

Publication status: This preprint has not been published elsewhere.

State of Knowledge on the Paleoenvironmental Evolution of the Tatuí Continental System during the Early Permian of the Paraná Basin

Artur Chahud

<https://doi.org/10.1590/SciELOPreprints.17296>

Submitted on: 2026-08-04

Posted on: 2026-10-26 (version 1)

(YYYY-MM-DD)

State of Knowledge on the Paleoenvironmental Evolution of the Tatuí Continental System during the Early Permian of the Paraná Basin

Artur Chahud

Department of Genetics and Evolutionary Biology, Institute of Biosciences, University of São Paulo, São Paulo, Brazil. E-mail: arturchahud@yahoo.com ORCID:

<https://orcid.org/0000-0001-7690-3132>

ABSTRACT

The Tatuí Formation records one of the most complex episodes of paleoenvironmental evolution in the Paraná Basin during the Early Permian, representing the transition between the glacial and periglacial conditions inherited from the Itararé Group and the establishment of a broad coastal system with a continental predominance. This evolution resulted from the interaction among fluvial, deltaic, lacustrine, lagoonal, and marine processes, developed over a paleotopographic surface inherited from the Late Paleozoic glaciation, whose compartmentalization into topographic lows and high areas controlled the significant faciological heterogeneity of the unit. In the depressions, fine-grained deposits associated with low-energy lacustrine and lagoonal environments predominated, whereas the elevated compartments acted as sediment source areas, giving rise to higher-competence fluvial systems such as the Ibicatu Paleoriver, a high-energy braided system responsible for the deposition of the Ibicatu Facies and the sediment supply to a broad progradational deltaic system. Low-energy environments, including ephemeral lakes, floodplains, abandoned paleochannels, and brackish lagoons influenced by incursions of the Rio Bonito–Palermo Sea, record periods of greater hydrodynamic stability, as evidenced by tidal structures and wave- and storm-generated reworking. Recurrent relative sea-level fluctuations promoted the alternation between continental and shallow-marine conditions, which is also reflected in the paleontological record. Siltstone deposits preserve conchostracans, crustaceans, and actinopterygian fish characteristic of temporary continental environments, while ichnofossils, acritarchs, and agglutinated foraminifera document episodes of marine connectivity. The Ibicatu Flora, represented by silicified trunks of *Tietea* and gymnosperms, demonstrates the presence of forested areas adjacent to the river

channels. Taken together, these records indicate that the Tatuí Formation constitutes a transitional depositional system between continental and shallow-marine environments, whose evolution was controlled by the paleotopography inherited from the Late Paleozoic glaciation, climatic seasonality, and fluctuations of the Rio Bonito–Palermo Sea, configuring an important archive for the paleoenvironmental and paleoclimatic reconstruction of the eastern margin of the Paraná Basin.

Keywords: Ibicatu, Guatá Group, Rio Bonito Formation, Palermo Formation, Conchostracans, Pteridophytes

1. INTRODUCTION

The Pennsylvanian–Permian lithostratigraphic units of the Paraná Basin in Brazil are composed, from oldest to youngest, of the Itararé, Guatá, and Passa Dois groups, which are grouped in the Gondwana I Supersequence (Milani and Ramos, 1998). In the central-eastern region of the State of São Paulo, almost the entire Neopaleozoic–Mesozoic section of the northeastern margin of the Paraná Basin is exposed. This sequence begins with the Permo–Carboniferous packages of the Itararé Group and the Permian deposits of the Tatuí Formation and Passa Dois Group (Irati and Corumbataí Formations) and culminates with the Mesozoic São Bento Group (Piramboia, Botucatu, and Serra Geral Formations) (Milani *et al.*, 2007).

The Tatuí Formation is dated to the Lower Permian, restricted to the State of São Paulo, and chronocorrelated with the Rio Bonito and Palermo formations, both belonging to the Guatá Group in southern Brazil (Stevaux *et al.*, 1986; Assine *et al.*, 2003; Milani *et al.*, 2007; Holz *et al.*, 2010; Chahud, 2011).

The name Tatuí ("Tatuhy") was formally proposed by Washburne (1930) for Permo–Carboniferous rocks. The unit was described as post-glacial and discordant at the top, marking the transition from a freshwater to a marine environment. Subsequently, Barbosa and Almeida (1949a; b) proposed the subdivision of the Tubarão Group (currently Supergroup) in the State of São Paulo into the Itu (basal), Capivari, Gramadinho, Tietê, and Itapetininga formations, the latter being divided into the Tupi, Tatuí and Taquaral members.

In the characterization by Almeida and Barbosa (1953), the Tatuí Member of the Itapetininga Formation was defined by a sandy constitution with planar-parallel

stratification, green coloration with reddish tones, and intercalated occurrence of calcareous layers. The depositional environment was interpreted as a shallow, warm marine environment, characterized by slow deposition on a muddy bottom of a stable platform, without evidence of clasts of glacial origin. At the top of the member, the authors recorded the presence of layers and lenses of chert, in addition to the presence of a fine conglomerate containing chert pebbles. Subsequently, Barbosa and Gomes (1958) maintained the name Tatuí Member and excluded the Taquaral Member from the Itapetininga Formation, considering the unit composed only of green sedimentary rocks with thicknesses ranging from 30 to 50 meters. Later, Petri (1964) revalidated the term Tatuí Formation and interpreted the greenish rocks as being of post-glacial continental origin, while Rocha-Campos (1967) defined the post-glacial boundaries at the contact between the Itararé Group and the Tatuí Formation.

Lithologically, the Tatuí Formation consists of successions of fine-grained sandstones, locally massive or with hummocky cross-stratification, siltstones, and claystones. Subordinate lithologies include levels and layers of coarse-grained to conglomeratic sandstones of fluvial-deltaic origin, which locally can exhibit significant thicknesses (Washburne, 1930; Soares, 1972; Massoli, 1980; Fulfaro *et al.*, 1984; Stevaux *et al.*, 1986; Assine *et al.*, 2003; Holz *et al.*, 2010; Chahud, 2011; Chahud *et al.*, 2012). These thick conglomeratic layers were informally known as the Ibicatu Facies (Soares, 1972). Since the type section of this facies was overlain by deposits of the Irati Formation, it was sometimes erroneously allocated to the basal strata of the Taquaral Member. However, the Ibicatu Facies actually occurs in different stratigraphic positions throughout the Tatuí Formation (Fulfaro *et al.*, 1984; Stevaux *et al.*, 1986; Assine *et al.*, 2003; Holz *et al.*, 2010; Chahud, 2011).

Paleontological knowledge of the unit is scarce and restricted to descriptions of crustaceans and bibliographic citations of plants and microfossils, such as fragments of fish, crustaceans, acritarchs, and agglutinated foraminifera (Fulfaro *et al.*, 1984; Cabral Jr. *et al.*, 1988; Mezzalira and Martins Neto, 1992). Furthermore, all known fossiliferous outcrops of the Tatuí Formation are located exclusively in the upper 10 meters of the unit (Mezzalira, 2000; Chahud *et al.*, 2010a; Chahud, 2011; Chahud *et al.*, 2012).

The main objective of this work is to present a collection of data, hypotheses, and paleoenvironmental proposals related to studies conducted on the continental depositional phase of the Tatuí Formation from the Permian of the Paraná Basin.

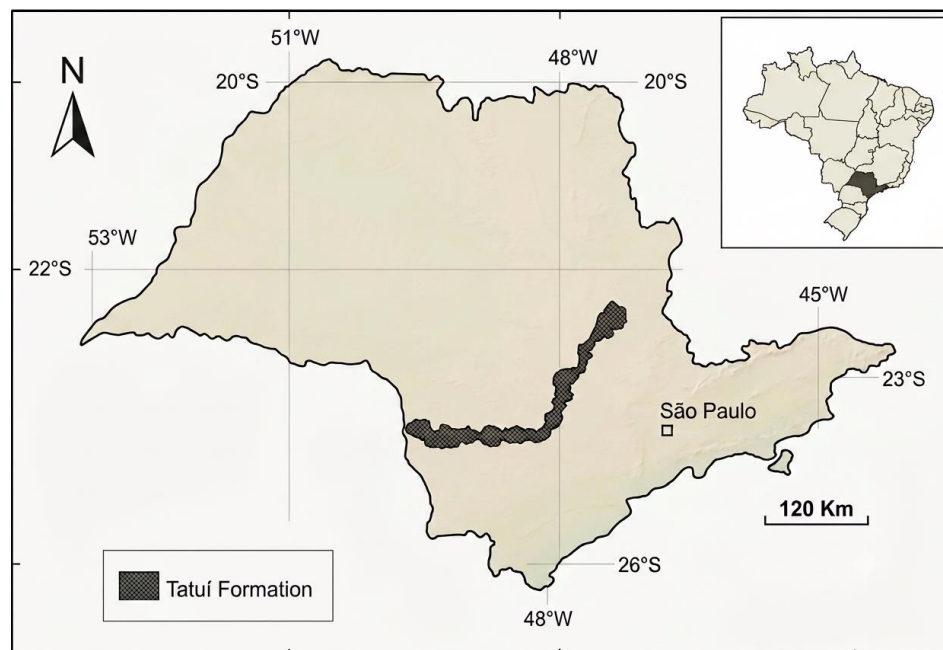


Figure 1 - Outcrop area of the Tatuí Formation in the State of São Paulo.

