Estudios Geológicos
enero-junio 2021, 77(1), e139
ISSN-L: 0367-0449
https://doi.org/10.3989/egeol.44141.594

The Taquaral Member, Irati Formation (Paraná Basin, Permian): a synthesis of paleontological studies

El Miembro Taquaral, Formación Irati (Cuenca del Paraná, Pérmico): síntesis de estudios paleontológicos

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ABSTRACT

The Irati Formation (Cisuralian, Kungurian) is noteworthy for many sedimentological, paleontological and taphonomic features, of great significance for unweaving paleoenvironmental details of deposition. Two members make up this formation: Taquaral, the lower, and Assistência. In the Taquaral Member, lithologic features, sedimentary structures and paleontologic data allowed the recognition of three facies. The lowermost sandy facies bears a rich and diversified vertebrate fauna. The second facies, a silty shale, contains a crustacean endemic family Clarkecariidae, never known in any other deposits of the world, attesting an isolation of the bodywater, during the deposition of this facies. The third facies, known only in the state of Paraná shows intermittent conditions for calcareous deposits. Bivalves are present only in the calcareous facies, deposited in the upper half of this member. This study provides a synthesis of the paleontological record of the member Taquaral and a interpretation of its depositional environments, based on sedimentological and paleontological data.

Keywords: Cisuralian; Kungurian; Paleozoic; Chondrichthyes; Crustacea; Anaspidacea

RESUMEN

La Formación Irati (Cisuraliense, Kunguriense) se destaca por sus características sedimentológicas, paleontológicas y tafonómicas, importantes para conocer detalles paleoambientales y deposicionales. Dos miembros componen esta formación: Taquaral, el inferior, y Assitência, superior. En el miembro Taquaral, las características litológicas, las estructuras sedimentológicas y los datos paleontológicos permitieron el reconocimiento de tres facies. Las facies arenosa inferior es caracterizada por una fauna de vertebrados rica y diversificada. La segunda facies, compuesta por lutitas limosas, contiene una familia endémica de crustáceos Clarkecariidae, desconocida en cualquier otro depósito del mundo, lo que deja evidente del cuerpo de agua durante la sedimentación de esta facies. La tercera facies, conocida solo en el Estado de Paraná, es la única que alcanza condiciones intermitentes para la sedimentación de carbonatos. Los moluscos bivalvos están presentes solo en estas facies, cuya sedimentación ocurrió solo en la mitad superior de este miembro. Este trabajo presenta una síntesis del registro paleontológico del miembro Taquaral y una interpretación de los distintos ambientes deposicionales obtenida a partir de datos sedimentológicos y paleontológicos.

Palabras clave: Cisuraliense; Kunguriense; Paleozoico; Chondrichthyes; Crustacea; Anaspidacea

Recibido el 26 de octubre de 2020; Aceptado el 22 de marzo de 2021; Publicado online el 21 de mayo de 2021

Citation / Cómo citar este artículo: Chahud, A. (2021). The Taquaral Member, Irati Formation (Paraná Basin, Permian): a synthesis of paleontological studies. Estudios Geológicos 77(1): e139. https://doi.org/10.3989/egeol.44141.594

Introduction

The Paraná Basin is a intracratonic basin located in southernmost Brazil, Uruguay and parts of Paraguay and Argentina. The basin covers a surface area of about 1,700,000 km2, has a present NE–SW elongated shape, and is approximately 1750 km long and 900 km wide. Late Paleozoic rocks along the eastern border of the Paraná Basin in east-central São Paulo state, southeastern Brazil, are represented, from the base up, by the Tubarão Supergroup (Upper Carboniferous to Permian), including the Itararé Group and the Tatuí Formation, and the Passa Dois Group (Permian), consisting of the Irati and Corumbataí Formations (Holz *et al.*, 2010).

