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The silty shale Taquaral Member of the early Permian Irati Formation (Paraná Basin, Brazil). Paleontology and paleoenvironments

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Abstract Two facies are recognized in the Taquaral Member, base of the Artinskian Irati Formation, Parana Basin, Brazil: (1) The sandstone and conglomerate facies, mostly present in the lower part of the member, is thin, commonly 10 cm, exceptionally 1 m thick; and (2) the silty shale facies overlaying the former. Some sandy lenticular beds may occur in the lowermost shale strata. The silty shale facies is thicker (5–30 m), more homogeneous and more widespread than the sandy facies. Facies has yielded crustaceans and fish remains as the only recovered fossils. Other taxa reported by previous authors without formal descriptions and illustrations were never found by later researches. The scrutiny of the paleontological content of the silty shale is here presented by the first time and constitutes one of the purposes of this contribution. The fossil content allowed the proposition of a paleoenvironment of deposition, without a direct connection to open ocean. Some of the species may have been adapted to the new conditions, brackish, from older marine taxa, not yet discovered or stripped off by erosion.

Keywords Crustacea · Taquaral Member · Irati Formation · Paraná Basin · Osteichthyes

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Introduction

The Parana Basin deposits, from Ordovician to Cretaceous are best developed in Brazil, extending also to Uruguay, Argentina and Paraguay. The Supersequence Gondwana I (Milani and Ramos 1998), from Late Paleozoic to earliest Triassic, is the best developed of the supersequences of this basin.

The Artinskian Irati Formation is the most important of the lithostratigraphic units of the basin on several points of view: (a) it is a milestone in the history of the basin, characterizing a change on the structural behavior of the basin; (b) its lithologies are unique as compared with other units, allowing a correlation with South African Whitehill Formation. Evaporites, dolostones and limestones in northern Irati stand out from the southern (and South Africa), where their presence is minor; (c) its fossils are noteworthy mainly the mesosaurid reptiles (Soares 2003), also present in the Whitehill Formation.

This paper deals with the Irati Formation as exposed in the northern Paraná Basin, different from the southern Paraná Basin and the South Africa equivalent, not enough strengthened in previous papers.

The Taquaral Member exhibits diversified lithologies, mainly in its lower beds, distinguished by a predominantly lower sandy facies. This facies is characterized by lenticular conglomeratic sandstones with granules and pebbles, intercalated with coarse to fine sandstones and muddy sandstones. In spite of its small thickness, it is rich in fish remains, scales, teeth and fragments of bone.

The Chondrichthyes are the most diversified, Osteichthyes and tetrapods, and less frequent. Many papers describing these fossils have recently been published (Chahud and Petri 2008a, b; 2010b; Chahud et al. 2010) in tetrapods (Chahud and Petri 2010a).

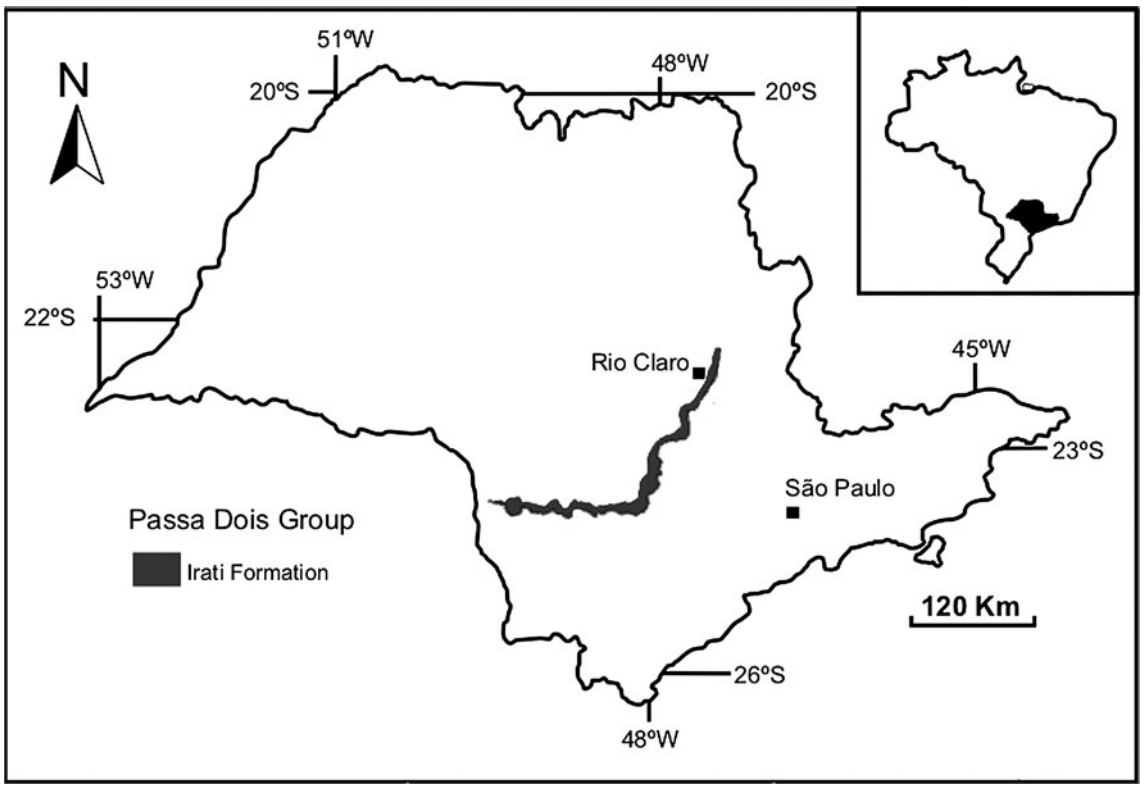

Fig. 1 *Black stripe*, along the map of the state of Sao Paulo, marks Irati Formation outcrops