This review was based on extensive bibliographic research on the Tatuí Formation, encompassing publications in scientific articles and proceedings of scientific events from the 20th century and the early 2000s (Almeida and Barbosa, 1953; Barbosa and Gomes, 1958; Petri, 1964; Soares, 1972; Petri and Fulfaro, 1983; Stevaux et al., 1986; Fulfaro et al., 1984; Mezzalira and Martins Neto, 1992; Assine et al., 2003). To these data are added field observations carried out by the author between 2003 and 2015 in outcrops of the unit, whose procedures, sampling, and detailed results are described or published in Chahud *et al.* (2010a; 2012), Chahud (2011) and Chahud and Petri (2015).

The paleoenvironmental and paleogeographic interpretations presented in this study result from the integration of lithostratigraphic and paleontological data available in the literature and field observations carried out between 2003 and 2015, configuring an interpretative model for the continental phase of the Tatuí Formation, which can be refined by future studies with additional quantitative data.

2. PIONEERING STUDIES ON STRATIGRAPHY

The Tatuí Formation has a history of stratigraphic studies marked by controversies regarding its subdivision and lithological complexity, contrasting with the relative preservation of the related units of the Guatá Group in southern Brazil. Formal

investigations were initiated by Soares (1972), who described the unit as predominantly silty (90%) and bounded by discontinuities. The author subdivided it into two main packages: a lower one, dominated by brownish-purple siltstones with thin intercalations of limestone, flint, and sandstone; and an upper one, composed of gray to yellowish-green siltstones. This framework was structured by different boundaries: the L2 diastem (which separates both packages), the L3 unconformity (internal to the upper package, dividing massive facies from facies intercalated with ripple marks and fossils), and the L4 boundary, which marks the abrupt and frequently erosive contact with the Irati Formation, where the so-called "Ibicatu clastic wedge" stands out.

In the following decades, several authors sought to position the unit within the regional context of the basin. Soares and Landim (1973) and Schneider *et al.* (1974) correlated the Tatuí Formation with the upper portion of the Rio Bonito Formation (Paraguaçu Member) and the Palermo Formation, highlighting its reduced thickness in São Paulo (less than 30 meters). On the other hand, Petri and Fulfaro (1983) and Fulfaro *et al.* (1984) argued that the Rio Bonito Formation was absent in the state, equating the Tatuí Formation directly with the Palermo Formation and proposing the Tietê Formation as the true representative of the Rio Bonito in the region.

From the 1990s onwards, studies refined the facies and sequential characterization of the unit. Castro *et al.* (1993a; 1993b) revalidated the nomenclature Tatuí Formation and divided it into three transgressive-regressive cycles, interpreting its top and base surfaces as discordant. During the same period, Perinotto and Fulfaro (1993) characterized eight distinct sedimentary facies (F1 to F8) for the unit, ranging from mudstones and sandstones with hummocky stratification to conglomerates and carbonate beds. In parallel, Pires and Petri (1993) positioned the transgressive maximum at the top of the formation, associating it with a highstand systems tract with a low sedimentation rate during the deposition of the Taquaral Member.

3. Initial Paleoenvironmental Proposals

The first proposals regarding the paleoenvironment of the Tatuí Formation were scarce and did not address the topic as a primary focus. Initially, Almeida and Barbosa (1953) and Barbosa and Gomes (1958) attributed a shallow marine origin to the rocks of the unit based on the presence of sponge spicules, an interpretation contested by Petri (1964), who argued that such sponge fossils did not constitute conclusive evidence of a marine environment. Subsequently, Stevaux *et al.* (1983) analyzed symmetrical ripple

marks from the "Tupi Member of the Itapetininga Formation" (sensu Barbosa and Almeida, 1949, equivalent to the top of the Itararé Group) and interpreted the depositional environment as marine, under a body of water with a depth between 0.36 m and 4.64 m and oscillating waves of 0.22 m and 1.57 m in height. In contrast, Petri and Fulfaro (1983) admitted a non-marine character for the Tatuí Formation, suggesting that the deposits would have formed in lagoons or lakes of variable salinity on a coastal plain, with a small opening to the open sea in the southern portion of the Paraná Basin.

Fulfaro *et al.* (1984) argued that the Ibicatu Facies (sensu Soares, 1972) was deposited in a fan delta resulting from the uplift of the basin margin, identifying two stages of deltaic progradation: the first, responsible for the formation of the SE-NW oriented deltaic complex in the Itapetininga region; the second, at the top of the Tatuí Formation, developed between Leme and Araras (Ibicatu). Stevaux *et al.* (1986) detailed four facies sections of the Tatuí Formation: the first corresponds to the Ibicatu clastic wedge (between Araras and Leme), composed of about six meters of conglomerates (with 1 to 2 cm flint pebbles) and trunks oriented W, WSW and WNW, associated with a deltaic system whose high-density flow was generated by marginal uplift of the basin, covered by gray shales of the Taquaral Member; the second section presents six meters of conglomeratic sandstones at the top of the unit, correlatable to the Leme and Araras deposits; however, they exhibit evidence of tidal currents (sigmoid stratification), although the authors emphasize that this type of structure does not always indicate tidal activity. The third and fourth sections are characterized by siltstones of the Tatuí Formation, occurring in contact with the Irati Formation, marked by gray argillites.

Assine *et al.* (1999) interpreted the upper portion of the Tatuí Formation in the central-eastern part of the State of São Paulo as a high-sea systems tract, characterized by the progradation of coastal alluvial systems (belonging to the Ibicatu clastic wedge) over a wave-dominated marine platform with evidence of tides, suggesting a source area to the north and paleocurrents directed southward. Subsequently, Assine *et al.* (2003) individualized the flint-rich conglomeratic levels of central-eastern São Paulo into two distinct horizons: the first, observed between Leme and Araras (Ibicatu Facies), refers to coastal alluvial fans later covered by the Irati Formation; The second level, stratigraphically superior, consists of layers of conglomeratic sandstones generated in a highstand systems tract, characterized by the progradation and reworking of the Ibicatu Facies on a tidal-dominated platform overlain by the shales of the Taquaral Member.

These second-level conglomerates constitute transgressive residual deposits (lags) that mark the beginning of the deposition of the Taquaral Member, without a direct link to the Ibicatu Facies of Leme and Araras.

4. Paleontology of the Tatuí Continental System

The paleontological sampling of the Tatuí Formation comprises a diverse record of ichnofossils, plant fossils, arthropods, and paleovertebrates (Figure 2). The bioturbated deposits of the unit were identified in two morphotypes distributed across two distinct lithologies.

The first morphotype was described by Chahud *et al.* (2012) as underlying deposits interpreted by the authors as being from a freshwater continental environment. These structures are characterized by simple, irregular conical excavations with irregular oval to elongated openings, visible both in bedding plane and in profile perpendicular to the layers. Although several ichnogenera could be applied to this morphology, *Arenicolites* appears to be the most appropriate. This ichnogenus occurs in laminated and stratified sandstones, in the form of simple or U-shaped structures arranged perpendicularly to the stratification, constituting a paleoenvironmental indicator that is not very diagnostic because it is present in freshwater, shallow marine, or subaerial environments. The second morphotype occurs in poorly sorted sandstones with sigmoidal stratification, interbedded with silty layers, which outcrop in the lateral extension of the remnant of the Ibicatu type locality (currently destroyed). This is a set of horizontal lines, 5 mm wide, exhibiting simple branching and an absence of preferred direction, with frequent perpendicular or oblique crossings between structures. The features were preserved in negative relief and, more commonly, positive relief. This ichnological pattern can be attributed to the ichnogenera *Gordia*, *Helminthopsis*, *Palaeophycus*, and *Planolites*, all documented in the Guatá Group (Fernandes *et al.*, 2002; Netto *et al.*, 2012). While *Gordia*, *Helminthopsis*, and *Planolites* have a wide distribution in the *Cruziana*, *Mermia*, and *Nereites* ichnofacies, the genus *Palaeophycus* is restricted to the *Cruziana* ichnofacies, and the taxonomy is attributed to this specimen. The aforementioned genus is also recorded in the Palermo Formation (Fernandes *et al.*, 2002; Netto, 2000; Netto *et al.*, 2012), a unit chronocorrelated to the Tatuí Formation.

The arthropod record is predominantly represented by conchostracans (Figure 2A) preserved as impressions and molds with few external morphological features,

occasionally showing the umbo. Growth lines with complete outlines are rarely preserved, and structural thicknesses and concave-convex curvatures are not identified. The best-preserved specimens allowed the determination of oval to rounded valves, similar to those found in the genera *Cyzicus* and *Asmussia* (Brito *et al.*, 2000; Ferreira de Oliveira, 2007); however, preservation limitations prevent precise generic attribution. A significant concentration of compacted conchostracans was recorded in a laminated silty bed characterized by free settling and absence of traction structures (Chahud *et al.*, 2012). These fossils are densely packed in the form of a shell bed, interspersed with less frequent layers, showing density variation both vertically and laterally.

Other crustaceans in the Tatuí Formation were reported exclusively by Mezzalira and Martins Neto (1992), who recorded the isopods *Pseudopalaega* and *Protourda* in a precarious state of preservation, associated with conchostracans and fish remains. Additionally, Chahud *et al.* (2012) mentioned indeterminate crustaceans in massive sandstones and finely laminated siltstones, where conchostracans and fish occurred.



Figure 2 – Fossils from the continental system of the Tatuí Formation. A) Conchostracan from Fazenda Ponte Nova (Chahud *et al.* 2012), scale bar: 1mm; B)

Paleoniscoid scale mold (Chahud *et al.* 2012), scale bar: 5mm; C) Trunk of *Tietea* sp. (Chahud and Petri 2015)

Paleovertebrates occur associated with concentrations of conchostracans (Figure 2B) or sparsely as isolated scales and teeth attributed to Palaeonisciformes and Coelacanthimorpha in fine sandstones (Ragonha, 1978; Chahud and Petri, 2009c). The only occurrence of a semi-articulated fish corresponds to an Actinopterygii of the superfamily Platysomoidea, reported by Silva Santos (1991) in the same outcrop from which the crustaceans described by Mezzalira and Martins Neto (1992) came.