The term Irati was initially proposed by White (1906) as "black schisto", rich in oil, then registered in the states of São Paulo and Paraná. Subsequently the research was extended to the entire Brazilian part of the Paraná Basin (Fig.1), White's proposal resulted in many stratigraphic researches, until reaching Barbosa & Gomes (1958) who subdivided the Irati into two members: Taquaral (lower) and Assistência (upper). This stratigraphic division was accepted by most of the researchers (Holz *et al.*, 2010; Chahud *et al.*, 2010a, 2010b, 2012).

Hachiro *et al.* (1993) and Hachiro (1996) proposed upgrade the Irati Formation to Subgroup and the Taquaral and Assistência members to formations. This proposition was not properly formalized, due to mapping problems, so the present researchers rather favor to keep the proposal of Barbosa & Gomes (1958).

Absolute dating on Assistência beds by Santos *et al.* (2006) and Rocha-Campos *et al.* (2007) yielded Cisuralian ages, between 279 - 276Ma (Kungurian).

The Taquaral Member occurs irregularly in the Paraná Basin, absent in some places and with thickness close to 30 m in others (Hachiro, 1996; Chahud, 2007, 2011). Dark gray and non-bituminous siltstones and mudstones are the main lithologies (Fig. 2). Three facies are distinguished based on lithologies, fossils and geographic areas.

The first facies is defined by lenticular layers of conglomeratic sandstones, with granules and chert pebbles. Maximum thickness is one meter, normally 10 to 40 cm. These lithosomas are disposed irregularly, without any order of deposition of granulometry. Hachiro (1996) distinguished several facies on granulometric basis. Diversified Chondrichthyes were studied by Chahud & Petri (2008a, 2009a, 2010b, 2010c, 2012a).

The second facies is an almost homogeneous non bituminous silty-shale, generally plane-parallel laminated, no sedimentary structures. The thickness range from 5 to 30 meters. The crustacean *Clarkecaris* Clarke 1920 is known only in this facies.

A third facies represented by fine carbonate layers can be observed in the thichest stratigraphic sections of the Taquaral Member, in the State of Paraná. The thickness of these carbonates around 30 cm. It is composed of dolomitic micrites, occasionally containing bivalves, located in the upper half of the unit (Hachiro, 1996; Lages, 2004; Matos *et al.* 2017).

The Taquaral Member has recently been the target of numerous paleontological and sedimentological contributions, with emphasis on the study of facies, vertebrates, arthropods, ichnofossils, palynology and taphonomy (Lages, 2004; Holz *et al.* 2010; Chahud *et al.* 2010b; Chahud & Petri, 2010a; 2015b). A synthesis of these contributions is the main goal of this contribution.

Paleontological Studies

Micropaleontology and Paleopalynology

Previous references on microfossils from Taquaral, are scarce and few illustrated. Lages (2004) issued the main palynological study on drilled cores. The Taquaral Member is characterized by a great diversity of pollens: *Alisporites* Daugherty, 1941; *Lueckisporites* Potonié & Klaus, 1954; *Striatopodocarpites* Sedova, 1956 and *Vittatina* Mildenhall, 1994 and spores: *Punctatisporites* Potonié & Kremp, 1954 and *Cirratriradites* Wilson & Coe 1940.

The biostratigraphy of the Taquaral Member allow some paleoenvironmental interpretations.

The acritarchs genera present in the beds are related to an environment wit salinity (Grice *et al.*, 2005). Marasco *et al.* (1993) reported only the genus *Micrhystridium* in the sandy-facies in the State of São Paulo while Cardoso (2010) reported four genera in the silty-shale facies of the State of Paraná (Fig. 1),

