

The outcrop, as showed by the vertical stratigraphic profile (Fig. 2), presents a major succession of siltstones and sandy siltstones with purple, grey and mainly red colors, intercalated with very fine to fine sandstones. Several sedimentary structures are observed, such as cross stratifications, laminations and mudcracks (Fig. 2). Toward the top, an increase in yellow medium sandstones, with sub-rounded and well-sorted grains, and meter-scale cross-stratifications, typical of the aeolian dunes and interdunes of the Piramboia Formation, can be observed. Schemiko *et al.* (2014), in order to distinguish the fluvial, aeolian and lacustrine depositional elements of the Morro Pelado Member, described 21 sedimentary lithofacies, and interpreted their genetic processes, as demonstrated in Table 2.

The outcrop is composed of architectural elements: SF (sheet-flood deposits), FF (fines of floodplain) and CS (crevasse splays). SF comprise metric (up to 3 m) or centimetric (20–80 cm), tabular and laterally extensive sandstones, with abrupt basal contact. In this setting, three vertical successions of lithofacies configure the SF. The first one has mainly sandstones with through cross-stratification 1 (lithofacies St_1), which may or may not grade to sinusoidal rippled laminations (lithofacies Sr_2). The second is composed of sandstones with plane bedding (lithofacies Sh_1) or low-angle cross-stratification 1 (lithofacies Sl_1). The third one is made up of heterolithics lithofacies (lithofacies Fhr), massive sandstones (lithofacies Sm), sandstones with sinusoidal and cross-rippled laminations (lithofacies Sr_2 and Sr_1) and parallel-laminated lamination (lithofacies Shl). The presence

Table 2. (A) Facies and lithofacies association identified on the São Jerônimo da Serra Site with the related architectural element and environmental interpretation. (B) Sedimentay lithofacies identified on the São Jerônimo da Serra Site with their descriptions and interpretations. Modified from Schemiko *et al.* (2014).

A.		
Facies	**Architectural-element**	**Environmental setting**
Fhr, St_1, Sm	CS	Fluvial floodplain
Fhr, Sr_1, Sr_2, Ff and P	FF	
Gt-i, St_1, Sr_1, Sr_2, Shl, Fhr, Shl, Sr_1, Sr_2 and P Gt-i, Sh_1 and Sl_1	SF	Fluvial terminal splays

B.		
Code	**Description**	**Interpretation**
Gt-i	Oligomitic grain-supported conglomerate, reddish, with small and medium-sized trough-cross stratification and reddish pelitic intraclasts in granules, pebbles and cobbles-sized	Migration of subaqueous dunes associated with bedload-dominated, hydrodynamic flows under lower flow regime, on poorly consolidated beds
St_1	Fine sandstones, yellowish or reddish, moderate to well sorted, with small and medium-sized trough-cross stratification	Migration of subaqueous sinuous-crested dunes, on lower flow regime
Sh_1	Fine to medium sandstone, yellowish or reddish, poorly a very poorly sorted, with parallel stratification	Traction currents on upper flow regime
Sl_1	Fine sandstone, reddish, poorly to very poorly sorted, with medium-sized low angle-cross stratification (< 15º)	Traction currents between upper and lower flow regime
Sr_1	Very fine sandstone, silty, reddish or yellowish, poorly to very poorly sorted, with current ripples with wave-length between 2 to 8 cm	Migration of subaqueous ripples, under tractive current, on lower flow regime

Continue...

Table 2. Continuation.

B.		
Code	Description	Interpretation
Sr_2	Very fine sandstone, silty, reddish or yellowish, poorly to very poorly sorted, with current ripples with low asymmetric and wave-length between 2 to 8 cm 4 and 20 cm	Migration of subaqueous ripples under current that have plenty suspended load
Shl	Fine sandstone, yellowish, poorly sorted, with parallel-laminated bed	Facies generated by traction currents on flat bed and lower flow regime
Sm	Fine to very fine sandstone, reddish or yellowish, poorly sorted and massive	Episodic dense flow
Fhr	Siltstone/ mudstone interbedded with very fine sandstone, often with current ripples flaser, wavy and linsen structures	Alternated deposition of sands under higher energy conditions and finer sediments on low energy stages of flow
Ff	Fossiliferous siltstones: osseous desarticulated elements and megaphytofossils in muddy bed	Fossiliferous deposits in subaquatic shallow environment
P	Mottled and nodular calcretes in arenitic and muddy beds	Diagenetic precipitation of calcium carbonate
F	Reddish mudstone, massive or laminated	Slowly deposition of finer sediments from suspended load

CS: crevasse splays; FF: fines of floodplain; SF: sheet flood deposits.

of conglomerates with intraclasts (lithofacies Gt-i or Gh-i) is common at the base of these three sets.

According to Schemiko *et al.* (2014), the different lithofacies that composes the SF are characterized by normal gradation, suggesting the loss of energy flow over time. The variations described in these tabular bodies were possibly the result from hydrodynamic features, with either more traction or more suspension. Analyzed in the context, that three sets make up a longitudinal continuous tract representing modifications of the flow in a depositional event, which means they belong to the same architectural element. The tabular geometry indicates flood sheets in which the sedimentation occurs in unconfined environment. The presence of mudcracks from FF (Fr) and carbonate nodules are common in the contacts.

The fossils recorded in the São Jerônimo da Serra Site include bivalve mollusks, ostracods, conchostracans crustaceans, sphenophytes stems (*Paracalamites* sp.), root marks, invertebrate trace ichnofossils (*Planolites* isp.), vertebrate coprolites, vertebrate tracks ichnofossils, paleonisciforms fish scales and bone elements of Temnospondyli amphibians (Rohn 1994, Ramos & Vega 2011, Souza & Vega 2011, Azevedo *et al.* 2012). According to Silva *et al.* (2012), this outcrop presents the most complete faunal association known in the Morro Pelado Member of the Rio do Rasto Formation.

DESCRIPTION AND ANALYSES

In this section, we describe the ten points wherein rock samples and/or bones were collected and comment the results of the thin section and x-ray diffractometric analyses when applicable (Figs. 3-9).

