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ARTICLE

Lowstand Turbidites and Delta Systems of the Itararé Group in the Vidal Ramos region (SC), southern Brazil

Sistemas Turbidíticos e Deltaicos de Mar Baixo do Grupo Itararé na Região de Vidal Ramos (SC), Brasil

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ABSTRACT: Turbidites have captioned the attention of sedimentologists during the last decades due their importance as hydrocarbon reservoirs. However, their relationship to delta systems still deserves further studies. This paper presents examples from a late deglacial to early post-glacial deltaic and turbidite strata exposed in the surroundings of Vidal Ramos (Santa Catarina State, Brazil), southern portion of the Paraná Basin. There, the uppermost part of the Mafra Formation and the Rio do Sul Formation onlap the Proterozoic basement and comprises an up to 360 m thick package. It includes (base to top) black shales, mass transport deposits (MTD) and sandy turbidites (Mafra Formation) as well as thin bedded turbidites (tbt), including one interval of black shales and sandy turbidites, overlain by proximal delta front sandstones (Rio do Sul Formation). The analysis of the succession shows two more than 150 m thick coarsening-upwards deltaic successions composed of turbidite sand sheets at their base (prodelta), followed by partially collapsed thin bedded turbidites (delta slope wedge) and delta front sandstones. Both turbidite sand-sheets abruptly overlay black shale intervals related to maximum flooding surfaces and therefore record correlative conformities. A detailed stratigraphic section elaborated from the correlation of four logs (1/100) suggests that distal delta front sands includes both thin bedded turbidites and wave reworked sands whereas the proximal delta front was dominated by long-lived underflows (hyperpycnal flows). The succession suggests that the most expressive turbidite beds (base of the delta systems) have resulted from relative sea-level falls (early lowstand) whereas the thin-bedded turbidites were related to the development of the late lowstand wedge. Black shales represent the transgressive systems tract and HST were not deposited or preserved in the area. High sediment supply associated with lowstand tracts could explain the occasional (Vidal Ramos) to common occurrence of slope failures (slumps and diamictites) involving thin bedded turbidites and delta front sandstones. This situation is quite logical in terms of deglacial periods, and resulting high sediment supply, within a long-term icehouse context, with prevalence of lowstand to transgressive settings.

KEYWORDS: Deltas; Lowstand Turbidites; Lowstand Wedge; Late Paleozoic Glaciation; Paraná Basin.

RESUMO: *Turbiditos tem sido foco de estudos ao longo das últimas décadas devido a sua importância como reservatórios de óleo e gás. No entanto, a relação destes depósitos com deltas é um tema que ainda merece atenção. Nesse sentido, esse artigo discute um exemplo de turbiditos e sistemas deltaicos deglaciais a pós-glaciais expostos na região de Vidal Ramos (Santa Catarina), na porção sul da Bacia do Paraná. Nessa área, uma sucessão com cerca de 360 metros de espessura associada à porção superior da Formação Mafra e à Formação Rio do Sul recobre o embasamento Proterozóico (Complexo Metamórfico Brusque). Da base para o topo, esse intervalo inclui folhelhos negros, depósitos de transporte de massa e turbiditos arenosos da Formação Mafra recobertos por turbiditos finamente acamadados, incluindo um intervalo de folhelhos negros e turbiditos arenosos, e arenitos de frente deltaica proximal (Formação Rio do Sul). Esse intervalo estratigráfico registra duas espessas sucessões deltaicas superpostas com espessura individual de mais do que 150 m. Cada sucessão comporta turbiditos arenosos na base (prodelta) seguidos por turbiditos finamente acamadados (talude deltaico) que gradam para arenitos de frente deltaica, ambos os tipos parcialmente colapsados. Os dois pacotes de turbiditos arenosos da base de cada sucessão deltaica recobrem de forma abrupta intervalos de folhelhos negros vinculados a inundações máximas, caracterizando assim duas conformidades relativas. Uma seção estratigráfica elaborada a partir da correlação de quatro perfis levantados na escala 1/100 próximo ao topo do intervalo de estudo sugere que a frente deltaica distal inclui turbiditos finamente acamadados e arenitos retrabalhados por ondas enquanto que a frente deltaica proximal é dominada por estratos vinculáveis a fluxos hiperpicnais de longa duração. A sucessão como um todo sugere que os turbiditos mais expressivos, que caracterizam a base dos sistemas deltaicos, foram gerados por quedas relativas do nível de base (trato de mar baixo precoce), enquanto que os turbiditos finamente acamadados representam cunhas de mar baixo formadas durante as fases mais tardias dos estágios de mar baixo. Os folhelhos negros, por sua vez, foram correlacionados a tratos transgressivos enquanto depósitos de mar alto não foram depositados ou preservados. Alto suprimento sedimentar associado a um nível de mar baixo poderia explicar a ocasional (Vidal Ramos) a frequente ocorrência de feições de remobilização de taludes deposicionais (escorregamentos e fluxos de detritos) que envolviam a remobilização de turbiditos finamente acamadados e areias de frente deltaica. Tal panorama é compatível com episódios de deglaciação, e resultante elevado suprimento sedimentar, vinculados as fases finais de um longo período de glaciação (icehouse) que controlava o domínio de tratos de sistemas de mar baixo e transgressivo.*

PALAVRAS-CHAVES: *Deltas; Turbiditos de Mar Baixo; Cunha de Mar Baixo; Glaciação Permo-Carbonífera; Bacia do Paraná.*

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INTRODUCTION

Mass and sediment gravity flows are not restricted to a specific depositional depth as they occur from subaerial to deep-marine environments. Besides, triggering mechanisms can include slope failures due to overloading or seismic shocks, storm-induced re-suspension and hyperpycnal flows, among others. Facies tracts are a result of sediment supply, flow transformation and flow efficiency, basin configuration and confinement, climate and relative sea-level. Therefore, facies association, facies tract, depositional architecture, morphological elements and sedimentary processes are a complex response to the interplay of several controlling factors, their relative weight being always specific for each case.

However, it is also known that subaqueous environments favour the maintenance of gravity flows due to the preservation of water in the dense, sediment plus water mixture, in opposition to subaerial environments, where ground infiltration is a restraining factor. Besides, high sediment supply coupled with steep slopes largely enhances the possibility of gravity flows development. And, probably more important, relative base-level drops strongly enhance upstream erosion and resulting high sediment supply into the deeper parts of the basins.

In this way, delta slopes associated with high sediment input, a typical, though not exclusive, aspect of deglacial succession due to the large amount of sediment released from calving glaciers, tend to be turbidite prone. In this sense, the delta systems that are common in the uppermost portion of the Rio do Sul Formation fulfil these conditions, hence their association with sandy and thin bedded turbidites is not surprising. However the delta facies of the Itararé group were not still extensively studied and neither their genetic relationship to turbidites, although mass transport deposits related to delta slope failure (delta front sandstone blocks and slumped thin-bedded turbidites) have been quoted elsewhere at the same stratigraphic level (*e.g.* D`Ávila 2009; Suss *et al.* 2014).

Therefore, this paper aims to describe one example of delta system typical of the latest deglacial to post-glacial stage of the Paraná Basin, which are usually involved into slope failures, and thus only partially preserved within mass transport deposits. And, also, to relate its development to distinct turbidite systems (turbidite sand sheets and thin-bedded turbidites).

