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Depositional Sequences of the Itararé Group in the Region of Mafra (SC) and their Regional Correlation

Sequências Deposicionais do Grupo Itararé na Região de Mafra (SC) e sua Correlação Regional

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Abstract
The Itararé Group, Permocarboniferous of the Paraná Basin, has its deposition associated with the Late Paleozoic Ice Age (LPIA), which encompassed multiple glacial advance-retreat cycles. Recognizing the nature of the processes that form these rocks is essential to understand the diversity of glacial and non-glacial depositional systems that were active during the LPIA. Previous authors have carried out sedimentological and stratigraphic studies in outcrops of the Itararé Group in the Santa Catarina and Paraná states, however, the integration between these areas and the delimitation of glacial cycles is still little known. Seeking to increase the knowledge on the stratigraphy of the Itararé Group, this work aims to investigate its facies in five shallow boreholes in the Mafra region, northern Santa Catarina state. In this region, 300 meters of cores sampled almost the entire stratigraphic succession of the Itararé Group. We further integrate our results with published data from Alfredo Wagner, Vidal Ramos, Presidente Getúlio, Doutor Pedrinho and São João do Triunfo in order to build a regional stratigraphic framework. A total of 33 sedimentary facies were recognized and organized in five genetic associations, corresponding to subaqueous outwash fans, rain-out and mud settling, thin-bedded turbidites, mass-transport deposits, and thick-bedded turbidites. The regional stratigraphic correlation allowed the recognition of 5 glacial cycles, corresponding to depositional sequences of deglaciation. They show signs of glacial influence that diminish toward the top, where deltaic deposits developed as climatic conditions improved. Diamictites are present in all areas and distributed preferentially in the lower and middle sequences. They consist of mass-transport deposits with origin attributed to gravitational instability due to sediment accumulation in melting and glacial retreat phases.

Keywords: Late paleozoic ice age; Glacial cycles; Stratigraphic framework

Resumo
O Grupo Itararé, Permocarbonífero da Bacia do Paraná, tem sua deposição associada à Era Glacial Neopaleozoica (EGN), que ocorreu em múltiplos ciclos de avanços e recuos glaciais. Reconhecer a natureza dos processos que formaram as rochas sedimentares desse intervalo é essencial para compreender a diversidade dos sistemas deposicionais glaciais e não glaciais atuantes durante a EGN. Diversos autores realizaram estudos sedimentológicos e estratigráficos em afloramentos do Grupo Itararé nos estados de Santa Catarina e Paraná, porém, a integração entre essas áreas e a delimitação dos ciclos glaciais ainda é pouco conhecida. Buscando aumentar o conhecimento sobre a estratigrafia do Grupo Itararé, este trabalho tem como objetivo investigar suas fácies sedimentares em cinco sondagens rasas na região de Mafra, norte do estado de Santa Catarina. Nesta região, 300 metros de testemunhos amostraram quase toda a sucessão estratigráfica do Grupo Itararé. Além disso, os resultados aqui obtidos foram integrados com dados publicados das regiões de Alfredo Wagner, Vidal Ramos, Presidente Getúlio, Doutor Pedrinho e São João do Triunfo, a fim de construir um arcabouço estratigráfico regional. Um total de 33 fácies sedimentares foram reconhecidas e agrupadas em cinco associações genéticas, correspondendo a leques de *outwash* subaquosos, *rain-out* e decantação de lama, turbiditos delgados, depósitos de transporte em massa e turbiditos espessos. A correlação estratigráfica regional permitiu o reconhecimento de cinco ciclos glaciais, correspondentes a sequências deposicionais de deglaciação, que exibem evidências de diminuição da influência glacial em direção ao topo, onde depósitos deltaicos se desenvolveram devido ao clima mais quente. Diamictitos estão presentes em todas as áreas, distribuídos preferencialmente nas sequências inferiores e intermediárias. Estes consistem em depósitos de transporte em massa com origem atribuída à instabilidade gravitacional devido ao acúmulo de sedimentos durante fases de derretimento e recuo glacial.

Palavras-chave: Era glacial neopaleozoica; Ciclos glaciais; Arcabouço estratigráfico

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1 Introduction

The Itararé Group, Permocarboniferous in age, is one of the main lithostratigraphic units of the Paraná Basin. Its facies include sandstones, conglomerates, diamictites, shales with dropstones, rhythmites with the presence of faceted, polished and striated clasts and pebbles, and other elements such as grooved pavements, attributing a glacially-influenced origin to these deposits (Schneider et al. 1974; França & Potter 1988; Eyles, Eyles & França 1993; Santos, Rocha Campos & Canuto 1996; Vesely & Assine 2006; d'Avila 2009; Aquino et al. 2016). The stratigraphy of Itararé Group has a complex architecture, mainly related to subaqueous outwash depositional systems, turbidites, mass transport deposits (MTDs), marine and delta systems, inserted in three large glacial cycles (França & Potter 1988; Schneider et al. 1974) which occurred during the Late Paleozoic Ice Age (LPIA) (Isbell et al. 2003).

In the outcropping portion located in southeastern Paraná Basin, studies seeking to understand the dynamics of deglaciation were conducted in locations in the state of Santa Catarina (Aquino et al. 2016; Carvalho 2014; d'Avila 2009; Fallgatter & Paim 2019; Puigdomenech et al. 2014; Schemiko, Vesely & Rodrigues 2019; Valdez et al. 2019) and in the state of Paraná (Vesely 2006), where authors elaborated stratigraphic vertical profiles. In the locality of Dr. Pedrinho, Aquino et al. (2016) and d'Avila (2009) recognized depositional sequences corresponding to high frequency glacial cycles, also observed by Fallgatter and Paim (2019) in the Alfredo Wagner area, and suggestive of shorter duration glacial advance and retreat events. The region of Mafra, in the southern Brazilian state of Santa Catarina, corresponds to the place from which Schneider et al. (1974) described the type sections of the Campo do Tenente and Mafra formations, which correspond to the lower and middle subdivisions of the Itararé Group respectively. Also, this location is considered one of the most important fossiliferous sites of the Itararé Group in the Paraná Basin, with a great variety of fossil groups. The fossiliferous Lontras shale (Hamel 2005; Ricetti & Weinschütz, 2011; Adami-Rodrigues et al. 2012; Mouro et al. 2014; Taboada et al. 2016; Wilner, Lemos & Scomazzon 2016; Mouro et al. 2018) is stratigraphically positioned at the base of the Rio do Sul Formation, which is the upper unit of the Itararé Group according to Schneider et al. (1974). In this locality, a collection of about 300 meters of drill cores were the object of study by Weinschütz and Castro (2004), Weinschütz and Castro (2005) and Weinschütz and Castro (2006).

