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ARTICLE

# Famennian glaciation in the eastern side of Parnaíba Basin, Brazil: evidence of advance and retreat of glacier in Cabeças Formation

## *A glaciação fameniana na porção leste da Bacia do Parnaíba: evidências do avanço e recuo de geleira na Formação Cabeças*

**Roberto Cesar de Mendonça Barbosa[1]*, Afonso César Rodrigues Nogueira[1], Fábio Henrique Garcia Domingos[2]**

**ABSTRACT:** Glaciotectonic features studied in the siliciclastic deposits of Cabeças Formation, Upper Devonian, represent the first evidence of Famennian glaciation in Southeastern Parnaíba Basin, Brazil. Outcrop-based stratigraphic and facies analyses combined with geometric-structural studies of these deposits allowed defining three facies association (FA). They represent the advance-retreat cycle of a glacier. There are: delta front facies association (FA1) composed of massive mudstone, sigmoidal, medium-grained sandstone with cross-bedding and massive conglomerate organized in coarsening- and thickening-upward cycles; subglacial facies association (FA2) with massive, pebbly diamictite (sandstone, mudstone and volcanic pebbles) and deformational features, such as intraformational breccia, clastic dikes and sills of diamictite, folds, thrust and normal faults, sandstone pods and detachment surface; and melt-out delta front facies associations (FA3), which include massive or bedded (sigmoidal cross-bedding or parallel bedding) sandstones. Three depositional phases can be indicated to Cabeças Formation: installation of a delta system (FA1) supplied by uplifted areas in the Southeastern border of the basin; coastal glacier advance causing tangential substrate shearing and erosion (FA1) in the subglacial zone (FA2), thus developing detachment surface, disruption and rotation of sand beds or pods immersed in a diamicton; and retreat of glaciers accompanied by relative sea level-rise, installation of a high-energy melt-out delta (FA3) and unloading due to ice retreat that generates normal faults, mass landslide, folding and injection dykes and sills. The continuous sea-level rise led to the deposition of fine-grained strata of Longá Formation in the offshore/shoreface transition in the Early Carboniferous.

**KEYWORDS:** Cabeças Formation; glaciotectonic structures; Famennian glaciation; Parnaíba Basin.

**RESUMO:** *Estruturas glaciotectônicas estudadas nos depósitos siliciclásticos da Formação Cabeças do Devoniano Superior representam a primeira evidência da glaciação fameniana na borda Sudeste da Bacia do Parnaíba, no Norte do Brasil. A análise estratigráfica e faciológica em combinação com estudos geométrico-estruturais desses depósitos permitiram definir três associações de fácies (AF) representativas de um ciclo de avanço-recuo de geleira, a saber: associação de fácies de frente deltaica (AF1), composta por pelitos maciços, arenitos finos a médios com estratificação cruzada sigmoidal e conglomerado maciço, organizados em ciclos grano- e estrato-crescentes; associação de fácies subglaciais (AF2), consistindo de diamictitos maciços seixosos (seixos de arenito, pelito e rochas vulcânicas) e feições deformacionais, tais como brechas intraformacionais, sills e diques clásticos de diamictitos, dobras, falhas normais e de cavalgamento, pods de arenitos e plano de descolamento; e associação de fácies de frente deltaica de degelo (AF3), constituída por arenitos maciços ou laminados (estratificação plano-paralela e/ou cruzada sigmoidal), localmente com deformações sin-sedimentares. Três fases deposicionais são indicadas para os depósitos da Formação Cabeças: instalação de um sistema deltaico (AF1), advindo de áreas soerguidas do Sudeste da bacia; avanço de geleiras costeiras, que causa cisalhamento tangencial e erosão do substrato (AF1), em zona subglacial (AF2), desenvolvendo superfície de descolamento, rompimento e rotação de camadas arenosas ou pods imersos em diamicton; e recuo das geleiras acompanhado pelo aumento relativo do nível do mar, pela instalação de um sistema deltaico de degelo de alta energia (AF3) e processos de alívio de pressão que geram falhas normais, escorregamento de massa, dobras e injeções de diques e sills. O aumento contínuo do nível do mar levou à deposição dos sedimentos finos da Formação Longá na zona de transição offshore/shoreface no início do Carbonífero.*

**PALAVRAS-CHAVE:** *Formação Cabeças; estruturas glaciotectônicas; glaciação fameniana; Bacia do Parnaíba.*

[1]Programa de Pós-graduação em Geologia e Geoquímica, Instituto de Geociências, Universidade Federal do Pará – UFPA, Belém (PA), Brasil. *E-mails: rbarbosa@ufpa.br; anogueira@ufpa.br*

[2]Instituto de Geociências, Faculdade de Geologia, Universidade Federal do Pará – UFPA, Belém (PA), Brasil. *E-mail: fabiodomingos@hotmail.com*

*Corresponding author.

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## INTRODUCTION

Gondwana glacigenic successions have been the focus of several recent stratigraphic studies, mainly due to their potential as possible petroleum systems. One of the key reasons is the favorable condition for hydrocarbon generation that is associated with the presence of thick layers of transgressive post-glacial black shale, whereas sandstones, sandwiched by fine-grained glacio-marine facies, represent possible reservoir rocks (Vesely *et al.* 2007, Assine & Vesely 2008, Fielding *et al.* 2012). The glacial deposits in Western Gondwana are well preserved in the Paleozoic basins of South America (Cunha *et al.* 1994, Loboziak *et al.* 2000, Streel *et al.* 2000, Isaacson *et al.* 2008). In Northern Brazil, Famennian rocks (374 to 359 Ma) of the Upper Cabeças Formation represent the main reservoir units of the Mesodevonian-Eocarboniferous petroleum system in the Parnaiba Basin (Figs. 1 and 2). Tillites with faceted clasts and rare striated pavements are yet the only basis to support a glacial influence/nature of this unit (Caputo *et al.* 1971, Carozzi *et al.* 1973, Carozzi *et al.* 1975, Caputo 1985, Caputo & Crowell 1985, Grahn 1991, Grahn & Caputo 1992, Grahn & Paris 1992, Costa *et al.* 1994, Rocha-Campos *et al.* 2000, Soares *et al.* 2005). On the other hand, glaciotectonic features result from the stress produced by the weight and movement of a glacier over underlying sediments, as well as the resulting features

