Upper Maastrichtian – Eocene benthic foraminiferal biofacies of the Brazilian margin, western South Atlantic

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Abstract

Benthic foraminiferal biofacies were delimited for the upper Maastrichtian through upper Eocene of five Brazilian marginal basins (Sergipe-Alagoas, Mucuri, Campos, Santos and Pelotas) and two DSDP Sites 356 and 20C of the western South Atlantic. The biofacies were determined based on the benthic foraminiferal assemblages and associated parameters, including percentage of planktic foraminifera (% planktics), lithology, and percentage of radiolarians (% rads). The biofacies show basin-to-basin differences, and are primarily distinguished by the agglutinated/calcareous taxon percentage and the dominant three or four species. Biofacies A is composed of 100% calcareous taxa and dominates in the Eocene. Biofacies B has up to 10% agglutinated taxa and occurs from the middle Paleocene through the upper Eocene. Biofacies C has 11% to 25% agglutinated taxa and is present from the upper Maastrichtian through the upper Eocene. Biofacies D contains a balanced percentage of calcareous and agglutinated taxa (~50% each), and is always associated with Biofacies E in the marginal basins. Biofacies E is dominated by agglutinated taxa, especially tubular forms (Bathysiphon, Nothia, Rhizammina, Psammosphonella). This biofacies correlates with the so-called “flysch-type” biofacies of Berggren and Gradstein (1981), and occurs exclusively in the marginal basins from the Maastrichtian through upper Eocene, although it dominates in the Paleocene. The biofacies distribution reveals distinct environmental settings as the Brazilian margin built outwards in response to tectonic activity and increased terrigenous input. The biofacies record a deep-water setting close to or below the calcite compensation depth (CCD) during the Maastrichtian–Paleocene along the entire eastern Brazilian margin. Progradation of the shelf and shoaling of the slope during the Eocene probably is the principal reason for the abrupt change from agglutinant-rich biofacies (E and D) to calcareous-rich biofacies (A, B, and C) in the early Eocene. The Campos Basin continued to record abyssal to lower bathyal conditions while the Sergipe-Alagoas and Mucuri basins shoaled to neritic palaeodepths by the late Eocene. Changes in relative sea level, including a global sea level fall in the late Paleocene followed by global sea level rise in the early Eocene, as well as changes in the position of the CCD along the Brazilian margin affected the development of foraminiferal biofacies in the marginal basins. The distal DSDP sites were at greater palaeodepths than the sites in the marginal basins, but were not below the CCD during the Maastrichtian–Eocene and biofacies were dominantly calcareous. We conclude that the CCD was shallower along the productive Brazilian continental than in the pelagic areas due to the greater flux of organic matter.

INTRODUCTION

Biofacies are discrete stratigraphic units based on micro-fossil content, which differ significantly from units above and/or below. They are recognised in stratigraphic sequences and can be used as mappable horizons in seismic profiles (Fillon, 2009). In this study, benthic foraminiferal assemblages are the microfossils used to recognise biofacies in the Brazilian marginal basins, which are compared with data from more offshore sites.

Benthic foraminiferal biofacies analysis has proven to be a powerful tool in palaeoenvironmental and palaeoecological investigations. Benthic foraminiferal biofacies of continental margins are strongly correlated to export productivity and organic flux to the seafloor, and depositional conditions at the seafloor, as well as seasonality of organic flux, lateral flux of refractory organic matter, oxygen lev-

Sea-level fluctuations may have greatly influenced the benthic foraminiferal biofacies distribution in the Maas- trichtian through Eocene of the marginal basins of the western South Atlantic. Low-stands of sea-level induce increased deposition of siliciclastics on the slope and rise and in marginal basins due to increased erosion/weathering on land (Leckie & Olsson, 2003, Catuneanu, 2006). In contrast, deep-sea depositional rates during transgressions and sea-level highstands are lower and there is greater potential for sediment condensation and generation of unconformities on the slope and rise, and in the marginal basins (Leckie & Olsson, 2003, Miller et al., 2005, Catuneanu, 2006).

A rise in the sea level may cause a rise in lysocline and calcite compensation depth (CCD) (Berger, 1970), providing an opportunity for the habitat space of abyssal agglutinated assemblages to expand into shallower depths along the continental margin. By contrast, lowering of sea level may cause the CCD to be depressed, thereby restricting dominantly agglutinated assemblages to deeper abyssal regions (Khunt & Collins, 1996, Kaminski & Gradstein, 2005).