Recognizing the depositional nature of the Itararé Group and of facies of glacial environments is difficult, since several types of depositional systems can be present in this environment, resulting in facies with ambiguous forming processes (Eyles, Eyles & Miall 1983; Eyles, Eyles & Miall 1985; Miller 1996; Hambrey & Glasser 2012). Despite several works with a stratigraphic focus on the outcropping portion of the Itararé Group, there is a lack of integration of detailed studies, the distribution of depositional sequences, and the stratigraphic positioning of the fossiliferous bed, especially between the areas of Paraná and Santa Catarina states.

Thus, the main objectives of this work are to define the depositional systems that formed the rocks sampled in the cores of the Mafra region, and recognize the evolution and regional distribution of these systems along depositional sequences of deglaciation. A secondary objective is to understand the origin of thick successions of diamictites in the area, analyzing the spatial evolution in a geological section in the outcropping region of the Itararé Group, in the states of Santa Catarina and Paraná.

2 Geological Setting

The Paraná Basin is an intracratonic basin divided into six supersequences separated by unconformities, called Supersequences Rio Ivaí, Paraná, Gondwana I, Gondwana II, Gondwana III, and Bauru, whose ages range from the Ordovician period to the Neo-Cretaceous period (Milani et al. 2007). The Itararé Group, object of this work, is positioned in the interval between the Pennsylvanian and Cisuralian epochs (Holz et al. 2010), as part of the Gondwana I Supersequence (Figure 1). This group is up to 1.3 km thick (França & Potter 1988) and covers the main glacial Gondwana record, called the Late Paleozoic Ice Age (LPIA), which is characterized by several short-lived glacial events (Eyles, Eyles & França 1993; Fielding, Frank & Isbell 2008; Isbell et al. 2003). Schneider et al. (1974) divided the Itararé Group into three intervals with lithostratigraphic connotation, named Campo do Tenente, Mafra and Rio do Sul formations. These units were defined by the description of outcrops and are roughly equivalent to the Lagoa Azul, Campo Mourão and Taciba formations later defined in the subsurface (França & Potter 1988). Although both divisions are equivalent, in this work it will be adopted the nomenclature proposed by Schneider et al. (1974) since this division was defined, in part, in the area of the present study.

A regional datum is represented by the so-called Lontras shale, positioned at the base of the Rio do Sul Formation (Schneider et al. 1974), which are recognized both in outcrop and the subsurface. This horizon is characterized by an elevated fossiliferous content including

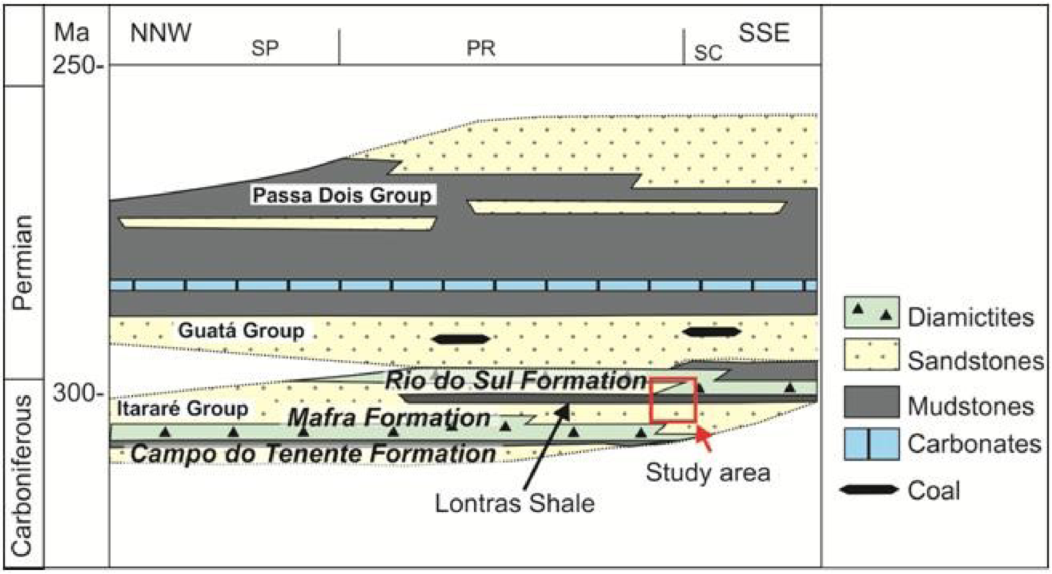

Figure 1 Simplified stratigraphic chart of the Gondwana I Supersequence, with the subdivisions of Schneider et al. (1974). The rectangle in red represents the approximate position of the study interval. Modified from Vesely et al. (2015).

fishes (Hamel 2005), brachiopods (Taboada et al. 2016), sponges (Mouro et al. 2014), crustaceans (Adami-Rodrigues et al. 2012), conodonts (Wilner, Lemos & Scomazzon 2016), scolecodonts (Ricetti & Weinschütz, 2011), insects (Ricetti, Adami-Rodrigues & Weinschütz 2012) and larval cocoons (Mouro et al. 2016).

3 Materials and Methods

We described 301.25 meters of cores recovered from five boreholes (Figure 2): VR01 (Vila Ruthes), with 57.70 m; SL02 (São Lourenço), with 58.60 m; RB03 (Rio Butiá), with 58.35 m; TC04 (Terreno Campáleo), with 78.60 m; and BR05 (BR280 highway), with 48.00 m. The facies were characterized by the lithological type, grain size, sedimentary structures, thickness, top and base contacts of beds, and the presence of post-depositional structures (Miall 1978). Mnemonics were adapted from Eyles, Eyles and Miall (1983) for the representation of facies. The facies description was followed by grouping facies into genetic facies associations.