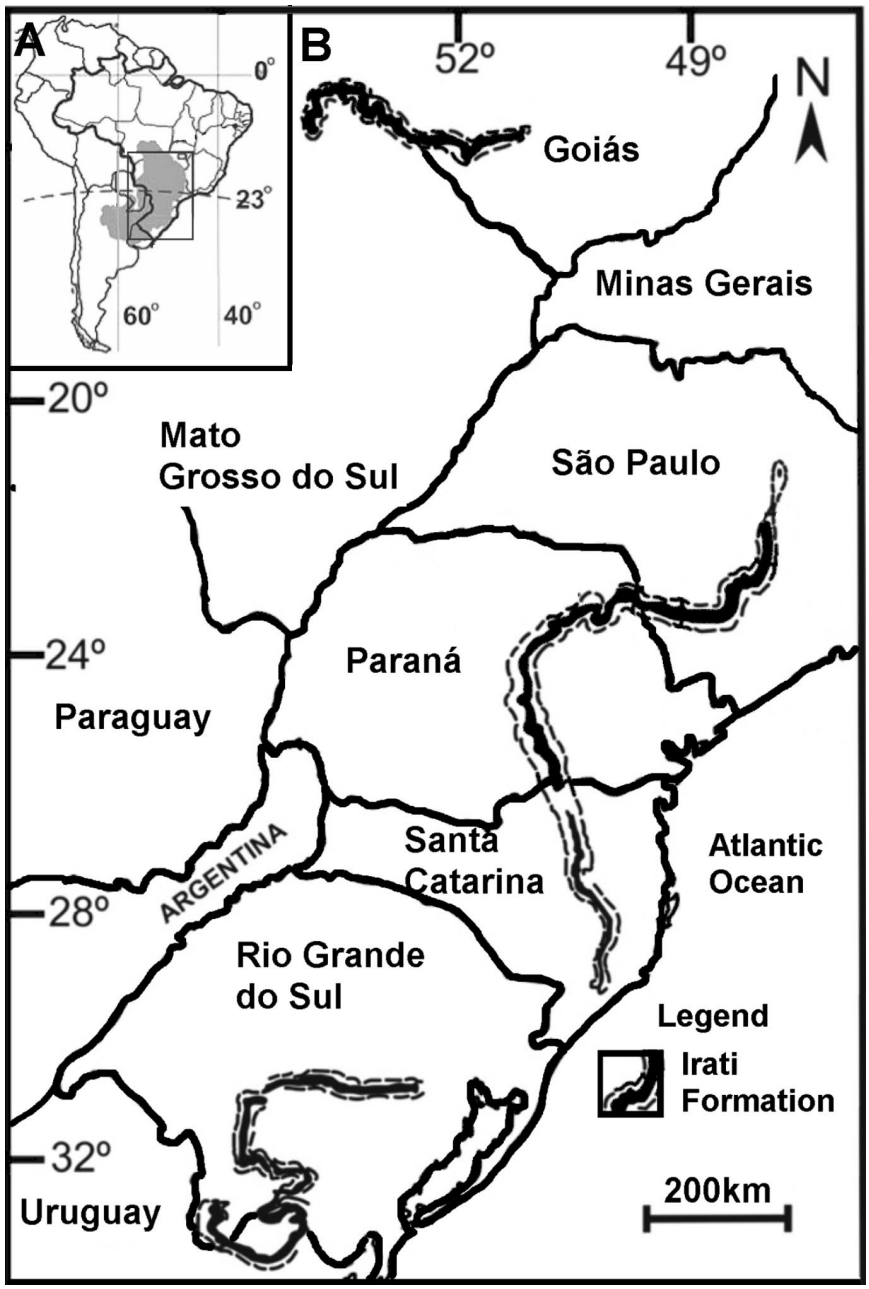

Figure 1— A) Map of the Paraná Basin (gray region) in map of South America; B) Outcrop belt of the Irati Formation (adapted from Hachiro, 1996 and Calça & Fairchild, 2012).

Micrhystridium Deflandre, 1938; *Veryhachium* Deunff, 1954; *Tasmanites* Newton, 1875 and *Deusilites* Hemer & Nygreen, 1967.