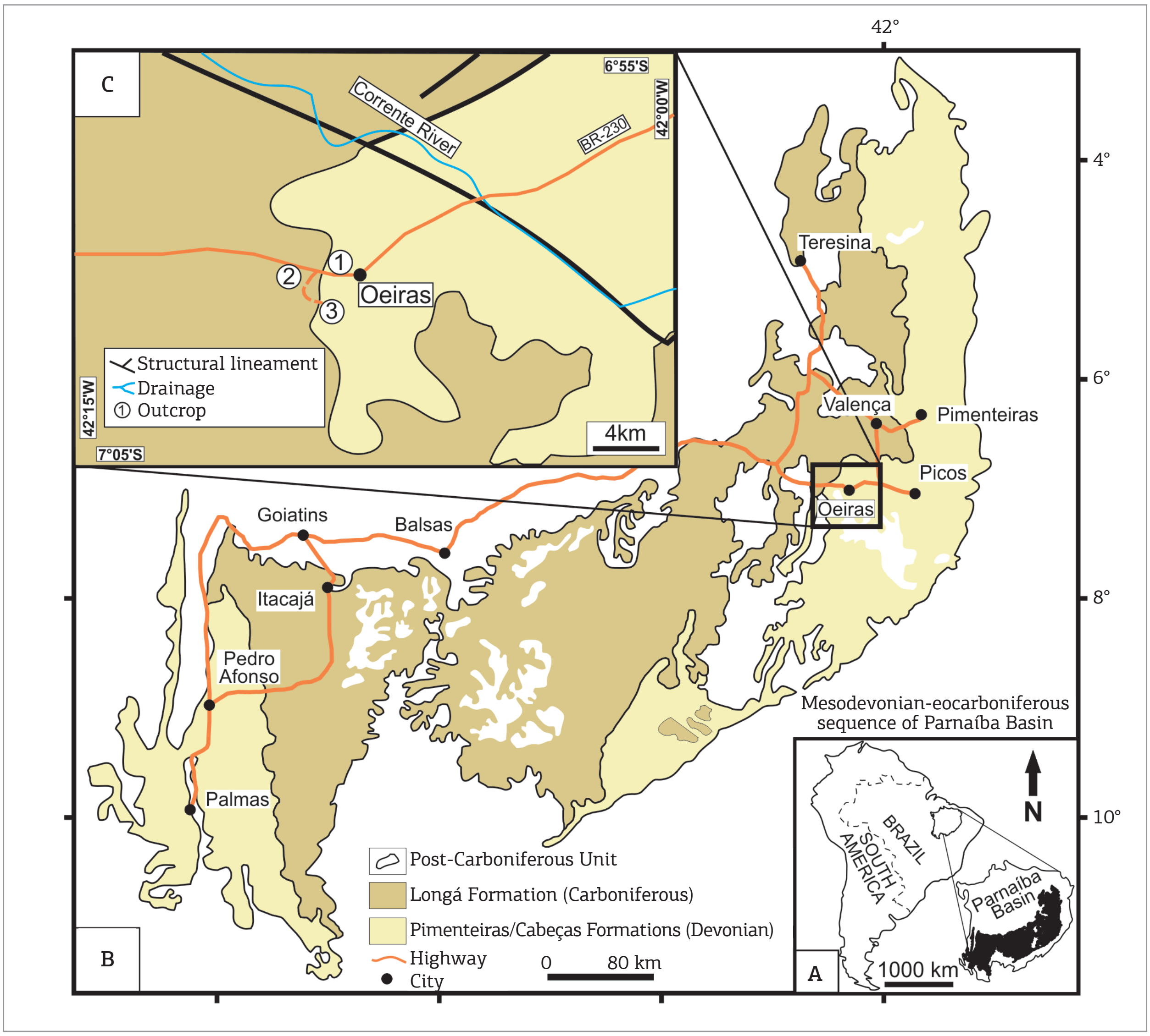


Figure 1. Geological and location map of the studied area. (A) Exposure area of Mesodevonian-Eocarboniferous sequence (marked in black) in Parnaíba Basin. (B) Spatial distribution of Pimenteiras, Cabeças and Longá formations. (C) Simplified geology of Oeiras town, State of Piauí, with location of the studied outcrops (Modified from Radam 1973).

are comparable to tectonic structures of shear belts, although generally much smaller, intraformational, and very shallow (Banham 1977, Nielsen 1988).

Within this context, this research includes the first description of deformed, pebbly tillites in Cabeças Formation in the Southeastern border of Parnaíba Basin, which represents the direct record of the Famennian Glaciation (Fig. 1). The outcrop-based stratigraphic and facies analysis combined with geometric-structural studies of the deposits allowed identifying a glacier advance-retreat cycle and its related glaciotectonic features, as well as to interpret it within a sedimentary evolution model. This work also contributes to understanding the role of glacial successions in the development of petroleum systems in the sedimentary basins of Western Gondwana.

## GEOLOGICAL SETTING

The Parnaíba Basin is located in Northern Brazil and covers approximately 600,000 $km^2$ (Fig. 1A). Its sedimentary record is up to 3,500 m thick and is composed of siliciclastic and chemical rocks mainly of Paleozoic age, but it also includes Jurassic to Cretaceous volcanic rocks. Biostratigraphic data and regional unconformities recognized in seismic sections allowed dividing the sedimentary succession of Parnaíba Basin into five supersequences (Almeida & Carneiro 2004, Vaz *et al.* 2007): Silurian, Mesodevonian-Eocarboniferous, Neocarboniferous-Eotriassic, Jurassic and Cretaceous.

The discovery of oil and gas in the Mesodevonian-Eocarboniferous supersequence, which is characterized by siliciclastic deposits of Canindé Group, enlarges the demand for new geological information in an attempt to improve the petroleum system characterization. The Mesodevonian-Eocarboniferous petroleum system includes Pimenteiras, Cabeças and Longá formations (Fig. 2). Black shales of Pimenteiras Formation shows 2% of total organic carbon content and types II and III kerogens. Sandstones of Cabeças Formation comprise the reservoirs, whereas shales of Longá Formation constitutes the seal. The Cabeças Formation includes medium-to-coarse-grained sandstones interbedded with siltstones and shales, deposited in a tidal-and storm-influenced shelf environment (Góes & Feijó 1994, Vaz *et al.* 2007, Ponciano & Della Fávera 2009).

Kegel (1953) suggested the first record of glacial strata in the upper portion of Cabeças Formation. Based on core data, this author identified tillites with striated and faceted pebbles of quartz and crystalline rocks. Later, Carozzi (1980) and Caputo *et al.* (2008) studied striated pavements on sandstones in the Eastern edge of Parnaíba Basin. Their findings are consistent with a glacier advance towards the Northwest part of the basin. Moore (1963) and Caputo (1985) analyzed outcrops of Cabeças Formation in the southwestern border of Parnaíba Basin and described foliated tillites with striated and faceted pebbles between layers of sandstones with massive bedding and waterscape structures. These investigators concluded that the glacier movement plastically deformed the sediments of Cabeças Formation, not affecting the older and younger Longá and Pimenteiras formations, respectively.

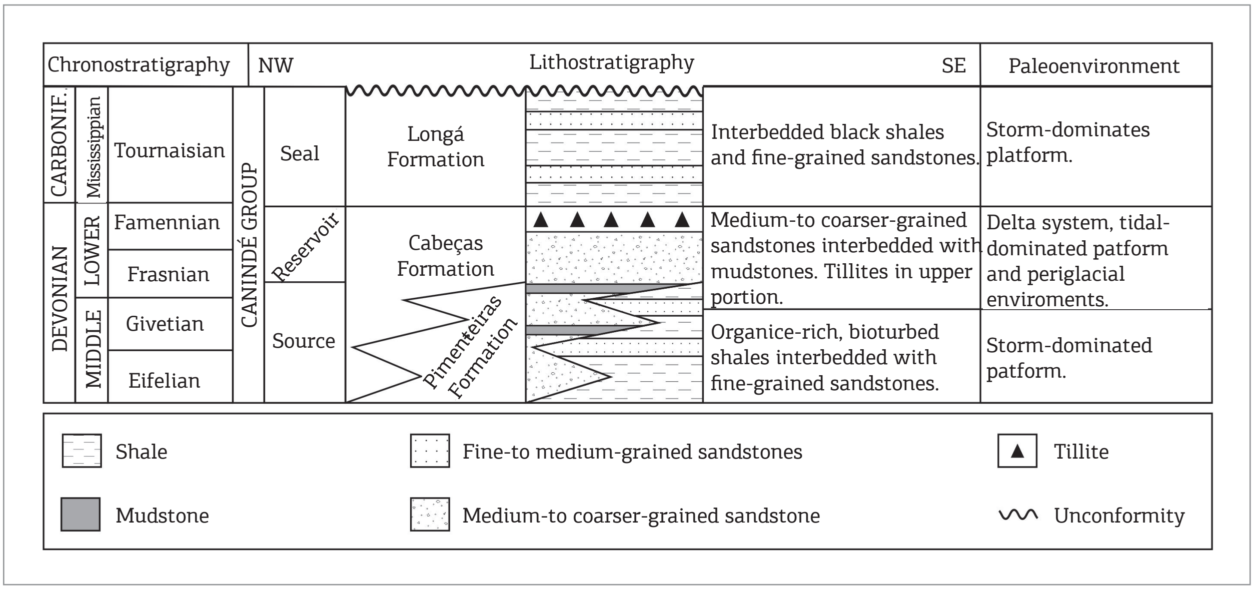


**Figure 2. Simplified stratigraphic column of the Mesodevonian-Eocarboniferous supersequence of Parnaíba Basin, represented by Canindé Group. The tillite of Cabeças Formation was dated as Late Famennian based on palinomorphs (Grahn *et al.* 2006, Vaz *et al.* 2007, Streel *et al.* 2013).**

Grahn *et al*. (2006) and Streel *et al*. (2013) inferred a Late Famennian age for these tillites based on the presence of miospores of LE (*R. lepidophyta – H. explanatus*) and LN (*R. lepidophyta – V. nitidus*) zones established to Western Europe.