A gray finely laminated silty shale facies almost everywhere covers the previously described facies. It is thicker, more homogeneous and more widespread than the sandy facies. The uppermost layers contain chert modules and pebbles.

While the fossils of the Assistência Member and sandy facies of the Taquaral Member are reasonably well known, described by many researchers, the fossils of the silty shale facies of the Taquaral are incompletely known, except for the crustacean *Clarkecaris*.

One of the purposes of this paper was to furnish an up-to-date paleontological contribution for a better knowledge of the fossils in the Taquaral silty shale facies, as well as describing new taxa.

The study was based on outcrops from the municipality of Rio Claro, center-east region of the state of São Paulo (Fig. 1). The fossils come from the Taquaral shales, which are predominant in the Taquaral Member. The described and illustrated specimens were registered at the Scientific Collections of the Systematic Paleontology Laboratory (LPS) of The Institute of Geosciences of the University of São Paulo.

Systematic Paleontology

Subphylum Crustacea Brünnich, 1772
Superorder Syncarida Packard, 1895
Order Anaspidacea Calman, 1904
Family Clarkecarididae Brooks, 1962
Genus *Clarkecaris* Mezzalira, 1952
Clarkecaris brasilicus (Clarke, 1920)

Synonymies
Gampsonyx brasilicus Clarke, 1920, N.Y. State Mus, Bull. 219:137. Est 4, Figs. 9, 10.
Clarkecaris brasilicus (Clarke, 1920) Mezzalira, 1952 Bol. Soc. Bras. Geol. 1(1):48 Est. 3.
Clarkecaris brasilicus (Clarke, 1920) Mezzalira, 1954 Vol. Com. 1° Cent. Paraná: 168.
Clarkecaris brasilicus (Clarke, 1920) Brooks, 1962 Crustaceana 4:229–242.
Clarkecaris brasilicus (Clarke, 1920) Brooks, 1969 Geo. Soc. Am. Part R Arthropoda 4(2) R 358.
Clarkecaris brasilicus (Clarke, 1920) Pinto, 1985 Bol. DNPM (27), 253–259.

Holotype Gampsonyx brasilicus Clarke, 1920; New York State Museum; number 9738, 9739.
Material Five *Clarkecaris brasilicus* specimens GP/1E-5689, GP/1E-5690a, GP/1E-5691, GP/1E-5692, GP/1E-5693.
Localization Rio Claro Municipality, center-east state of São Paulo