GEOLOGICAL SETTING

The Paraná Basin is a huge intracratonic basin (syneclise) covering about 1,500,000 km^2 of southern Brazil, south-eastern Paraguay, north-eastern Argentina and northern Uruguay (Fig. 1). It evolved from Ordovician to Cretaceous and encloses up to 7,000 m of volcano-sedimentary rocks subdivided by Milani (1997) into six 2nd order sequences (or supersequences). The Itararé Group (Gordon Jr. 1947), which encompasses the studied interval herein, comprises the lower portion of the Gondwana I Supersequence and registers the Late Paleozoic Ice Age in the Paraná Basin. The Late Pennsylvanian to Sakmarian Itararé Group reaches up to 1,300 m in thickness in the basin depocentre (França & Potter 1988) and encloses rare glacial, and mostly deglacial strata accumulated within subglacial, and mainly proglacial environments, respectively.

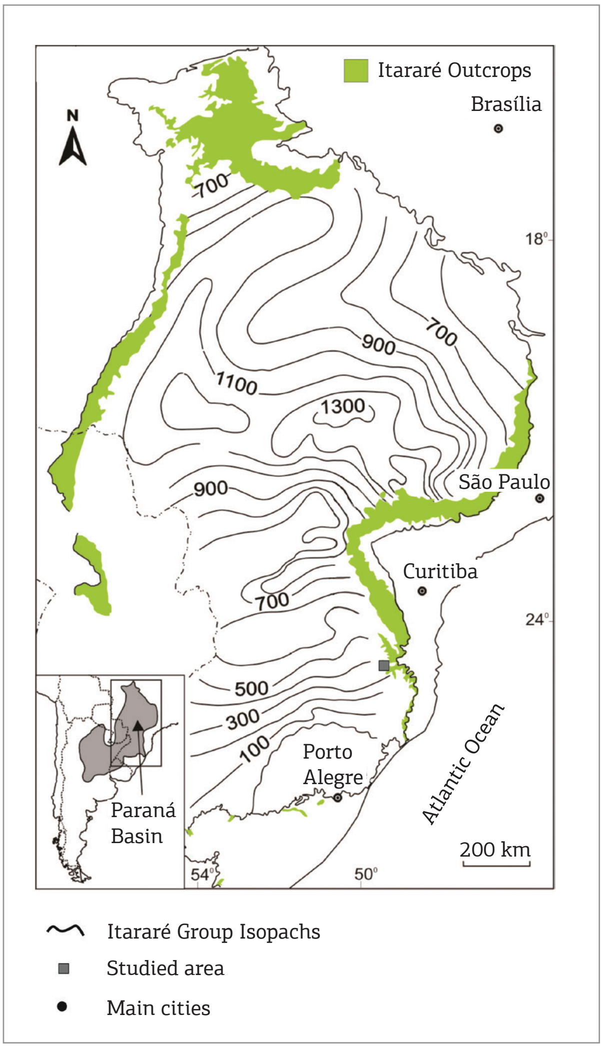

Figure 1. Outcrop belt and isopach map of the glaciogenic Itararé Group in the Paraná Basin (see basin location in the inset). Only the upper portion of the Itararé Group is exposed along the south-eastern and north-western outcrop belts of the basin. The position of the study area is indicated with a dark grey rectangle (from França & Potter 1991).

Based on outcrop studies in Santa Catarina and Paraná, Schneider *et al.* (1974) divided the Itararé Group into the Campo do Tenente, Mafra and Rio do Sul formations, from base to top. Up to 350 m thick, the Rio do Sul Formation essentially comprises fine-grained strata (mudstone and shale) deposited in a marine setting. Whereas its base includes a dark, fine-grained interval (black shale and siltstone), informally known as the "Lontras Shales", the rest of the unit includes siltstones, diamictites, rhythmites and fine-grained sandstones that display, in the upper part of the succession, wave ripples and flaser bedding ascribed by Schneider *et al.* (1974) to shallow water.

On the other hand, but now founded on subsurface data, França and Potter (1988) also subdivided the Itararé Group into three formations: the Lagoa Azul, Campo Mourão and Taciba formations, from base to top. The Taciba Formation was further subdivided into a lower, sandy member (Rio Segredo); a diamictite-rich member (Chapéu do Sol) and a shale-rich member (Rio do Sul). It covers the entire Paraná Basin and is the only one exposed around the whole basin. Sandstones of the Rio Segredo Member are characterized by massive and graded facies interpreted as turbidites. Some shallow water pieces of evidence, such as wave ripples, were recorded in cores from the northern part of the basin. The Chapéu do Sol Member consists of massive to crudely stratified diamictites, interpreted as rain-out deposits (mudstones with ice-rafted clasts), locally modified by resedimentation processes. In the southern part of the basin, these diamictites interfinger with dropstone-rich marine shales of the Rio do Sul Member. A correlation between surface- and subsurface-based stratigraphic schemes is shown in Tab. 1.

METHODS AND CONCEPTS

The first step of this work comprises the mapping the Itararé Group along the study area (Fig. 2). A Trimble GPS was used to locate outcrops on satellite images and previous maps published on internal reports, whereas the new geological map (1:60,000) was elaborated in the ArcGis 10. A total of 453 outcrops were described in terms of the classical procedures adopted for facies and facies association description and interpreted in terms of sedimentary processes. After that, their mapped vertical stacking were then interpreted in terms of sequence stratigraphy principles, basically accommodation *versus* supply.

Once the map was ready and the delta front interval mapped along the entire area, some detailed sedimentological logs (1:100) were acquired within strategic locations of the study area recording vertical succession of lithologies, textures, sedimentary structures and paleocurrent readings. Four of them were chosen and used to build up a stratigraphic section that allowed a more detailed interpretation of the delta front strata.

The adopted sequence stratigraphic scheme was the one proposed by Posamentier *et al.* (1988). Therefore, sequence boundaries (correlative conformities and one subaerial unconformity) were ascribed to the onset of base-level fall. Lowstand systems tract (LST) was subdivided into two successive components (early LST or fan and late LST or wedge). No highstand systems tract (HST) was identified. The identification of mass transport deposits (MTD) in outcrop was based on identification of synsedimentary deformation of previous deposits (protholite) with deformation ranging from minimal redistribution of large slide blocks

Table 1. Correlation between the schemes proposed by Schneider *et al.* (1974) and França and Potter (1988) for the Itararé Group based on surface and subsurface data, respectively (after Weinschütz & Castro 2004).