## METHODS

Facies and stratigraphic data (cf. Miall 1985 and 1988, Wizevic 1991, Arnot *et al*. 1997) were collected along cuts of BR-230 and secondary roads near Oeiras town, in the State of Piauí (Fig. 1C). The semiarid climate and predominance of savanna vegetation contribute to the excellent preservation of outcrops.

The structural analysis of the deformed facies was based on the concepts of Ramsay and Huber (1983, 1987) and Hancock (1994). This technique deals with linear and planar elements of the rocks, using geometric and kinematic analyzes. In this investigation, however, only a geometric analysis was performed to investigate the nature, spatial behavior and relationships of overlapping structures. The spatial orientation of geological structures was measured with a geological compass and their attitudes were represented in stereographic projection diagrams (network-Lambert Schmidt, lower hemisphere) using the OpenStereo software (version 7, Free Software). The analysis and interpretation of the glaciotectonic structures followed the proposal of Hart and Boulton (1991).

The diamictite matrix was characterized by counting the points of components under the optical microscope, with at least 300 points. The microfabric was described in ten rock slabs that were coated with a thin gold film and analyzed in a Scanning Electron Microscope (SEM), model 1450 – LED VP, in the laboratory of *Museu Paraense Emílio Goeldi*. Identification of clay minerals was carried out through X-ray diffraction (XRD) using the X'Pert Pro PANalytical diffractometer (40 kV and 40 mA), which was equipped with copper tube and graphite monochromator, in *Universidade Federal do Pará*.

## GLACIO-DELTAIC DEPOSITS

### Facies and stratigraphic analysis

The studied outcrops of Cabeças Formation are up to 14 m thick and 60 m wide. Lithologies include white-gray sandstones, diamictites, and purple-red mudstones. Eight sedimentary facies were identified and represented in a composite columnar log (Fig. 3). The studied facies were grouped (Tab. 1) into three facies associations (FA) that comprised deposits of delta front (FA1), subglacial environment (FA2) and melt-out delta front (FA3).

#### Delta front (FA1)

This association is 5 m thick and consists of amalgamated, sigmoidal beds of fine-to medium-grained sandstones, generally in contact with the subglacial deposits of FA2 (Fig. 3). The main facies of FA1 are massive mudstone (facies Fm), sigmoidal cross-bedded sandstone (facies Sts) and massive conglomerate (Gm) generally organized in coarsening/thickening upward, meter-scale cycles (Tab. 1, Figs. 3 to 5). The sigmoidal lobes are internally composed of facies Sts with sigmoidal cross-bedding that passes laterally into subcritical climbing ripple cross-lamination. Locally occurs waterscape structure. Lenticular beds of the facies Gm and Fm are interbedded with sand lobes.

#### Interpretation

The sigmoidal lobes (facies Sts) indicate unidirectional migration of bedforms preferentially to the NW with rapid deceleration of water flow. Climbing ripple cross-lamination (facies Sts) in the distal portions of the sigmoidal lobes is in agreement with the interpretation (Bhattacharya 2010). The presence of a waterscape structure is the evidence of partial liquefaction of unconsolidated, water-saturated sediments (Lowe 1975, Owen 2003). The facies Sts and Fm are associated with flow deceleration along the sigmoidal lobes, which are defined by combined bedload and suspended load processes in the proximal reaches (facies Sts) that progressively pass into clay fall out (facies Fm) in the distal reaches (Potter *et al*. 2005, Olariu & Bhattacharya 2006). Lenticular bodies of facies Gm suggest a limited contribution of sandy gravels associated with the deltaic lobes (Mutti *et al*. 2003, Olariu & Bhattacharya 2006). Sigmoidal sandstone bodies with complex geometry arranged as coarsening- and thickening-upward cycles are compatible with sand progradation (delta front) into a low energy receiving basin, such as lakes (Bhattacharya 2010). Structures related to wave-and tidal-processes, as well as subaerial exposure, are absent and corroborate a calm receiving basin.

#### Subglacial deposits (FA2)

The FA2 laterally forms lenticular bodies that continue for tens of meters and generally interbedded with the FA1 (Tab. 1, Figs. 3, 4, 6 and 7). The FA2 comprises massive, pebbly diamictite (facies Dm), diamictite with sandstone pods (facies Dp), and mudstone breccia (facies Fb). Boulders and polished and/or faceted pebbles, immersed in sandy mud matrix (facies Dp), are composed of sandstone, mudstone, volcanic rocks and chert (Fig. 6A). In thin section, very poorly sorted, fine-to coarser-grained muddy-sandstone comprises the diamictite matrix. It displays a loose packing (packing index between 7 and 13) and is classified as quartz wacke (Fig. 8, Folk 1974). The diamictite matrix has sub-rounded to sub-angular grains, displaying low sphericity and moldic porosity (Fig. 8). Eventually, the matrix is composed of siltstone and claystone, locally showing deformational structures similar to waterscape features and contorted lamination. The primary components of the diamictite matrix are monocrystalline quartz grains, with undulose extinction (mean of 40%, Fig. 8A) and rare feldspar grains (<1%). K-feldspar is more common than plagioclase and both generally exhibit dissolution features. Rock fragments include siltstone and mudstone (maximum of 0.30% of the rock volume), however deformed siltstone lenses are also found in the matrix. Heavy minerals are represented mainly by zircon and staurolite (maximum of 0.60% of the rock volume). The intergranular space is filled with silt-grained quartz, muscovite (0.90% average), and iron oxides/hydroxides (maximum of 49.70% of total volume). Clay minerals identified by XRD include kaolinite, smectite, and illite. The secondary porosity of the diamictite matrix was characterized as moldic (0.90%), shrinkage (0.60%), and intragranular (0.30%). Moldic pores have sizes ranging from 130 μm to 450 μm and often exhibit tabular form (Fig. 8C). Shrinkage pores are irregular and developed in the siliciclastic matrix, but in the regions of contact between pores and framework they tend to follow the grain edge, partially isolating the