The facies descriptions resulted in profiles that were correlated and stacked as a continuous composite graphic log. It was complemented in the lower portion with data from Weinschütz and Castro (2006), referring to the PM06 (Pedreira Motocross) and adjacent outcrops, and complemented in the upper portion with data from the descriptions of outcrops and the borehole PP10 (Projeto Pioneiro), available in the work of Weinschütz and Castro (2004).

Published stratigraphic profiles from areas situated to the south and north of Mafra (Figure 2) were standardized and represented according to the interpretations assumed by the respective authors. These include São João do Triunfo (Vesely 2006), Doutor Pedrinho (Aquino et al. 2016), Presidente Getúlio (Schemiko, Vesely & Rodrigues 2019), Vidal Ramos (Valdez et al. 2019) and Alfredo Wagner (Fallgatter & Paim 2019). This allowed the elaboration of a regional section oriented approximately north to south, in which depositional sequences limited by surfaces of unconformities and correlative conformities were correlated.

4 Results

4.1 Facies

The description of five boreholes from Mafra resulted in the recognition of 33 sedimentary facies, whose descriptions and depositional processes are summarized in Table 1.

4.2 Facies Association

A total of five associations were interpreted:

Subaqueous Outwash facies association: It is present in the lower and middle parts of the borehole TC4 and in the entire borehole BR5, consisting, in decreasing order of occurrence, to the facies Sr, Sr(d), Sm, S(d), Sp, H(d), Sm-g, Sh, Sg-ic, Dmm, Hr(d), Sc(d), Gg, Fl-d, Fl, Sm-ic, Sg(d), Gm, Sg-c, F-bp, Sg, Si, Hg, Gm-ic, Si-ic and Sp-ic.

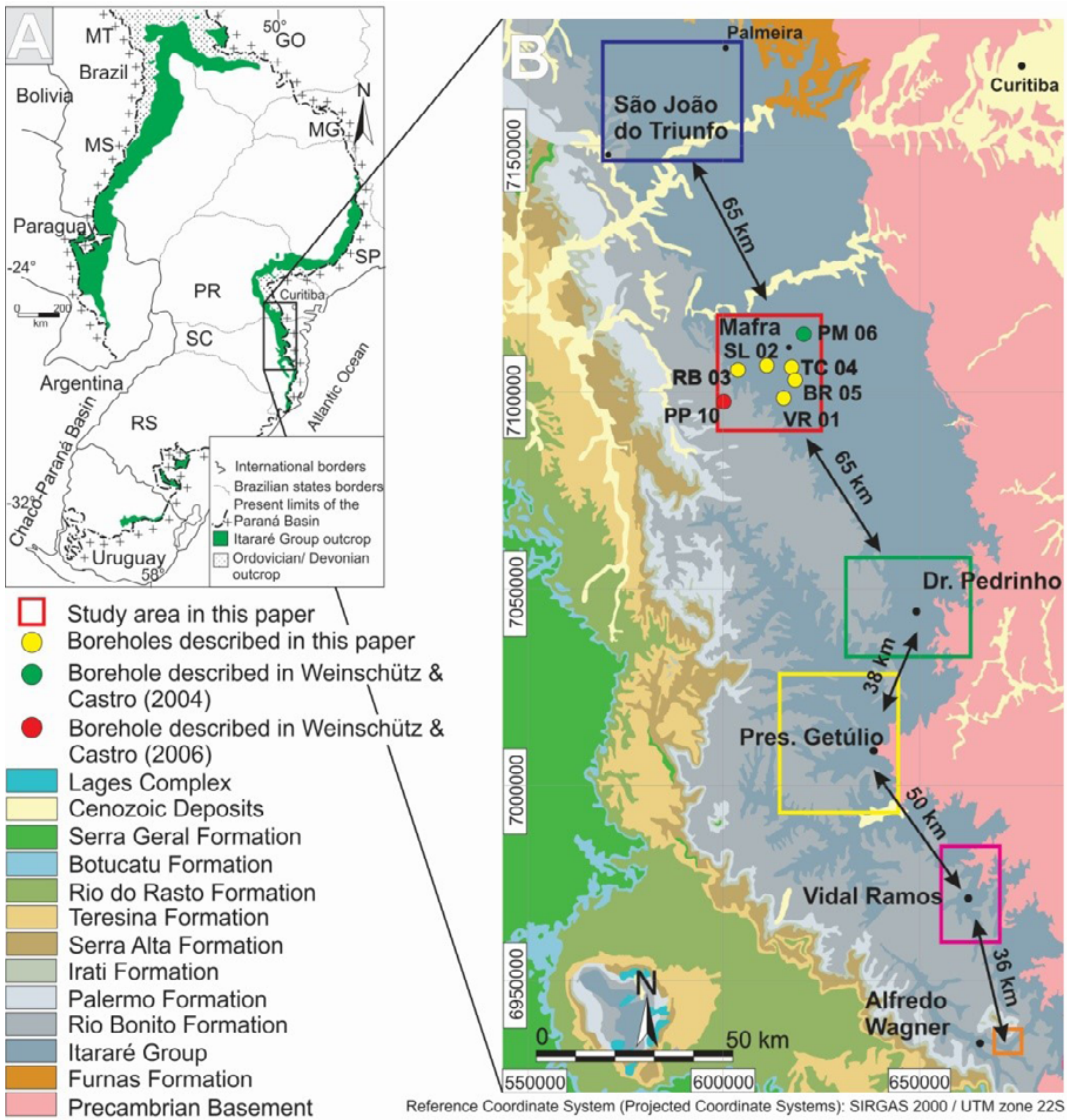

Figure 2 A. Paraná Basin and Itararé Group outcrop range, modified by Vesely et al. (2015); B. Location of the shallow boreholes in the Mafra region and areas with correlated vertical profiles in geological map of Parana Basin: São João do Triunfo (Vesely 2006); Dr. Pedrinho (Aquino et al. 2016); Pres. Getúlio (Schemiko, Vesely & Rodrigues 2019); Vidal Ramos (Valdez et al. 2019); Alfredo Wagner (Fallgatter & Paim 2019) (geological map modified from Perrotta et al. 2004).