The main objective of this paper is to present a biofacies analysis of benthic foraminiferal assemblages combined with other parameters (planktic foraminiferal percentage, radiolarians, lithology) to improve the interpretation of palaeoenvironments recognised in marine sections in cores and borehole samples from the hydrocarbon-rich marginal basins of Brazil, and compare these with environments in more offshore settings in DSDP drill sites. The biofacies provide the framework for investigation of Maaschichtian-Eocene evolution of the Brazilian margin in the western South Atlantic.

MATERIAL AND METHODS
Biofacies were defined based on the benthic foraminiferal assemblages of wells from five Brazilian marginal basin and two Deep Sea Drilling Project (DSDP) sites in the western South Atlantic (Fig. 1). The samples came from a

Figure 1. Bathymetry of the study area, including the five Brazilian marginal basins (Sergipe-Alagoas - SEAL, Mucuri - BA, Campos - CAM, Santos - SAN, and Pelotas - PEL) and DSDP Sites 20C and 356.
variety of sources: cores, cuttings and sidewall samples. Core samples were obtained from discrete cored intervals in an industry well and DSDP sites. Cutting samples are formed by drilled rock fragments that are transported up the well bore by the mudstream in the well. Sidewall core samples are obtained by percussion sidewall coring systems that shoot cylindrical bullets into the borehole wall. The core samples are the majority of the analysed samples. The cuttings and sidewall samples are from the Petrobras petroleum industry wells, and were selected for intervals where coring was not continuous.

The Petrobras petroleum industry wells are located in five Brazilian marginal basins (Sergipe-Alagoas, Mucuri, Campos, Santos, and Pelotas) and the DSDP samples are from Leg 39 Site 356 (São Paulo Plateau) and Leg 3 Hole 20C (Rio Grande Rise) (Fig. 1). The locations were selected based on their stratigraphic continuity over the Paleocene–Eocene interval, although some locations also recovered the upper Maastrichtian (Table 1).

The samples were processed at the Biostratigraphy and Paleoecology Department at Petrobras Research Center, Rio de Janeiro, Brazil. The DSDP core samples consisted of stiff, unconsolidated to weakly consolidated sediment, and were washed over a 63 µm sieve and dried. The core/cutting samples of the petroleum wells were crushed and

<table>
<thead>
<tr>
<th>Well/Site</th>
<th>Location</th>
<th>Present water depth (m)</th>
<th>Samples</th>
<th>Sample type</th>
<th>Age</th>
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<td>3203</td>
<td>107</td>
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</tr>
<tr>
<td>Basin</td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td></td>
<td></td>
<td></td>
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<td>middle to upper Eocene</td>
</tr>
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</tr>
<tr>
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<td>14</td>
<td>sidewall</td>
<td>lower Eocene</td>
</tr>
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<td>16</td>
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<tr>
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<td></td>
<td>Basin</td>
<td></td>
<td></td>
<td></td>
<td>upper Maastrichtian</td>
</tr>
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</table>

Table 1. Present geographic locations and age interval of samples in this study.
soaked in solution of 40% hydrogen peroxide washed over a 63µm sieve and dried, following standard procedure of the company. These industrial samples were provided in slides, picked. The picking follows the standard company procedure to pick ~300 tests (planktics and benthics).

We acknowledge that this is not ideal process for studies focused on benthic foraminiferal assemblages, where ~200 –300 benthic foraminiferal tests would be required to fully represent the high diversity of the deep sea assemblages in the Paleogene (see Fig 2 in Thomas, 1985). The availability of these samples, however provides a unique opportunity to compare deep-sea sites with the Brazilian marginal basins, at least semi-quantitatively. As a result of selecting a sum of ~300 benthic and planktics specimens, most samples have low numbers of benthic foraminifera that only partially represent the diversity of the community (Figs 2 and 3). Despite the relatively low number of specimens, we argue that we were able to recognise the main trends of the benthic foraminiferal assemblages. We demonstrate this by performing Q-mode cluster analysis for all samples of the Pelotas and Sergipe-Alagoas basins, and separately for all samples containing at least 100 specimens, and for samples containing at least 35 specimens, then comparing the results of these separate analyses. In all the cases, the same major clusters are generated, despite the low number of specimens in some samples (Fig. 4). Therefore, we conclude that we can use benthic foraminiferal assemblages to establish the biofacies, but with limitations on the statistical significance.