The phytofossil record of the Tatuí Formation reported in the literature is predominantly based on isolated and fragmented plant remains. Early occurrences of larger specimens in better condition were recovered from the Ibicatu Facies conglomerate (Fulfaro *et al.*, 1984; Assine *et al.*, 2003; Chahud and Petri, 2009a). These fossils, which constitute the largest specimens in the present study, correspond to trunks of Pteridophyta and Spermatophyta. The large fragments of Pteridophyta stems, with elongated morphology and centimetric extension, were analyzed by Chahud (2011) and Chahud and Petri (2015), who attributed them to the genus *Tietea* Solms-Laubach, 1913 (Figure 2C). This taxonomy was based on the morphology of the meristems, analogous to that described by Solms-Laubach (1913), Derby (1915), and Tavares (2007) for the Corumbataí Formation, a younger unit than Tatuí, and on the absence of organized meristems in the central portion of the stele, a characteristic that distinguishes them from *Psaronius*, a genus defined by well-individualized and organized meristems. In parallel, Herbst (1987) described similar specimens from the Permian of Paraguay and proposed the genus *Tuvichapteris*, which also exhibits meristem disorganization and a central stem region equivalent to that of *Tietea*. The differentiation between the two genera was based on the number of fronds attached to the trunk, a feature not preserved in the Ibicatu fossils. However, Tavares *et al.* (2011) contested the taxonomic value of morphological variations in fronds, attributing them to distinct ontogenetic stages and ratifying the priority of the taxon *Tietea*. Another stem morphotype recorded in Ibicatu, although smaller and less frequent, was associated with Spermatophyta, consisting of cylindrical, compact, deformed gymnosperm stems with an irregularly elongated profile.

The phytofossil assemblage was dispersed within the conglomerate, containing clasts ranging in size from 5 mm to 30 mm. None of the specimens were preserved in

their life position; all were deposited horizontally by the action of currents, whose hydraulic flow showed an east-west orientation for both types of stems (Chahud and Petri, 2015). The diagenetic process acted significantly during fossilization, with compression by sedimentary influx being the most prominent, promoting the widening of plant structures and internal deformations in the tissues.

5. HISTORICAL LITHOSTRATIGRAPHY

The Tatuí Formation has been classically interpreted as consisting essentially of two distinct lithological bodies, characterized by contrasting colors and separated by a diastema (Soares, 1972; Fulfaro *et al.*, 1984). The lower part is composed of a thick layer of finely laminated siltstone, brown to purplish (occasionally whitish), containing intercalations of chert and limestone with thicknesses varying from a few millimeters to 30 cm, and is a rarely exposed unit. For this lower unit, there are scarce references to the occurrence of foraminifera, which lack description or illustration and have never been confirmed by subsequent studies. The second lithological body is composed of grayish-green to yellowish-green siltstones, fine sand, and conglomerates that exhibit reasonably rounded clasts, as well as cross-stratification and ripple marks, with additional records of angular to rounded chert pebbles.

Chahud and Petri (2015) described three lithotypes (Figure 3) that are difficult to correlate with the classic lithological bodies of the Tatuí Formation. These lithotypes constitute the only proven fossiliferous layers of the unit.

The first lithotype is composed of fine to very fine-grained, well-sorted sandstones, yellowish, whitish, or greenish, sometimes exhibiting pitting or spots, and characterized by hummocky cross-stratification. It generally occurs immediately below the strata of the Irati Formation, forming layers with thicknesses ranging from a few centimeters to two meters, whose hummocky structures can reach up to 0.5 m in height. In the upper portion of this facies, Chahud (2007) recorded small, apparently symmetrical wave marks, oriented N20E, with a height of less than 0.5 cm.

Associated with this lithotype are very fine-grained, massive or planar-parallel laminated sandstones, whitish and containing rare Osteichthyes fossils. These sandstones are located immediately below the basal sandy layer of the Irati Formation. The light yellow coloration observed in some levels is probably the result of weathering of pyrite nodules from the basal layer of this formation.

This sandy facies of the Taquaral Member is interbedded with shales and presents abundant remains of Chondrichthyes (Ragonha, 1978; Chahud and Petri, 2008a, 2008b, 2009b, 2010b, 2012). Excavations also occur that pierce the top of the Tatuí Formation and are filled with sandy sediments from the Taquaral Member (Chahud et al., 2010a; Chahud and Petri, 2018), structures interpreted as a result of the depositional processes that marked the beginning of the sedimentation of the Irati Formation.

The second lithotype comprises very fine sandstones and siltstones, massive or finely laminated, characterized by excellent grain sorting and brownish-white coloration, with occasional parallel or cross-lamination. Although lateral grain size variation occurs, it never exceeds the fine sand fraction. Fossil sampling in this unit is scarce and identified only in unweathered samples, including rare arthropods (conchostracans and indeterminate crustaceans), scales, and disarticulated fish remains. This lithology sometimes occurs in abrupt contact with the Taquaral Member of the Irati Formation, which is represented by coarse sandstones or siltstones (Assine *et al.*, 2003; Chahud *et al.*, 2010a; Chahud and Petri, 2013a, 2013b).

The third lithotype consists of conglomerates, informally known as the Ibicatu Facies since Soares (1972), composed of one- to three-centimeter-wide flint pebbles “floating” in a light brown coarse sandstone matrix. The type locality, whose thickness reached six meters according to Fulfaro *et al.* (1984) and Stevaux *et al.* (1986), was located in a road cut that was later destroyed; in this section, the deposits of the Taquaral Member of the Irati Formation overlapped in abrupt contact. The type section stood out for the large quantity of large plant fossils, including stems with a length close to one meter. Conglomerates similar to the Ibicatu facies have been identified in other outcrops in the State of São Paulo, but without direct stratigraphic contact with the Irati Formation (Stevaux *et al.*, 1986; Assine *et al.*, 2003; Chahud, 2011; Chahud *et al.*, 2012); in these occurrences, the upper layers exhibit sigmoidal structures and ichnofossils, features absent in the type locality (Stevaux *et al.*, 1986).

A synthetic columnar section (Figure 3) was developed by Chahud and Petri (2015) based on outcrops from the central-eastern region of the State of São Paulo (Stevaux *et al.*, 1986; Assine *et al.*, 2003; Chahud *et al.*, 2010b; Chahud and Petri, 2010b), where most of the exposures of this unit are concentrated.

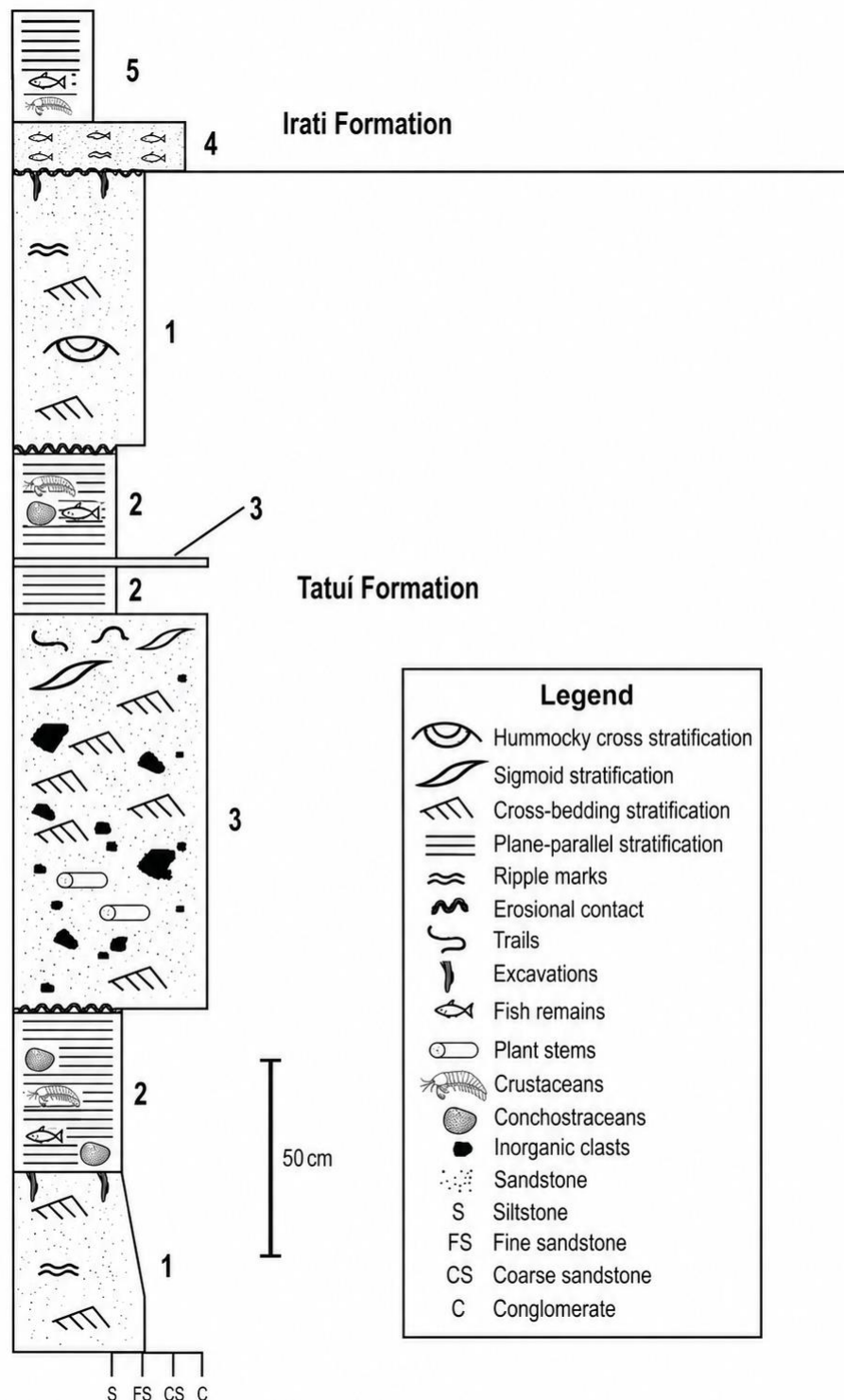


Figure 3 – Proposed columnar section of the upper Tatuí Formation according to Chahud and Petri (2015), as it occurs in the central-eastern part of the State of São Paulo. 1) Fine to very fine sandstones with undulations; 2) Very fine sandstones and siltstones, massive or finely laminated; 3) Conglomerates; 4–5) Taquaral Member of the Irati Formation; 4) Basal sandy layers; 5) Silty-clayey facies.