The bedding sets have recurrence of coarsening-upward followed by fining-upward, which are marked by basal conglomerates (Figure 3). There are deformation features in the lower part of the association while, at the top, there are horizontal lamination, planar cross stratification and climbing ripples. Conglomerates with a basal erosive character, possible scour structure, are suggestive of channelized flows, while the load structures (F-bp facies) suggest the rapid deposition of sediments. This may also explain the deformation features present in the basal part of the association, where unconsolidated sediments would be subject to instability of the front of the fans due to an excess of sedimentary load (Lønne 1995; Suss et al. 2014).

Table 1 Recognized sedimentary facies, with brief description of facies, structures and depositional processes.

Facies Codes	Facies	Sedimentary Structures	Depositional Process
Fm	Mudstone	Massive	Settling of mud
Fl-d	Shale with dropstones	Horizontal lamination disrupted by clasts; fine sandstone lenses	Settling of mud and dropstones by ice rafting
Fl	Shale	Horizontal lamination	Settling of mud
Fl(c)	Shale with concretions	Horizontal lamination with pyritized concretions	Settling of mud and biological activity
F-bp	Siltstone with load structures	Horizontal lamination/ load structures in the form of balls-and-pillows	Settling of mud and traction flows
Fl(d)	Shale with deformation	Horizontal lamination with convolute folds	Settling of mud and slumps
Rg-d	Rhythmite of very fine sandstone and siltstone, with dropstones	Horizontal lamination, normal grading, disrupted by dropstones, subcritical climbing ripples cross lamination	Waning flows and dropstones by ice rafting
Rg(d)	Rhythmite of very fine sandstone and siltstone, deformed	Horizontal lamination with normal grading and small folds	Waning flows, and slumps
Hg	Heterolithic interbedded of very fine sandstone and siltstone	Horizontal stratification with normal grading of very fine sandstone to siltstones	Turbulent, low-density waning flows
Hr(d)	Heterolithic interbedded of siltstone and very fine sandstone, deformed	Discontinuous climbing ripple cross-lamination, deformed	Traction flows and slumps
H(d)	Heterolithic interbedded of very fine sandstone and shale, deformed	Layers discontinuous with open and close folds	Slumps
Dmm	Massive Diamictite	Massive	Debris flows
Dms	Diamictite stratified	Horizontal parallel stratification	Rain-out
Dms(d)	Diamictite stratified, deformed	Discontinuous or ruptured layers of sandstone	Mass transport
Sm	Massive fine sandstone	Massive	Gravity flows
Sm-ic	Massive fine sandstone with muddy rip-up clasts	Massive	Gravity flows
Sm-g	Massive fine sandstone with granules	Massive	Gravity flows
Sh	Very fine sandstone with horizontal lamination	Horizontal lamination	Traction flows
Sr	Very fine/ fine sandstone with climbing ripple cross-lamination	Climbing ripple cross-lamination	Traction flows and settling of mud
Sp	Fine/ medium sandstone with planar cross stratification	Planar cross stratification	Traction flows
Sp-ic	Fine/ medium sandstone with planar cross stratification and muddy rip-up clasts	Planar cross stratification	Traction flows
Sg	Coarse to medium sandstone, graded	Normal grading	Hyperconcentrated waning flows
Sg-c	Coarse to medium sandstone, graded, conglomeratic	Normal grading	Hyperconcentrated waning flows
Sg-ic	Coarse to medium sandstone, graded with rip-up clasts	Normal grading	Hyperconcentrated waning flows
Si	Medium to coarse sandstone with inverse grading	Inverse grading	Hyperconcentrated waxing flows
Si-ic	Medium to coarse sandstone with inverse grading and muddy rip-up clasts	Inverse grading	Hyperconcentrated waxing flows
S(d)	Very fine homogenized sandstone	Ruptured, homogenized beds	Remobilization of previously deposits
Sr(d)	Very fine sandstone with climbing ripple, deformed	Climbing ripple cross-lamination, small convolute folds, rare flame structures	Traction flows and slumps
Sg(d)	Very fine sandstone to silt normally graded, deformed	Normal grading, isoclinal folds and horizontal lamination	Hyperconcentrated waning flows and slumps
Sc(d)	Conglomeratic sandstone, deformed	Stretched, broken and inclined beds of sandstones and mudstones	Gravity flows
Gm	Massive conglomerate	Massive	Hyperconcentrated flows
Gm-ic	Massive conglomerate with muddy rip-up clasts	Massive	Gravity flows
Gg	Conglomerate graded	Normal grading	Hyperconcentrated waning flows