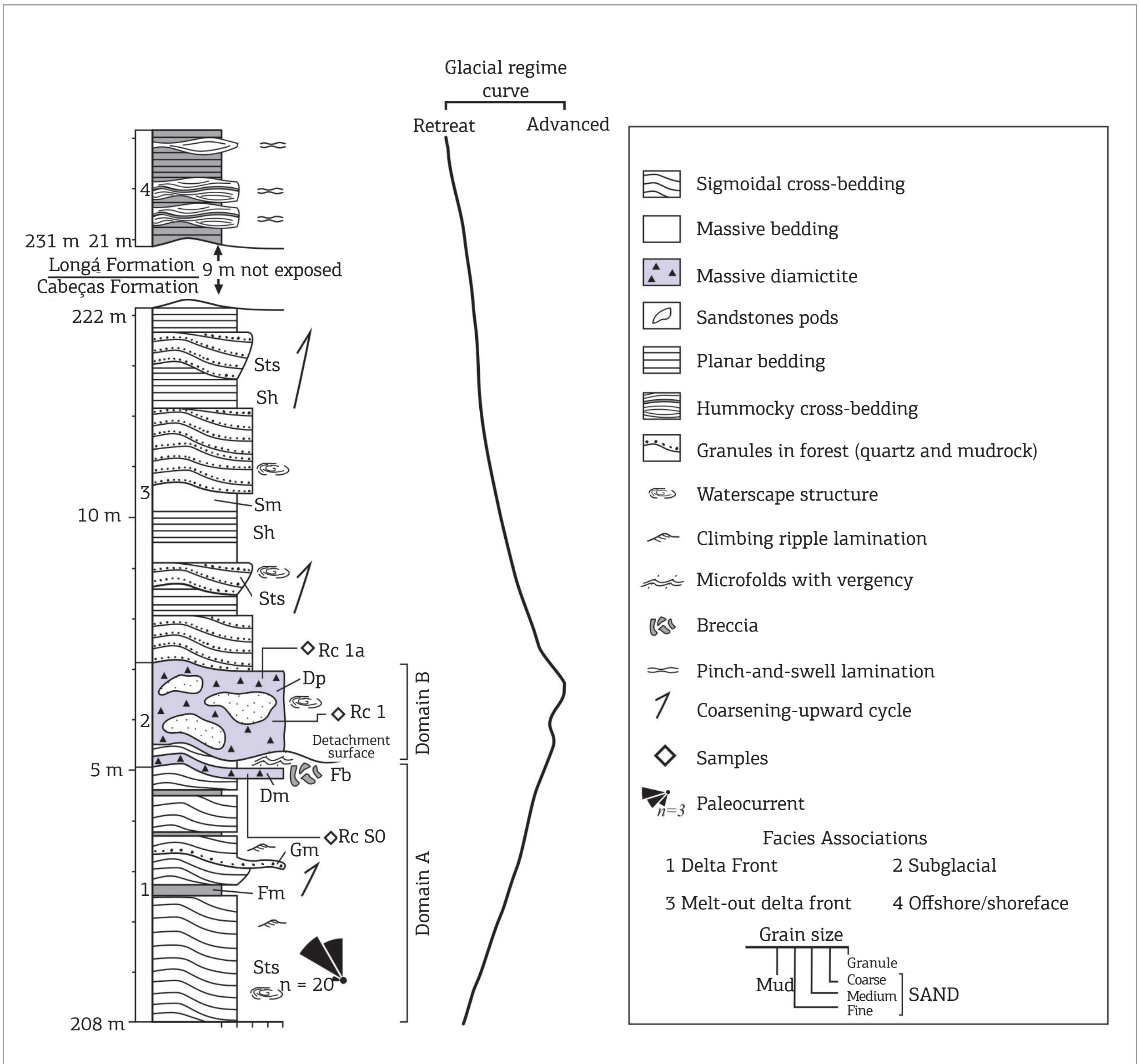


**Figure 3. Composite columnar log of Cabeças and Longá formations in Oeiras region with the advanced and retreat curve of the glacier and stratigraphic position of petrography samples. Delta deposits of Cabeças Formation are overlined by transgressive deposits of Longá Formation. Structural domains A and B represent glaciotectonic partitioning (see text in "subglacial deposits").**

matrix in the form of cutans (Fig. 8D). In general, shrinkage pores are isolated, up to 20 μm thick and 900 μm long. Intragranular pores are primarily found in feldspar grains and range from 15 to 35 μm.

The contact between FA1 sandstones and FA2 diamictite corresponds to a deformed zone characterized by an expressive subhorizontal plane herein interpreted as a detachment surface, which bounds not deformed and deformed strata (Figs. 3 and 4). This surface varies from subhorizontal to gentle dipping (25° to 30°). It is truncated by late NE-SW trending normal faults with low to moderate dips (21° to 42°) and subordinate reverse faults. Fault planes are highlighted by up to 30 mm thick layer of rusted siltstone, which locally includes up to 6 cm wide, angular fragments of sandstone (Fig. 9). Some of the fault planes exhibit steps and striation plunging 40° towards NW (sector I, Fig. 7B) and kinematic indication of roof displacement to the NW.

Two structural domains bounded by the detachment surface were defined. Domain A includes structures in the FA1, whereas B comprises structures in the FA2 (Figs. 3 and 4). The structures observed in Domain A are represented by normal and reverse faults, sub-horizontal sills (facies Dm), breccia (facies Fb), and open folds in the sedimentary bedding. Domain B is characterized by sandstone pods, reverse and normal faults (sector IV, Fig. 7A), disrupted beds (sector V, Fig. 7D), and sub-vertical injection dikes filled with fine-to medium-grained sandstone crosscutting facies Dp (Fig. 6B). Locally, sandstone pods show a sigmoidal geometry that suggest rotation towards NW. This rotation was caused by the displacement of an adjacent NE-SW trending, gently dipping (18° to 30°) reverse fault (sector IV) and a NE-SW trending, steeply dipping (60°-80°) normal fault, which crosscuts the detachment surface (sector I). These faults deform the sandstone bedding of facies Dp, forming open folds in the facies Sts with inter limbs angles between 150° and 170° (sector III, Fig. 4B). Faults are oriented to NW-SE and ENE-WSW with moderate to high, up to 60° dip angles (sector II).

Synsedimentary structures such as folds, normal and reverse faults are indicated by undulated beds and displacement

**Table 1. Facies and interpreted sedimentary processes of the Upper Devonian Cabeças Formation in Oeiras region**

| Facies | Description | Sedimentary process |
|---|---|---|
| Massive mudstone (Fm) | Lenticular, massive mudstones. | Deposition of fine-grained sediments through the decantation process. |
| Massive sandstone (Sm) | Lenticular beds of massive and fine-grained sandstones. | Fast sand fall-out ensuing liquefaction and/or lack of grain-size contrast. |
| Horizontal laminated sandstone (Sh) | Lenticular or tabular beds of fine-grained sandstones with parallel lamination. | Deposition from sandy plumes induced by hyperpycnal flows and/or sand sheet deposition under upper-flow regimen conditions. |
| Sigmoidal cross-bedding sandstone (Sts) | Fine- to medium-grained sandstones with sigmoidal cross-bedding, whose toe sets pass distally into climbing ripple cross lamination. This facies represents the top of coarsening-upward cycles. Sometimes, foresets show concentrations of coarser grains (quartz and silex), as well as water-scape structures. Paleocurrents to NW. | Migration of bedforms with rapid deceleration of the water flow, climbing current-ripple associated. Coarser-grained grains on foresets associated with grain flow and partial liquefaction related to plastic readjustment in water-saturated sediments. |
| Massive diamictite (Dm) | Sub-horizontal sills and dyke of massive para-conglomerates mostly hosted within sigmoidal cross-bedded sandstones. Faceted clasts (volcanic rocks, silex, quartzite, and mudstone) as well as micro lenses of deformed siltstone dispersed in a sandy mud matrix. Micro folds verging to NW. | Abrasion and erosion of the substrate by subglacial flow. Injection of plastic material (diamicton) towards lower pressure regions associated with the advance of glacier. |
| Diamictite with pods (Dp) | Massive para-conglomerates with up to 2-m thick (minor axis) irregular sandstone pods, faceted clasts (volcanic rocks, silex, quartzite and mudstone) immersed in a sandy mud matrix. Deformation structures (faults and folds) are highlighted by sandstone pods. Up to 40 cm thick vertical sandy dikes occur occasionally. | Abrasion and erosion of the substrate by subglacial flow. Water-saturated sediments detached from substrate by subglacial mass transport. Brittle and ductile deformation related to glacial advance. |
| Mudstone breccia (Fb) | Tabular and curved mud clasts about 15 cm long (major axis), immersed in a sandy mud matrix, restricted to the tillite/massive mudstone contact. | Hydraulic fracturing and deformation of tabular mudstone clasts related to injection of diamicton. |
| Massive conglomerate (Gm) | Thin lenses of massive conglomerate with sub-rounded pebbles (quartz and mudstone) supported by a sandy matrix. | Debris flow deposits (residual lag). |

of sandstone bodies isolated in the facies Dp (Figs. 7A, 7B and 7D). Sub-horizontal sills of facies Dm occur between FA1 beds and are associated with chaotic intraformational breccia (facies Fb), including tabular and curved mudstone clasts immersed in facies Dm (Fig. 7C).

## Interpretation

Glacial transport is characterized by sediments with assorted grain sizes and shapes, incorporated into the substrate (FA1) in conditions of relatively high stress. The nature of texturally immature glacial deposits (diamicton) with faceted, polished and striated clast was interpreted as the result of interplay of the stresses imposed by a glacier in motion and abrasive friction process. The intergranular spaces are completely filled with siliciclastic matrix (Eyles

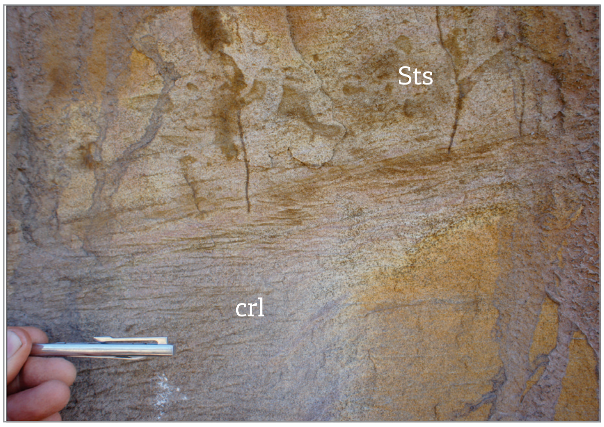


Figure 5. Climbing ripple cross-lamination (crl) in the distal portion (toe set) of the sigmoidal lobes (facies Sts); scale = 10 cm.