6. DATA INTEGRATION AND PALEOENVIRONMENTAL MODEL

Characterizing the Tatuí Formation in the central-eastern region of the State of São Paulo requires an integrated approach that articulates lithofacies, stratigraphic, and paleontological data within a regional evolutionary framework. The post-glacial transition in the Paraná Basin promoted a complex reorganization of depositional systems, in which inherited paleotopography, fluvial dynamics, and recurrent marine incursions acted as the main determinants of sedimentary architecture. The following section presents proposals regarding the regional geological context, paleogeography, and the reconstruction of the main paleoenvironments that governed the evolution of this unit during the Early Permian.

6.1 Regional Geological Context

The geological evolution of the Tatuí Formation in the central-eastern region of the state of São Paulo is directly related to the paleoenvironmental reorganization that occurred after the end of the Neopaleozoic glaciation in the Paraná Basin. The sedimentation of this unit was controlled by the interaction between the paleotopography inherited from the Itararé Group, the continental fluvial systems, and the episodic influence of the marine environment, resulting in a succession of lithofacies that record different depositional and hydrodynamic conditions. To understand the genesis and distribution of these facies, the main depositional units and systems that make up the regional geological context are presented below, from the sedimentary basement represented by the Itararé Group to the main siliciclastic deposits of the Tatuí Formation.

6.1.1 *Permo-Carboniferous rocks or rocks predating the Tatuí Formation*

The rocks of the Itararé Group constitute the geological unit underlying the Tatuí Formation, representing the record of the final stages of the Neopaleozoic glaciation that affected the Paraná Basin during the Upper Carboniferous (Neocarboniferous). Lithologically, the package is composed of diamictites, sandstones, rhythmites, siltstones, and shales, related to the dynamics of continental glaciers, gravitational flows, and subaqueous and marine glacial environments. The prolonged action of the glaciers promoted intense erosion of the pre-existing relief, carving valleys, generating topographic depressions, and producing an irregular surface that remained preserved even after the definitive retreat of the ice. This residual relief played a decisive role in

subsequent Permian sedimentation: the inherited low-lying areas became preferential areas for the accumulation of fine sediments and the establishment of low-energy lacustrine and lagoonal environments, while the structurally higher compartments, remnants of the Itararé Group itself, functioned as source areas for fluvial systems, supplying large volumes of siliciclastic sediments to the basin.

Thus, the Itararé Group represents not only an underlying stratigraphic unit, but also a true controlling element of regional paleoenvironmental evolution, explaining a large part of the facies heterogeneity observed in the Tatuí Formation as a direct result of the paleotopography inherited from the Carboniferous glaciation.

6.1.2 *Fine sandstone rocks of the Tatuí Formation*

The fine to very fine sandstones constitute the first siliciclastic deposits established after the paleoenvironmental reorganization that followed the end of the Neopaleozoic glaciation. They are compositionally quartzose to quartz-feldspathic, with high textural maturity, good grain sorting, reduced clay matrix content, and moderate to high grain rounding, evidencing intense and prolonged hydrodynamic reworking before final deposition. The preserved sedimentary structures, tabular and channel cross-stratifications associated with the migration of underwater dunes, planar-parallel laminations, symmetrical and asymmetrical ripple marks, and reactivation surfaces, indicate sedimentation under the combined action of currents.

Levels with abundant ichnofossils and bioturbation features record the establishment of benthic communities during periods of low sedimentation rates, interbedded with tempestite deposits exhibiting hummocky cross-stratification, erosional bases, and upward-fining, formed by coastal storms associated with the influence of the Rio Bonito–Palermo Sea. Together, this record characterizes a highly dynamic depositional system, located in a broad coastal plain where the interaction between continental and marine processes produced complex successions, marked by frequent changes in hydrodynamic conditions and the position of the coastline.

6.1.3 *Poorly sorted and conglomeratic sandstone deposits of the Ibicatu Facies*

The Ibicatu Facies corresponds to the highest-energy deposits of the Tatuí Formation, representing the fluvial system that developed parallel to coastal sedimentation. It consists of medium to coarse sandstones and locally conglomeratic levels, reflecting high hydraulic competence and significant transport capacity of the

channels. Its lithologies exhibit erosional bases, large-scale cross-stratification, and channelized geometries, characteristic of braided channels subject to intense lateral migration. This system transported large volumes of sand, pebbles, plant fragments, and silicified trunks (Ibicatu Flora), originating from topographically elevated source areas on the basin margins.

The flow of the ancient Ibicatu River was not constant, being strongly controlled by seasonal fluctuations in precipitation: during wetter periods, the increased flow promoted intense erosion of the banks, reworking of previously deposited sediments, and expansion of active channels; while during periods of lower flow, calmer depositional processes predominated, favoring the accumulation of fine sediments. Thus, the Ibicatu Facies represents the main record of the fluvial processes responsible for supplying the sediment that fed the depositional evolution of the Tatuí Formation during the Early Permian.

6.1.4 Silty deposits of the Tatuí Formation

The silty deposits interbedded within the sandstones of the Tatuí Formation record intervals of significant reduction in hydrodynamic energy, with sedimentation predominantly occurring through the decantation of fine particles. They occur as thick, massive or finely laminated packages, deposited in floodplains, shallow lakes, marginal lagoons, abandoned paleochannels, and coastal lagoons with restricted circulation, reflecting conditions that varied from freshwater to brackish environments.

The good preservation of the original lamination and reduced bioturbation indicate environments favorable to fossil preservation. These horizons constitute the main fossiliferous levels of the unit, concentrating abundant levels of conchostracans, crustaceans, and fish, preserved due to rapid burial and reduced current action. In addition to the thicker regional successions, there are lenticular silty lenses of reduced thickness, associated with small coastal depressions, as well as packages of silts and clays accumulated in the filling of paleochannels abandoned by fluvial avulsion. The oscillations of the relative sea level directly controlled the salinity and connectivity of these environments with the adjacent fluvial or marine systems so that the siltstones of the Tatuí Formation function as important paleoenvironmental indicators, recording periods of relative hydrodynamic stability between higher-energy depositional events.

6.2 Paleogeographic Proposals

The integration of sedimentological, stratigraphic, paleontological, and facies data allows us to propose a paleogeographic model for the Tatuí Formation during the Early Permian. Although some of these reconstructions remain interpretive, the available evidence indicates a highly dynamic depositional system, controlled by the interaction between the paleotopography inherited from the Itararé Group, the activity of continental fluvial systems, and the recurring incursions of the Rio Bonito–Palermo Sea. The proposals presented below synthesize the main elements that composed this landscape, highlighting the processes responsible for the distribution of depositional environments and the regional paleoenvironmental evolution.

6.2.1 *Ibicatu River forming a deltaic system*

The Ibicatu Paleoriver constituted the main drainage system responsible for the sedimentary input of the Tatuí Formation, culminating in the construction of a broad progradational deltaic system developed along the margin of the ancient Rio Bonito–Palermo Sea. Its architecture comprised active and continuously migrating distributary channels, mouth bars, deltaic plains, interdistributary bays, lagoons, and extensive swampy areas. The progradation of the delta occurred discontinuously, controlled by the interaction between river discharge, sediment availability, and oscillations in relative sea level. During periods of higher precipitation and high discharge, large volumes of sand were transported to the delta front, promoting the advance and expansion of sandy deposits. During periods of lower sediment input or rising relative sea level, marine influence became predominant, favoring the reworking of the Ibicatu Facies fluvial bars by wave and tidal action and the development of lagoonal and estuarine environments, recorded by diagnostic features such as sigmoid stratifications, reactivation surfaces, and herringbone cross-stratification. As a result, the delta's architecture exhibited high spatial and temporal complexity, marked by successive phases of expansion and contraction of the deltaic lobes, producing a mosaic of intimately connected depositional environments and reflecting the continuous interaction between continental and marine processes that characterized the paleoenvironmental evolution of the Tatuí Formation in the Early Permian.

6.2.2 *Possible flat and low paleoterrain generating lacustrine environments*

Much of the landscape associated with the sedimentation of the Tatuí Formation consisted of extensive surfaces with a low topographic gradient, a flat and low

paleoterrain inherited from the residual relief and depressions left by glacial erosion of the Itararé Group. These gently sloping surfaces favored the development of shallow lagoons, floodplains, small distributary channels, swampy areas, and depressions filled with freshwater, where water circulation was limited and sedimentation occurred predominantly by decantation of fine particles, generating thick packages of massive or laminated siltstones and clays. These environments were fed both by the seasonal floods of the Ibicatu Paleoriver and by the direct accumulation of rainwater, exhibiting strong seasonal variation in the depth and extent of the water bodies.