- Points 1 and 2: these points are characterized by reddish laminated mudstones and reddish siltstones (facies F and Fb), identified by Schemiko *et al.* (2014) as deposits generated from mud decantation. From these points, remains of two lower jaws of Temnospondyli were recovered and studied by Ramos & Vega (2011). The specimen UFPR 0097 PV, an anterior portion of a left mandible with a single preserved tooth, was collected in the point 1 (Fig. 3), and UFPR 0100 PV, a dentary fragment with six sectioned teeth, came from the point 2. The bones display a dark color due to the presence of hematite. In the petrographic thin section (UFPR 0097 PV B) of the rock associated to the lower jaw from the point 1, it was noticed that the bone material is preserved in a sandy siltstone with sub-rounded quartz grains (Fig. 8A);
- Point 3: the bed is composed of reddish or yellowish very fine to silty sandstone, with nodular calcrets. The depositional context interpreted by Schemiko *et al.* (2014) indicates migration of subaqueous ripples, under tractive current in lower flow regime (facies Sr_1). At this point, small and/or fragmented material as fish scales and temnospondyl bones, as recorded by Souza (2011), were collected. The bones that range from millimeters to few centimeters are especially isolated and/or fragmented. The prevalent materials are temnospondyl

vertebral intercentra, fish scales (Fig. 4) coprolites and indeterminate bones. At least 20 samples were collected in this location. In a petrographic thin section from a non-identified bone fragment and its adjacent rock (UFPR 0208 PV B), it was observed that the lacunae of osteons and osteocytes are filled with quartz, as well as a huge amount of hematite. Thus, in general, the fossils exhibit a dark gray color. Concerning the matrix associated to the fossil, it was also possible to identify quartz in its composition (Fig. 8B). The results of the X-ray diffractometry analyses from rocks of this point are shown in Figure 9A. Hematite, quartz, feldspar, smectite, mica/ilite and plagioclase were identified;

- Points 4 and 5: in these points, the fossils were found in a massive mudstone level as the product of settling of suspended mud (facies Fm). Jaws and skulls from two

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Figure 3. Point 1 and a lower jaw UFPR 0097 PV found at this point (scale bar: 5 cm).

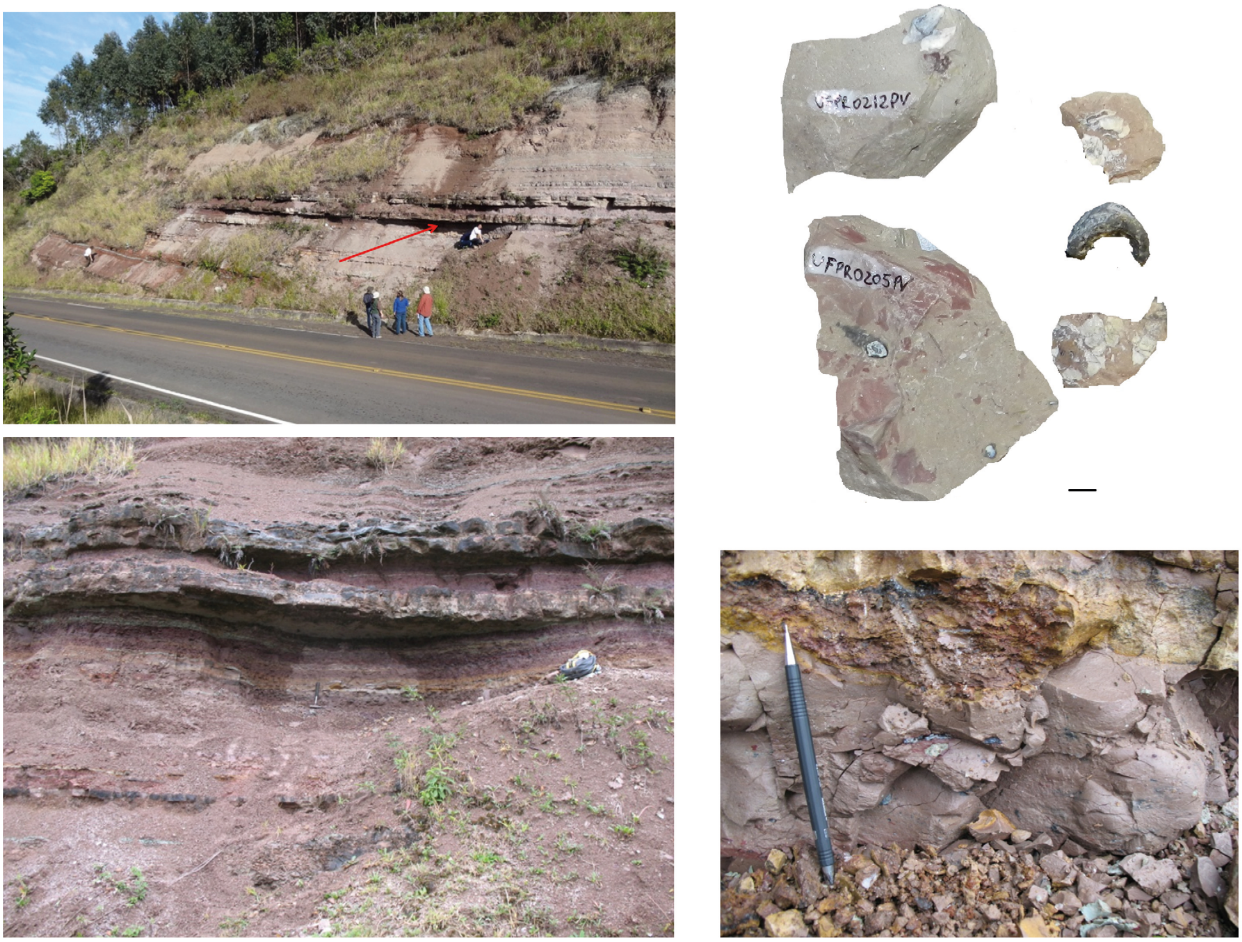

Figure 4. Point 3 and undetermined bone fragments found at this point (scale: 1 cm).