A low number of specimens was also observed in samples from DSDP Sites 20C and 356, even though all benthic foraminifera were picked in each sample, possibly due to the relatively small sample volume (~10 cc). However, Site 20C has a relatively higher number of benthic specimens than Site 356. Despite both sites being situated above the palaeo-CCD, Site 20C was possibly deeper in the lysocline than Site 356, which likely affected the flux of fragile planktic foraminiferal tests and thereby increasing the concentration of benthics within the sediment. The very low sedimentation rates in the upper Cretaceous-Paleocene of Site 20C (1.42 m/myr) compared to Site 356 (20 m/myr) support the deeper position in the lysocline for the Site 20C.

Q-mode cluster analysis and correspondence analysis (CA) were performed using PAST 3 software (Hammer & Harper, 2006). The CA and Q-mode cluster analysis took into account the absolute percentage of the most abundant species, defined as >5% absolute percentage in at least two samples. The cut off of 5% was adopted after repeated attempts in using CA for each well or site in order to separate the biofacies optimally.

The percentage of total assemblage (% total assemblage) include: planktic and benthic foraminifera (% planktics + % benthics = % total assemblage) or planktic and benthic foraminifera and radiolarians (% radiolarians) when they occur. The percentage of tubular agglutinated benthic foraminifera (% tubular forms) was calculated from the

![Figure 2](image.png)

**Figure 2.** Number of Specimens versus Number of Species plot including all samples of upper Maastrichtian through Paleocene. The number of species does not increase drastically in samples with ≥ 50 specimens.
benthic foraminiferal assemblage, and includes the elongate, tubular agglutinant taxa (e.g., Bathysiphon, Psammo-siphonella, Nothia, and Rhizammina).

Age models were based on calcareous nannofossil biostratigraphy, except for Site 20C, where the age model is based on planktic foraminiferal biostratigraphy. The planktic foraminiferal biozones (*) are from Wade et al. (2011) and the nannofossil biozones (**) from Gradstein et al. (2012).

The bathymetric zones follow Van Morkhoven et al. (1986) in agreement with Berggren & Miller (1989):
- Neritic: 0 – 200 m inner <30 m
- middle 30 – 100 m
- outer 100 – 200 m
- Bathyal: 200 – 2000 m upper 200 – 600 m
- middle 600 – 1000 m lower 1000 – 2000 m
- Abyssal: >2000 m
- upper 2000 – 3000 m
- lower > 3000 m (below the CCD)

GEOLOGICAL SETTING

The Proximal Brazilian Marginal Basins

The Brazilian marginal basins (Pelotas, Santos, Campos, Mucuri, Bahia-Sul, Sergipe-Alagoas and Pernambuco-Paraiba) have a similar formation and evolution that began with rifting in the South Atlantic during the break-up of Pangea (Milani et al., 2001, Mohriak, 2003, Zalan, 2004, Torsvik et al., 2009). The tectono-stratigraphic evolution pattern of these basins is quite similar, and can be divided into four stages: pre-rift, rift, restricted marine and open marine. The pre-rift package (upper Jurassic-lower Cretaceous) occurs in the Sergipe-Alagoas basin and southward to the Pelotas Basin. This sequence is generally represented by reddish fluvo-lacustrine sediments deposited in a shallow lacustrine palaeoenvironment (Milani et al., 2007). The rift sediments are diachronous (lower Barremian to Aptian ages), and several lacustrine depocenters formed during the Early Cretaceous. These depocenters contain shale deposits that are important hydrocarbon source rocks. The syn-rift rocks are more abundant in the southern basins (Pelotas and Espírito Santo). During the Aptian, the restricted marine section was deposited, typically represented by a thick evaporite package (mostly halite and gypsum-anhydrite) and has importance in the Santos, Campos, and Mucuri basins. A thinner succession of evaporites reaches the northern basin of the Sergipe-Alagoas. Evaporite deposition spanned the late Aptian to earliest Albian (Cainelli & Mohriak, 1999, Milani et al., 2001, Mohriak, 2003). Above the salts, carbonate and siliciclastic deposits accumulated in a large proto-oceanic gulf, locally with some associated magmatism. Such deposits, together with the evaporites,
characterise the section of the eastern Brazilian margin. During the Albian, marine conditions established, first represented by carbonates then by thick siliciclastic sediments, predominantly shales and sandstones, shallow platform, coastal fans, and slope and basin turbidites. This siliciclastic sequence consists of transgressive-regressive cycles characterise the Upper Cretaceous through Pleistocene (Asmus & Baisch, 1983, et al., During the Cenozoic, the Mucuri experienced an important magmatic event formed the Abrolhos Volcanic Complex, which was covered by the Abrolhos coral reef. The Abrolhos carbonate sequence comprises the largest and the richest reef complex of the western South Atlantic (Leão, 1999). The volcanics are intercalated with shales and carbonates. Ar-Ar ages indicate that the volcanic activity spanned the Paleocene–Eocene (60–40 Ma, Szatmari et al., 2000, Milani et al., 2001, Mohriak, 2003, Torsvik et al., 2009). Of all basins, the Campos and Santos basins are by far the most affected by salt mobilization, which generated new depocenters basinwards. The Espírito Santo-Mucuri and Sergipe-Alagoas basins had less salt tectonics, which mostly occurred in deep-waters and onshore respectively, whereas the Pelotas Basin has incipient (northern part) or no significant salt tectonic activity (Cainelli & Mohriak, 1999).