The good preservation of lamination and low turbidity provided suitable conditions for aquatic life and the fossil preservation of conchostracans, crustaceans, and vertebrates; the recurring presence of conchostracans reinforces the ephemeral and seasonal nature of these water bodies, since these organisms inhabit environments subject to cycles of flooding and desiccation. At various times, marginal lagoons and abandoned paleochannels transformed into important centers of organic matter accumulation, further expanding the potential for fossil preservation. This geomorphological configuration reveals that the coastal plain of the Tatuí Formation was dominated by a mosaic of tranquil lacustrine and lagoonal ecosystems, whose evolution was mainly controlled by seasonal drainage oscillations, the low regional slope inherited from the Carboniferous glaciation, and small variations in base level.

6.2.3 Possible rugged paleoterrain generating high-energy rivers

In contrast to the extensive low-relief surfaces predominant during the deposition of the Tatuí Formation, there were discreetly elevated compartments that played a decisive role in the regional sedimentary dynamics, functioning as marginal source areas of sediments. These paleoterranes corresponded to interfluvies and structural remnants of the relief inherited from the glacial erosion of the Itararé Group, or even to small elevations associated with ancient tectonic structures. In these steeper sectors, fluvial systems of high hydraulic competence were established, represented by the Ibicatu Facies, deposits formed by the ancient Ibicatu River, whose transport capacity was amplified during periods of higher seasonal precipitation.

The rivers that drained these areas were capable of transporting large volumes of medium to coarse sand, gravel, conglomeratic layers, and abundant tree trunks and plant fragments toward the lower regions of the coastal plain. This dynamic is recorded in the medium to coarse sandstones, locally conglomeratic, with erosional bases, large-scale

cross-stratification, and channelled geometries of the Ibicatu Facies, which exhibit braided geometry and intense lateral migration, forming sandbars and erosion surfaces.

During flood episodes, these rivers continuously reshaped the landscape, promoting bank erosion, sedimentary reworking, and the formation of new sandbars. The coexistence of these elevated compartments and adjacent depressed areas explains the significant facies variability observed in the Tatuí Formation, alternating sandy deposits generated by strong currents with fine sediments deposited in calm waters, and reflecting the continuous influence of the paleotopography inherited from the Itararé Group on the organization of the Early Permian depositional systems.

6.2.4 Rio Bonito–Palermo Sea

The Rio Bonito–Palermo Sea corresponded to an extensive shallow epicontinental platform that directly influenced the paleoenvironmental evolution of the Tatuí Formation during the Early Permian. In response to eustatic oscillations and regional subsidence of the Paraná Basin, successive transgressive incursions allowed its waters to penetrate the coastal plain, flooding river channels, lagoons, deltas, and depressions previously occupied by continental environments. This influx of seawater reduced the strength of the river systems and established estuarine, lagoonal, and coastal environments subjected to the combined action of littoral storms, tides, and waves. As a result, heterolithic stratifications, herringbone cross-stratifications, sigmoid structures, reactivation surfaces, and tempestite deposits developed, evidencing a constant alternation between continental and marine flows.

Marine influence is also paleontologically confirmed by the record of shallow-water bivalves from the Taió Fauna (Rocha-Campos, 1970; Rocha-Campos and Simões, 1993) and echinoderms (Boardman, 2006), proving the existence of periodic connections between the continental environment and the open ocean. The Rio Bonito–Palermo Sea thus played a fundamental role in the sedimentary reorganization of the Paraná Basin, controlling the migration of the coastline, the diversity of depositional environments, and the composition of fossil assemblages recorded in the Tatuí Formation, configuring a transitional and estuarine environment under constant variation in salinity and hydrodynamics.

The Tatuí Formation underwent complex diagenetic processes (Gimenez and Chang, 1997; 2010) characterized by the dissolution of unstable minerals, replacement of framework grains by carbonate cement, clay minerals, and albitization of feldspars.

According to Gimenez and Chang (2010), during the eodiagenetic phase, the dissolution of unstable minerals would have occurred, resulting from the replacement of calcareous bivalve shells; however, no bivalve has been confirmed or illustrated in any study in the formation. Nevertheless, as mentioned earlier, they were observed in the Taió Fauna of the Rio Bonito Formation (Rocha-Campos, 1970; Rocha-Campos and Simões, 1993) and in the São Sepé Fauna of the Palermo Formation (Simões, 1992 and 2000; Simões and Rocha-Campos, 1993), and likely also occurred further north in the São Paulo Formation.

6.3 Paleoenvironmental Proposals

By integrating sedimentological, stratigraphic, taphonomic, and paleontological evidence, it is possible to reconstruct the main paleoenvironments that comprised the Tatuí System during the Early Permian. These environments reflected the continuous interaction between fluvial, lacustrine, deltaic, and marine processes, strongly conditioned by seasonal climate variations, oscillations in the relative sea level of the Rio Bonito–Palermo region, and the paleotopography inherited from the Neopaleozoic glaciation. The reconstructions presented below represent hypotheses based on the characteristics of the lithofacies, the fossil record, and the distribution of sedimentary deposits, allowing us to visualize the ecosystems that coexisted along the coastal plain of the Tatuí Formation and its paleoenvironmental dynamics.

6.3.1 *Freshwater lake*

Freshwater lakes constituted one of the most characteristic environments of the floodplain associated with the Ibicatu Paleoriver. They developed in small topographic depressions distributed among the active river channels, many of them corresponding to residual lows inherited from the glacial relief of the Itararé Group, being supplied mainly by seasonal river floods and the direct accumulation of rainwater.

During periods of higher rainfall, the increased flow caused the channels to overflow, temporarily flooding extensive areas of the plain and creating new lagoons or expanding existing ones. Conversely, during drier seasons, many of these lagoons remained partially or totally isolated from the river system, becoming environments with restricted circulation and low hydrodynamic energy, where sedimentation by decantation of silts, clays, and suspended organic matter predominated.



Figure 4 – Paleoenvironmental reconstruction of a freshwater lake in the Tatuí continental system. 1) Actinopterygii of the superfamily Platysomoidea; 2) Conchostracans; 3) Isopod crustacean.

This seasonal dynamic provided excellent conditions for fossil preservation. The associated fauna consisted mainly of conchostracans, small branchiopod crustaceans common in ephemeral lakes that are extremely tolerant of seasonal cycles of flooding and desiccation, and a few fish brought by the Ibicatu Paleoriver. The alternation between flooding and isolation phases directly controlled the depth, extent, and ecological conditions of these lakes, configuring dynamic continental ecosystems that played an important role in the paleoenvironmental organization of the Tatuí System.

6.3.2 Coastal Lagoons Influenced by the Rio Bonito–Palermo Sea

The coastal lagoons associated with the incursions of the Rio Bonito–Palermo Sea developed during transgressive episodes that flooded the most depressed portions of the coastal plain and the deltaic mouth of the Tatuí Formation. Unlike continental lagoons, these environments maintained temporary communication with the sea through distributary channels and shallow estuaries, being governed by the constant interaction between the flows of the river channels and the tidal regime. The alternation between flood and ebb currents generated complex and bidirectional hydrodynamic conditions,

recorded by heterolithic stratifications, reactivation surfaces, sigmoid structures, and herringbone cross-stratifications, important sedimentological indicators of tidal action.

The currents intensely reworked the sandbars previously built by the fluvial systems of the Ibicatu Facies, redistributing large volumes of sand and intercalating them with packages of fine sedimentation; the marine influence on these lagoonal bodies could extend for tens of kilometers inland. As a consequence, brackish environments of variable salinity were established, in which shallow marine or estuarine organisms, such as acritarch remains and agglutinated foraminifera, temporarily coexisted, but there were no exclusively freshwater fossils like conchostracans, evidencing salinity and direct connectivity with the sea.

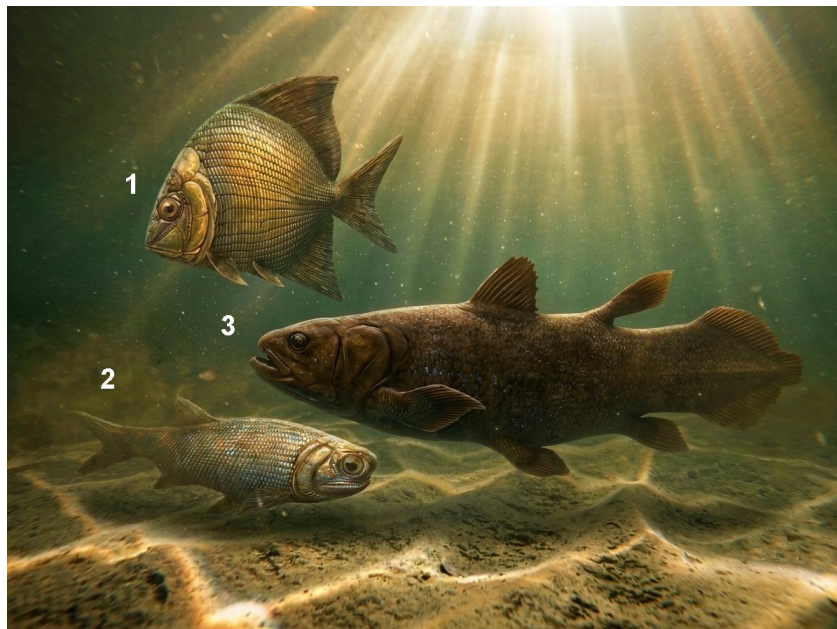


Figure 5 – Paleoenvironmental reconstruction of a brackish lagoon in the Tatuí continental system. 1) Actinopterygii of the superfamily Platysomoidea; 2) Paleoniscoid Actinopterygii; 3) Actinistia.