<table>
<tr><th colspan="3">Schneider et al. (1974)</th><th colspan="2">França and Potter (1988)</th></tr>
<tr><td rowspan="8">Itararé Group</td><td rowspan="3">Rio do Sul Formation</td><td rowspan="2">Fine-grained, heterolithic deposit.</td><td rowspan="3">Taciba Formation</td><td>Rio do Sul Member (shale)</td></tr>
<tr><td>Chapéu do Sol Member (diamictite)</td></tr>
<tr><td>"Lontras Shale"</td><td>Rio do Segredo Member (sandstone)</td></tr>
<tr><td rowspan="3">Mafra Formation</td><td>Upper: sandstone, siltstone, diamictite</td><td rowspan="3">Campo Mourão Formation</td><td>"Lontras Shale"</td></tr>
<tr><td>Middle: silty-muddy rhythmite</td><td rowspan="2">Diamictite, sandstone.</td></tr>
<tr><td>Lower: sandstone.</td></tr>
<tr><td rowspan="2">Campo do Tenente Formation</td><td rowspan="2">Shale, diamictite, sandstone and conglomerate.</td><td rowspan="2">Lagoa Azul Formation</td><td>Tarabaí Member (diamictite)</td></tr>
<tr><td>Cuiabá Paulista Member (sandstone)</td></tr>
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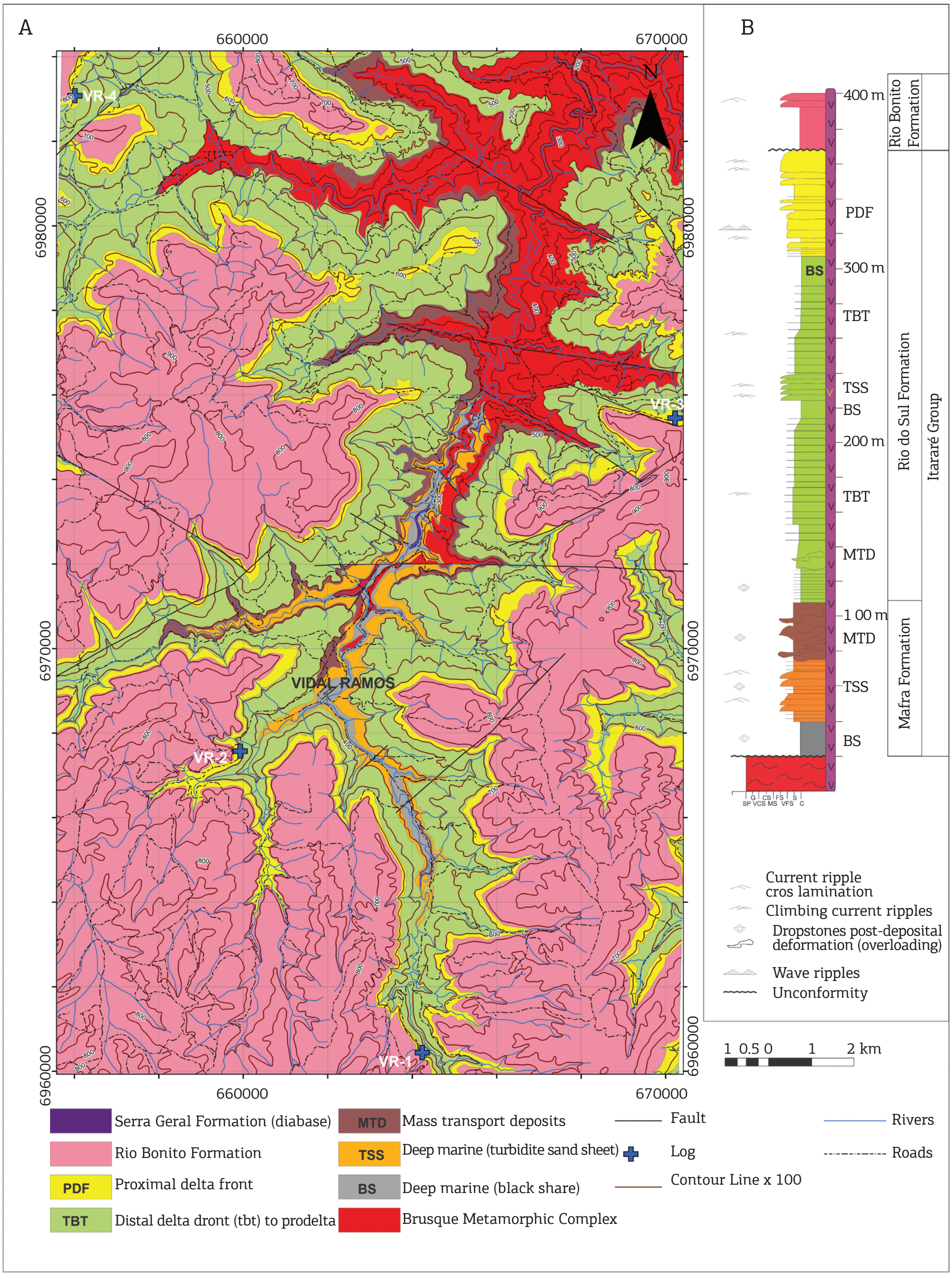

Figure 2. (A) geological map. (B) composite log of the study area. Detailed logs acquired in the proximal delta front facies association are indicated by blue crosses. Note that both Mafra shale and lower turbidite sand sheet are restricted to the southern portion of the map, probably confined to a NW/SE glacial paleovalley (Carvalho 2014).

to complete disaggregation typical of debris-flow deposits (Posamentier & Martinssen 2011).

RESULTS

Local Stratigraphy and Depositional Systems

The succession exposed around Vidal Ramos region (Fig. 2) is up to 360 m thick in its local depocentre and fills an irregular topography carved by glacial processes (Carvalho 2014) into Paleoproterozoic schists and marbles of the Brusque Metamorphic Complex (Fig. 3). It is comparable to the upper part of the Mafra (basal black shale and overlying sandstone) and Rio do Sul (rhythmite-rich succession) formations. Likewise, it is equivalent to the upper part of the Campo do Mourão and Taciba formations, the last one including the Rio do Segredo, Chapéu do Sol and Rio do Sul members. The exposed Itararé Group (Fig. 2) encompasses five main intervals described from base to top in the following paragraphs.

1. Black shale: A 20 m thick interval composed of black shale defines the base of the Paleozoic succession in the studied area. It correlates to the upper part of the Mafra Formation due to the fact that it rests underneath the turbidite sand sheets, and not above them like the Lontras Shale in the homonymous region. This interval includes both dropstone-bearing, black shales and mm-scale couples of dark grey siltstones and black shales (Fig. 4A and 4B). It is confined to a glacial carved, north-westward striated paleovalley and was ascribed to deep marine, proglacial sedimentation derived from distal, low concentration turbidity plumes and hemipelagic material disturbed by dropstones (Carvalho 2014). The informally named Mafra Shale represents a regional-scale, stratigraphic marker and one (the lower one) of three maximum flooding surfaces recorded in the Itararé Group in the area. A correlative conformity delineates its upper boundary.
2. Lower Turbidite Sand Sheet: A 30 m thick, mostly sandy, turbidite succession rests on the Mafra Shale and is also confined to the above mentioned glacial valley (Carvalho 2014). Turbidites form a sandstone sheet composed of amalgamated, decimetre-scale sandstone beds intercalated with centimetre-scale, graded sandstone and mudstone couples with dropstones (heterolithic rhythmites interpreted as thin-bedded turbidites - TBT) (Fig. 4C and 4D). The thicker sandstone beds are massive to plane-bedded, medium- to fine-grained and occasionally bounded by thin, usually discontinuous mudstone layers. On the other hand, TBT are composed of very fine- to fine-grained, massive, plane- and cross-laminated sandstones and siltstones. Sole marks and mudclasts are common. The sharp basal boundary of the entire turbidite succession (correlative conformity) suggests a relative-sea level fall here interpreted as a result of a climate change (cooling and resulting ice advance into the basin). The entire coarsening-upward, mostly sandy succession was related to the initial deglaciation stages and resulting high ice melt rates and sediment discharge from carving glaciers into the flooded valley (early lowstand turbidites). The intercalation of mostly amalgamated, thick sandstone beds and TBT with dropstones is understood as a result of short-term climate changes, i.e. warmer and higher sand deliver versus cooler and lesser sand deliver associated with dropstones, respectively (Carvalho 2014).