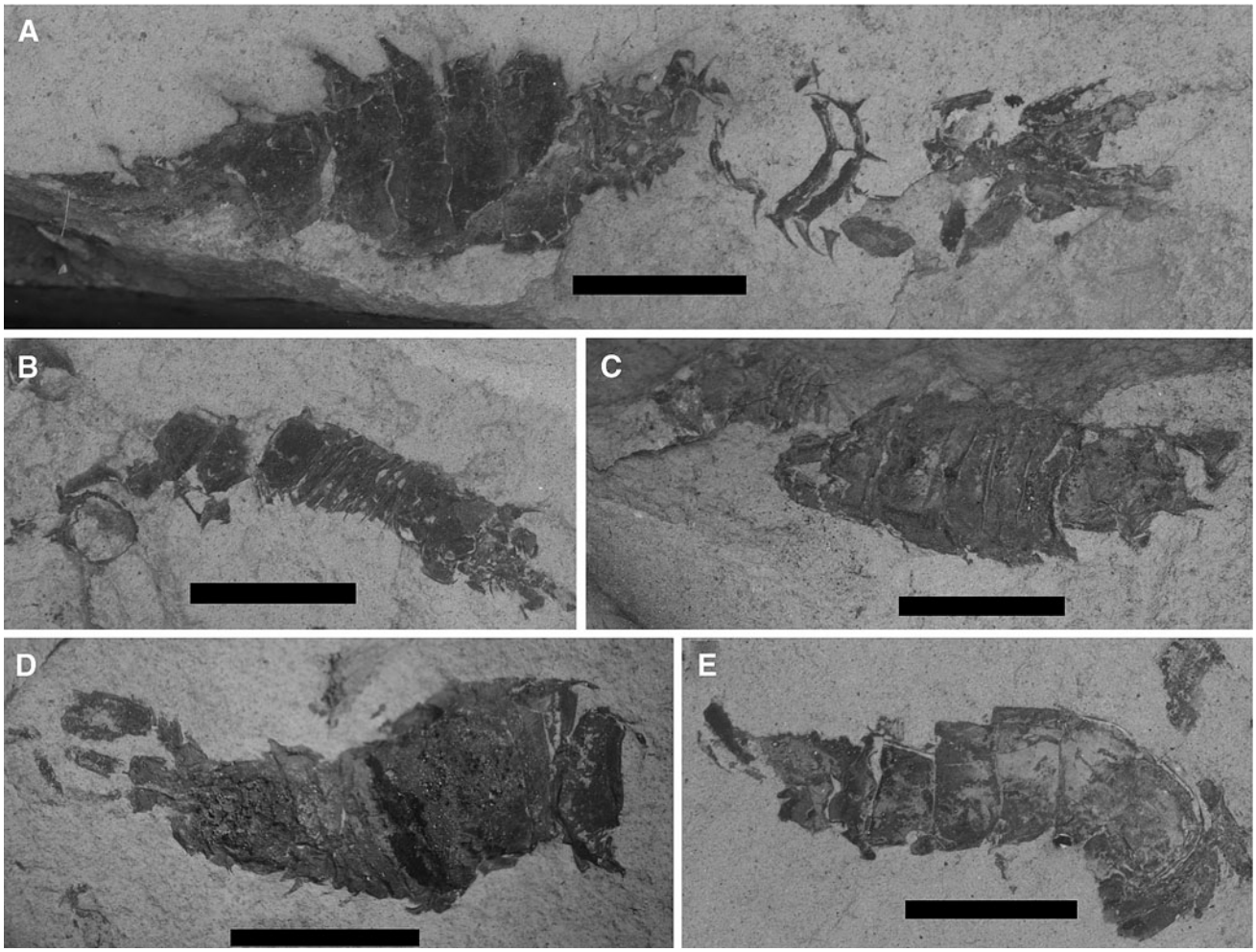

Fig. 2 *Clarkecaris* specimens found out in Rio Claro. **a** GP/1E-5691, **b** GP/1E-5689, **c** GP/1E-5692, **d** GP/1E-5693, **e** GP/1E-5690a. *Scale bar* 5 mm

Diagnosis (after Pinto 1985): Strong transverse sulcus divides the cephalon in two parts, both presenting two large pterygostomial spines. Eyes pedunculate; second antennae with scaphocerite. Suture between head and first thoracic tergite vestigial: long spinelike thoracic and abdominal pleurae directed anteriorly and posteriorly, respectively, two large supraorbital and two hepatic spines dorsally; furcae present.

Description The complete cephalon is seldom fossilized, so no collected specimens for this study preserved the cephalon entirely. In three of them, only abdominal tergites are reasonably preserved. The species body is narrow and elongate.

Part of the cephalon and impressions of pterygostomial spines are seen in the specimen GP/1E-5691 (Fig. 2a), two of them are laterally disposed. Two small disarticulated thoracic tergites, 0.4 mm long and 4.1 mm wide, containing small spines turned to the frontal part of the fossil.

Only the specimen GP/1E-5692 (Fig. 2c) presents thoracic tergites, which are smooth, with no large ornamentation, almost 1 mm long and 4.1 mm wide, bearing small spines visible on the extremities, turned to the anterior parts of the specimens.

Every specimen, GP/1E-5689 (Fig. 2b), GP/1E-5691 (Fig. 2a), GP/1E-5692 (Fig. 2c) and GP/1E-5693 (Fig. 2d), have the same abdominal tergite features, large rectangular in shape and curved lateral spines, as seen in the specimens GP/1E-5691 and GP/1E-5693. The spines are turned backward on the entire lateral tergite.

The telson is elongate, tapering toward the extremity as seen on the specimens GP/1E-5689, GP/1E-5690a and GP/1E-5693 (Fig. 2b, d, e). The specimen GP/1E-5693 bears uropod remains at one of the flattened sides, turned backward.

The largest figured specimen, GP/1E-5691 is 34 mm long, the body of only 19 mm without the broken up cephalon, and the tergite maximum width is 6 mm.

The maximum lateral spine is about 2 mm in size. The lengths of the remaining specimens are 15 mm for GP/1E-5689 (not considered the disarticulated fragment); 16 mm for GP/1E-5692 and 19 mm for GP/1E-5690a.

Discussion The described specimens are typical of the genus *Clarkecaris*, the preservation of specimens in this silty shales is similar to the preservation of specimens found out elsewhere (Mezzalira 1952).

The holotype, from Guareí Municipality, State of Sao Paulo, was described by Clarke (1920) who considered it a new species of *Gampsonyx*, on the basis of two fragmented specimens, preserved only the thorax, abdomen and the tail.

Mezzalira (1952) collected better preserved specimens, observing details unavailable before, so he got elements for proposing a new genus, *Clarkecaris* in the family Uronectidae. Later Brooks (1962) proposed the family Clarkecarididae under the order Anaspidacea, based on fossils in the United States National Museum collection.

Mezzalira (1971) and later Pinto (1985) elaborated detailed descriptions of the pterygostomial spines and cephalic appendices. Only one specimen discovered by Brito and Quadros (1978) and described by Pinto (1985) was not found in the state of São Paulo, coming from State of Paraná, being one of the few complete specimens.