Lei *et al.* (2013) were not able to uphold a clear distinction between *Micrhystridium* and *Veryhachium* calling both genera as a complex, though they cited in China, Late Permian, different species as *Micrhystridium* and *Veryhachium*. In China they occur in different Late Permian palaeoenvironments from nearshore to continental slopes. The poor taxa representation on Taquaral, might be caused by a rather isolated lagoon, where the sea phytoplankton would easily enter with the tides.

Lages (2004) observed the typical freshwater algae, *Botryococcus* Kützing, 1849, in Taquaral Member, but the presence of this genus only indicates that

the environment received freshwater in the system.

Another microfossil observed was identified by Mezzalira (1980), a monoaxial spongy spicules associated with fish and crustacean remains.

Molluscs

The molluscs, in despite of hard shells resistant to transport, are not frequently found in the Irati Formation.

Bivalves are scarcely mentioned in Taquaral deposits, but when uncommon calcareous thin layers interbed with shales, then lots of specimens, with 5 mm long, were found in the outcrops (Kazubek & Simoes, 2002, 2003; Rohn et al, 2003; Lages, 2004). Matos *et al.* (2017) studied their taxonomy and identified a poor fauna, composed only of the genera *Runnegariella* Simões & Anelli, 1995 and *Plesiocyprinella* Holdhaus, 1918 and some indeterminate forms densely concentrated.

Arthropods

The arthropods are the most well preserved fossils in the Taquaral Member. All the fossils are from the silty-shale facies. The most common species is *Clarkecaris brasilicus*. It is easily recognized by a narrow, elongated body composed of 8 narrow pustular thoracic somites, 6 distinctly wider abdominal somites, without pustulation and two large pterygostomial spines. It is endemic in Taquaral Member of the states of São Paulo and Paraná (Fig. 1). According to Brooks (1962) this genus belongs to the family, Clarkecarididae, within the order Anaspidacea, but without relation to other families.

The paleoenvironment inhabited by *Clarkecaris* is controversial, whether inhabited saline or freshwater paleoenvironments. Beurlen (1931) suggested freshwater, based on the recent Anaspidacea. Mezzalira (1952) discussed the paleoenvironment of *Clarkecaris,* but although phylogenetically close genus *Anaspidites* Chilton, 1929, prefer freshwater. Beurlen (1931) and Mezzalira (1952) agreed that this genus probably inhabited coastal regions rather than the deepest part of the Paraná Basin so they are present in regions closer to the basin border.

Clarkecaris brasilicus was compared with the Paleocaridacea of the Carboniferous, *Squillites* Scott, 1938 and *Palaeocaris* Schram, 1984. According to Schram & Schram (1974) *Clarkecaris* have features transitional between the more primitive Paleocaridacea and the living Anaspidacea of the genus *Anaspidites*. The *Squillites* paleoenvironment is doubtful, because its remains have been found associated with freshwater and euryhaline fossils. Other genus, *Palaeocaris* has long been considered freshwater, but fossils associated with estuarine paleoenvironments or with variable salinity have been found (Schultze, 2009). Schram & Schram (1974) and Schram (1977) considered the earliest Devonian Syncarids, marine, passing in the Early Carboniferous to less saline and freshwaters. Many Syncarida Anaspidacea groups have restricted themselves to the South American and Australian continents; therefore Gondwana is their refuge at the end of the Paleozoic.

Another crustacean, very rare, is represented only by caudal uropods. The first citations were from Foehringer & Langer, (2003, 2004) who identified them as chelae, subsequently correctly identified by Chahud & Petri (2013b).

Vertebrates

Vertebrates remains are found throughout the Taquaral Member, however the greatest abundance and diversification are in the sandy facies. In spite of the great variety and frequence, the fossils are, in general, disarticulated, only teeth, scales, finspines and scattered bones.

Chondrichthyes

Chondrichthyes are the most diversified group, with spines and teeth of different sizes and states of preservation (Chahud & Petri, 2015a, 2015b, Chahud, 2018).