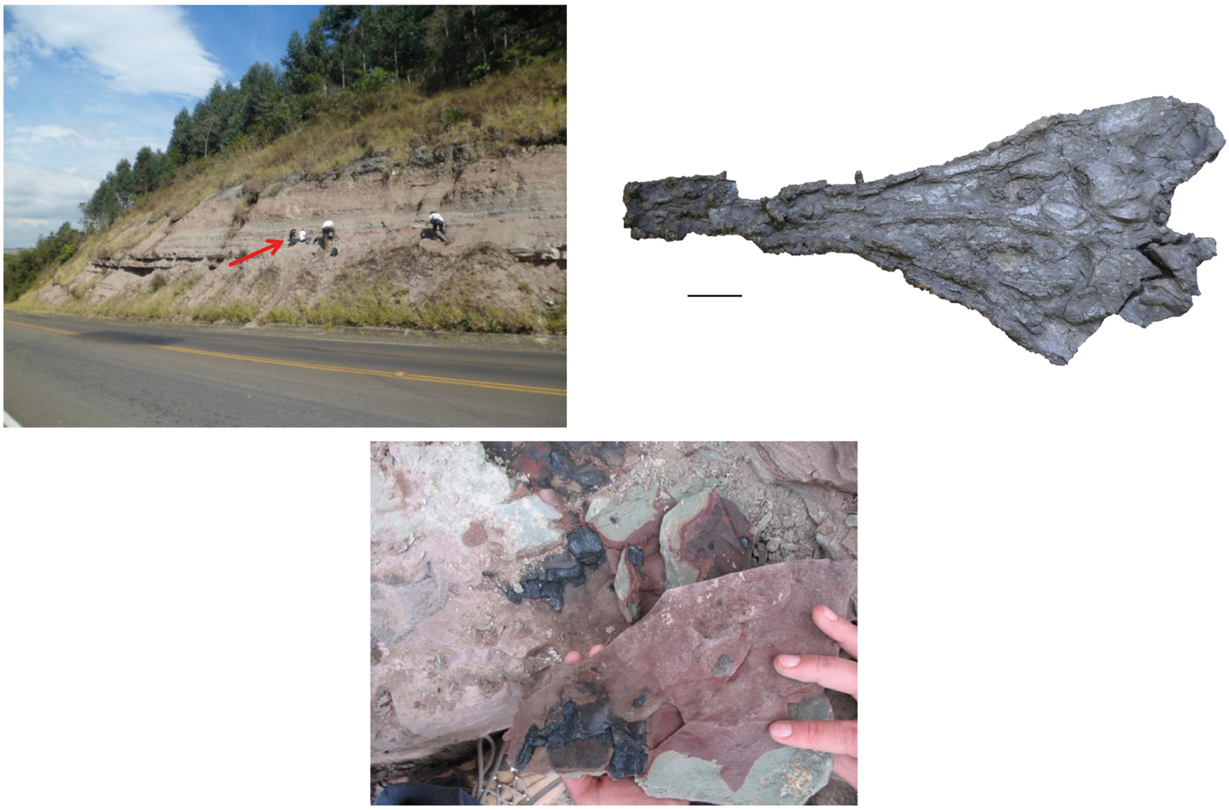

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Figure 5. Point 5 and a skull of a long snout temnospondyl UFPR 0199 PV found at this point (scale bar: 5 cm).

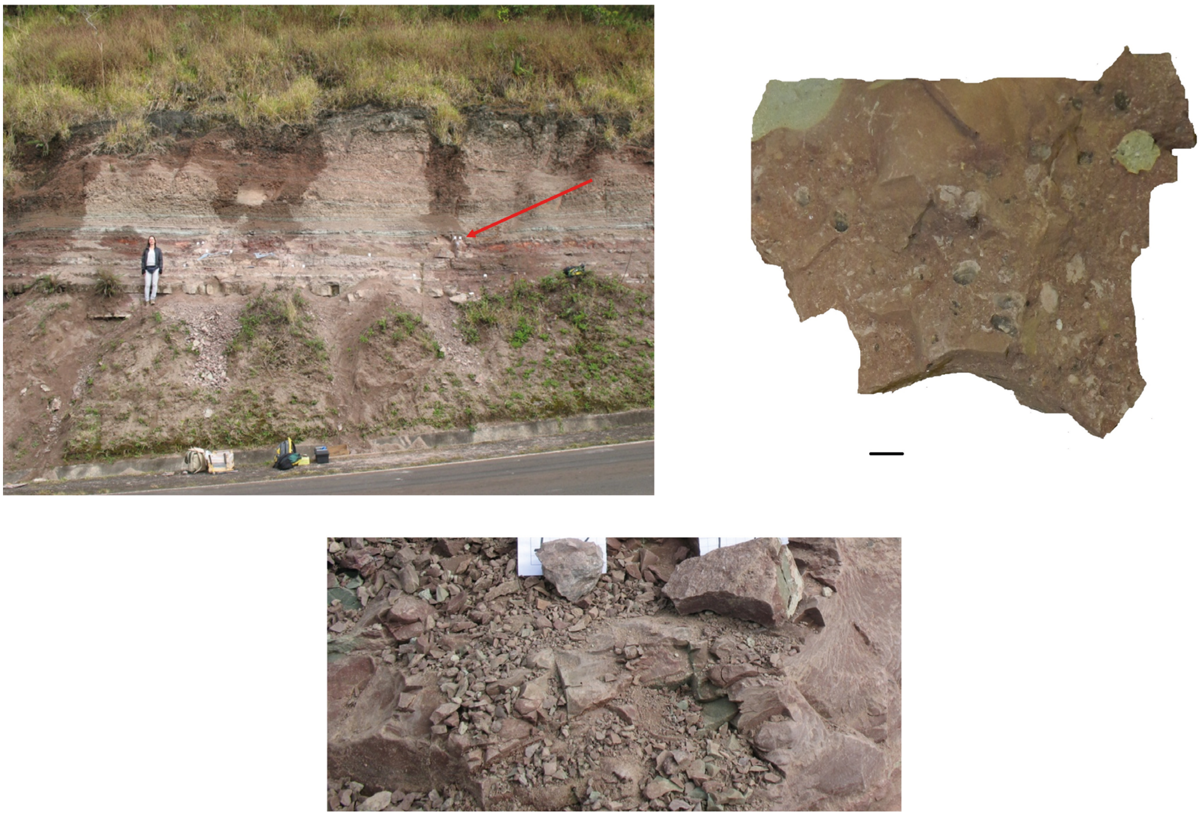

Figure 6. Point 6 and bivalves found at this point (scale bar: 1 cm).

temnospondyls specimens were recorded. UFPR 0150 PV, from the point 4, corresponds to a short snout skull and jaws (Souza & Vega 2010, 2011). On the other hand, UFPR 0198 PV and UFPR 0199 PV from the point 5 are respectively a long snout skull and jaws, from a single specimen (Azevedo *et al.* 2012) (Fig. 5). Another indeterminate vertebrate lower jaw was also recorded. The results of the X-ray diffractometry analysis from the rocks surrounding the fossils, as well as the fossils shown in the charts (Figs. 9B and 9C). It is possible to observe the presence of clay minerals (smectite and ilite), besides plagioclase, quartz and hematite, while in the fossil bone hematite, calcite, plagioclase and quartz were found. Additionally, five thin sections were prepared, being four from the fossils UFPR 0199 PV and UFPR 0198 PV and one from a tooth belonging to the skull UFPR 0199 PV with its adjacent rock (UFPR 0199 PV B 3). In this point, the bones are covered by a thin layer of hematite, which caused a very dark gray color. Essentially, the same mineral composition evidenced by the diffractometric analysis of fossils was observed in the thin sections (Fig. 8C). The bone structure is poorly preserved, although the lacunae of osteons and osteocytes filled with quartz, and also with hematite, can be noticed (Figs. 8D, 8E and 8F);