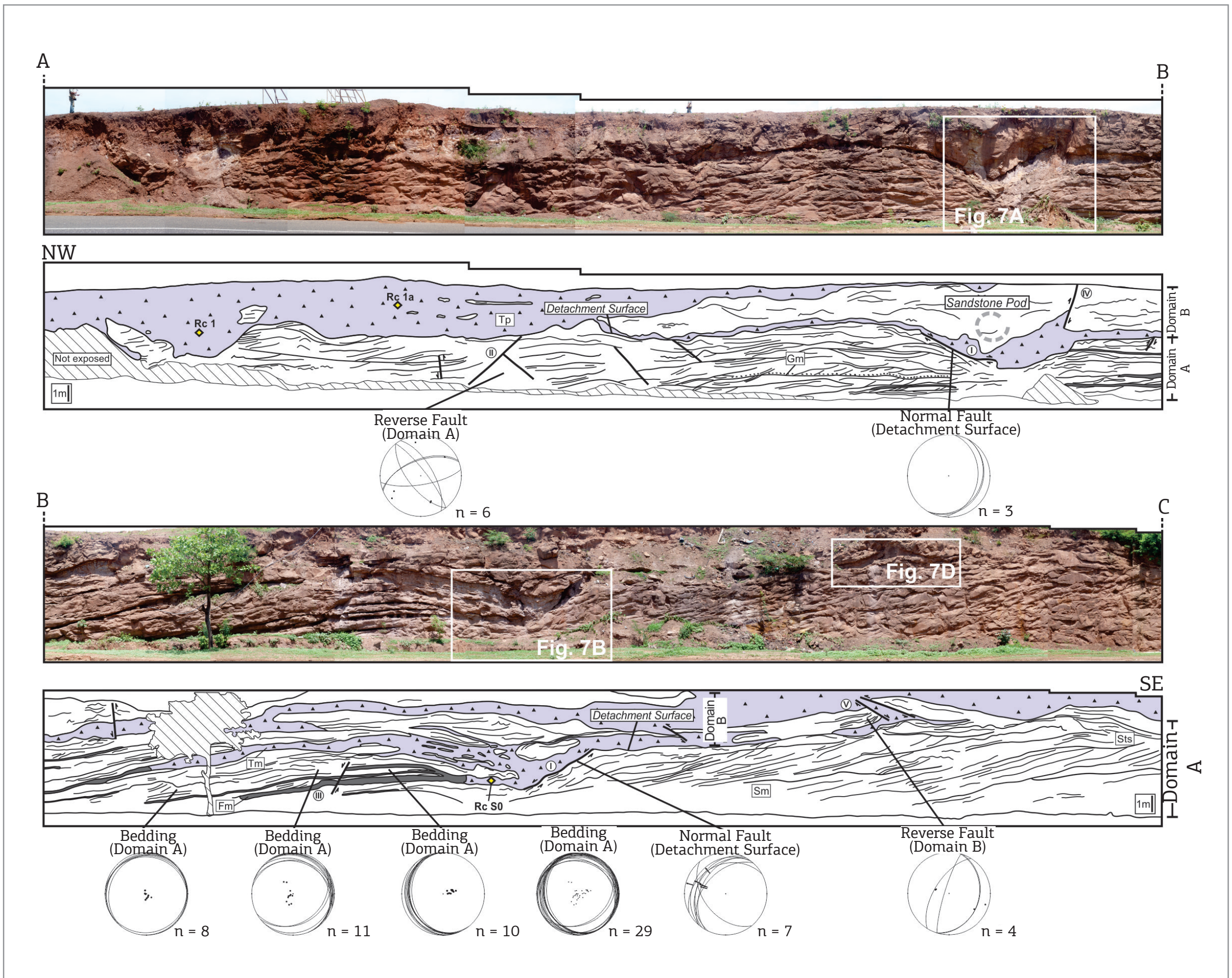


Figure 4. Panoramic view (photomosaic and associated sketches) showing the internal structure and geometry of Cabeças Formation delta deposits. Bedding and glaciotectonics features readings are plotted in the stereographic projection diagrams. Samples for petrographic analysis are indicated (Rc S0, Rc 1, Rc 1a). The exposure was divided into two structural domains (A and B) bounded by a detachment surface. Numbers I to VI indicate specific glaciotectonic structures (see FA2).

& Eyles 2010). When the stress caused by the glacial flow during the advance and retreat of a glacier exceeds the shear strength of the underlying sedimentary deposits, brittle (failure) and ductile (folds) structures can be formed, based on the magnitude of the accommodated strain and rheology of the deformed sediments. Thus, the deformed lenses of

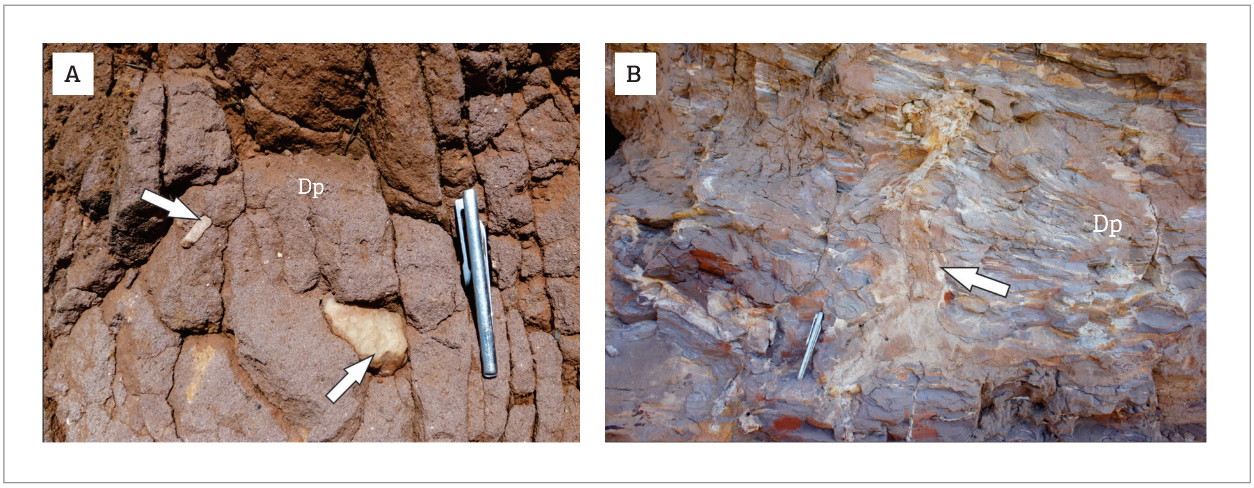


**Figure 6. Subglacial deposits of Cabeças Formation. (A) Quartzite pebbles (arrows) dispersed in sandy mud matrix of the diamictite. (B) Diamictite with sandstone pods (facies Dp) and sub-vertical injection dykes (arrow).**