The dorsal finspines of Elasmobranchii are rare, but it was possible to identify the genera *Sphenacanthus* Agassiz, 1837; *Amelacanthus* Maisey, 1982 and indeterminate species (Chahud *et al.*, 2010b, 2012; Chahud & Petri, 2014).

The Chondrichthyes teeth are the most abundant remains. Among the indeterminate forms, three different cladodonts were recognized (Chahud & Petri, 2012a).

The Xenacanthiformes are the most abundant elasmobranchs. The most common species is *Taquaral-*

odus albuquerquei Silva Santos, 1946 (Silva Santos 1946, Chahud & Petri, 2010c). This species was first described in the Pedra de Fogo Formation, Parnaíba Basin by Silva Santos (1946), with the name *"Pleuracanthus" albuquerquei*. Ragonha (1978) was the first to identify this species in the Taquaral Member. Ragonha (op. cit.) recognized external morphological differences of *"Pleuracanthus"*, informally suggesting the genus "*Taquaranthus"*, but without adequate revision. Chahud & Petri (2010c) reviewed this species and observed different morphological characteristics from any other genus of Xenacanthiformes, such as cuspids and coronal button, therefore they considered more appropriate a new genus, *Taquaralodus*.

Other Xenacanthiformes in the sandy facies of the Irati Formation are represented by the genus *Xenacanthus* Beyrich, 1848 and indeterminate species (Chahud & Petri, 2009b).

The oldest occurrence of the genus *Orodus* in Brazil is from the Taquaral Member, *O. ipeunaensis* Chahud, Fairchild & Petri, 2010 (Chahud *et al.* 2010b), older than *O. milleri* Würdig-Maciel, 1975 from the Teresina Formation in southern Brazil (Würdig-Maciel, 1975, Richter, 2004a, 2004b). Only these two species of this genus are recognized in Brazil.

Teeth of two above mentioned species of Chondrichthyes, *Taquaralodus albuquerquei* and *Itapyrodus punctatus* Silva Santos, 1990 are described both in Pedra de Fogo and Irati formations (Ragonha, 1978; Silva Santos, 1990; Chahud & Petri, 2008a, 2010c; Chahud *et al.*, 2010b).

Ragonha (1978) and Silva Santos (1990) placed *Itapyrodus* within the Petalodontiformes, however Chahud & Petri (2016) put it in Holocephali, inasmuch new classification of this order is suggested by Lund *et al.* (2014) and Grogan *et al.* (2014).

Indeterminate Holocephali were observed from isolated, irregularly shaped teeth, comparable to the genus *Itapyrodus* at the base of the Taquaral Member.

No Chondrichthyes are known in the silty-shale facies, suggesting that environmental changes restricted these fishes in shallower areas of the basin or in regions that maintained tolerable salinity.

The Holocephali first appeared in the Paraná Basin, in deposits of the lowermost Taquaral Member, so the most probable hypothesis for its origin in the basin would be a link between the Paraná and Parnaíba basins (Chahud & Petri 2014, 2016).

Palaeonisciformes, Sarcopterygii and tetrapods

Remains of bony fish are present throughout the Permian of the Paraná Basin. They are the most abundant group of paleovertebrates, but few species have been described, due to the scarcity of articulated specimens.

The Palaeonisciformes are known by teeth, scales and indeterminate bones. Teeth are usually conical and simple; however the size and surface ornamentation are variable in every units of the Paraná Basin (Würdig-Maciel, 1975, Richter *et al.*, 1985, Chahud & Petri, 2008b, 2010a, Chahud, 2020). The fossils are more abundant and diversified in the sandy facies (Chahud & Petri, 2008b, 2016) than in silty-shale facies when only small scales and teeth are identified (Chahud & Petri, 2013a, 2013b).

The Sarcopterygii occur in the form of teeth, scales and bony parts. Coelacanthiformes scales are the most common in silty-shale (Chahud & Petri, 2013a, 2013b) and very rare in sandy facies, in which bones and possible teeth are present (Chahud & Petri, 2009b, 2012b). They are rare in sandy facies which may be caused by the fragility of the scales which would not resist the high energy environment characteristic of this facies.