- Points 6 and 7: these points are composed of finer sediments, which were slowly deposited from suspended load (Fm) interbedded with fine to very fine sandstone, reddish or yellowish, poorly sorted and massive (Sm). They are also represented by two sandy beds, poorly selected comprising bivalves that extend laterally through almost the whole outcrop, and which constituted a stratigraphic marker to the description (Fig. 6). These shells have no more than 1 cm length, are disarticulated and some of them are fragmented. Besides bivalves, scales from paleonisciform fishes and a fish spine were collected. The results of the X-ray diffractometry of the rocks from the point 7 showed similarities with the point 3 (quartz, plagioclase, ilite/mica, smectite), though hematite was not identified. Additionally, the analysis showed the presence of calcite probably originated from the shells (Fig. 9F);
- Point 8: this point is composed of laminated mudstones identified by Schemiko *et al.* (2014) as deposits generated from mud settled from suspension. Besides fish scales, a partially articulated post-cranium (ribs, femur, tibia, humerus, chleitrum, phalanx, metatarsals and dermal scutes) of a temnospondyl UFPR 0275 PV was collected (Fig. 7). One conchostracan is preserved within this sample. The post-cranium exhibits a dark gray color and, despite the apparent good preservation, some of the

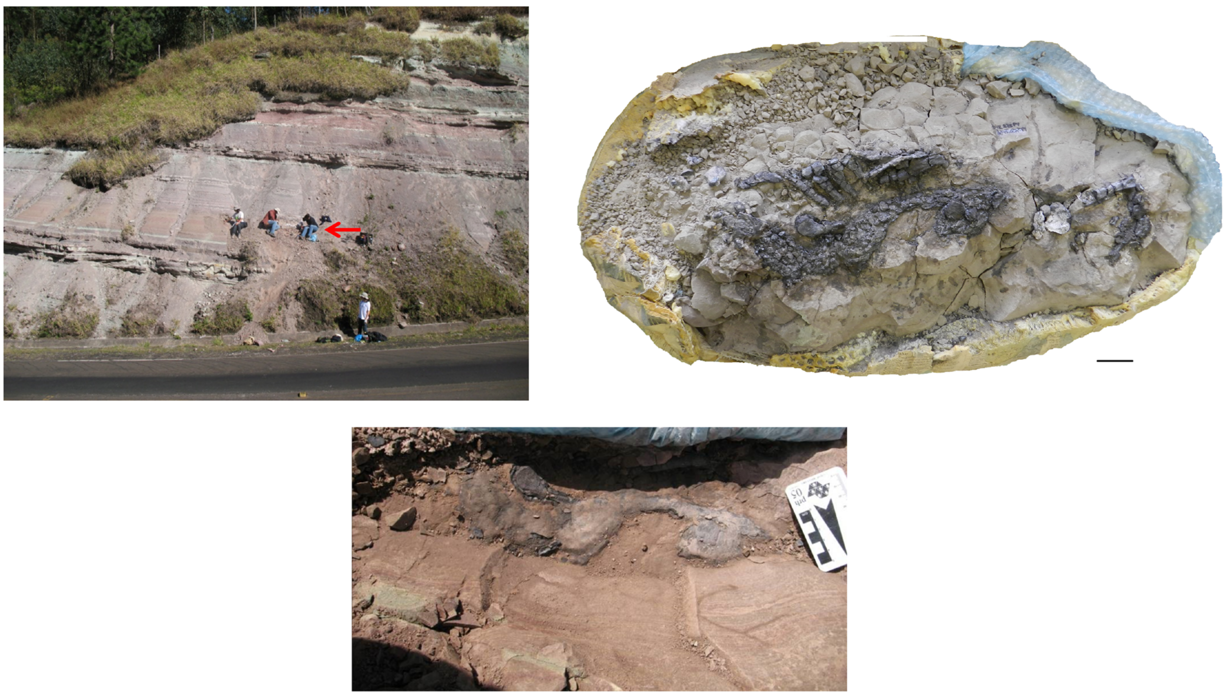

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Figure 7. Point 8 and a Temnospondyli post-cranium UFPR 0275 PV found at this point (scale bar: 5 cm).

long bones are broken. An X-ray diffractometric analysis was performed on the fossil and matrix. As shown in Figure 9D, clay minerals (smectite and mica), feldspar and quartz were identified in the rock; the petrographic thin section shows the same. Hematite, calcite, plagioclase and quartz are observed in the fossil diffractometric diagram (Fig. 9E). Four thin sections from the UFPR 0275 PV were made, in which the bone structures are infilled and damaged by the hematite. In one thin section (UFPR 0275 PV B 3), a transverse cross-section of a femur, it is possible to observe growth lines (LAGs) and the lamellar bone tissue (Figs. 8G and 8H);

- Point 9: although no fossils were recorded in this point, two petrographic thin sections were analyzed. Both samples correspond to laminated mudstones with the presence of carbonate, quartz and feldspar. Some of these feldspars were changed to white mica during diagenesis. Besides that, this bed is plenty of hematite and represents the facies Fl (reddish laminated mudstone) (Fig. 8I);
- Point 10: this point is related to the aeolian-dune sandstones from the Piramboia Formation. No fossils were found.

TAPHONOMIC ANALYSIS

Although fossils have been recorded in several strata of the São Jerônimo da Serra Site (Appendix A), until this moment it was possible to recognize three different taphonomic