These lagoons therefore functioned as transition zones between continental systems and the shallow marine environment, recording successive oscillations in the relative level of the water body and significant changes in salinity, circulation, and the composition of biological communities.

6.3.3 Ibicatu Flora (Trunks from the Leme and Araras region)

The Ibicatu Flora is the main known paleobotanical record for the Tatuí Formation in the central-eastern region of the State of São Paulo, especially in the municipalities of Leme and Araras. This paleofloristic association is predominantly composed of trunks and silicified trunks, preserved in a reworked position or transported before final burial.

These fossils provide evidence of the presence of medium to large trees that occupied relatively elevated and forested sectors of the Permian landscape, functioning as source zones of organic matter for the adjacent sedimentary environments and indicating that extensive wooded areas coexisted with rivers, floodplains, and deltaic environments. The preferred orientation of many trunks, associated with the low degree of fragmentation and the different levels of surface abrasion observed in the specimens, demonstrates that the wood was transported short distances in water channels before being buried, suggesting that the forests developed in the vicinity of the channels of the Ibicatu Paleoriver.

In addition to documenting the Gondwanan vegetation of the time, these trunks provide important taphonomic and sedimentological information, allowing the reconstruction of the dynamics of the fluvial systems responsible for the transport of plant matter. Thus, the Ibicatu Flora constitutes an excellent indicator of the proximity between vegetated areas and depositional environments, revealing a scenario in which vegetation cover played a central role in the stability of the banks, the supply of organic matter, and the paleoenvironmental evolution of the Tatuí Formation during the Early Permian.



Figure 6 – Paleoenvironmental reconstruction of the Ibicatu Flora in the Tatuí continental system.

The Ibicatu Flora can be partially correlated temporally with the Irapuá Flora, one of the most important Gondwanan paleobotanical associations of the Early Permian, originally described in deposits of the Rio Bonito Formation in the state of Santa Catarina and representative of the classic *Glossopteris* Flora. This plant community developed after the retreat and decline of the Neopaleozoic glaciation, under a predominantly temperate climate, seasonally humid and with moderate temperature fluctuations, being dominated by medium to large arboreal glossopterids adapted to humid substrates, in addition to associated arborescent gymnosperms and pteridophytes. These plants formed extensive forests along coastal plains, riverbanks, deltas and

swampy areas subject to periodic flooding or permanent waterlogging, playing a fundamental role in soil stabilization and in supplying organic matter to sedimentary environments. In areas with low substrate oxygenation, high plant productivity favored the progressive accumulation of organic remains and the formation of thick peat bogs, which later gave rise to the coal levels of the Rio Bonito Formation.

Although the Irapuá Flora itself has not been identified in the Tatuí Formation, its occurrence in the Rio Bonito Formation shows that similar plant communities occupied large areas of the eastern margin of the Paraná Basin during the Early Permian; in the State of São Paulo, its equivalent expression is recorded by the silicified trunks of the Ibicatu Flora.

These paleofloras constitute a relevant paleoclimatic indicator, demonstrating that the progressive warming following the decline of the Neopaleozoic glaciation allowed the establishment of typically Gondwanan plant communities along the coastal plains of southern Brazil.

A summary of the main events that occurred during the continental phase of the Tatuí Formation can be seen in the block diagram in Figure 7, which shows all possible observable phases.

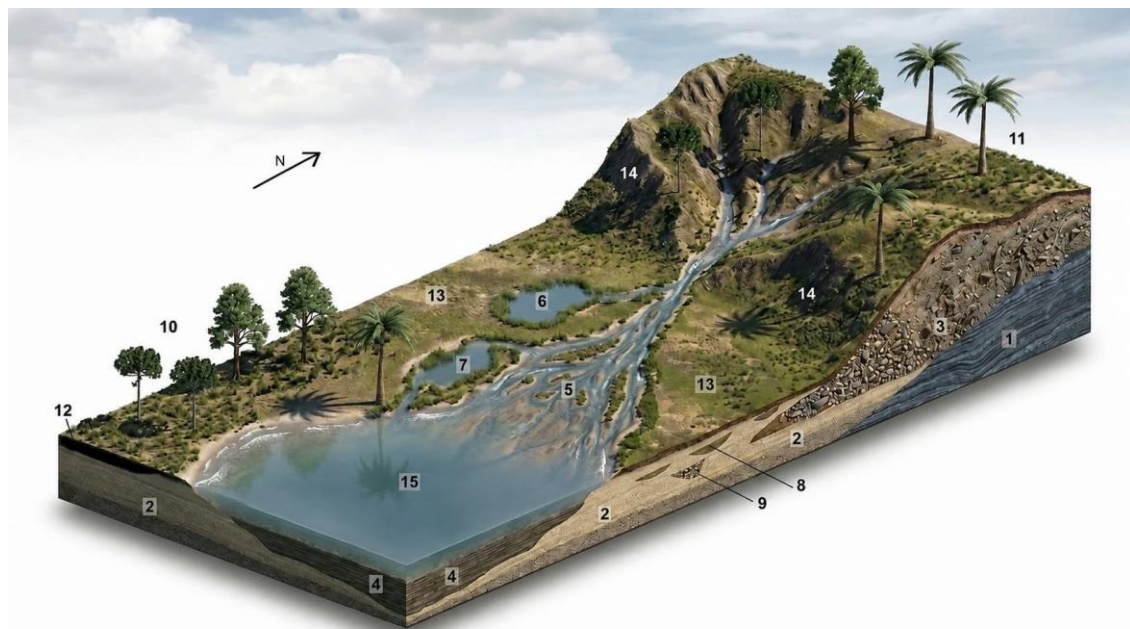


Figure 7 – Reconstructed block diagram of the continental phase of the Tatuí Formation in the state of São Paulo and its continuation in the Guatá Group (Rio Bonito and Palermo Formations) in southern Brazil. 1) Permo-Carboniferous rocks or rocks prior to the Tatuí Formation (Itararé Group); 2) Fine-grained sandstone rocks of the Tatuí

Formation; 3) Coarse deposits of the Ibicatu Facies; 4) Silty deposits of the Tatuí Formation; 5) Ibicatu River forming a deltaic system; 6) Freshwater lagoon formed by rain or flooding of the Ibicatu Paleoriver during rainy seasons; 7) Lagoon formed by the tidal system of the “Rio Bonito-Palermo Sea”; 8) Silty lens formed by freshwater lagoons or saline lagoons; 9) Abandoned paleochannel of the Ibicatu Facies; 10) Irapuá Flora (*Glossopteris Flora* of the Santa Catarina region); 11) Ibicatu Flora (Trunks from the Leme and Araras region); 12) Coal deposits of the Rio Bonito associated with the Irapuá Flora; 13) Possible flat and low paleoterrain generating lagoons or bodies of water of low energy; 14) Possible rugged paleoterrain (slightly higher generating rivers of high energy); 15) Rio Bonito-Palermo Sea.

7. CONCLUSIONS

The integrated synthesis of stratigraphic, sedimentological, paleontological, and paleoenvironmental data gathered in this work allows us to reconstruct the Tatuí Formation as the record of an extensive Early Permian coastal depositional system, predominantly continental, located on a paleotopography inherited from the Neopaleozoic glaciation of the Itararé Group. This geomorphological heritage, marked by the alternation between low-lying topographic areas and higher residual compartments, directly conditioned the pronounced facies heterogeneity of the unit: the lower-lying portions favored the accumulation of fine deposits by sedimentation and the establishment of low-energy lacustrine and lagoonal environments, while the higher compartments acted as sediment source areas and conditioned the development of fluvial systems with greater hydraulic competence, such as the Ibicatu Paleoriver.

The Tatuí continental system was characterized by a complex and strongly seasonal depositional dynamic, developed in a broad, low-relief coastal plain, in which the interaction between fluvial, lacustrine, and marine processes generated a mosaic of interconnected subenvironments. The Ibicatu Paleoriver, a high-energy braided fluvial system represented by the Ibicatu Facies, acted as the main sedimentary transport pathway, feeding a broad progradational deltaic system that supplied sedimentary material and fossil plant specimens to the coastal plain, with architecture varying in response to oscillations in relative sea level and sedimentary availability. In contrast, low-energy environments, ephemeral freshwater lagoons fed by rainfall and seasonal floods, floodplains, abandoned paleochannels, and brackish lagoons associated with the incursions of the Rio Bonito–Palermo Sea record phases of relative hydrodynamic

stability, evidenced by tidal structures (heterolithic, sigmoid, and herringbone stratification) and by reworking associated with waves and storms. The successive oscillations of the relative level of this sea promoted the alternation between continental and coastal conditions, explaining the coexistence of typically continental and marine sedimentary structures throughout the succession, culminating in the definitive drowning of the continental systems and the subsequent deposition of the Taquaral Member (Irati Formation).

The paleontological record corroborates this paleoenvironmental reconstruction and accurately reflects the oscillations in environment and salinity. The silty deposits, the main fossiliferous horizons of the unit, preserve assemblages of conchostracans, crustaceans, and actinopterygian fish, indicative of temporary continental water bodies subject to cycles of flooding and desiccation, while marine incursions are evidenced by ichnofossils and sparse microfossils, demonstrating recurring episodes of connection with the epicontinental sea.