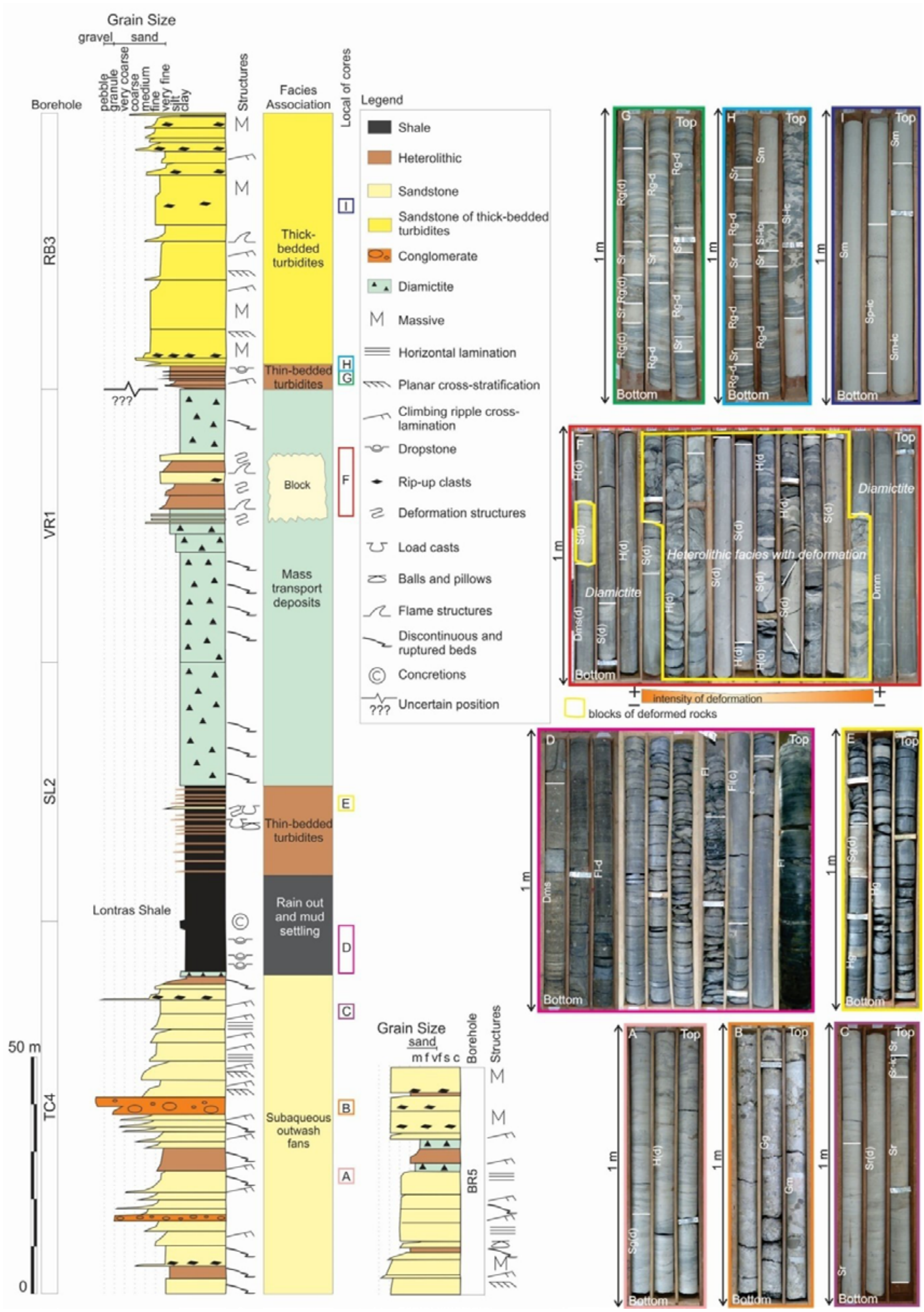

Figure 3 Composite graphic log of the distribution of facies associations in the boreholes BR5, TC4, SL2, VR1 and RB3. The colored rectangles indicate the position of the cores on the log. Facies codes in Table 1.

This facies association is interpreted as subaqueous outwash fans and channels deposits, whose faciological characteristics and similar stacking patterns were recognized in outcrops of the Itararé Group by Aquino et al. (2016), Suss et al. (2014) and Vesely et al. (2007), to which they attributed the same origin. According to Boulton (1986), outwash deposits are formed near the margins of glaciers, whose sedimentary load is provided by meltwater jets from their base, forming conglomeratic channels and sandy fans by deconfinement, where retrogradation patterns are common due to the evolution of the retreat of the glacier during deglaciation (Rust & Romanelli 1975). The release of meltwater jets may have characteristics of being continuous, resulting in thick beddings formed by traction processes, or rapidly (Lønne 1995), generating erosive channels, in which it is common the deposition of conglomeratic facies, produced by hyperconcentrated flows (Mulder & Alexander 2001), similar to Gm, Gg and Gm-ic facies.

Rain-out and mud settling facies association: Present in the upper part of the borehole TC4 and the bottom of the borehole SL2, consists of the facies Fl, Fl-d, Fl(c), Fm and Dms (Figure 3). The base of this association is marked by the deposition of one meter of stratified diamictite, in an abrupt contact above the outwash subaqueous association. It is followed by about 20 meters of shales with dropstones, decreasing the number of clasts toward the top, becoming then absent. They are marine environment deposits, being that the diamictite positioned at the base of the association refers to a rain-out deposit (Eyles, Eyles & Miall 1985), still close to the base of a retreating glacier, and that the shale deposits correspond to the settling of mud with concomitant dropstones released from ice rafts of a possible retreating glacier (Eyles, Eyles & Miall 1985; Hambrey & Glasser 2012). This shale succession corresponds to the Lontras Shale (Schneider et al. 1974; Weinschütz & Castro 2005).

Thin-bedded turbidites facies association: They occur in two stratigraphic intervals, representing 19 meters in the intermediate part of the borehole SL2 (Hg and Sg(d) facies), and in the basal part of the borehole RB3 (Sr, Rg-d, Rg(d) and Fl(d) facies), with less than five meters of thickness (Figure 3). In the borehole SL2, the intercalation of thin layers of siltstones and very fine sandstone, grading to shales, occurs with increased frequency toward the top, with consequent increase in the thickness of the beddings of siltstone and very fine sandstone. At the base of the layers there are load structures and rare dropstones. Subordinately, a thick bed of normally graded, internally deformed, fine-grained sandstone takes place. In the borehole RB3, this association is represented by thin layers of heterolithic facies consisting of the interleaving of very fine sandstone and shale, with flame-like load structures, rare recumbent folds, and rare dropstones disrupting the lamination. The presence of thin beds of siltstones and very fine sandstone, grading to shales, suggest that gravity flows of sediments gave rise to these deposits located in a deep-water environment (Kuenen & Migliorini 1950; Mutti & Ricci Lucchi 1972; Normark 1978; Walker 1978). They are interpreted as deposits of thin-bedded turbidites, possibly deposited in distal parts of subaqueous fans (Normark 1970), where the rapid deposition would have conditioned the formation of load structures at the base of the layers deposited on a still unconsolidated substrate (Owen 2003). The deformation structures present in sandy layers would be the result of the water escaping with the rapid deposition of sediments (Owen 1987).

Mass transport deposits facies association: Present in the SL2 and VR1 boreholes (Figure 3), it corresponds to Dms(d) and Dmm diamictites facies and has thickness reaching 90 meters. In the borehole SL2, the Dms(d) facies sits in a discordant way on a thin-bedded turbidites association, with the presence of ruptured and deformed laminae of very fine sandstone and siltstones which have reduction of occurrence to the top (Dmm facies). In the borehole VR1, the Dms(d) and Dmm facies occur intercalated, sometimes with intervals of up to 3 meters with discontinuous laminae of siltstones. Several levels of sandstone and heterolithic facies S(d) and H(d) with intense deformation and up to 9 meters thick occurs abruptly amidst the diamictites. The contact relationship of the top of this association with the immediately deposited one was not observed in the drill cores, making its real thickness uncertain.