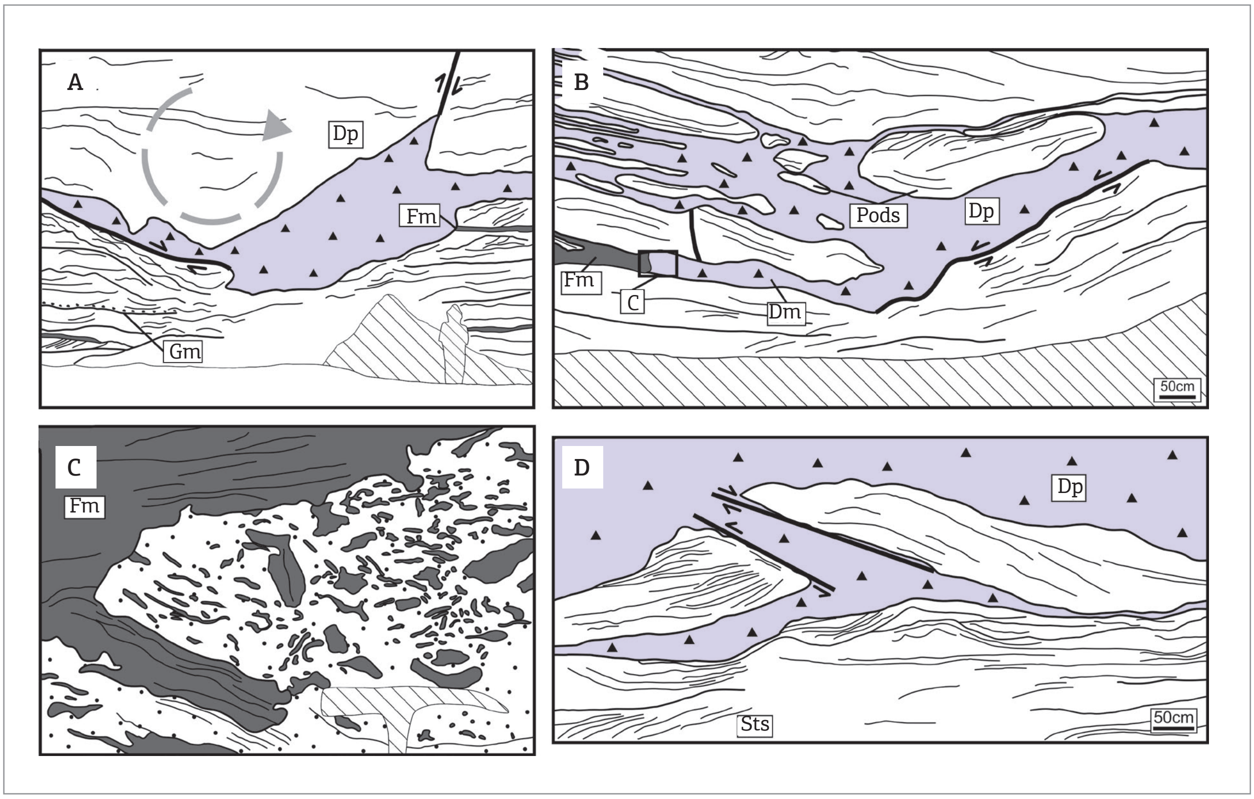


**Figure 7. Deformational structures in the subglacial deposits of Cabeças Formation. (A) Conjugate faults related to sinistral rotation in normal fault system and sandstone pods in the diamictite (facies Dp), associated with massive conglomerate (facies Gm) and mudstone (facies Fm). (B) Faults and pods of fine-grained sandstone inside the facies Dp. Note the diamictite behavior like a sill intruding the sandstone beds of the delta front facies association (FA1), with the development of a low angle detachment surface at its lower contact. (C) Tabular and irregular rock fragments in the intraformational breccia (facies Fb). The fragments show very irregular to curved outlines. (D) Disruption of lenses of sigmoidal cross-bedded sandstone and beds of facies Sts. The sketches are located in the panoramic section of Fig. 4.**

sandstones in the facies Dp are interpreted as the result of the assimilation of unconsolidated or partially consolidated (frozen?) deposits affected by shearing of the FA1, during a cycle of glacier advance-retreat. The detachment surface is preferentially developed in the contact between diamicton and sigmoidal sandy lobes. This contact zone, due to rheology differences, was favorable for the propagation of the movement induced by glaciers, generating a detachment surface similar to those described by van der Wateren (1986), Boulton and Hindmarsh (1987), Fernlund (1988), and Kessler *et al.* (2012). Tangential surfaces of detachment combined with tillites with sandstone pods indicate the subglacial shearing responsible by erosion and disruption of the substrate (FA1) at glacier advance periods (Boulton & Hindmarsh 1987, Kessler *et al.* 2012).

Glacial transport takes place in basal sliding and is more effective in wet base glaciers due to the lubricating action of a thin water film (Eyles & Eyles 2010). The presence of deformed lenses or sandstone pods indicates that the glacier base slid over a water saturated sedimentary substrate (FA1), which was plastically deformed. Partially preserved sedimentary structures in the sandstone pods are evidence of erosion and assimilation of pre-existing sedimentary deposits in the substrate (FA1) into the base of the glacier in above water melting temperature (warm permafrost). The ice in sediments porosity increases the cohesion and increases the material strength to the deformation (Waller *et al.* 2009, Kessler *et al.* 2012). Despite the FA2 being similar to subaqueous gravity driven flow deposits (Shanmugam 2000, Canuto *et al.* 2010), it was interpreted as a product of subglacial erosion because it is limited by sub-horizontal detachment surface. Furthermore, the FA2 is not associated with deeper deposits as turbidities, which are common in

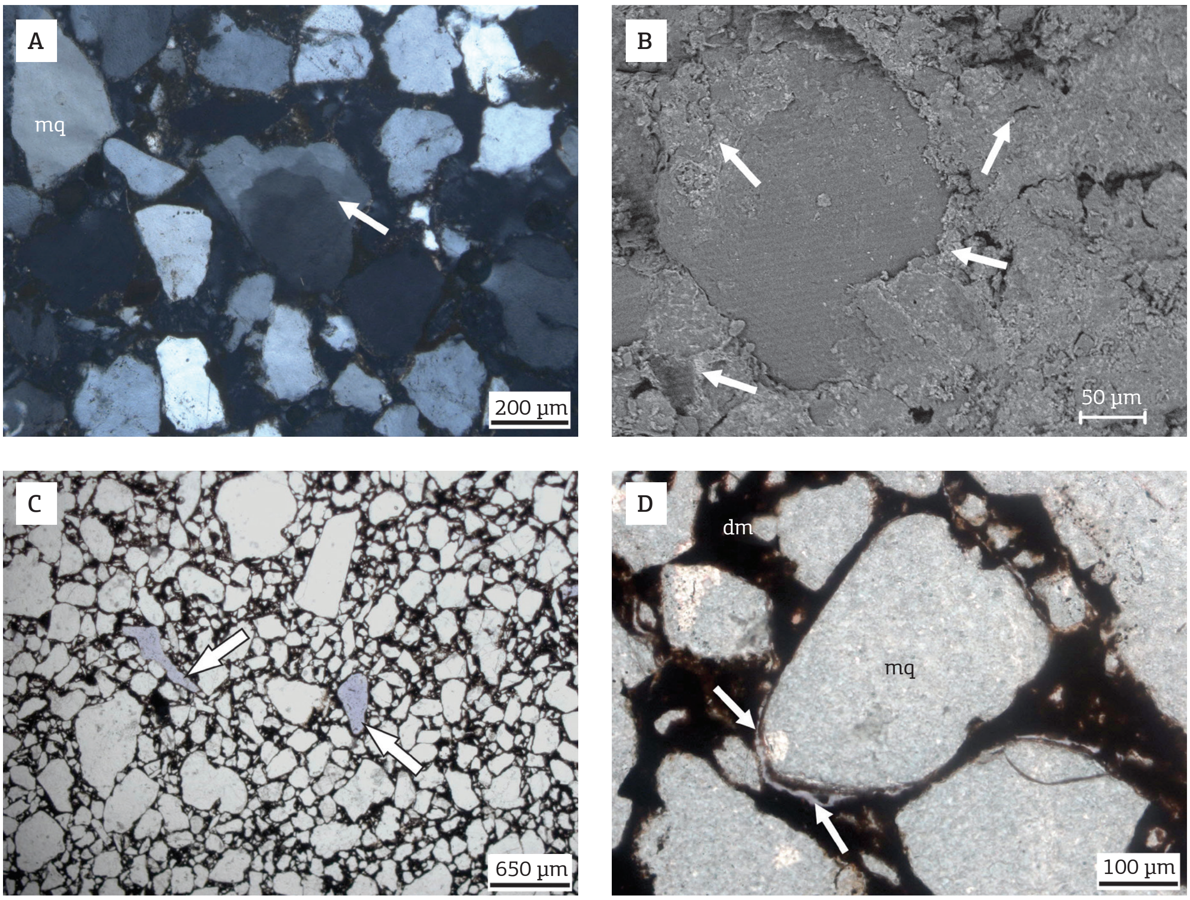


Figure 8. Aspects of the primary composition and pore system of the diamictite matrix. (A) Undulose extinction in monocrystalline quartz (mp) indicated by arrow. (B) SEM image of secondary electrons with details of the siliciclastic depositional matrix with iron oxide/hydroxide (light gray). (C) Moldic pores (arrows). (D) Interstitial shrinkage pore (arrows) in depositional matrix (dm). Note the presence of matrix between the pore and grain. Fig. A with XN (cross nicols); Figs. C and D with //N (parallel nicols).

subaqueous gravity driven flow deposits (Hart & Robert 1994, Eyles & Eyles 2010).