The Ibicatu flora, composed of silicified trunks of *Tietea* trees and Spermatophyta/gymnosperms transported by river channels, evidences the existence of forested areas with medium to large arborescent vegetation, established in elevated sectors adjacent to the channels and which provided organic matter to the neighboring sedimentary systems. The partial correlation of this flora with the Irapuá flora (Rio Bonito Formation, Santa Catarina) reinforces its paleoclimatic significance, associated with the progressive post-glacial warming that allowed the expansion of Gondwanan plant communities of the *Glossopteris* type along the eastern margin of the Paraná Basin.

Taken together, the data corroborate the hypothesis that the Tatuí Formation represents a transitional paleoenvironmental system, situated between distinctly continental and shallow marine domains, whose evolution was simultaneously governed by the paleotopography inherited from the Carboniferous glaciation, the climatic seasonality of the Early Permian, the dynamics of continental drainage and subsidence of the Paraná Basin, and the relative fluctuations in sea level of the Rio Bonito–Palermo region. This integrated paleogeographic model contributes to a new interpretation of the continental evolution of the Tatuí Formation, provides a framework capable of explaining the distribution of sedimentary facies and fossil deposits and the paleoenvironmental evolution of the unit, and reinforces the role of the Tatuí Formation, in correlation with the Guatá Group in southern Brazil, as an important

paleoenvironmental and paleoclimatic archive of the eastern margin of the Paraná Basin during the Early Permian.

DECLARATION OF USE OF AI

The author declares that Artificial Intelligence (AI) was used to perform the reconstructions presented in the text.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interest regarding this work.

DATA AVAILABILITY STATEMENT

The concepts and ideas developed and/or analyzed in this study are available in the manuscript. The author agrees that the approved manuscript will be made available under a Creative Commons CC-BY license.

ACKNOWLEDGEMENTS

The author expresses special thanks to Prof. Dr. Setembrino Petri and Prof. Dr. Thomas Rich Fairchild for their friendship, collaboration, support, and assistance at various stages of this research and to the Department of Sedimentary and Environmental Geology for permitting fossil preparation work in its laboratories.

REFERENCES

- Almeida, F. F. M., & Barbosa, O. (1953). *Geologia das quadrículas de Piracicaba e Rio Claro, Estado de São Paulo* (Boletim do DNPM/DGM n.º 143). Rio de Janeiro.
- Assine, M. L., Zacharias, A. A., & Perinotto, J. A. J. (1999). O trato deposicional Tatuí e a transgressão Taquaral no Centro-Leste do Estado de São Paulo. In *Resumos do VI Simpósio de Geologia do Sudeste* (p. 53). SBG/UNESP.
- Assine, M. L., Zacharias, A. A., & Perinotto, J. A. J. (2003). Paleocorrentes, paleogeografia e seqüências deposicionais da Formação Tatuí, centro-leste do Estado de São Paulo. *Revista Brasileira de Geociências*, 33(1), 33–40.
- Barbosa, O., & Almeida, F. F. M. (1949a). Nota sobre a estratigrafia da Série Tubarão em São Paulo. *Anais da Academia Brasileira de Ciências*, 21(1), 65–68.

- Barbosa, O., & Almeida, F. F. M. (1949b). *A Série Tubarão na bacia do Rio Tietê, Estado de São Paulo* (Boletim do DNPM/DGM n.º 48). Rio de Janeiro.
- Barbosa, O., & Gomes, F. A. (1958). Pesquisa de petróleo na bacia do rio Corumbataí (Boletim do DNPM/DGM n.º 171). Rio de Janeiro.
- Boardman, D. R. (2006). Tafoflora de Taió, Santa Catarina (Permiano Inferior, Formação Rio Bonito, Bacia do Paraná) [Dissertação de mestrado, Universidade Federal do Rio Grande do Sul].
- Brito, I. M., Carvalho, I. S., Vicalvi, M. A., & Carvalho, M. G. P. (2000). Artrópodes. In I. S. Carvalho (Ed.), *Paleontologia* (pp. 423–451). Editora Interciência.
- Cabral Jr., M., Campanha, V. A., Motta, J. F. M., & Saad, A. R. (1988). Contribuição à estratigrafia e paleogeografia da interface Itararé e Tatuí (P) e considerações sobre sua potencialidade para carvão no Estado de São Paulo. In *Anais do 35º Congresso Brasileiro de Geologia* (Vol. 2, pp. 879–892). SBG.
- Castro, J. C., Michel, U., Alves, C. F. C., & Grecchi, R. C. (1993a). O Subgrupo Guatá na margem nordeste da Bacia do Paraná: Uma revisão. In *Boletim de Resumos do I Simpósio de Cronoestratigrafia da Bacia do Paraná* (pp. 55–56). FUNDUNESP.
- Castro, J. C., Sampaio, R. F., & Schneider, R. L. (1993b). Eventos e ciclos T-R na evolução dos membros Paraguaçu e Siderópolis (Fm. Rio Bonito), porção sudeste da Bacia do Paraná. In *Boletim de Resumos do I Simpósio de Cronoestratigrafia da Bacia do Paraná* (pp. 52–53). FUNDUNESP.
- Chahud, A. (2007). Paleontologia de vertebrados da transição entre os grupos Tubarão e Passa Dois no centro-leste do Estado de São Paulo [Dissertação de mestrado, Universidade de São Paulo].
- Chahud, A. (2011). Geologia e paleontologia das formações Tatuí e Irati no centro-leste do Estado de São Paulo [Tese de doutorado, Universidade de São Paulo].
- Chahud, A., Duque, J. M., & Petri, S. (2010a). Consideraciones geológicas y paleontológicas de las formaciones Tatuí e Iratí (Pérmico), Cuenca de Paraná, Brasil. *Geología Colombiana*, 35, 36–49.

- Chahud, A., Fairchild, T. R., & Petri, S. (2010b). Chondrichthyans from the base of the Irati Formation (Permian, Paraná Basin), São Paulo, Brazil. *Gondwana Research*, 18(2–3), 528–537.
- Chahud, A., Pacheco, M. L. A. F., Meira, F. E., Romero, G. R., & Petri, S. (2012). Paleontology and depositional environments of the Tatuí and Irati formations (Permian) in the Ponte Nova Farm, Ipeúna, state of São Paulo. *Revista Brasileira de Geociências*, 42(1), 198–212.
- Chahud, A., & Petri, S. (2008a). Chondrichthyes no Membro Taquaral, base da Formação Irati, no centro-leste do Estado de São Paulo, Brasil. *Revista de Geologia*, 21(2), 169–179.
- Chahud, A., & Petri, S. (2008b). Registro de paleoniscóides na base do Membro Taquaral, Formação Irati, Permiano da Bacia do Paraná. *Revista do Instituto Geológico*, 29(1/2), 33–40.
- Chahud, A., & Petri, S. (2009a). Levantamento inicial dos fósseis vegetais da Fácies Ibicatu, Formação Tatuí (Permiano) do Estado de São Paulo. In *Boletim de Resumos do PALEO 2009*.
- Chahud, A., & Petri, S. (2009b). Novos Xenacanthidae (Chondrichthyes, Elasmobranchii) da base do Membro Taquaral, Formação Irati, Permiano da Bacia do Paraná. *Revista do Instituto Geológico*, 30(1/2), 19–24.
- Chahud, A., & Petri, S. (2009c). Sarcopterygii do topo da Formação Tatuí e base da Formação Irati, Permiano, São Paulo, Brasil. *Revista Ung Geociências*, 8(1), 39–46.
- Chahud, A., & Petri, S. (2010a). Anfíbio e Paleonisciformes da porção basal do Membro Taquaral, Formação Irati (Permiano), Estado de São Paulo, Brasil. *Geologia USP. Série Científica*, 10(1), 29–37.
- Chahud, A., & Petri, S. (2010b). O tubarão *Taquaralodus albuquerquei* (Silva Santos, 1946) do Membro Taquaral (Permiano, Formação Irati) no Estado de São Paulo. *Acta Biológica Paranaense*, 39, 1–17.
- Chahud, A., & Petri, S. (2012). Levantamento dos cladodontes sul-americanos e novos espécimes do Membro Taquaral (Formação Irati, Permiano), Bacia do Paraná. *Boletim Paranaense de Geociências*, 66–67, 23–29.

- Chahud, A., & Petri, S. (2013a). Paleontology of Taquaral Member silty shale in the State of São Paulo. *Brazilian Journal of Geology*, 43(1), 117–123.
- Chahud, A., & Petri, S. (2013b). The silty shale Taquaral Member of the early Permian Irati Formation (Paraná Basin, Brazil): Paleontology and paleoenvironments. *Swiss Journal of Palaeontology*, 132(1), 119–128.
- Chahud, A., & Petri, S. (2015). The Tatuí Formation (Early Permian, Paraná Basin), Brazil: Paleontology and paleoenvironmental considerations. *Earth Sciences Research Journal*, 19(2), 153–158.
- Chahud, A., & Petri, S. (2018). Novos Dados Paleontológicos da Formação Tatuí (Eopermiano, Bacia do Paraná) no Centro-Leste do Estado de São Paulo. *Revista de Biologia e Ciências da Terra*, 1(1), 70-77.
- Derby, O. A. (1915). Illustrations of the stem structure of *Tietea singularis*. *American Journal of Science*, 36(4), 251–260.
- Fernandes, A. C. S., Borghi, L., Carvalho, I. S., & Abreu, C. J. (2002). *Guia dos icnofósseis de invertebrados do Brasil*. Editora Interciência.
- Ferreira de Oliveira, L. G. (2007). *Conchostráceos permianos da Bacia do Paraná: Taxonomia, evolução, bioestratigrafia e paleobiogeografia* [Tese de doutorado, Universidade Estadual Paulista].
- Fulfaro, V. J., Stevaux, J. C., Souza-Filho, E. E., & Barcelos, J. H. (1984). A Formação Tatuí (P) no Estado de São Paulo. In *Anais do 33º Congresso Brasileiro de Geologia* (Vol. 2, pp. 711–723). Sociedade Brasileira de Geologia.
- Gimenez, N. L. B., & Chang, M. R. C. (1997). Diagênese dos arenitos da Formação Tatuí no NE da Bacia do Paraná. In *Resumos do V Simpósio de Geologia do Sudeste* (pp. 54–55).
- Gimenez, N. L. B., & Chang, M. R. C. (2010). Diagênese de arenitos da Formação Tatuí no estado de São Paulo. *Revista Brasileira de Geociências*, 40(1), 68–79.
- Herbst, R. (1987). Studies on Psaroniaceae II. *Tuvichapteris solmsi* nov. gen. et sp. from the Permian of Paraguay and Uruguay. In *Anais do 4º Congresso Latino-Americano de Paleontologia* (pp. 267–282).