The deposition of the facies of this association took place with the evolution of the retreat of ice masses and concomitant increase of the accommodation space. The presence of discontinuous and deformed beds and laminae, being part of the constitution of most diamictites, is suggestive that these facies are products of gravitational processes of sediment remobilization (Sobiesiak et al. 2016), where the intensity of deformation is proportional to the degree of homogenization of the rocks (Eyles & Eyles 2000; Rodrigues et al. 2020). Facies S(d) and H(d), present in this association, would be allochthonous blocks incorporated and transported in the same flow originating these diamictites, where the disaggregation of the edges of the blocks is reflected by the irregularity of their limits and consequent incorporation as constituents of the matrix (Rodrigues et al. 2020). The presence of pebbles and granules in the clayey matrix is attributed to materials from pre-existing deposits (Vesely et al. 2018), and may configure, for example, dropstones in heterolithic facies, which, by homogenization of fine fractions, resulted in the segregation of pebbles immersed in the matrix. Thus, this association is interpreted as a product of mass transport, which remobilized a large amount of sediment, in view of the recorded thickness and dimensions of existing blocks. Considering that high sedimentation rates may be responsible for forming deposits with steep slopes, in which instability is recurrent (Lønne 1995), blocks can be remobilized along fault planes in deposits such as delta fronts (Nemec et al. 1988), or in progradational fans. The characteristics of the blocks present in these MTDs are suggestive of relatively more proximal facies, possibly of fringe-equivalent deposits in outwash fans, or of collapsed fronts of turbiditic fans in a plastic state.

Thick-bedded turbidites facies association: Present in the borehole RB3, it is represented by about 55 meters of amalgamated sandstone, corresponding to facies Sm, Sr, Rg-d, Sm-ic, Sp, Sp-ic, Si-ic, S(d), Rg(d), Fl(d), Sc(d) and Fl (Figure 3). These thick layers are laid abruptly and erosively on facies of the thin-bedded turbidites association. The stacking of facies is represented by bed sets wich massive sandstone at the base of beds (Sm), then presenting cross-planar stratification (Sp) and climbing ripple cross-lamination toward the top (Sr). It is common the presence of heterolithic rip-up clasts up to 10 cm at the base of massive sandstones, and a few millimeters in the upper interval of this facies association. The sedimentary stack, marked by graded massive sandstone passing to facies with climbing ripple cross lamination, indicate processes with waning flow, being interpreted as turbidite deposits (Kuenen 1957; Zavala & Arcuri 2016), deposited below wave base. The evidence that the base of this facies association is highly erosive, marked by a large amount of heterolithic rip-up clasts, together with the low presence of muddy facies, may be related to high energy and steady velocity, possibly sustained by hyperpycnal flows from fluvial discharges (Mulder et al. 2003; Mulder & Syvitski 1995; Zavalla & Pan 2018), for which the relatively warmer climate was a controlling factor of these deposits (Bouma 2004).

5 Stratigraphic Correlation

The analysis of facies in the drill cores, complemented with data from the works of Weinschütz and Castro (2004) and Weinschütz and Castro (2006), allowed the characterization of the stratigraphic stacking of the Itararé Group in the Mafra region. To understand the regional distribution of these rocks, was elaborated a geological section has an approximate SE-NW orientation (Figure 4), which correspond to the directions of ice flow recognized for the Itararé Group in the region (Fallgatter & Paim 2019; Rosa, Vesely & França 2016). The region of Presidente Getúlio, positioned with a shift to the west in relation to the geological section, is in a more internal position of the Rio do Sul depocenter (Santos, Rocha Campos & Canuto 1996; Schemiko, Vesely & Rodrigues 2019), with paleocurrents having predominant direction toward SW.

Depositional sequences of deglaciation (Vesely & Assine 2006) were recognized in the areas of Doutor Pedrinho and Vidal Ramos (Aquino et al. 2016; d'Avila 2009; Valdez et al. 2019), corresponding to cycles of glacial advance and retreat, were correlated using the Lontras shale as datum. Sequence S1, below the deposition of the Lontras shale, is equivalent in the Mafra region to the deposits studied by Weinschütz and Castro (2004), who in drill cores and outcrops recognized heterolithic facies, denominating them varvites, diamictites and sandstones. The varvites in this sequence are interpreted here as thin-bedded turbidites, referring to diluted fringes, whose interval corresponds to the turbidites identified by Salamuni, Marques Filho and Sobanski (1966) in the Mafra region, which were the first records of turbidites identified in Brazil (Vesely et al. 2021). The presence of dropstones is due to the transport of sedimentary load by floating ice detached from a retreating glacier (Bennett, Doyle & Mather 1996; Gilbert 1990; Thomas & Connel 1985). Turbidites with dropstones are also recognized in Doutor Pedrinho, which sits directly on basement rocks, and have thick interval of massive diamictite above. To Aquino et al. (2016), these diamictites have characteristics of MTDs, whose origin is attributed to the remobilization of these turbidites with dropstones, a context that can also be attributed to the diamictites of this sequence in the Mafra and São João do Triunfo areas, where in the cores exhibit erosive base and incorporate layers of turbidites. In the area of Presidente Getúlio this depositional sequence corresponds to glacial tillites sitting directly on the basement, followed by MTDs. This sequence is absent further south, characterizing an onlapping pattern.