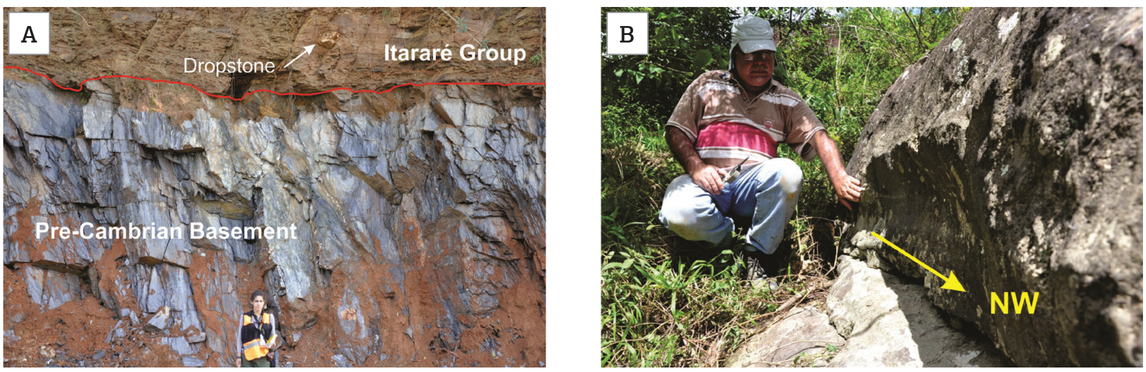

Figure 3. (A) fine-grained facies of the Rio do Sul Formation resting of basement rocks (schists) that display (B) ice-scoured striation.

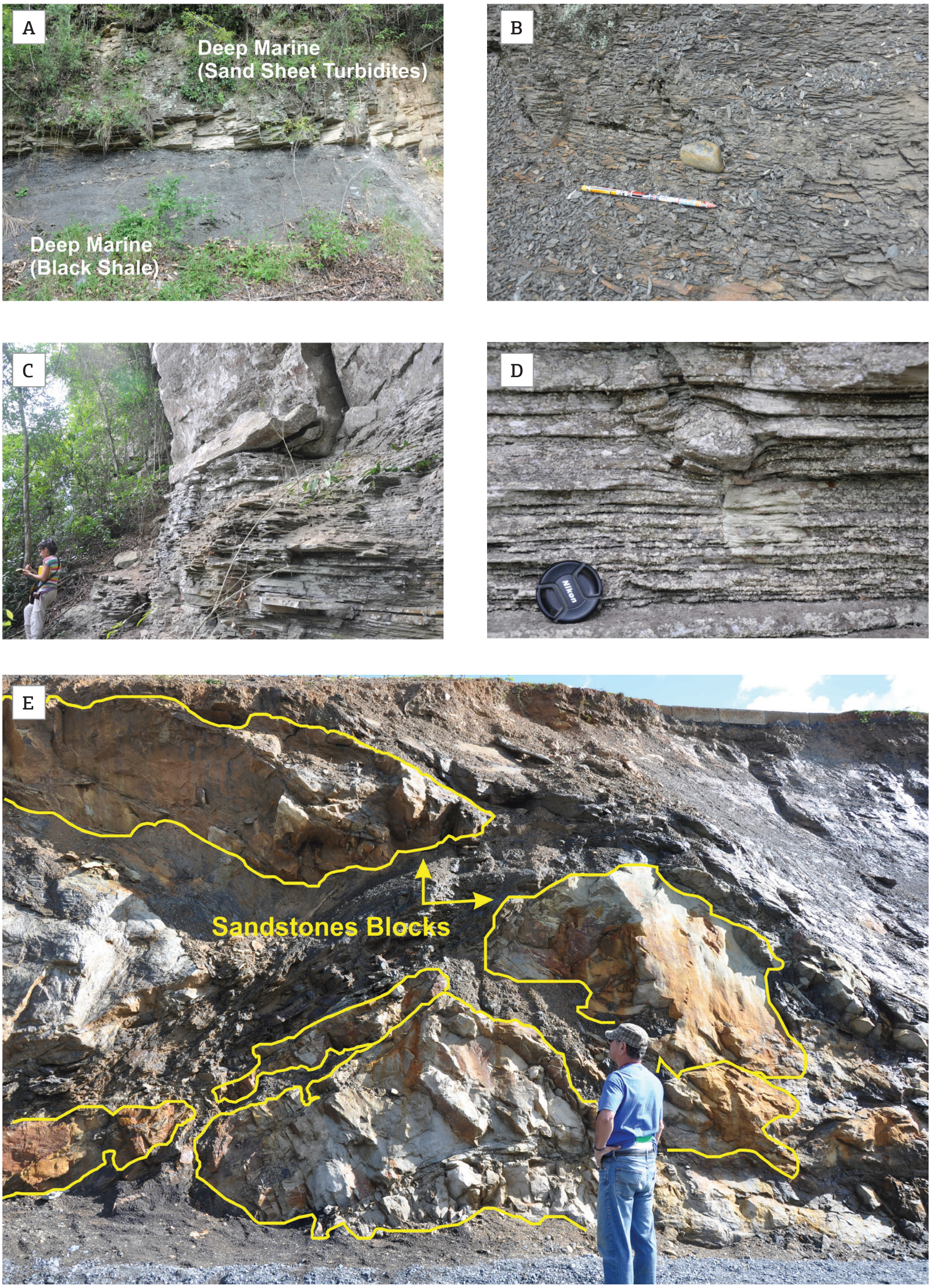

Figure 4. Mafra Formation. (A) black shale and minor tbt overlain (correlative conformity) by thicker, sandy turbidites. (B) dropstones in the Mafra Shale. (C) tbt and sandy turbidites of the lower turbidite sand sheet. (D) dropstones in tbt (detail of photo C). (E) slumped beds and related diamictites (MTD) with large blocks of fine-grained sandstone within a muddy matrix.

3. Mass Transport Deposits (MTD): They rest either above the confined sandy turbidites or directly on the basement, and comprise an up to 30 m thick package of slumped beds and linked diamictites. It includes folded to broken mudstone and sandstone beds as well as pebble- to cobble-size extra-clasts (dropstones) dispersed within a dominantly silty matrix (Fig. 4E). The MTD was ascribed to the partial failure of the following, late lowstand delta slope (lowstand wedge). The development of a slope physiography in an intracratonic basin was interpreted as the result of a basal, irregular and glacially-carved topography associated with high rates of sediment deliver into the basin during subsequent deglaciation episodes.
4. Distal delta front (thin-bedded turbidites): A rather uniform, about 200 m thick interval, mostly composed of rhythmites interpreted as thin-bedded turbidites, rests above the mass transport deposit (Fig. 5A). At its base it contains fine-grained rhythmites (siltstone and claystone) with dropstones and a relatively thin slumped interval (Fig. 5B). Upwards it becomes coarser-grained, with rhythmites composed of 2 to 5 cm thick, usually massive or current-rippled sandstones intercalated with mudstones. About 100 metres above the base of this rhythmite-prone interval occurs a second 20 metres thick black shale interval. Like the lower one (Mafra Shale), it is abruptly overlain by a second expressive turbidite sand sheet (about 20 m thick) that delineates the base of second TBT succession (Fig. 5C). The later register a fining-upward trend and finishes with dark grey mudstones. Paleocurrent readings on flute casts and current ripples indicate north-westwards low concentration turbidity currents (TBT). An abrupt boundary delineates the contact between the TBT dominated succession (delta slope including prodelta and distal delta front facies) and the following sandstone-prone interval (Fig. 6).
5. Proximal Delta Front (Fig. 2): It comprises fine- to very fine-grained sandstones and mudstones, forming an overall coarsening- and thickening-upward succession. Its maximum thickness is 47 m, but mapping suggests a total thickness of 60 m. This interval encompasses a proximal delta front facies association that will be detailed in the following section.