Crustacean occurrences in the Taquaral Member as well as in the Assistência Member were taken by Barbosa and Gomes (1958) as a basis to put them within the Irati Formation. However, *Clarkecaris* is present only in the Taquaral Member. The Assistência Member crustaceans belong to different taxa. Besides, fossils cannot be taken as criterion for defining lithostratigraphic units. Nevertheless, every Brazilian stratigrapher group together both units in the Irati Formation for the following reasons: (a) no discordance separates them; (b) gradual evolution to a restricted basin is observed as Taquaral passes up to Assistência.

Clarkecaris occurs only in the states of São Paulo and Paraná. It does not occur in Southern Paraná Basin, South Africa, Paraguay, Uruguay and nor in Permian Brazilian basins (Amazonas and Parnaiba Basins).

The paleoenvironment where *Clarkecaris* lived is an open question, whether salty or fresh water. According to Beurlen (1931), a possible fresh water would be reasonable, because recent Anaspidacea live in freshwater. Mezzalira (1952), in spite of the phylogenetic affinities with *Anaspidites*, which prefers freshwater, was reticent to admit freshwater. Both Beurlen (1931) and Mezzalira (1952) agreed that a coastal region would be the paleoenvironment which this genus, thus discarding deep waters.

Clarkecaris brasilicus has been compared to Syncaridan (Palaeocaridacea) genera from the Carboniferous of North American as *Squillites* and *Palaeocaris* (Brooks, 1962; Schram and Schram, 1974); According to Schram and Schram (1974), *Clarkecaris* would be an intermediate taxon between the most primitive Palaeocaridacea and the living Anaspidacea.

Squillites was discovered in association with freshwater and euryhaline fossils. *Palaeocaris*, during long time considered a freshwater genus, was recently mentioned in paleoestuarine environment, with varied salinity (Schultze 2009). The Devonian Syncarida was marine (Schram and Schram 1974) but, in Early Carboniferous, they were adapted to transitional paleoenvironments, brackish and even freshwaters.

Superorder: Indeterminate
Fig. 3

Material One specimen GP/1T-6174.
Localization Rio Claro Municipality, center-east state of São Paulo.
Discussion No pereonite or thoracic somites and other parts of the animals are preserved. The bifurcated structures of the extremities are the main diagnostic feature of this crustacean. The specimen was collected at the same outcrop where *Clarkecaris* specimens came from.

Foehringer and Langer (2003, 2004) suggested that this taxon would be decapods, Reptantia, based on possible "chelas". However, Decapoda and Eucarida are rare in the Paleozoic and the few present, are devoid of chelas (Schram and Schram 1974; Schram 1978, 1980, 1981, 2006). The bifurcated structures of the extremities were not used for grabbing objects. Probably they would be a locomotion apparatus, based on the weakness of these articulations. They look like two-tail uropod branches, also present in other Malacostraca (Knopf et al. 2006; Haug et al. 2010; Kutschera et al. 2012). The remains from Taquaral are similar to those of *Squillites* (Schram and Schram, 1974). However, better preserved fossils will be necessary to get a definition of its taxonomic affinities.

Subphylum Vertebrata Cuvier, 1812
Class Osteichthyes Huxley, 1880
Subclass Actinopterygii Woodward, 1891
Order Indeterminate
Fig. 4

Material Scales (GP/2E-6222a, GP/2E-6222b GP/2E-6223, GP/2E-6225) and one isolated maxilla (GP/2E-6231).
Localization Rio Claro Municipality, center-east state of São Paulo
Description of the scales The scales are well preserved, rhombohedral, as seen from above. Their margins generally are smooth, commonly without the articulatory "peg-and-socket" system, although it is clearly seen in some

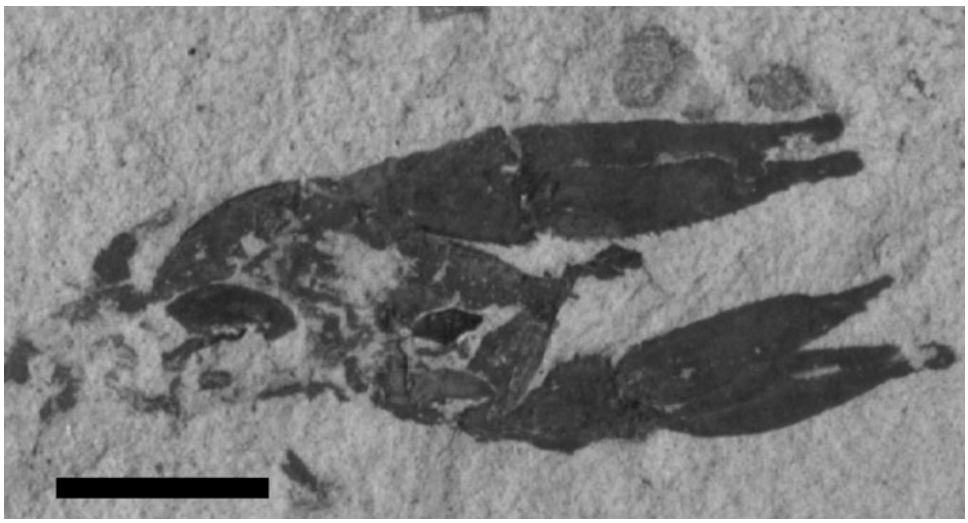

Fig. 3 Indeterminate crustacean. Specimen GP/1E-6174. *Scale bar* 5 mm

specimens (Fig. 4a–d) sometimes standing out as a projected off point at one side of the scale (Fig. 4c). Sometimes this system is weakly distinguished at one side (Fig. 4a, b, d).