The Sequence S2 in Alfredo Wagner and Vidal Ramos corresponds to shales directly on the basement, in fjords that were flooded after ice retreat (Fallgatter & Paim 2019, Valdez et al. 2019). In the northernmost areas, more internally to the basin, this confinement characteristic is not recognized, and the sequence is represented by the initial deposition of sandy turbidites in Presidente Getúlio. In Doutor Pedrinho, there are interpreted outwash fans of a grounded glacier, which, by melting the base, provided a lot of conglomerates and sandstones in a jet efflux process (Aquino et al. 2016). Deformations are reported at the top of the diamictites of the sequence below, which were interpreted as a result of glaciotectonism (Aquino et al. 2016), characterizing an advance of the ice prior to the

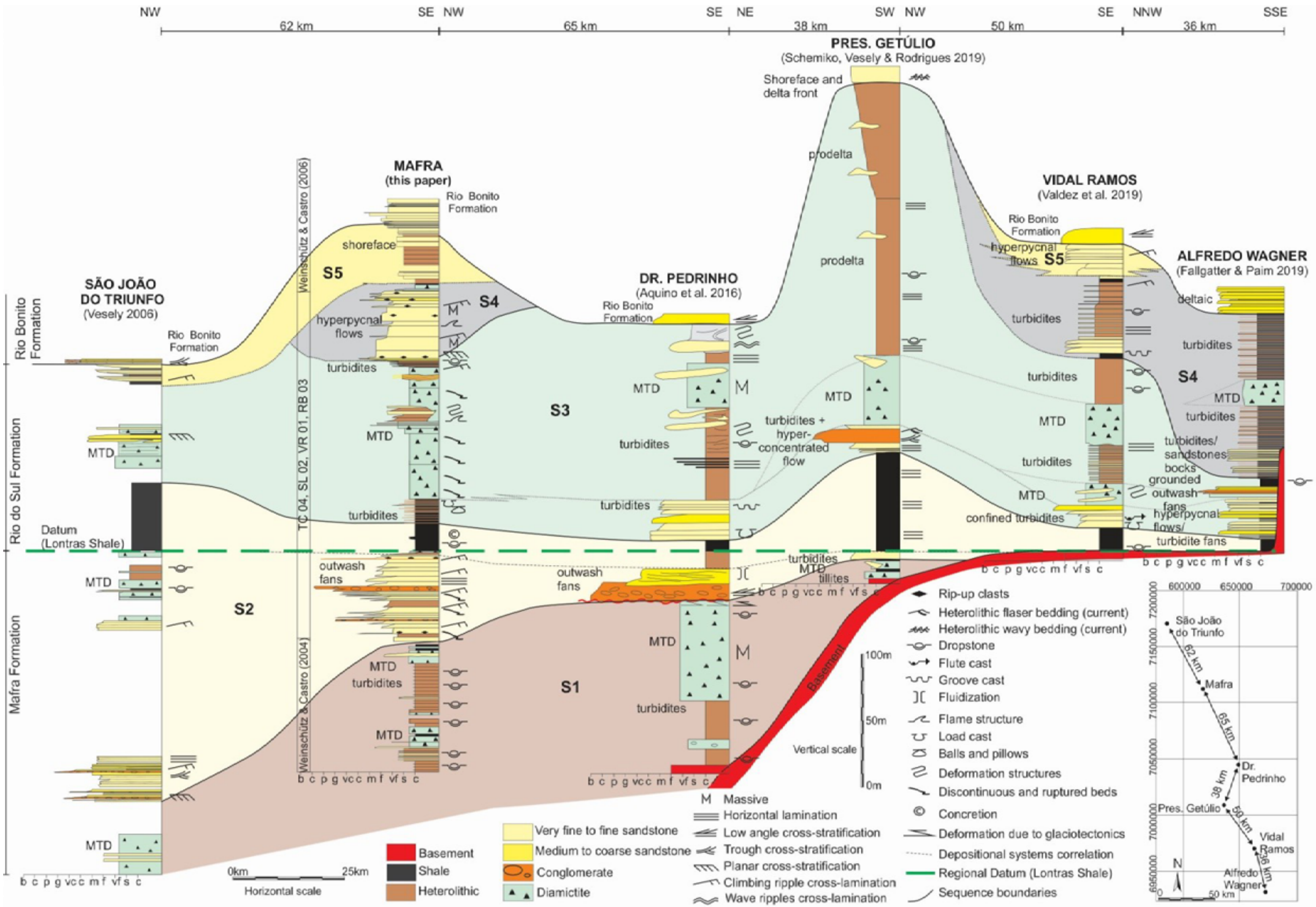

Figure 4 Geological section between Mafra and the areas of São João do Triunfo, Doutor Pedrinho, Presidente Getúlio, Vidal Ramos and Alfredo Wagner. Stratigraphic stacking of the Mafra area complemented with data from Weinschütz and Castro (2004) and Weinschütz and Castro (2006). Correlation intervals correspond to depositional sequences S1 to S5. The base of the occurrence of Lontras shale was used as datum for the correlation.

deposition of the outwash conglomerates. In the drill cores described in Mafra, sandy and conglomeratic facies were recognized corresponding to more distal parts of the outwash fans recognized by Aquino et al. (2016) and d'Avila (2009), also present in the base of the sequence in São João do Triunfo (Vesely 2006). In the cores of Mafra, it is common the presence of deformation structures with origin attributed to deformation in unconsolidated sediments (Owen 1987; Owen 2003), produced by the high sediment supply, which could provide gravitational instability by sediment accumulation. This process may have formed the mass transport deposits in São João do Triunfo. The Lontras shale that covers this sequence has an increase in thickness recorded in Presidente Getúlio, which may be due to the positioning of this area in relation of the Rio do Sul depocenter.

The deposition of the Sequence S3 occurred over the Lontras shale, whose lower limit is equivalent to a correlative conformity. In Alfredo Wagner, it starts with deposits produced by hyperpycnal flows and confined turbidites, with origin attributed by Fallgatter and Paim (2019) to early stages of a new glacial cycle, marked by the advance of ice masses, with the sediment supply released from their basal part within a paleovalley as outwash fans. In Vidal Ramos, Carvalho (2014), Puigdomenech et al. (2014) and Valdez et al. (2019) recognized that the base of the glacial sequence above the Lontras shale is characterized by sandy confined turbidites, possibly already recording positions further away from the ice. The equivalent of these deposits in Presidente Getúlio is represented by sandy turbidites and conglomerates resulting from hyperconcentrated flows in a deconfined situation (Schemiko, Vesely & Rodrigues 2019), which are recurrent in the region of Doutor Pedrinho, but with a reduction in the presence of conglomerates, as observed by Aquino et al. (2016). Equivalence in the most distal position is found in cores from Mafra, represented by heterolithic beds deposited in terminal fringes of turbidity fans. MTDs are present in all areas in a diachronous configuration, with distinct vertical positions. They are represented by silty-clayey matrix diamictites and clasts of igneous and metamorphic rocks, with deformed blocks of sandstone and heterolithic layers, usually with a massive aspect. They are interpreted as products of remobilization of turbidites and delta fronts, due to similarity between these deposits and the blocks, in which the degree of homogenization is a reflection of the intensity of remobilization (Eyles & Eyles 2000; Rodrigues et al. 2020). The origin is attributed to the high sediment supply (d'Avila 2009; Schemiko, Vesely & Rodrigues 2019; Suss et al. 2014; Valdez et al. 2019) in phases of glacial retreat and melting. The top of this sequence has a complex correlation because it has been eroded by sandstone facies of delta fronts attributed to the Rio Bonito Formation in Doutor Pedrinho and occurs in a transitional way to shallow facies of prodelta and delta front in Presidente Getúlio; and, finally, when with a more complete record, is limited by shale deposits in the areas of Vidal Ramos and Alfredo Wagner. In Mafra this sequence ends with the deposition of thin-bedded turbidites which have possibly been trapped on substrate irregularities at the top of mass transport deposits (Kneller et al. 2016; Nelson et al. 2011). In São João do Triunfo the turbidite facies were not recognized in this sequence by Vesely (2006), probably due to the absence of outcrops, making the upper and lower limits of the sequence uncertain.