Figure 5. Rio do Sul Formation. (A) mm- to cm-scale couples of fine-grained rhythmites. (B) slumps and diamictites (sandstone blocks and dropstones within a muddy matrix) related to mass-transport deposits. (C) heterolithic rhythmites (tbt) and black shale sharply overlain by turbidite sand sheet. (D) thick beds of fine-grained sandstone related to distributary bars.

Figure 6. Coarsening-and thickening upward succession (tbt to sandy delta front deposits) abruptly resting above dark shale (upper interval of the Rio do Sul Formation).

Finally, and beyond the scope of this paper, a regional unconformity delineates the boundary between the Rio Bonito and Rio do Sul formations, as already pointed by former authors (*e.g.* Castro 1999). The Rio Bonito Formation encompasses whitish, yellowish to pinkish, fine- to very fine-grained, cross-stratified sandstones interlayered with grey mudstone lenses.

Proximal Delta Front Facies Association

This up to 60 m thick interval comprises a coarsening- and thickening-upwards succession. It is composed of fine- to very fine-grained, yellowish sandstones and dark grey to black mudstones and shale. Its lower contact is abrupt, with sand-rich TBT resting directly onto mud-rich TBT and dark shales (Fig. 6). Four representative 1:100 logs (see location in Fig. 2) were described and correlated. The sedimentary facies that characterize this facies association are indicated in Tab. 2 and described in the following paragraphs.

Fine-grained facies

Fine-grained rhythmites (facies Frh; Fig. 7A and 7B): It occurs as up to 3 m thick packages defined by the stacking of mm to few cm thick, fine-grained graded pairs. Each couple is composed of a lower siltstone that grades upwards to a dark grey to black shale. A faint horizontal lamination is at times discernible in the silty interval. Each graded bed (couple or pair) is interpreted as the result of a low concentration turbidity current followed by the settling down of hemi-pelagic material. Deposition taking place on proximal delta front areas subject to temporary abandonment (distributary avulsion) is deduced from facies features and their lateral association.

Fine grained, deformed beds (facies Fd; Fig. 7C and 7D): This facies was observed in the lower part of two logs (VR-1 and VR-4). Consist of 1 to 4 m thick packages (VR- 1) of contorted mudstone strata, locally including micro faults and minor amounts of folded sandstone beds and/or blocks. It represents mass transport deposits (slumps) and indicates fine-grained facies deposition on calm, but relatively steep depositional surfaces. Its vertical association with delta front facies as well as folded sandstone beds and blocks involved in the mass transport suggests oversteepening of depositional slopes due to high sedimentation rates on a proximal delta front setting.

Heterolithic facies

Heterolithic rhythmites (facies Hrh, Fig. 8): This facies consists of successive pairs individually composed of fine- to very fine-grained sandstone grading upwards to mudstone (Fig. 8A). Typical bed thickness ranges from 2 to 20 cm. From base to top, the sandy interval can be massive or display plane-bedding (Fig. 8B) and/or ripple cross-lamination. Massive intervals (Fig. 8C) are composed of fine-grained sandstones and may include mud-clasts, dewatering structures and sole marks, such as grooves and tool marks, as well as load and flute casts. These features indicate an initial turbulent stage (flute casts, grooves and tool marks, and mud clasts) followed by flow separation and bi-partition (massive fabric and dewatering structures) during the depositional stage of the low concentration turbidity currents. Its massive aspect is related to the rapid upward movement of water due to high rates of sand fall out during the initial depositional phase of bi-partite turbidite currents. Dewatering processes,

Table 2. Proximal delta front facies association: description and interpretation (facies code adapted from Miall, 1977).

Lithology	Sedimentary features	Code	Interpretation
Fine- to very fine-grained sandstone beds.	Climbing ripple cross-lamination	Sr	Proximal delta front (distributary bar)
	Wave ripple cross-lamination	Srw	
	Fluidized beds	Sf	
	Massive beds	Sm	
	Deformed beds	Sd	
Heterolithic beds (cm-scale rhythmites).	Graded sandstone to shale. Sandy interval can be massive or display plane bedding, current ripple cross lamination, sole marks and fluid-scape features.	Hrh	Proximal delta front (bar fringe)
Fine-grained beds (siltstone and shale)	Deformed beds	Fd	Delta front avulsion
	Rhythmites (mm-scale, graded siltstone to shale pairs).	Frh	

Figure 7. Fine-grained facies. (A) Sharp-contact with the delta front sandstones at the base of the VR-2. (B) Fine-grained rhythmites (Facies Frh). (C) four metres thick slump observed at the south of the study area including both Fd and Sd facies. (D) deformed mudstones (Fd facies) at the base of VR-4.

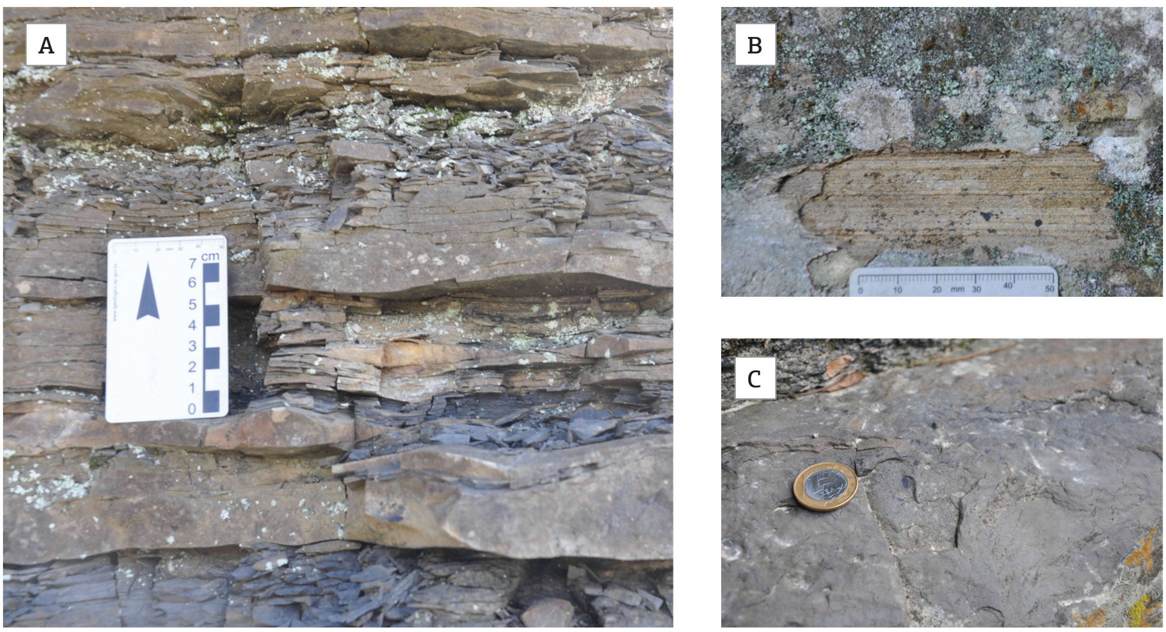

Figure 8. Heterolithic facies. (A) tbt represented by pairs of sandstone grading to mudstones. Note the current rippled interval at top of some beds (Tc interval). (B) plane-bedding (Tb interval) at the top of a graded bed. (C) mud-clasts at the top of massive interval (Ta).

and resulting fluidisation have also took place during the deposition of the Tc interval (Bouma 1962). Plane-bedded and subsequent current rippled intervals represent deposition under upper and lower flow regimes of waning surges, respectively. Palaeocurrent readings indicate main flow direction to NW. Although similar to the distal delta front thin bedded turbidites, this facies was attributed to a proximal delta front setting because of its upward replacement by distributary sand bars and usual intercalation with wave rippled sandstones (Srw).