Description of the maxilla Only one bone makes up the maxilla, with two distinguished parts: one frontal suborbital, below the ocular region and the other posterior to the orbit, behind the ocular region. Suborbital is narrow, gradually thinning on the frontal face, with the posterior ventral region elongate, projected forward, from the articulation with the lower jaw. The postorbital region is 16.7 mm long and 2.9 mm high. The thinner region of suborbital is practically straight, without any curves, high and elongate, 7.9 mm long, with small teeth along the inferior face.

The poor preservation does not allow the observation of possible features like ornamentations or irregularities on the surface.

The conical teeth are very small but strong, their lengths are smaller than 1 mm, commoner on the internal face, near this postorbital.

Discussion Richter et al. (1985) proposed informal morphological classification (P1–P5 morphotypes) for the Parana Basin, Late Paleozoic, paleoniscoid scales. The Taquaral Member silty shale facies bears two types of smooth scales (P1 and P5) and only one ornamented scale (P3).

Besides the rhombohedrical scales, few angular scales may be associated with several dermic bones and fulcral scales. These bones and scales are similar to those associated with northern hemisphere *Elonichthys*, interpreted by Schultze and Bardack (1987) as belonging to fins of this genus.

Unfortunately only one maxilla was found in the Taquaral silty shale facies. Its pattern is typical of Paleoniscoid maxilla. The elongate shape of the postorbital is observed in older forms, like the North American Carboniferous *Paratarrasius* (Lund and Poplin, 2002), as well as in younger forms, like *Brasilichthyes* (Cox and Hutchinson, 1991), from the northern Brazil Permian Pedra do Fogo Formation, Parnaiba Basin.

Several genera bearing jaws were described from the Permian Parana Basin formations, as from the Rio do Sul formation, which is older than the Irati Formation, bears the genus *Roslerichthys*, described by Hamel (2005). From the Corumbataí Formation, younger than Irati, three genera were described: *Tholonotus* (Dunkle and Schaeffer, 1956), *Angatubichthys* (Figueiredo and Carvalho, 2004) and *Santosichthys* (Figueiredo and Gallo, 2006a, b).

The postorbital maxillas of these genera are not so elongate as the presently described. Possibly the maxilla, described here, belongs to a new taxon.

The narrow suborbital and elongate postorbital maxilla of the North American Carboniferous genus *Wendyichthys* (Lund and Poplin, 1997) are similar to those of the Taquaral maxilla, but the lack of other Taquaral fossils prevents a closer comparison with this genus.

Subclass Sarcopterygii Romer, 1955
Infraclass Actinistia Cope, 1871
Order Coelacanthiformes Berg, 1937
Family Indeterminate

Material Isolated scales part and counterpart: GP/2E-5969a and b; GP/2E-6233a and b.
Localization Rio Claro Municipality, center-east state of São Paulo.
Description The scales, part and counterpart are well preserved, revealing details of their anatomy. The imbrication region is marked by several longitudinal short and thick