The sequence S4 has occurrence in the areas of Alfredo Wagner, Vidal Ramos and Mafra. In Alfredo Wagner the initial record has been marked by the deposition of thin-bedded turbidites, originated by turbidity currents from the high sediment supply in deltas located in the headwaters of a paleo fjord (Fallgatter & Paim 2019), with intercalation of MTDs. In Vidal Ramos, the base of the sequence is characterized by sandy turbidites, with fining and thinning-upward, in a decreasing energy system finalized by the deposition of shales. In the drill cores from Mafra, this sequence is characterized by fine to medium sandstone, erosively deposited over thin-bedded turbidites, with the incorporation of centimetric fragments of heterolithic facies at the base of the sequence. The character of thick layers with absence of fine fractions allowed the interpretation of these deposits as thick turbidites produced by continuous hyperpycnal flows. However, the origin of these deposits requires a further study, with analysis of paleocurrents in equivalent outcrops, as it is not possible to establish a direct correlation with the other areas in the elaborated section, which may suggest other sources of sediment supply.

Sequence S5 has a more localized occurrence, representing transition facies to the unit defined as Rio Bonito Formation, being recognized in Mafra (Castro, Weinschütz & Castro 2005; Weinschütz & Castro 2006) and São João do Triunfo (Vesely 2006), which they interpreted as delta front deposits, of post-glacial or periglacial origin, and thicker sandstone layers may be products of episodic flows in response to increased discharge regimes in more distant fluvial environments. In Vidal Ramos, Puigdomenech et al. (2014) related the occurrence of sandstones of this sequence as products of hyperpycnal flows associated with gravity flows in delta fronts, the transition of which occurs to the facies of the Rio Bonito Formation, identified by the cessation of evidence of glacial influence.

The five depositional sequences correspond to five glacial cycles, traceable over 250 km, whose disposition refers to the evolution of a marine environment with glacial influence and significant improvement of the climatic conditions in at least two moments: in a first event, the ice retreated to the point of raising the base level and there was a wide deposition of the fossiliferous Lontras shale, including filling paleovalleys in the southern portion; and in a second event, at the top of the interval, with the deposition of proximal facies, transitional to the Rio Bonito Formation. Evidence of glacial proximity is recorded by deformation due to glaciotectonics on top of MTDs (Dr. Pedrinho), by tillites (Presidente Getúlio), by channels and outwash fans facies, and by dropstones. The lower sequences S1 and S2 were deposited in deep water conditions, on topography with paleovalleys in the south portion. During deposition of sequence 2, a larger accommodation space in São João do Triunfo allowed the development of MTDs, originated by gravitational instability in depositional slopes of outwash fans located in the southern areas. The sequence S3 has a wide distribution, with basal facies corresponding to outwash deposits by meltwater of a retreating glacier, followed by MTDs, already configuring a situation with greater accommodation space and resedimentation processes. The distribution of these facies in all regions suggests a wide glacial retreat cycle. The sequences S4 and S5 have restricted occurrences, with registration of S4 in the southern portion and isolated in Mafra, and, with an increasingly warm weather, the proximal facies of sequence S5 were deposited. Finally, in relation to the distributions of diamictites, these correspond to MTDs with lateral equivalents in turbidites and outwash fans.

6 Conclusions

The facies analysis of the drill cores of shallow boreholes in the Mafra region and the correlation with studies in adjacent areas allowed the following conclusions to be drawn:

- The composite graphic log allowed to establish a continuous vertical stacking of facies, in a locality from which the type sections of the Mafra and Rio do Sul formations units had been defined;
- the correlation section with adjacent areas identified five deglaciation depositional sequences, suggesting that deposition was controlled by glacier advance and retreat events, with the record prevailing in retreat episodes;
- advance and retreat events evolved in the southern portion, with both geomorphological evidence, such as the presence of paleovalleys in the southern areas, and sedimentological, with depositional systems exhibiting distal and unconfined characteristics to the north;
- high sediment supply rates, due to the meltwater and retreat of ice masses, may have been responsible for the high sediment accumulation in outwash systems, with consequent instability in depositional slopes, resulting in mass transport deposits (MTDs);
- the MTDs correspond to diamictites that were formed under glacial influence, but without evidence of being direct products of glaciers, so that only the occurrences of diamictite deposits in the studied areas should not be used as paleoclimatic criteria of maximum extension of glaciers in the Itararé Group;
- the presence of dropstones, as direct evidence of glacial influence, is gradually reduced to the top, corresponding to the improvement in climatic conditions, with warmer climates and the installation of delta systems of the Rio Bonito formation;
- this work adds information to the existing depositional models of the upper portion of the Itararé Group, which have even been used as analogues for studies of petroleum systems in the Paraná Basin.

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Ronaldo Paulo Kraft: conceptualization; formal analysis; methodology; writing-original draft; writing – review and editing; visualization. **Fernando Farias Vesely:** conceptualization; methodology; validation; writing-original draft; writing – review and editing; supervision. **Luiz Carlos Weinschütz:** validation; writing-original draft.

Conflict of interest

The authors declare no potential conflict of interest.

Data availability statement

Original datasets can be are available on request. Other data included in this study are publicly available in the literature.

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