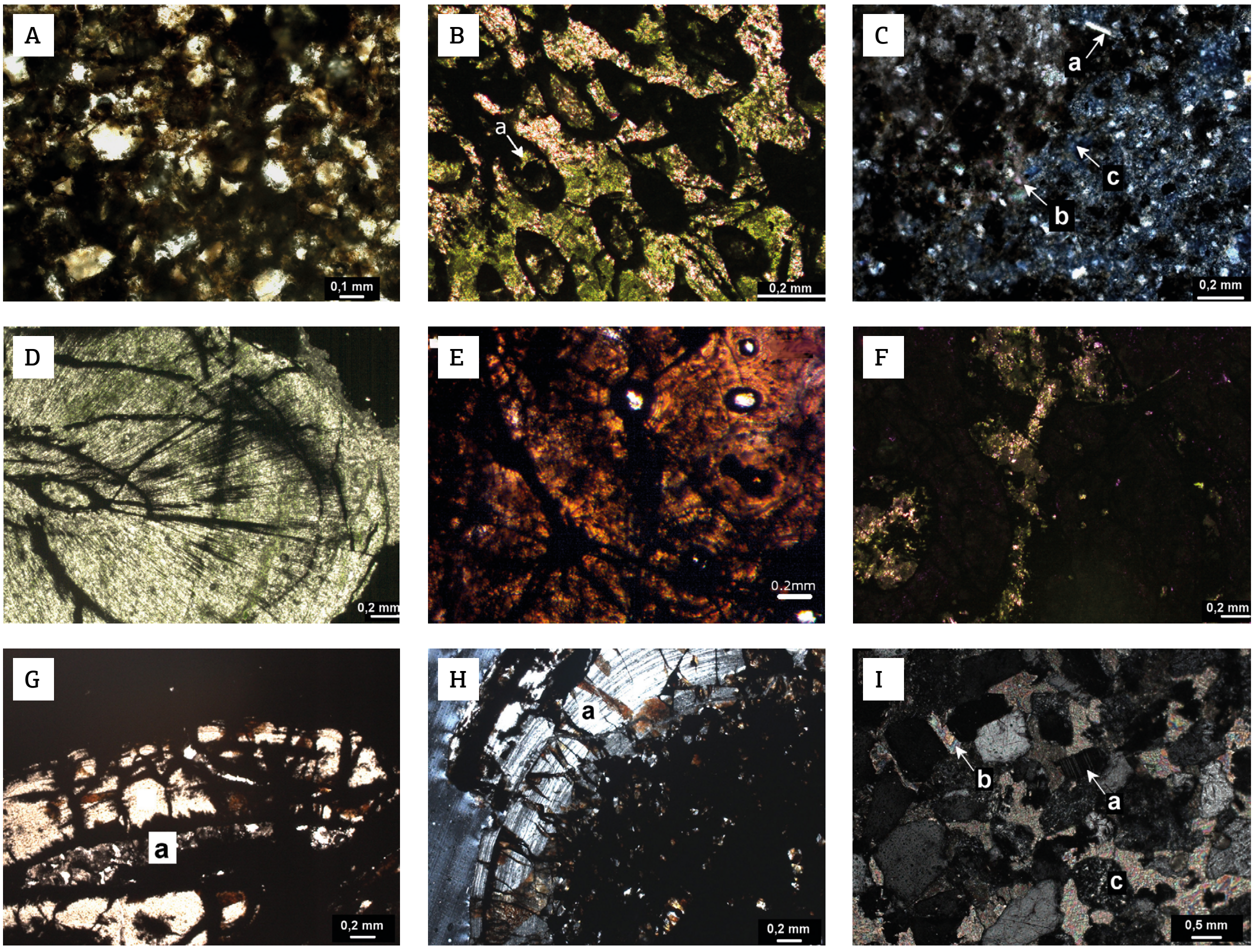

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Figure 8. Thin sections. (A) UFPR 0097 PV B from Point 1. Detail of the sandy siltstone with sub-rounded quartz grains associated with a jaw of temnospondyl. (B) A non-identified bone fragment UFPR 0208 PV B from Point 3. Note the presence of hematite (black) and quartz (a). (C) Detail of the siltstone adjacent to UFPR 0199 PV B 3 from point 5. Mica (a); carbonate (b); quartz (c). (D) Temnospondyl tooth UFPR 0199 PV B 3 from Point 5. Note the presence of the hematite (black). (E) Temnospondyl lower jaw UFPR 0198 PV B 1 from point 5. Note the osteons filled by quartz (white) and hematite (black). (F) Temnospondyl lower jaw UFPR 0198 PV B 2 from point 5. Note the osteons filled by hematite and fractures due to diagenetic quartz. (G) Temnospondyl femur UFPR 0275 PV B 2 from point 8. Bone tissue with the presence of hematite (black), and quartz (a). (H) Temnospondyl femur UFPR 0275 PV B 3 from point 8. Bone tissue with growth marks filled with quartz (a) and hematite (black). (I) Rock from point 9. Feldspar (a), carbonate (b), and altered feldspar (c). All images are shown under ordinary light except A, C, H and I (polarized light).

signatures and relate them to the faciological context from some points. As a result, basically three taphofacies (*sensu* Brett & Baird 1986, a body of rock with fossils of similar taphonomic attributes) in which a satisfactory number of elements were recovered could be identified (Fig. 10).

The first taphofacies (TF-I) is represented by fossils from the points 1, 2, 4, 5 and 8 preserved in fluvial floodplain environments (FF architectural elements). The fossils were preserved either in deposits of laminated mudstone (Fl) and massive mudstones (F) generated from mud settling (FF architectural element). The specimens from all these points share a similar diagenetic pattern, that is the presence of calcite, plagioclase, quartz and hematite as predominant filling minerals, which are also found in the sediment adjacent to the fossils. The hematite is also present covering the bones. In a biostratinomic context, the fossils are characterized by cranial, mandibular and post-cranial specimens either complete or partially complete, without any orientation pattern. The