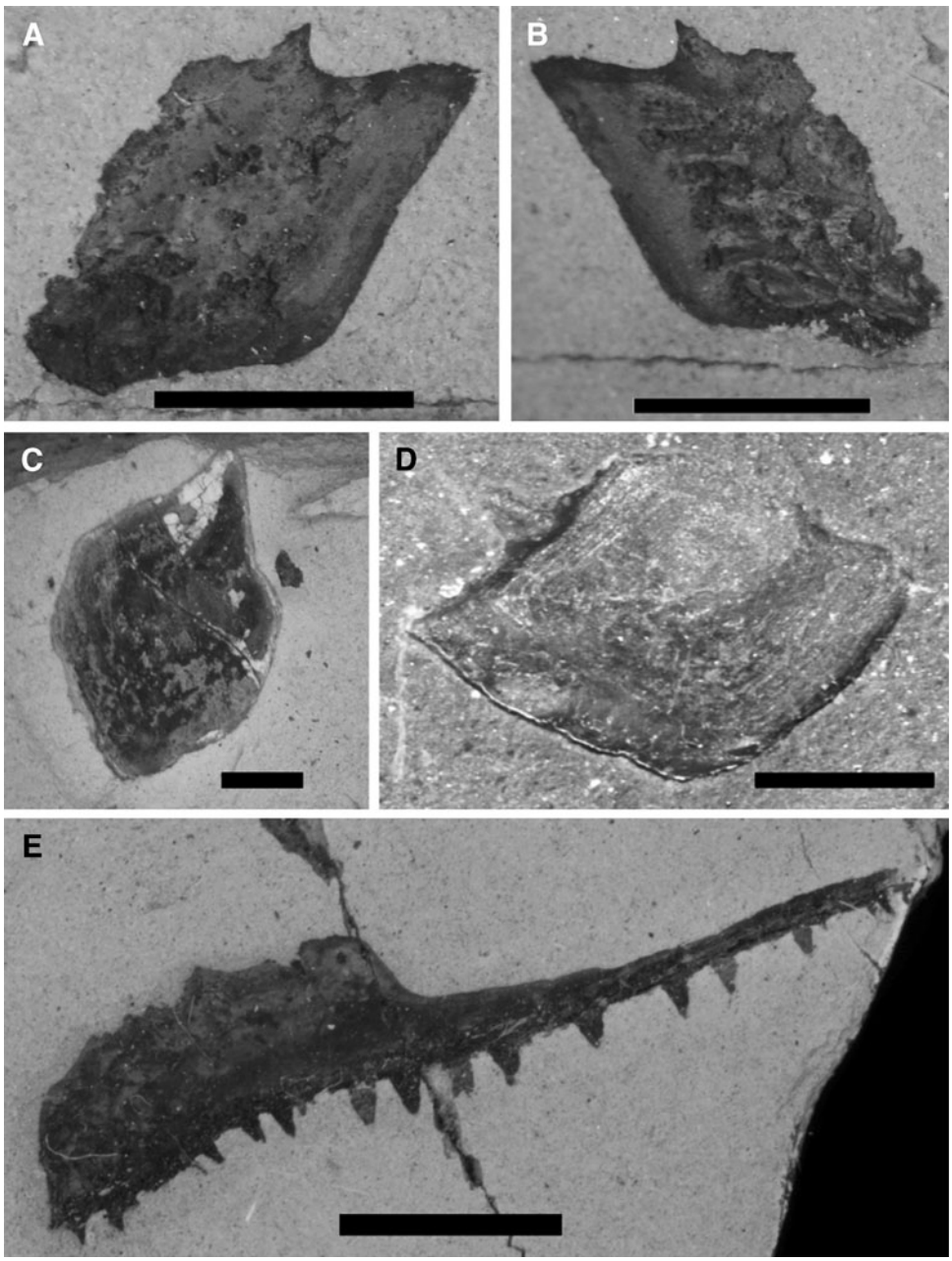

Fig. 4 **a** Palaeonisciformes scale part (GP/2E-6222a), **b** counterpart (GP/2E-6222b), **c** Palaeonisciformes scale (GP/2E-6225), **d** Palaeonisciformes scale (GP/2E-6223), **e** Palaeonisciformes maxilla (GP/2E-6231). *Scale bar* at **a**–**d** 2 mm. **e** Maxilla. *Scale bar* 4 mm

ribs, sometimes overlying each other but not ramifying (Fig. 5a–e). The ribs are smooth, shaping as small irregular cylindrical tubes of different sizes.

The growth lines, near the imbrication zone, are joined and slightly curved. However, lines represent growing, thus they acquire different orientations.

The scale GP/2E-5969 (Fig. 5a–b) is 6.8 mm long, 6.2 mm wide and 0.1 mm thick. The distal part is 4.5 mm long. The imbrication zone is around 2.3 mm long. The width of the articulatory region is smaller than the maximum width of the scale (4.0 mm).

The specimen GP/2E-6233 (Fig. 5c, d) is larger, 12 mm long and 12.8 mm wide. The thickness does not exceed 0.1 mm. The preservation of the distal part is incomplete, so with different lengths, however, it was possible to measure the imbrication zone length, which is approximately 8.5 m. The articulatory region is 10 mm long.

Discussion The described scales are very similar to those of the living Indian Ocean Coelacanthidae (*Latimeria*) so they are placed in the Coelacanthiformes.

The shapes of the growth lines and articulatory zone of the Taquaral scales are very similar to those from the State of Sao Paulo late Carboniferous Itararé Subgroup (Bryant 1929) as well as from the State of Rio Grande do Sul, early Permian of the same Subgroup (Barcellos 1975). Also the scale identified by Richter (1985), from the Irati Formation