Sandstones facies

Deformed sandstones (facies Sd; Fig. 9): It is similar to Fd, except for the prevalence of sandstone. This facies is composed of disturbed beds and/or blocks of formerly massive (Sm), fluidized (Sf), ripple cross-laminated (Sr) or horizontally-laminated (Sh) sandstones and minor amount of muddy facies. Such deformed beds range from 0.5 up to 2 m thick and represent formerly deposited sands displaced downslope (slumps) due to high sedimentation rates and resulting failure of steep, unstable delta slopes.

Massive sandstones: This facies occurs as 0.5 to 4 m thick beds of fine-grained sandstone. Mud-clasts and sole marks (grooves, loading and flute casts) are common and indicate turbulent eddies eroding substrate before deposition. This facies was associated with the granular, basal layer of bi-partite turbidite currents flowing to NW-NE according to flute casts orientation on a proximal delta front setting.

Fluidized sandstones (facies Sf): This facies consists of fine- to very fine-grained, up to 40 cm thick sandstones that grade to mudstones and displays dewatering and loading structures. It results from rapid upward movement of water during sedimentation and is typically linked to high sedimentation rates. It was also related to the basal layer of bipartite turbidity currents on proximal delta front reaches.

Wave rippled sandstones (Facies Srw; Fig. 10): This facies is present at the lower part of one log (VR-2) and in the eastern portion of the study area (VR-3). It comprises fine- to very fine-grained sandstones with wave-ripples and associated cross-lamination. Both bi-directional cross-lamination within single set (Fig. 10A) and ripple-form asymmetry opposite to the internal cross-lamination (Fig. 10B) are clear pieces of evidence of oscillatory flows (de Raaf *et al.* 1977). Wave rippled sandstone may also include upper flow regime plane bedding (Fig. 10A). When intercalated with mudstone, this facies display a wavy appearance (Fig. 10B). Its usual connection to mudstone suggests deposition bellow fair-weather wave base-level, hence a relation to storms eventually affecting proximal delta front reaches.

Current rippled sandstones (facies Sr; Fig. 11): This facies occurs as 0.5 to 3 metres thick, fine-grained sandstone beds. Each bed usually comprises a single cosset of asymmetric climbing ripples, although some cross-stratification may also be present at the base of the bed. A single cosset of climbing ripples along meter-scale beds suggest long-lived hyperpycnal flows and high rates of sand fall out. This statement is also supported by the presence of 3D dunes at the base of some current rippled sandstone beds. All these remarks suggest sandy bars accumulated at the mouth of distributary channels on a proximal delta front. Paleocurrent readings indicate main flow direction towards NW (Fig. 12).

DISCUSSION

The analysis of the data indicates that both stratigraphic context and sedimentary processes have played

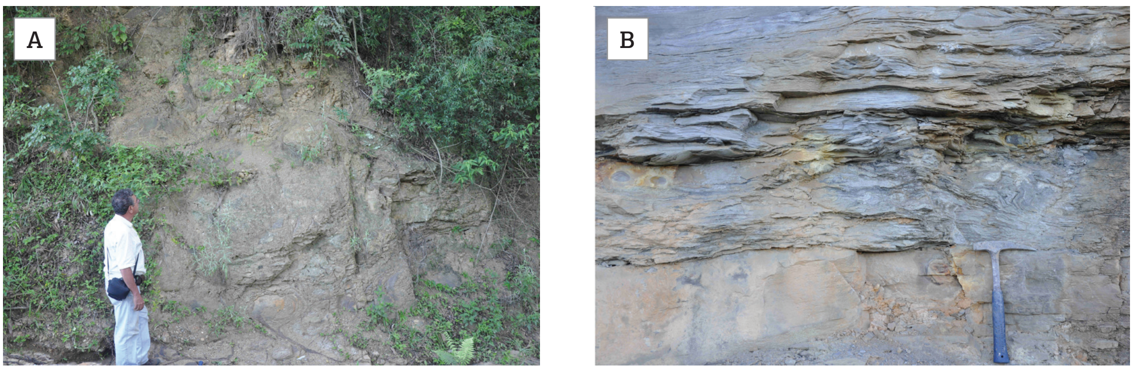

Figure 9: Facies Sd. (A) deformed, very fine-grained sandstones observed in the south of the study area (VR-1). (B) slumped bed along the VR-2.

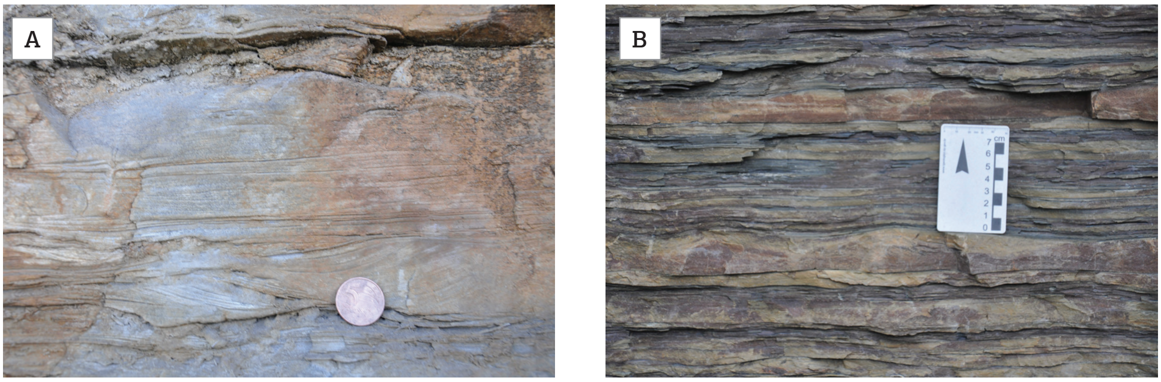

Figure 10. Facies Srw. (A) fine-grained sandstones (VR-2) with two sets of wave-ripple cross lamination, including two opposite flow direction in the lower cross laminated set, enclosing an upper flow-regime, plane-bedded interval. (B) wavy bedding (VR-3) with asymmetrical wave-ripple with slipface dipping to the left, in opposition to the cross-lamination dip (to the right).