The main deformational structure observed in the FA2 was the sub-horizontal detachment surface, generated by normal and shear stresses resulting from the weight and motion of the glacier, respectively (see Moran 1971, Nielsen 1988, Owen 1989). Structures created under these conditions were described by several authors in Quaternary subglacial environments (e.g. Moran 1971, Berthelsen 1979, Thomas 1984, Ingolfsson 1988, Nielsen 1988, Owen 1989, Kluiving *et al*. 1991, Hicock *et al*. 1996). The subglacial environment is relatively complex, because it involves the superposition of different events that include deposition, erosion, and deformation (Hicock *et al.* 1996). Both theoretical and field observations indicate that abrasion, crushing, and grinding of clasts strongly influence the lithological characteristics of subglacial deposits (Brodzikowski & van Loon 1991). The sedimentary rocks in the studied region do not record tectonic deformations nor are geographically close to a major fault zone, which strongly agrees with the glacial interpretation for the origin of the studied deformational structures. Additionally, these glaciogenic structures are distinct from tectonic structures due to their relative small size and intraformational character (Banham 1977, Nielsen 1988).

Sandstone dikes and sills of facies Dm were formed by the injection of fluidized sediments from high-pressure zones, mainly along the primary anisotropy (bedding) of the FA1 (von Brunn & Talbot 1986, Jolly & Lonergan 2002). The injection of sediments of facies Dm under relatively high pressures induced hydraulic fracturing of the host rock (facies Fm) and generated intraformational breccia (Rijsdijk *et al.* 1999, Passchier 2000). Plastic adjustment along the lower pressure zones was a relief consequence of the lithostatic pressure associated with glacier mass loss (Passchier 2000).

The glacier retreat reduced the normal and shear stresses caused by weight and movement on the substrate, generating subordinated normal faults through isostatic adjustments. The spatial position of the NW-SE thrust faults and interpreted kinematic of the sandstone pods suggest a mass transport from SE to NW.

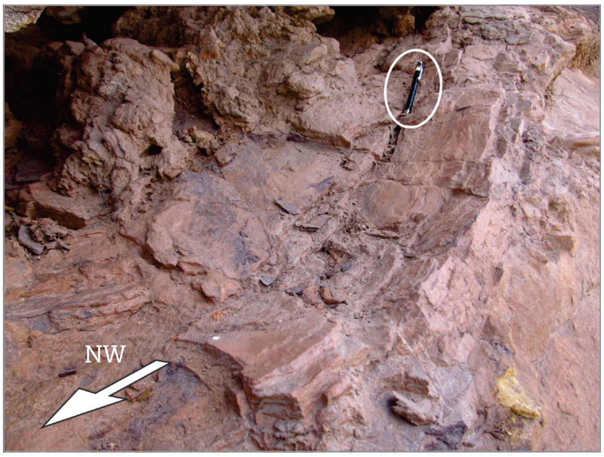


**Figure 9. Ferruginized siltstone (fault gouge) highlights the NE-SW normal fault plane. It corresponds to a displacement surface in the sector I responsible for the open folds in the facies Sts. Folds exhibit interflank angles between 150° and 170° (sector III, Fig. 4B). Faults have strike to NW-SE and ENE-WSW and moderate to high dip angles (60° to 70°, Sector II). Sills of facies Dm have mostly intruded into FA1 and are associated with breccia (facies Fb). Scale indicated by a circled pen.**

## Melt-out delta front (FA3)

The melt-out delta front comprises a 7 m thick facies association with lenticular and subordinate tabular beds that are composed of fine-to medium-grained sandstones overlying the subglacial deposits of FA2 (Tab. 1, Figs. 3 and 4). The FA3 includes massive sandstone (facies Sm), sandstone with horizontal lamination (facies Sh), and sigmoidal cross-bedded sandstone (facies Sts). The sigmoidal lobes form a complex bedform that includes the facies Sts characterized by cross-strata interbedded with tabular beds of fine-grained sandstones (facies Sh). The concentration of coarse-grained sand in the foresets highlights the cross-strata of facies Sts (Fig. 10). Sandstones with massive bedding (facies Sm) are associated with synsedimentary deformation (waterscape structure), which are commonly seen in sigmoidal lobes.

## Interpretation

The interpretation for FA3 and FA1 is partially comparable. The presence of tabular beds (facies Sh) interbedded with the sigmoidal lobes suggests sand migration through unidirectional flow, under transitional to upper flow regimes with high rates of suspended load (Røe 1987, Mutti *et al*. 2003, Olariu *et al*. 2010). Facies Sm is also an indication of high rates of sand fall out and water saturated sediments, resulting in total or partial liquefaction, which produced massive bedding or waterscape structures, respectively (Lowe 1975, Owen 2003). Coarse sand grains along the foresets of sigmoidal cross-bedding were produced through coarse grain segregation during the migration of small-scale bedforms in the stoss side of the sigmoidal lobes and deposited in the lee side (Slingerland 1984, Reesink & Bridge 2007). Tabular beds with horizontal stratification (facies Sh) interbedded with sigmoidal lobes indicate the deposition of sand sheets during periods of high-energy flood and sediments influx (Mutti *et al.* 2003, Blazauskas *et al.* 2007). The presence of sandstone bodies with both planar and lobe geometries suggest changes in the post-glacial sedimentation pattern.

The FA3 stratigraphic position, immediately above the subglacial deposits of FA2, indicates that deposition was influenced by the energy variation of ice-melt waters discharge in a delta front (Eyles & Eyles 2010). The dominance of fluidization and liquefaction of sand beds, high sediment inflow and occurrence of coarse-grained sand segregated in the lobes foresets reinforce this interpretation. FA3 and FA1 were interpreted as being formed in the same paleoenvironmental conditions. However, the relative FA3 stratigraphic position, the absence of glaciotectonic structures, and the proximity to lower shoreface/offshore transition deposits of the overlaying Longá Formation, are indications of deposition in the distal region to the glacier margin (Knight 2012).

## STRATIGRAPHIC IMPLICATIONS AND DEPOSITIONAL MODEL

Previous studies carried out in Oeiras region have interpreted the analyzed succession only as delta deposits (e.g. Santos & Carvalho 2004). This research, based on stratigraphic and geometric studies of the same succession, confirmed the presence of delta deposits and described, for the first time, lenticular beds of tillites with faceted clasts and glaciotectonic structures. These structures represent an unequivocal evidence of glacial influence during the deposition of the upper part of Cabeças Formation. The record of the regional-scale Famennian glaciation is limited to the top of Upper Devonian Cabeças Formation. The occurrence of these Famennian glaciogenic strata allows more precise regional correlation between both borders of Parnaíba Basin and indicates that glacial sedimentation in the basin was much more extensive than it was previously thought.