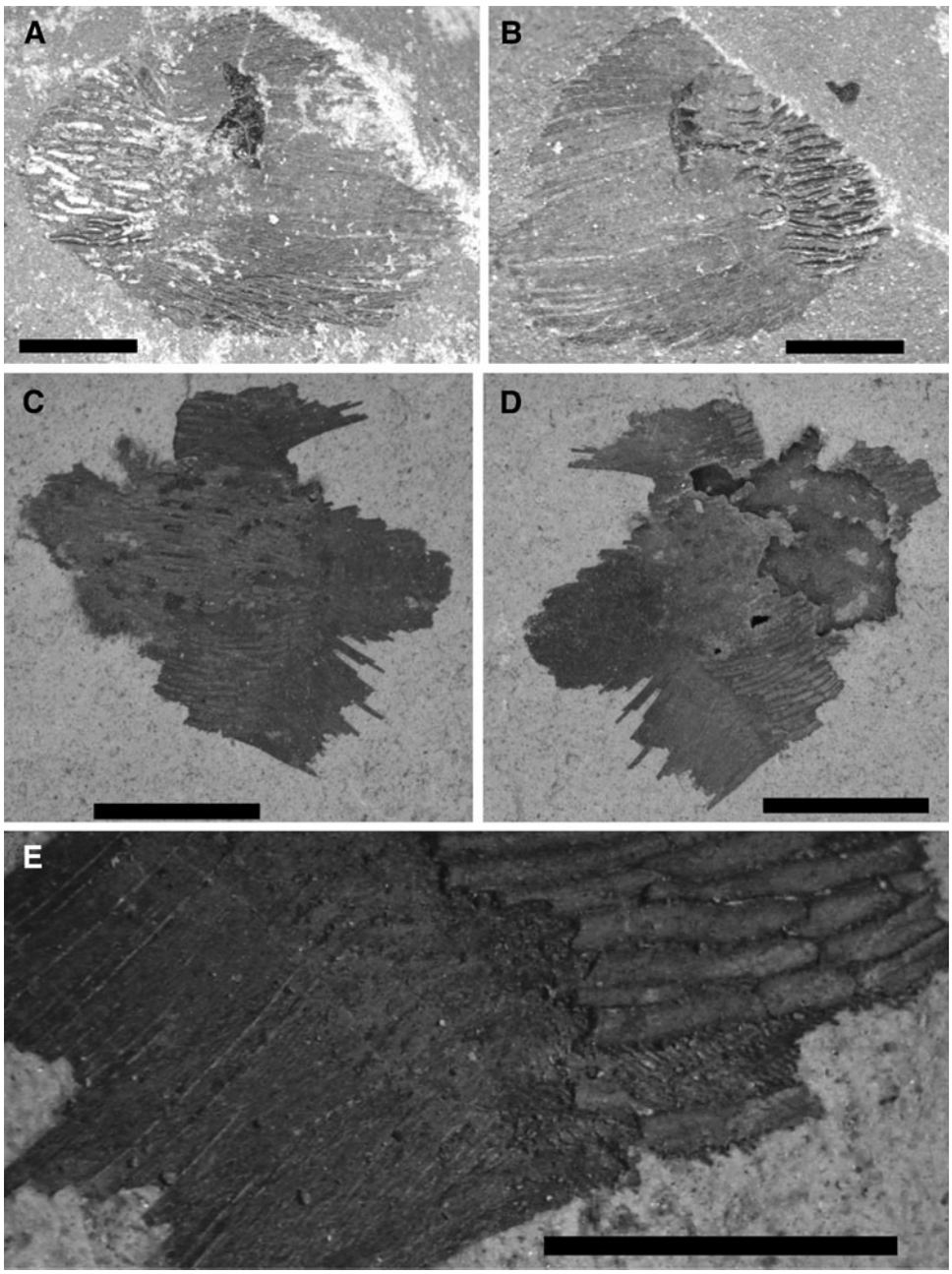

Fig. 5 **a** Coelacanthiformes scale part (GP/2E-5969a), **b** counterpart (GP/2E-5969b). *Scale bar* 2 mm. **c** Coelacanthiformes scale part (GP/2E-6233a), **d** counterpart (GP/2E-6233b). *Scale bar* 10 mm. **e** Articulation zone and growth lines of the specimen GP/2E-6233d. *Scale bar* 2 mm

of Rio Grande do Sul and the scales from state of São Paulo Corumbataí Formation, have similar imbrication zones.

Scales of Coelacanthiformes are rarely found out in beds of the Permian Tatuí Formation, State of Sao Paulo, located under the Taquaral Member, as well as, in the basal sandy facies of the Taquaral Member (Chahud and Petri 2009). They are otherwise, rather common in the silty shale facies of the Taquaral Member, frequently associated with the crustacean *Clarkecaris* and with remains of Palaeoniscifformes. These differences of fossil contents probably would be responses from different conditions of preservation.

Taphonomic signatures

Most of the Taquaral fossils, both invertebrate and vertebrate fragments, few millimeters to centimeters in size, are practically preserved in two dimensions, both compressed and flat.

The Taquaral crustaceans are variably preserved. Several chitin fragmented, somites and disarticulated pieces are observed. Some complete or almost complete specimens of *Clarkecaris* may be found (Fig. 1). Some specimens appear either in the form of folded, imbricated or stretched out tergites.

The *Clarkecaris* frontal cephalothorax seldom is preserved, as mentioned by Mezzalira (1952), due to its fragility in relation to other parts of the carapace. The occurrence of *Clarkecaris* carapace completely or almost completely preserved in a Taquaral bed from the State of Paraná (Brito and Quadros 1978) and in the center-east state of São Paulo (Mezzalira 1952, 1954; Chahud et al. 2010) could be caused by a sudden influx of fine sediments, choking the living organisms. However, sudden increase of the influx of fine sediments would cause mass mortality, not seen in any occurrences in the Taquaral beds. Other interpretations would be occasional storms, revolving the bottom sediments and changing the salinity. Anyway the fossil density must have been small; otherwise, these abrupt environmental changes would be accompanied by dense fossil accumulations.

The vertebrates from the silty shale of the Taquaral are scarce and dispersed, as is also the case for the above-mentioned crustaceans. Most of these remains are isolated Coelacanthiformes and Actinopterygii scales, some of them found together with well-preserved small fragments of bone pieces. The scales preserved the articulatory structures and large parts of the internal and external morphologies.