- Holz, M., França, A. B., Souza, P. A., Iannuzzi, R., & Rohn, R. (2010). A stratigraphic chart of the Late Carboniferous/Permian succession of the eastern border of the Paraná Basin, Brazil, South America. *Journal of South American Earth Sciences*, 29(2), 381–399.
- Massoli, M. (1980). Geologia da folha de Santa Rita do Passa Quatro. *Revista do Instituto Geológico*, 1(1), 7–14.
- Mezzalira, S. (2000). *Os fósseis do Estado de São Paulo: Parte II. Período 1987 (parcial) – 1996* (Boletim do Instituto Geológico n.º 15). Instituto Geológico.
- Mezzalira, S., & Martins-Neto, R. G. (1992). Novos crustáceos paleozóicos do Estado de São Paulo com descrição de novas taxa. *Acta Geologica Leopoldensia*, 15(36), 49–65.
- Milani, E. J., Melo, J. H. G., Souza, P. A., Fernandes, L. A., & França, A. B. (2007). Bacia do Paraná. *Boletim de Geociências da Petrobras*, 15(2), 265–287.
- Milani, E. J., & Ramos, V. A. (1998). Orogenias paleozóicas no domínio sul-ocidental do Gondwana e os ciclos de subsidência da Bacia do Paraná. *Revista Brasileira de Geociências*, 28(4), 473–484.
- Netto, R. G. (2000). Paleoicnologia do Rio Grande do Sul. In M. Holz & L. F. De Ros (Eds.), *A paleontologia do Rio Grande do Sul* (pp. 25–43). CIGO/UFRGS.
- Netto, R. G., Tognoli, F. M. W., Gandini, R., Lima, J. H. D., & Gibert, J. M. (2012). Ichnology of the Phanerozoic deposits of southern Brazil. In R. G. Netto, N. B. Carmona, & F. M. W. Tognoli (Eds.), *Ichnology of Latin America: Selected papers* (Vol. 2, pp. 37–68). Sociedade Brasileira de Paleontologia.
- Perinotto, J. A., & Fulfaro, V. J. (1993). Possibilidades de fatiamento cronoestratigráfico da Formação Palermo e sua extensão no Estado de São Paulo. In *Boletim de Resumos do I Simpósio de Cronoestratigrafia da Bacia do Paraná* (pp. 57–58). FUNDUNESP.
- Petri, S. (1964). Grupo Tubarão. *Boletim do Instituto Geográfico e Geológico*, 41, 56–63.
- Petri, S., & Fulfaro, V. J. (1983). *Geologia do Brasil (Fanerozóico)*. TAQ-EDUSP.

- Pires, F. A., & Petri, S. (1993). Estratigrafia da Bacia do Paraná (Carbonífero Superior – Triássico Inferior) no Estado de São Paulo. In *Boletim de Resumos do I Simpósio de Cronoestratigrafia da Bacia do Paraná* (pp. 60–61). FUNDUNESP.
- Ragonha, E. W. (1978). *Chondrichthyes do Membro Taquaral (Formação Irati) no Estado de São Paulo* [Dissertação de mestrado, Universidade de São Paulo].
- Rocha-Campos, A. C. (1967). The Tubarão Group in the Brazilian portion of the Paraná Basin. In J. J. Bigarella, R. D. Becker, & I. D. Pinto (Eds.), *Problems in Brazilian Gondwana Geology* (pp. 27–102). Instituto de Geologia, Universidade Federal do Paraná.
- Rocha-Campos, A. C. (1970). *Moluscos permianos da Formação Rio Bonito (Subgrupo Guatá), Santa Catarina* (Boletim da Divisão de Geologia e Mineralogia n.º 251). DNPM.
- Rocha-Campos, A. C., & Simões, M. G. (1993). *Australomya sinuosa* sp. n., um novo megadesmídeo (Mollusca, Pelecypoda) da Formação Rio Bonito (Permiano), Bacia do Paraná, Brasil. *Anais da Academia Brasileira de Ciências*, 65(1), 29–39.
- Schneider, R. L., Muhlmann, H., Tommasi, E., Medeiros, R. A., Daemon, R. F., & Nogueira, A. A. (1974). Revisão estratigráfica da Bacia do Paraná. In *Anais do XXVIII Congresso Brasileiro de Geologia* (Vol. 1, pp. 41–65). Sociedade Brasileira de Geologia.
- Silva Santos, R. (1991). Palaeonisciformes do Estado de São Paulo. In *Boletim de Resumos do 12º Congresso Brasileiro de Paleontologia* (p. 11). IG-USP.
- Simões, M. G. (1992). Pelecípodes da Formação Palermo (Permiano) de São Sepé (RS) e Guiratinga (MT): Implicações na evolução da fauna neopaleozóica da Bacia do Paraná, Brasil [Tese de doutorado, Universidade de São Paulo].
- Simões, M. G. (2000). Assembléias de invertebrados marinhos do Neopaleozóico da Bacia do Paraná, no Estado do Rio Grande do Sul. In M. Holz & L. F. De Ros (Eds.), *Paleontologia do Rio Grande do Sul* (pp. 107–125). UFRGS/CIGO.
- Simões, M. G., & Rocha-Campos, A. C. (1993). Systematics and paleoecology of the pelecypods of the Palermo Formation (Permian), Paraná Basin, Brazil. *Anais da Academia Brasileira de Ciências*, 65(3), 324.

- Soares, P. C. (1972). O limite glacial/pós-glacial do Grupo Tubarão no Estado de São Paulo. *Anais da Academia Brasileira de Ciências*, 44(supl.), 333–342.
- Soares, P. C., & Landim, P. M. B. (1973). Aspectos regionais da estratigrafia da bacia do Paraná no seu flanco nordeste. In *Anais do XXVII Congresso Brasileiro de Geologia* (Vol. 1, pp. 243–256). Sociedade Brasileira de Geologia.
- Solms-Laubach, H. (1913). *Tietea singularis*: Ein neuer Pteridinenstamm aus Brasilien. *Zeitschrift für Botanik*, 5, 673–700.
- Stevaux, J. C., Souza-Filho, E. E., & Landim, P. M. B. (1983). Marcas de ondas simétricas do topo do Subgrupo Itararé e seu significado paleogeográfico. In *Atas do IV Simpósio Regional de Geologia* (pp. 175–183). SBG.
- Stevaux, J. C., Souza-Filho, E. E., & Fulfaro, V. J. (1986). Trato deposicional da Formação Tatuí (P) na área aflorante do NE da Bacia do Paraná, Estado de São Paulo. In *Anais do 35º Congresso Brasileiro de Geologia* (Vol. 1, pp. 219–229). Sociedade Brasileira de Geologia.
- Tavares, T. M. V. (2007). *Filicíneas permianas permineralizadas da Formação Corumbataí, Nordeste da Bacia do Paraná* [Dissertação de mestrado, Universidade Estadual Paulista].
- Tavares, T. M. V., Rohn, R., & Merlotti, S. (2011). Caules permineralizados de *Tietea* e *Psaronius* na Bacia do Paraná (Formação Corumbataí, Permiano). *Pesquisas em Geociências*, 38(2), 114–131.
- Washburne, C. W. (1930). *Petroleum geology of the State of São Paulo – Brazil* (Boletim da Comissão Geográfica e Geológica do Estado de São Paulo n.º 22). São Paulo.

This preprint was submitted under the following conditions:

- The authors declare that the necessary Terms of Free and Informed Consent of participants or patients in the research were obtained and are described in the manuscript, when applicable.
- The authors declare that the preparation of the manuscript followed the ethical norms of scientific communication.
- The authors declare that they are aware that they are solely responsible for the content of the preprint and that the deposit in SciELO Preprints does not mean any commitment on the part of SciELO, except its preservation and dissemination.
- The authors declare that the data, applications, and other content underlying the manuscript are referenced.
- The deposited manuscript is in PDF format.
- The authors declare that the research that originated the manuscript followed good ethical practices and that the necessary approvals from research ethics committees, when applicable, are described in the manuscript.
- The authors declare that once a manuscript is posted on the SciELO Preprints server, it can only be taken down on request to the SciELO Preprints server Editorial Secretariat, who will post a retraction notice in its place.
- The authors agree that the approved manuscript will be made available under a [Creative Commons CC-BY](#) license.
- The submitting author declares that the contributions of all authors and conflict of interest statement are included explicitly and in specific sections of the manuscript.
- The authors declare that the manuscript was not deposited and/or previously made available on another preprint server or published by a journal.
- If the manuscript is being reviewed or being prepared for publishing but not yet published by a journal, the authors declare that they have received authorization from the journal to make this deposit.
- The submitting author declares that all authors of the manuscript agree with the submission to SciELO Preprints.