The tetrapods Temnospondyli are present in the sandy facies by teeth, mandibulars fragments (Chahud & Petri, 2010a) and small appendicular bones of probable small species, which may be attributed to Osteolepiformes (Chahud & Petri, 2009b, 2012b).

Taphonomy

The presence of abraded specimens together with teeth, scales and spines with few little breaks or even no kinds of abrasion, are interpreted as deposits laid down under episodic events of storms (Chahud & Petri, 2015b).

The crustaceans of the silty-shale facies are complete or almost complete with scarce examples of little abrasion or broke. The vertebrates are disarticulated, represented mainly by well preserved scales of Sarcopterygii and Palaeonisciformes (Chahud, 2017).

The Taquaral Member bivalves were taphonomically studied by Matos *et al.* (2017) who noticed a preferential orientation in a unimodal or bimodal arrangement, characterizing shallow water transport to more distant regions through episodic events of storms.

Paleoenvironmental Considerations

The Irati stratigraphy is heterogeneous, with geographical differences. It is important therefore, to analyze local sections which clarify different paleoenvironments, along the time.

The overall details of the Taquaral basal deposits allow interpretation of a transgressive tract system (Hachiro, 1991, 1996; Assine *et al.*, 2003; Holz *et al.* 2010).

According to Holz *et al.* (2010), the Taquaral Member was laid down in a shallow environment with very restricted connection with the open ocean. However Chahud & Petri (2013a, 2013b, 2014) questioned this connection due to the absence of exclusively marine fossils based on comparison with the current Black Sea system, where typical freshwater animals were replaced by a marine fauna after a connection with the Mediterranean Sea, during a few thousand years (Sorokin & Kuprin, 2007).

The silty-shale facies exhibits preserved complete crustaceans and fragile Actinistia scales (Chahud & Petri, 2013a, 2013b), attesting good conditions of preservation. However, no exclusively marine fossil are present, in spite of a long history of Taquaral researches.

The sandy facies, located at the base of the Taquaral Member, is the only evidence of connection with an outside basin. According to Chahud & Petri (2014) the Taquaral waterbody might be connected with the Parnaiba Basin, Pedra de Fogo Formation, northeastern Brazil, during the Permian, for a short time, which might have helped to increase the level of the Taquaral waterbody in the Paraná Basin. The Chondrichthyes *Itapyrodus punctatus* and *Taquaralodus albuquerquei* present in both basins, are evidence for this connection (Silva Santos, 1946, 1990; Chahud *et al.*, 2010b; Chahud & Petri, 2010c, 2014). The absence of these fishes in any other basins suggest that they did not migrate from other territories.

Itapyrodus punctatus is reported, in Paraná Basin, only in the Taquaral sandy facies and only in the State of São Paulo and Parnaiba Basin, as seen above. Other species of *Itapyrodus*, as yet not named, was also reported only in the State of São Paulo, but in the Corumbataí Formation, younger than Irati (Chahud & Petri, 2016).

The *Taquaralodus albuquerquei* also is known only in the Taquaral sandy facies of the State of São Paulo, without any similar fossils, being later replaced by Xenacanthidae of the genera *Xenacanthus* and *Triodus* in more recent units, Corumbataí, Teresina and Rio do Rasto formations (Würdig-Maciel, 1975; Ragonha, 1984; Pauliv *et al.*, 2014; 2017).

The sudden disappearance of the Chondrichthyes in the Taquaral Member after the sandy facies, possibly was a result of decreasing salinity of water body after the sandy facies deposits, isolated forever from the Parnaíba Basin and, eventually, from the open ocean.

After the beds bearing *Itapyrodus punctatus* and *Taquaralodus albuquerquei* in the Pedra de Fogo Formation, Parnaíba Basin turned over to a continental paleoenvironment bearing plant fossils and tetrapods (Cisneros *et al.*, 2015; Conceição *et al.*, 2016).