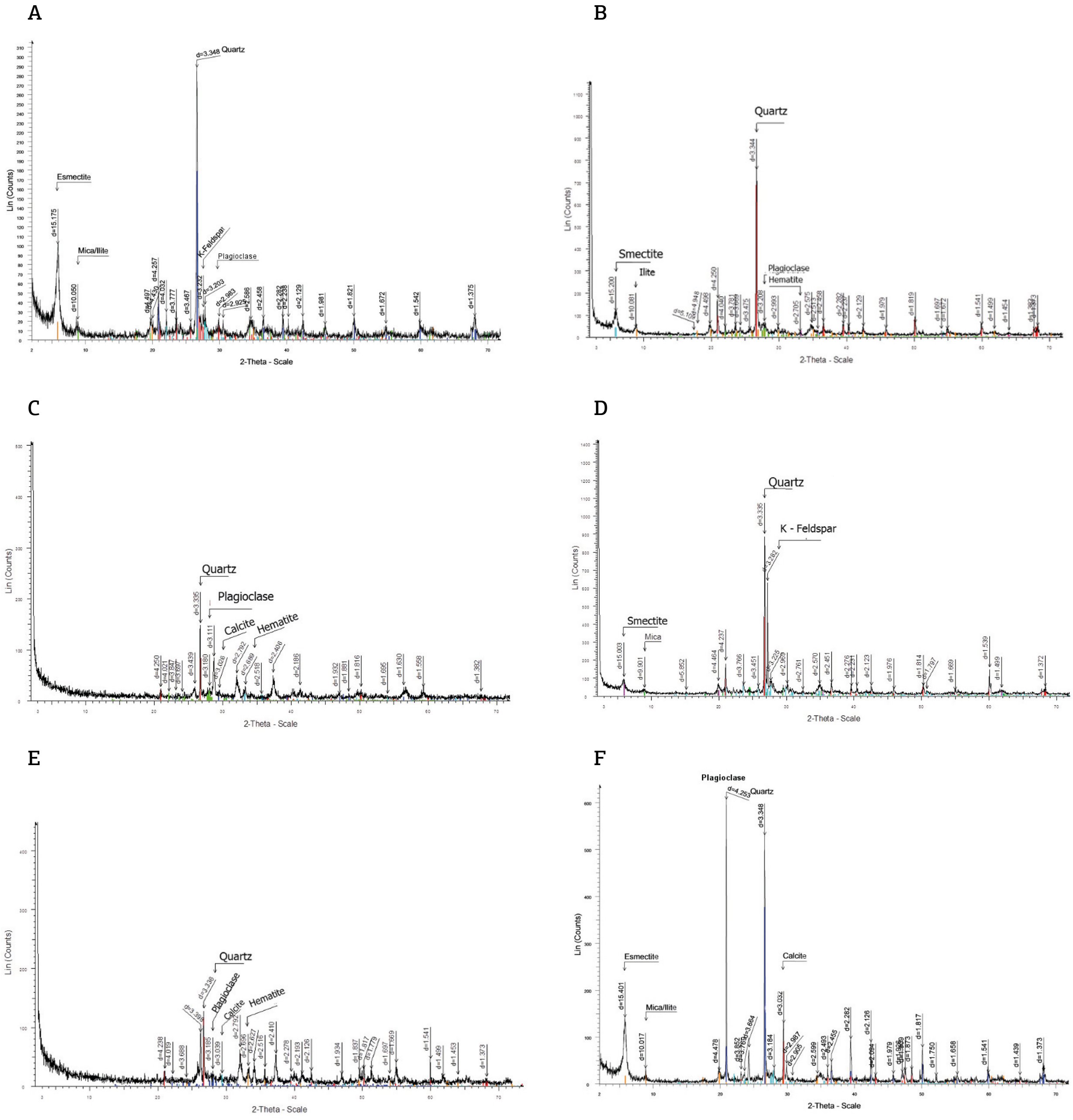

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Figure 9. X-ray diffractometry diagrams. (A) Silty sandstone from Point 3. (B) Mudstone from point 5. (C) Fossil fragment (UFPR 0198 PV) from point 5. (D) Mudstone from point 8. (E) Fossil fragment (UFPR 0275 PV) from point 8. (F) Fine sandstone bearing bivalves from point 7.

mixture of bones from distinct Voorhies' Groups (Voorhies 1969), as skull, lower jaws, long bones, ribs, phalanx and dermal scutes, reflects no sorting processes caused by hydraulic transportation (Behrensmeyer 1975). Despite some differences between the deposits from points 1, 2, 8, 4 and 5, all of them are characteristic of low energy environments. In such floodplain deposits, currents were usually too weak to transport and orient the bones in a preferential direction (Cincotta *et al.* 2015). The lack of hydraulic selection is reinforced by the presence of diminute conchostracans and fish scales, respectively in the points 8, 4 and 5. Thus, the vertebrate carcasses should have been exposed on the floodplain surface for longer or shorter time interval, suffering biostratinomic processes that led to the disarticulation and dispersal of the skeletons (Behrensmeyer 1975). Additionally, the absence of a pattern concerning the degree of disarticulation of the temnospondyl skeletons (more or less complete) corroborates the different subaerial exposure times between the death and the final burial. These processes normally result in far less preserved taphocenosis as in the case herein discussed.

The second taphofacies (TF-II) characterizes the fossils from point 3 preserved in fluvial terminal splays (SF architectural elements). The fossils are disarticulated, isolated and/or fragmented small bones and fish scales (from millimeters to few centimeters) preserved in very fine to silty sandstones related to the migration of subaqueous ripples by tractive current under lower flow regime (facies Sr_1). Quartz and hematite are present in the rock matrix, as well as inside and outside the fossil bones. The size of the bone elements corresponds to the Voorhies' Group I (Voorhies 1969) indicating selection by hydraulic sorting (Berhensmeyer 1975). The fragmentation of bones probably reflects biostratinomic processes that occurred before the transportation, when the skeletons were exposed in the floodplain, suffering intemperism and scavenging. Fragmentation due to transport, however, cannot be ruled out. This kind of facies allied to the taphonomic signatures of fossils points out to a floodplain close to a fluvial channel where presumably periodic flooding events produced low energy splays, but sufficiently dynamic to transport, sort and even fragment bioclastic elements.

The third taphofacies (TF-III), from the points 6 and 7, is compounded by small elements (mainly bivalves and fish scales), densely accumulated and preserved in massive reddish fine to very fine sandstone (Sm), related to CS architectural elements (crevasse splays). It is made up of two layers, which stand almost entirely the outcrop. The bivalves range from millimeters to 1 cm and are oriented concordantly/obliquely to the plane bedding. The sandstone is composed mainly by

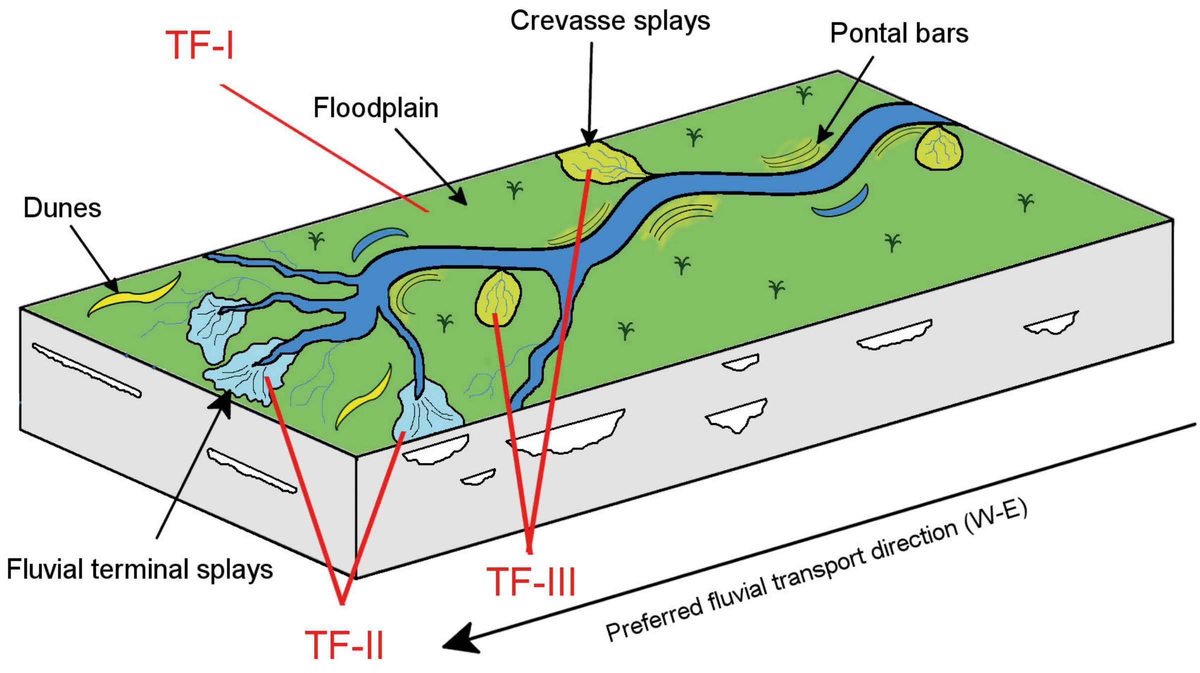

Figure 10. Environmental interpretation of the Morro Pelado Member, Rio do Rasto Formation with emphasis on the environments preserved in the São Jerônimo da Serra Site and respective taphofacies. Modified from Schemiko *et al.* (2014).

quartz, plagioclase, ilite/mica and smectite plus calcite probably originated from the shells. The shells should have been transported during intense water flows and accumulated on more energetic-derived layers. Taphonomic signatures that corroborate this assumption are the densely packed fossils and their concordant orientation, besides the disarticulation and fragmentation of bivalves.