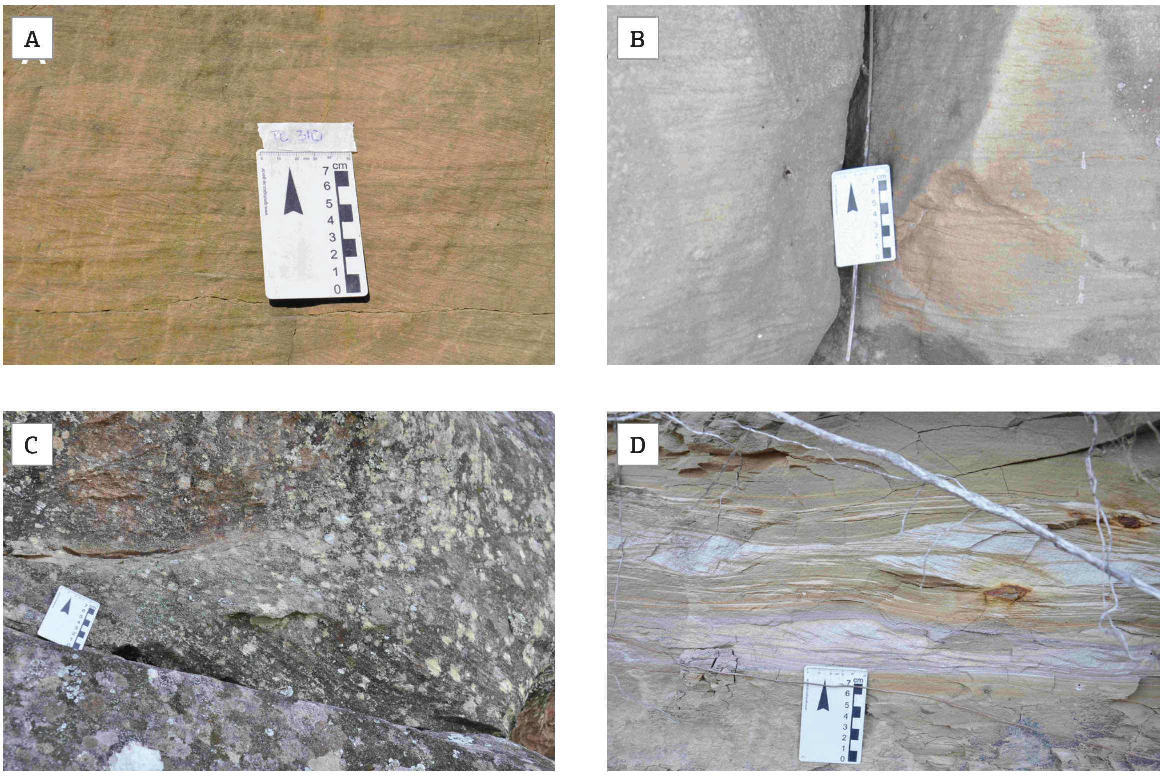

Figure 11. Examples of current rippled sandstone beds (facies Sr) in (A) VR-2 and (B and D) VR-4. (C) notice a cross-stratified set at the base of the rippled sandstone bed.

important, although distinct roles. In a broad view, the prevalence of gravity flow deposits (MTD and turbidites) along the Itararé Group can be explained by an irregular, glacial-carved topography associated with high-sediment supply (deglacial episodes) and a long-term lowstand setting (upper Paleozoic ice-house). These points explain both regional and local conditions that prevailed during the deposition of the base (Itararé Group) of a second-order

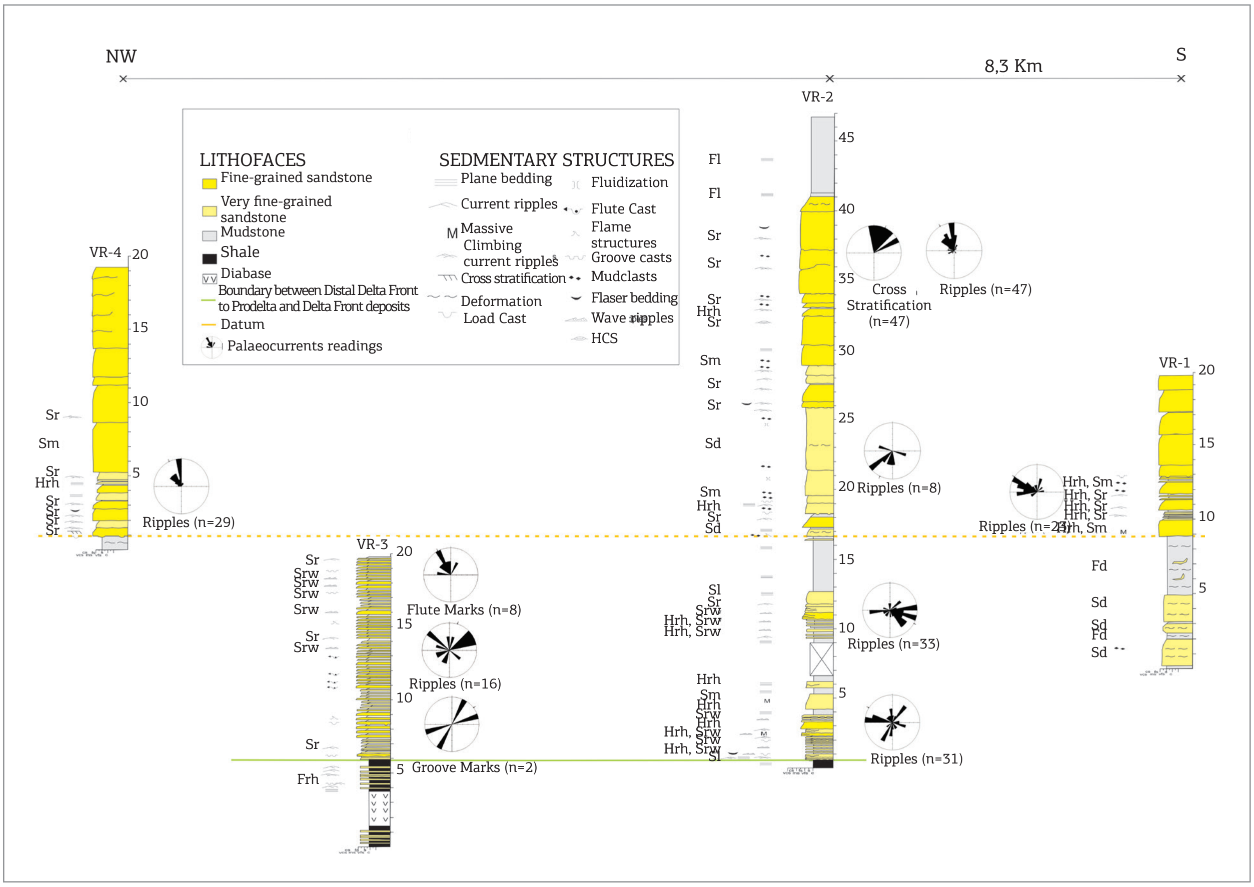

Figure 12. Stratigraphic section of the delta system (falling-stage system tract) of the younger 3rd order depositional sequence. Palaeocurrent data set is shown in the rose diagrams (note the wider flow dispersion in the lower, distal delta front fringe composed of wave-influenced tbt. The yellow dashed line corresponds to the chosen datum (For facies code references see Tab. 2).

depositional sequence (Gondwana I Supersequence of Milani 1977).

Higher-frequency sea-level changes and linked 3rd order depositional sequences, within a longer-term 2nd order lowstand, can also explain regional and local stacking of facies (mostly lowstand and transgressive systems tracts) and sequence boundaries (correlative conformities rather than subaerial unconformities). In the studied area, four 3rd order sequences bounded by correlative conformities have been identified (Fig. 13). The lower one (Fig. 13A) comprises a transgressive system tract, represented by black shales here named Mafra Shale (roughly equivalent to the Lontras Shale).

The following two 3rd order sequences (Fig. 13) include turbidite sands sheets (early lowstand turbidites) followed by thin bedded turbidites (late lowstand wedge) at their base overlain by black shales (transgressive system tracts). At last, the uppermost 3rd order depositional sequence (Fig. 13G) involves only the delta front to prodelta strata (falling-stage system tract). Similar, but not identical sequence stratigraphic schemes and associated depositional systems tracts were proposed by Castro (1999), Vesely and Assine (2004), Vesely (2006), D'Ávila (2009) and Suss *et al.* (2014) from studies of the Itararé Group in areas situated further to the north. Like here, these authors associated glacial/deglacial cycles with the repeated stacking of depositional facies tracts (depositional sequences).