The influence of rivers leading to freshwater environments for the Taquaral Member was first suggested by Mussa *et al.* (1980) based on the presence of *Clarkecaris*, which, as Anaspidacea, has been associated with freshwater. However, as discussed earlier, *Clarkecaris* is a transitional form between the present freshwater Anaspidaceae and the Carboniferous Palaeocaridaceae of marine origin or of variable salinity, so it is not a good indicator.

Although no fossils in Taquaral is exclusively freshwater, on the other hand, no ocean fossils are present. Besides, freshwater flows were recognized by the presence of pollen, spores and algae *Botryococcus* (Lages, 2004).

Carbonate layers bearing bivalve coquinas (Facies 3, Fig. 2) are solely as yet present in the state of Paraná (Matos *et al.*, 2017). They interfinger with the facies silty shale.

During the carbonate layers deposition, the waterbody keep decreasing, caused by the dry climate, resulting a low energy paleoenvironment and the beginning of Assistência Member, anoxic phase (Matos *et al.*, 2017).

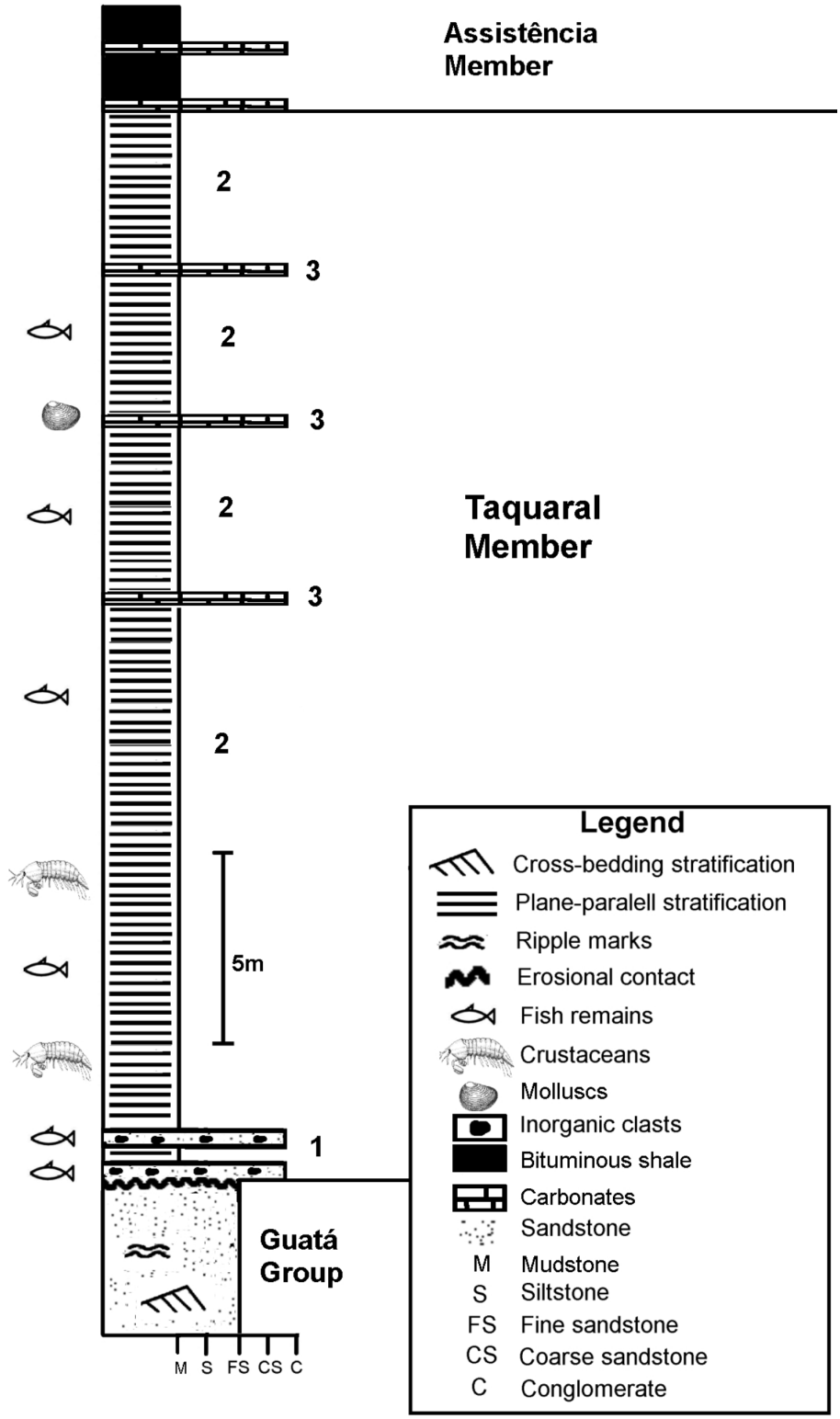

Figure 2— Sketched columnar section of the Taquaral Member, Irati Formation as occurring at the States of São Paulo and Paraná. 1) Sandy-facies; 2) Silty-shale facies; 3) Carbonate layers.

Episodic events, such as storms, have always been common during the deposition of the Irati Formation. According to Chahud & Petri (2015a) and Matos *et al.* (2017), the storms were responsible for the fish and bivalves deposits.

Many fossils occur in paleoenvironments of variable salinity such as acritarchs, bivalves and fishes. Related species are known in older units, Palermo and Tatuí formations and Itararé Group (Silva Santos, 1946; Fúlfaro *et al.* 1984; Cazzulo-Klepzig *et al.* 1989; Marasco *et al.* 1993; Holz *et al.* 1998; Chahud & Petri, 2015b; 2015c). Many species may have survived paleoenvironmental changes, reaching younger units due to their adaptability (Chahud & Petri, 2016, Matos *et al.*, 2017). These species were restricted to specific conditions of the basin, allowing survival, in restricted or epicontinental seas, like Baltic, Caspian and Aral (Zenkevich, 1957; Brenner, 2005).