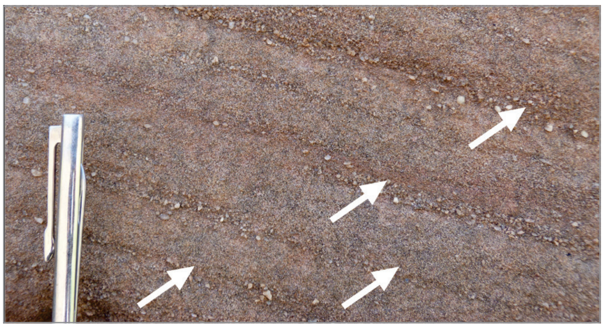

**Figure 10. Segregation of coarser grains in the foresets (arrows) of facies Sts in the melt-out delta front deposits; scale = 10 cm.**

Five depositional phases were interpreted in the studied geological record and include a glacier advance-retreat cycle, which was modeled for the studied succession as follows (Fig. 11):

- The first phase marks the delta system progradation (FA1) towards NW during the interglacial period (Fig. 11A).
- The second depositional phase was marked by the formation of glaciers during the Famennian, which caused local sea-level fall and exposure of delta deposits (FA1) in the Southeastern part of Parnaíba Basin (Fig. 11B). The Famennian glaciation initial phase represented the advance of the coastal glaciers towards the sigmoidal lobes of a delta front (FA1). The unconsolidated, water saturated substrate was frozen with temperatures slightly above the ice melting point (hot permafrost). The action of normal and shear stresses on the substrate produced a detachment surface that developed as the glacier advance. The glacier migration caused disruption of the sand supply and further assimilation of the delta beds into the diamicton (FA2); and abrasion of crystalline and sedimentary rocks on the glacier substrate. The glacial structures generated during this stage were interpreted as compatible with those formed under the brittle-ductile regimen related to glacial advance periods (McCarroll & Rijsdijk 2003, Kessler *et al.* 2012).
- The third depositional phase is represented by the final stage of glacier advance, thus the ice mass was reduced and the diamicton deformation took place under glaciotectonism static conditions (Jhaer & Kruger 2001, Fig. 11C).
- The fourth depositional phase was dominated by collapse structures that indicated gravitational instabilities (Fig. 11D). The glacier mass loss resulted in isostatic rebound and development of normal faults, folding, rotation of sandstone pods, sills and dykes injection, and intraformational breccia (Mörner 2005). The NW-SE shear trend would have produced the plastic flow migrating from high- to low-pressures zones through the primary anisotropy in the sigmoidal lobes. This phase also refers to the final stages of the glacier retreat, in which the diamicton deposits were succeeded by the installation of a new delta system (FA3) fed by melt-water (Fig. 11D). At such period, isostatic rebound due to ice retreat caused regional uplift lasting about few thousands of years, and therefore reducing accommodation due to sea level rise. Additionally, fast flow flooding formed the tabular beds interbedded with the sigmoidal strata.
- At last (fifth depositional phase, Fig. 11E), an expressive sea-level rise took place during the post-glacial phase and formed a storm-influenced shallow platform. In this setting, the fine-grained sediments of Longá Formation were

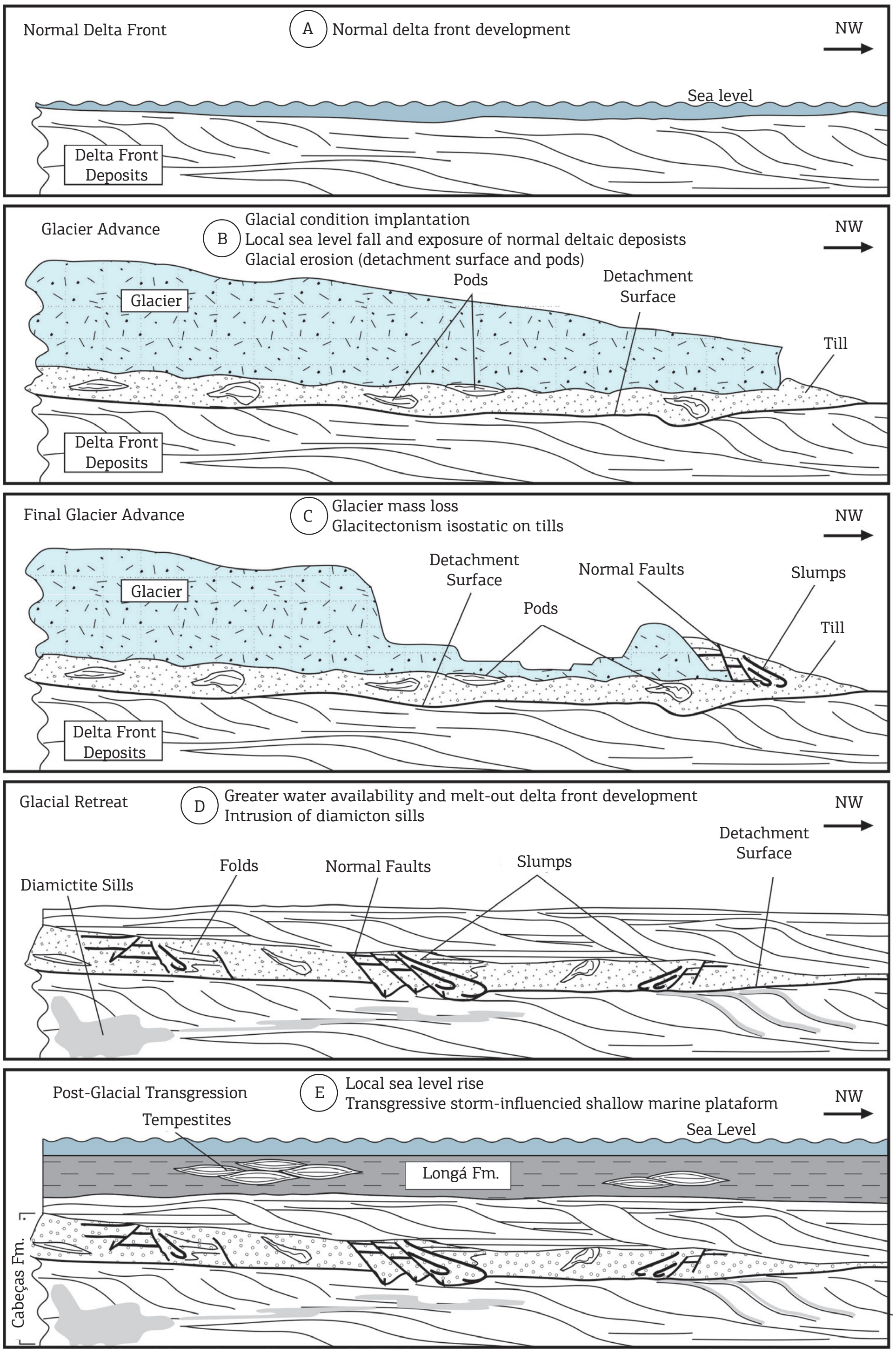


Figure 11. Paleoenvironmental evolution of Cabeças Formation in the Southeastern border of Parnaíba Basin. The first phase is related to the progradation of a delta system to NW in the Southeastern border of Parnaíba Basin (A). The second phase corresponds to the formation of glaciers and local sea level fall with partial exposure of the delta front deposits, which were eroded by glacial dynamics (B). During the final glacial advance phase, there is a mass loss and the till was deformed under conditions of static glaciotectonism (C). Subsequent glacial retreat provided a large sediment supply and consequent development of a melt-out delta system. The loss of glacier mass resulted in a generalized pressure decrease with frequent intrusion of liquefied diamicton as sills and dykes into lower pressure zone (D). Post-glacial conditions produced a sea-level rise and deposition of the retrogradational deposits of Longá Formation that started a long-term transgression in Parnaíba Basin (E)

deposited in the shoreface/offshore transition zone, therefore indicating the prelude of a long-term transgression during the terminal Famennian and Early Carboniferous. The record of the post-glacial transgression in the Late Famennian is characterized by the presence of black shales above tillites in the sedimentary basins of South America and Europe (e.g. Caplan & Bustin 1999, Streel *et al.* 2013).

This study proposes that tillites with limited porosity (quartz wakes with inter-granular spaces entirely filled by matrix) interbedded with delta front deposits may represent permo-porous barriers in the Cabeças reservoir, and hence a secondary seal in the Mesodevonian-Eocarboniferous petroleum system of Parnaíba Basin.

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