On the other hand, a major difference is related to our interpretation as depositional sequences bounded by correlative conformities and comprising lowstand (lowstand fan and wedge) and transgressive systems tracts in opposition to depositional sequences bounded by unconformities and enclosing lowstand, transgressive and highstand systems tracts (*e.g.* Vesely & Assine 2004, 2006, Vesely 2006; D'Ávila 2009).

Therefore, a long-term (2nd order) lowstand modulated by shorter-term (3rd order) sea-level fluctuations added by a rather irregular, glacial-carved physiography explain the prevalence of lowstand, gravity flow deposits and transgressive black shales bounded by correlative conformities. Turbidity currents were favoured during higher frequency (3rd order)

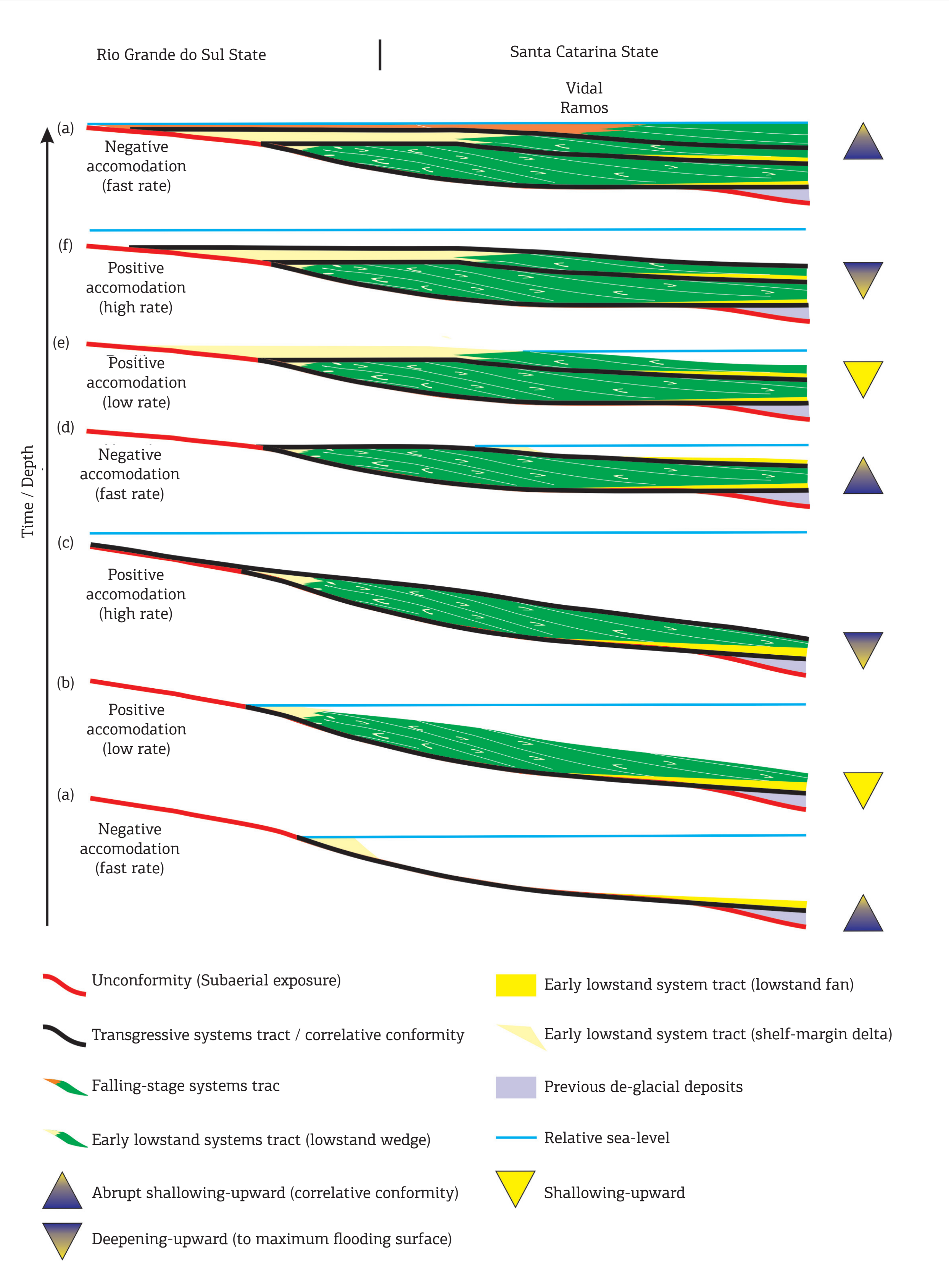

Figure 13. Itararé Group: turbidite and delta deposition within a sequence stratigraphic context. Overall succession is part of a 2nd order lowstand strata onlapping to the south whereas sandy turbidites and deltas are interpreted as 3rd order, early to late lowstand stages, respectively.

lowstand either as turbidite sand sheets (early lowstand) or thin-bedded turbidites (late lowstand or lowstand wedge).

Final stages suggest a much broader and shallower setting with the replacement in the uppermost 3rd depositional sequence of the lowstand turbidites by delta front sandstones (falling-stage system tract) overlain by a regional unconformity that delineates the boundary with the Rio Bonito Formation. The falling-stage systems tract comprises a coarsening-upward succession (Fig. 12) that includes wave-reworked TBT (Fig. 10) and distributary bar strata (Fig. 11) related to the distal (fringe) to proximal (bars) delta front reaches, respectively. Mass flows were still active (Fig. 9) on the delta system, displacing and deforming delta front facies (VR-1) and producing through flow transformation sand-rich (VR-2) to finer-grained (VR-3) northward turbidity currents (Fig. 12). Similar facies tracts have been earlier reported in the Itararé Group by former authors (*e.g.* Gama Jr. *et al*. 1992, D'Ávila 2009).

The genetic relationship between delta slope, mass flow and sand-rich to fine-grained turbidity currents envisaged on the falling-stage system tract suggest that the previously described lowstand wedges related to the older 3rd depositional sequences represent the distal portion of lowstand deltas. It also suggests that the turbidite sand sheet would be related to lowstand fluvial input either directly (hyperpycnal flows) or through the remobilization (short-lived surges) of lowstand delta front bars to deeper realms.

CONCLUSIONS

The Itararé Group in the studied area represents a deglacial to post-glacial succession recorded in the Mafra and Rio do Sul formations. The entire record is part of a 2nd order lowstand (base of the Gondwana I Supersequence of Milani, 1977) ascribed to the Upper Paleozoic Ice Age. Its divisions comprise glacial / deglacial cycles (3rd order sequences) with deposition taking place during ice retreat and their boundaries (correlative conformities) being during episodes of ice advance.

Both lower 3rd order sequences encompass deep water, lowstand and transgressive systems tracts. On the other hand, the upper 3rd order comprises a mainly post-glacial sequence, which encompasses a falling-stage, shallow water system tract (mostly delta front deposits) overlain by an subaerial unconformity (base of the Rio Bonito Formation). Gravity flows were favoured by a rather irregular basement morphology sculpted by glacier erosion and an overall lowstand setting (2nd order lowstand). The triggering mechanism of both mass flows and turbidity currents seems to be related to lowstand (and falling stage) delta slope instability due to high sediment discharge on delta front settings, which reach its maximum during the early lowstand phase (turbidity sand sheets).

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