Conclusions

The Taquaral Member, the basal unit of the Irati Formation, is composed mainly of non-bituminous silty-shales, with sandy layers located at the base, near the border of the basin and thin carbonates layers in the upper half, of the thickest stratigraphic sections.

The microfossils include several genera of palynomorphs, spores, pollen, acritarchs and the *Botryococcus* algae. None were found to be reliable indicators of oceanic, freshwater, or continental environments for their adaptability for changing or ease of transportation.

The lowermost Taquaral sandy-facies, in spite of thin (ten to forty centimeters, seldom 1 meter) is noteworthy for testifying an unique happening a connection between two basins, Paraná and Parnaíba.

Other noteworthy characteristic of the sandy-facies as the great diversity and frequency of fishes and the presence of both Taquaral Member and Pedra de Fogo Formation, of the species *Itapyrodus punctatus* and *Taquaralodus albuquerquei*. These species occur only in these two units, absent in any other basin in Brazil and abroad, evidence of the connection between two basins as mentioned above. Several groups of fishes still upholder the lower salinity but others were extinct, like the genus *Taquaralodus*.

The better preserved fossils are the crustaceans from the silty shale facies. The *Clarkecaris* crustacean is the most common, endemic, different from all existing Anaspidacea, its evolution in isolation resulted in an unique form, no descendants in the geological record.

ACKNOWLEDGEMENTS

The author thank the Prof. Dr. Setembrino Petri and Prof. Dr. Thomas Rich Fairchild for support and jointing field researches, and the proprietors of the Santa Maria homestead, Luiz and Bernadete Esposti, and Ponte Nova Farm, Mr. Bartman. The authors thank also the Departamento de Geologia Sedimentar e Ambiental of the Institute of Geoscience of the University of São Paulo which allowed the preparation of fossils in its laboratories.

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