DISCUSSION

The Morro Pelado Member of the Rio do Rasto Formation is composed of fluvial, aeolian and lacustrine deposits with increasing amount of aeolian layers toward the top. According to Schemiko *et al.* (2014), this indicates a progressive dryness at the depositional environment and the expansion of dunes and interdunes toward the border of the Paraná Basin. Those authors remark, moreover, that the sedimentation is characterized by fluvial systems, aeolian dunes and sand sheets, being the fluvial and lacustrine (deltaic) facies of subordinated occurrence, characterizing a semi-arid environment.

The faciological features found there corroborate the paleoenvironmental interpretation by Schemiko *et al.* (2014), in which terminal splays and ephemeral floodplain lakes grade upward to dune fields of the Piramboia Formation (Fig. 10). The increase of aridization is clearly evinced by the enlargement of the sandstone levels at the top of the sequence (Fig. 2).

The fossiliferous content of the São Jerônimo da Serra Site (*e.g.*, bivalves, conchostracans, temnospondyl bones, fish scales, plants, vertebrate coprolites and footprints) corroborate the assumption of a continental shallow aquatic environment (Rohn 1994, Leonardi *et al.* 2002, Ramos & Vega 2011, Souza 2011, Silva *et al.* 2012, Azevedo *et al.* 2012). The retraction of the aquatic environment and the increase of the terrigenous influence toward the top of the outcrop are corroborated by the more conspicuous presence of terrestrial fossils such as footprints of *Procolophonichnium isp*. (Procolophonidae), *Rhynchosauroides gangresci* (basal Diapsida), *Dicynodontipus penugnu* (Dicynodontia), Planolites (worm-like burrows) and plants (roots, sphenopsids fronds) (Silva *et al.* 2012). In this context, no fossils have been recorded from the dunes and interdunes of Piramboia Formation.

In mineralogical terms, the feldspar grains of the rocks from Morro Pelado Member present chemical traces of alterations/replacements like albitization, overgrowth and sericitization that preferentially occur in carbonate cement (Schemiko 2013). In fact, the substitution of the feldspars by carbonates and also the reprecipitation of the carbonate are related to semi-arid environments (Zambonato 2004, Morad *et al.* 2010). Through electron microscopy analysis, Schemiko (2013) also confirmed the presence of the clay mineral ilite as part of the outermost cover of the grains. The thin sections analyses of rocks from the São Jerônimo da Serra Site done in this work revealed the presence of quartz, carbonates, hematite, clay minerals, and altered feldspars. Besides the observation of sandstones with intense carbonatic cementation, there are clay minerals (illite-smectite or smectite) that should have been deposited before the carbonates.

The hematite, ilite and smectite were identified in siltstones and sandstones by both the x-ray diffractometry and thin sections analyses herein performed and by scanning electron microscope performed by Schemiko (2013). The presence of these minerals were related to climatic variations, showing the action of flooding processes interspersed with evaporation periods and without deposition.

The vertebrate fossils of the São Jerônimo da Serra Site occur in layers with the presence of hematite. Therefore, the fossils are covered by this iron oxide, and details of bone and tooth morphology are obscured. The thin sections showed that the hematite also occurs inside the bones, which difficult the observation of the bone microstructure due to its dark color. In several cases, the hematite fills the osteocytes lacunae and the osteons channels after the quartz. This type of preservation is the same of the other tetrapods recovered from other sedimentary succession of the Morro Pelado Member of the Rio do Rasto Formation, both in Paraná and Rio Grande do Sul states, Southern Brazil. They share the same dark gray color, being covered by a thin crust of hematite, as observed by Boos *et al.* (2015). In this scenario, the origin of the iron of hematite coatings and infillings could be attributed to hydrothermal fluids, upwelling of reduced groundwater or dissolution and remobilization from iron-bearing minerals in the soil material (Bao *et al.* 1998).

At Morro Pelado Member, Schemiko (2013) has identified the deposition of the oxide during the eodiagenesis and the telodiagenesis, and more analyses would be necessary to affirm the source of the iron found in the São Jerônimo da Serra Site. At this outcrop, in general, the hematite coatings are very similar to those observed by Colombi *et al.* (2013) on vertebrate fossils recovered from floodplain facies of the Triassic Ischigualasto Formation, Argentina. There, the bones commonly exhibit hematite coatings and are permineralized with hematite, barite, and secondary calcite (Colombi *et al.* 2013). Bao *et al.* (1998) have already reported hematite coatings on bones from Paleocene/Eocene paleosol deposits in the Bighorn Basin, Wyoming, United States, claiming that the hematite was formed in close association with pedogenic processes. In this case, the authors assumed that anoxic poorly drained conditions, both pre- and post-burial, should had played a role in the decay of the carcasses, what prompted the precipitation of iron minerals, mainly hematite

(Bao *et al.* 1998). The same is postulated by Colombi *et al.* (2013) remarking that hydromorphic anaerobic conditions in some burial environments of the Ischigualasto Formation (floodplain deposits) should facilitate the precipitation of hematite on and inside bones.

At the São Jerônimo da Serra Site, the architectonic elements show the action of floods intercalated to periods of evaporation and lack of deposition. The presence of mudracks at the floodplain facies (between points 7 and 8 and points 8 and 9) and calcrets (nodular calcrets from point 3; and mottled calcrets below point 1, and between points 9 and 10) indicates the beginning of soil formation with sub-areal exposure (Fig. 2) (Alonso-Zarza 2003). The predominant reddish color observed mainly in the mudstones facies probably corresponds to successive subaerial expositions with phases of iron oxidation, as interpreted by Rohn (1994) and Warren *et al.* (2008) for the whole Rio do Rasto Formation. This model complies with the requirements to the hematite formation and its posterior action in the fossildiagenese processes.