In spite of well-preserved bone pieces as the above Palaeonisciformes maxilla, nowhere, up to now, articulated ichthiofossils were found.

Occasionally poorly preserved local accumulations of scales and badly preserved inarticulate bone pieces occur, not necessarily from the same animal.

The Coelacanthiformes scale weakness would be the reason why these scales are more frequent in the silty shale facies of the Taquaral Member, laid down on lower energy conditions, than those from the sandy facies. On the other hand, the higher energy deposition of the sandy facies would be favorable for increasing the number of the stronger Chondrichthyes scales (Chahud and Petri 2008a, b).

The presence of the weaker scales and other remains of Coelacanthiformes, the Palaeoniscoformes scale and bone remains and complete *Clarkecaris*, in the silty shale facies, are suggestive that the absence of Chondrichthyes in this facies would indicate that they did not live in this environment.

The probable reason for the sudden change of faunal content from the sandy to the silty shale facies would be the sharp paleoenvironmental change caused by freshwater influx during the deposition of the silty shale. The presence of the Anaspidacea crustacean *Clarkecaris*, adapted to low salinity water, contrasts with some isopod crustaceans from the Tatuí Formation (Mezzalira and Martins-Neto 1992) located under Irati Formation.

The absence of completely preserved specimens of fishes and the presence of articulated crustaceans would probably be caused by different habitats. The fishes would be nektonic, whereas the crustaceans might be benthonic, though they cannot be quoted as sure.

Biostratigraphic correlations

The Irati Formation is 70 m thick and Taquaral Member, 23 m thick as developed at the central-south Paraná Basin (Hachiro 1996; Holz et al. 2010).

The sandy facies, base of the Taquaral Member, bears the Chondrichthyes species *Itapyrodus punctatus* and *Taquaralodus albuquerquei* (Chahud and Petri 2008a, 2010b), is also present in the Pedra do Fogo Formation, Parnaíba Basin, Northeast Brazil, but in different lithologies. The presence of these two species allows a partial chronocorrelation of the Taquaral sandy facies with some part of the Pedra do Fogo Formation. The Taquaral sandy facies with its rich Chondrichthyes teeth and other remains is found only in the state of São Paulo.

Few paleontologic researches were done in Taquaral beds, besides those herein disclosed, some pollens grains and spores (Souza et al. 1992), scarce references with acritarch genera, with their polemic paleoenvironment interpretations (Cazzulo-Klepzig et al. 1989; Cardoso 2010), bivalves (Kazubek and Simoes 2003; Lages 2004) and *Bothryococcus* algae (Cazzulo-Klepzig et al., 1989; Lages, 2004).

The Coelacanthiformes and Actinopterygii scales, commonly attributed to *Elonichthyes*, are reported in every Carboniferous and Permian formations of the Paraná Basin (Bryant 1929; Würdig-Maciel 1975; Chahud and Petri 2008a).

The basins of North Brazil (Amazonas, Solimões Acre, Parecis) had different Permian histories without relationships with the Paraná Basin on the point of view of lithology, fossils and paleoenvironments.

Mesosauridae appear in the Assistência Member (basically in bituminous and non-bituminous shales and calcareous as well as in similar lithologies in Uruguay (Mangrullo Formation) and South Africa (Whitehill Formation). However, no Taquaral beds were recognized for sure, both in Uruguay and South Africa. On the other hand, Mesosauridae in Paraguay appear in sandstones (Harrington 1950).

The Mangrullo Formation, with Mesosauridae and bituminous shales, is correlated with Assistência Member. The presence of Taquaral equivalent in Uruguay is uncertain. Even the Piñeiro et al. (2012) "Mangrullo, Lower actinopterygian level" bears bituminous shale, which discards the correlation with Taquaral, where bituminous shales are completed absent. Also no volcanic ashes are present in Taquaral Member.

Conclusions

The main animal fossils from the silty shale facies of the Taquaral Member of the Irati Formation, Permian of the Brazilian Paraná Basin, are the crustacean *Clarkecaris* and scales and bone fragments of Osteichthyes, predominantly Palaeonisciformes. Coelacanthiforms occur in small numbers.

Chondrichthyes, as well as tetrapods, have not yet been found in this facies. They are present in the basal sandy facies (Chahud and Petri 2008a, 2010a, b) and above, in Assistência Member and the Corumbataí and Serra Alta formations (Würdig-Maciel 1975).

The presence of euryhaline fossils and absence of stenohaline fossils suggest that the Taquaral silty shale facies was laid down in isolated, low salinity, large body of water fed by rivers.

Clarkecaris might come from a salty water taxon, then evolved in isolation, living in a huge restricted lake, covering part of the Brazilian States of São Paulo and Paraná. Such an isolation allowed the evolution up to the level of family, Clarkecarididae.

The fossils reported from the Taquaral Member represent groups known to occur in paleoenvironments of variable salinities, such as, the Chondrichthyes Petalodontiformes (Chahud et al. 2010). Possible connections with the open sea and marine beds are known in the Palermo Formation (and the Tatuí, northern equivalent to Palermo) and mainly in the Itarare Group. The absence of connections with the open sea during deposition of the Taquaral Member is suggested by the lack of stenohaline fossils.

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