The faciological succession and taphonomic signatures allied to the mineralogical data allow an environmental reconstruction of the São Jerônimo da Serra Site (Fig. 10). The three taphofacies reflect environments associated to different modes of fossil preservation. The most common taphofacies (TF-I) reflects a type of environment recurrent at several levels of the outcrop (points 1, 2, 4, 5 and 8). These points correspond to low energy seasonal floodplain facies where the hematite precipitation in shallow and water sheets used to be a common process. The spectrum of disarticulation patterns exhibited by the tetrapod skeletons, from semi-articulated post-cranial to isolated skulls and lower jaws, in addition to their association with conchostracans, attests the absence of hydraulic transport. The taphocoenosis is product of attritional deposition of carcasses along time. That is, the longer the time of exposure, the higher is the chance of loss of bone elements by scavengers and necrophagous agents, weathering, bioturbation etc. before being incorporated into the burial environment (Behrensmeyer & Hook 1992).

The point 3 is related to fluvial terminal splays characterized by fine to silty sandstones. It becomes evident the sorting and the transportation of the fossil elements. Only small and disarticulated bone elements (isolated and/or fragmented) are recorded together with tiny fish scales, characterizing the Taphofacies II (TF-II). The bones from this taphofacies exhibit the same diagenetic pattern of the Taphofacies I. Thus, the bones should have been kept exposed to the above-mentioned iron enriched floodplain conditions, before the transport. The fragmentation of the bones could have occurred during the exposition time, as well as during the hydraulic transport.

The two layers bearing bivalves and fish scales, from the points 6 and 7, occur in a sandy strata characteristic of crevasse splay deposits. The shells were probably transported during stronger water flows and accumulated on these more energetic layers producing the signature of the Taphofacies III (TF-III). Iron oxide was absent both in the sandstones and in the fossils, probably due to the energy concerning sediment transport and deposition.

CONCLUSIONS

The São Jerônimo da Serra Site, Paraná State, Brazil, is currently the locality with the most complete faunal association of the Morro Pelado Member of the Rio do Rasto Formation. It represents, therefore, a very promising field for the expansion of the knowledge about the southern Brazilian Permian. More fossils from systematic collections are needed to corroborate the considerations here presented. But, besides the information provided by the different fossil groups, the sedimentological, faciological and taphonomic signatures corroborate with the paleoenvironmental model already proposed to Morro Pelado Member, which includes fluvial, lacustrine and aeolian environments, with an arid climate trend. The faciological and taphonomic analysis with the identification of eight points of fossil occurrences, allied to mineralogical data, refined the understanding of the environmental conditions that have influenced the preservation processes (both the biostratinomic and diagenetic ones). Our data showed that the São Jerônimo da Serra Site results from a very sensitive hydraulic system, in which fossil preservation was conditioned to intermittent water supply. The iron-rich and shallow-water environments established in the floodplain areas point to direct influence in the preservation of the tetrapod bones, which are predominately filled and covered by hematite.

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Appendix A. List of fossil specimens from the São Jerônimo da Serra Site with the points discussed in the paper.

Collection number	Collection date	Identification	Location	References
UFPR 0169 PI	2011	Bivalves	Point 7	
UFPR 0097 PV	2007	Temnospondyl lower jaw	Point 1	Ramos & Vega 2011
UFPR 0099 PV	2009	Temnospondyl lower jaw	Point 1	Ramos & Vega 2011
UFPR 0100 PV	2009	Temnospondyl lower jaw	Point 2	Ramos & Vega 2011
UFPR 0109 PV	2009	Temnospondyl intercentra	Point 2	Ramos & Vega 2011
UFPR 0150 PV	2010	Temnospondyli skull	Point 4	Souza 2011
UFPR 0153 PV	2010	Temnospondyl lower jaw fragment	Point 4	Souza 2011
UFPR 0154 PV	2010	Temnospondyl intercentra	Point 3	Souza 2011
UFPR 0164 PV	2011	Temnospondyl lower jaw	Point 4	Souza 2011
UFPR 0172 PV	2011	Temnospondyl intercentra	Point 3	Souza 2011
UFPR 0195 PV	2009	Temnospondyl tibia ?	Point 5	Souza 2011
UFPR 0198 PV	2011	Temnospondyl lower jaw	Point 5	Azevedo *et al.* 2012
UFPR 0199 PV	2011	Temnospondyl skull	Point 5	Azevedo *et al.* 2012
UFPR 0200 PV	2011	Temnospondyl lower jaw	Point 5	
UFPR 0201 PV	2011	Temnospondyl lower jaw	Point 5	
UFPR 0202 PV	2011	Indeterminate bone fragment	Point 5	
UFPR 0204 PV	2011	Indeterminate bone fragment	Point 3	
UFPR 0205 PV	2011	Indeterminate bone fragment	Point 3	
UFPR 0206 PV	2011	Temnospondyl femur fragment	Point 3	
UFPR 0207 PV	2011	Paleonisciform scale	Point 3	
UFPR 0208 PV	2011	Paleonisciform scale and bone fragment	Point 3	
UFPR 0209 PV	2011	Paleonisciform scale	Point 3	
UFPR 0210 PV	2011	Paleonisciform scale	Point 3	
UFPR 0211 PV	2011	Paleonisciform scale	Point 3	
UFPR 0212 PV	2011	Paleonisciform scale	Point 3	
UFPR 0214 PV	2011	Paleonisciform scale	Point 3	
UFPR 0226 PV	2011	Fish spine?	Points 6/7	
UFPR 0229 PV	2012	Paleonisciform scale	Point 8	
UFPR 0230 PV	2012	Temnospondyli scale?	Point 3	
UFPR 0231 PV	2012	Paleonisciform scale	Point 8	
UFPR 0232 PV	2012	Paleonisciform scale	Point 8	
UFPR 0233 PV	2012	Paleonisciform scale	Point 8	
UFPR 0234PV	2012	Paleonisciform scale	Point 8	
UFPR 0235 PV	2012	Paleonisciform scale	Point 8	
UFPR 0236 PV	2012	Paleonisciform scale	Point 8	
UFPR 0237 PV	2012	Paleonisciform scale	Point 8	

Continue...

Appendix A. Continuation.

Collection number	Collection date	Identification	Location	References
UFPR 0238 PV	2012	Tooth?	Point 8	
UFPR 0252 PV	2012	Procolophonid jaw?	Points 4/5	Pietsch & Vega 2016, Melo & Vega 2015
UFPR 0275 PV	2012	Temnospondyli post cranium	Point 8	
UFPR 0287 PV	2016	Coprolite	Point 3	
UFPR 0288 PV	2016	Coprolite	Point 3	
UFPR 0289 PV	2016	Coprolite	Point 3	
UFPR 0327 PV	2016	Indeterminate bone fragment	Point 3	
UFPR 0330 PV	2016	Paleonisciform scale and bone fragment	Point 3	
UFPR 0361 PV	2016	Temnospondyli scale?	Point 3	
UFPR 0362 PV	2016	Indeterminate bone fragment	Point 3	

UFPR-PV: vertebrate collection from Laboratório de Paleontologia of the Universidade Federal do Paraná; UFPR-PI: invertebrate collection from Laboratório de Paleontologia of the Universidade Federal do Paraná.