The Distal DSDP Sites

DSDP Leg 39 Site 356 – São Paulo Plateau

Site 356 was drilled on the southeastern edge of São Paulo Plateau on the Brazilian continental margin (28° 17.22’S, 41°05.28’W, 3175 m water depth), reaching upper Albian at 741 m sbf (Perch-Nielsen et al., 1977). Sediments across the Cretaceous/Paleogene boundary
were deposited under oxidizing conditions (Supko et al., 1977). The uppermost Maastrichtian to upper Paleocene sequence consists of relatively pure nannofossil and foraminifer chalk (Supko et al., 1977), but with deposition of biogenic silica during the Eocene. Depositional hiatuses span the uppermost Paleocene to lowermost Eocene, and the upper middle Eocene to lower Miocene (Supko et al., 1977).

This site was selected because of the relatively good recovery of the Paleocene, represented by a thick and nearly complete sequence recovered in Cores 29 to 16, although with a gap spanning the lower Paleocene Zone P1b (Boersma, 1977). Foraminifera are very well preserved in the Danian (Boersma, 1977). The hiatus of ~5 myr (~57–52 Ma) between the uppermost Paleocene and the lowest Eocene may be due to a break in accumulation, or deposition followed by erosion.

Eocene sediments were recovered in Cores 356-15 to 6. The lower Eocene varies from chalky, foraminifera-rich sediments to radiolarian and diatom-rich sediments with very few foraminifera (Perch-Nielsen et al., 1977). Lower Eocene silicified chalks (Cores 15 to 10) are overlain by a thin sequence of siliceous calcareous ooze associated with a strong dissolution of calcareous sediments in Core 356-10 (Perch-Nielsen et al., 1977). The middle Eocene sediments vary from chalky, foraminifer-rich sediments to radiolarian and diatom-rich sediments containing very few foraminifera (Perch-Nielsen et al., 1977).

**DSDP Leg 3 Hole 20C – Rio Grande Rise**

This site is located on the Rio Grande Rise (28° 31.47’S and 26° 50.73’W – present water depth 4506m) in the western South Atlantic. A relatively thin and incomplete uppermost Maastrichtian to Paleocene sequence was recovered in Hole 20C (Maxwell et al., 1970). The Cretaceous/Paleogene boundary interval is disturbed by sedimentary processes, possibly sediment reworking (Maxwell et al., 1970). The upper Paleocene to lower Eocene is nearly complete, although the dissolution interval across the Paleocene/Eocene boundary interval was not recovered in the cored section. There is a stratigraphic break between the lower and middle Eocene (Maxwell et al., 1970).

The upper Maastrichtian through Paleocene consists of very pale brown-pink and pink nannofossil chalky oozes. The lower to middle Eocene consists of nannofossil marly oozes and clays in various shades of brown, somewhat enriched in zeolites (Maxwell et al., 1970). This unit may have been deposited near the carbonate compensation depth (CCD) with the calcium carbonate content varying from 16 to 52 wt% (Maxwell et al., 1970).

**PALAEOCEANOGRAPHIC SETTING OF THE SOUTH ATLANTIC**

Global temperature were variable during the Upper Cretaceous, including global cooling in the early Maastrichtian, and warming some 200-300kyr prior to the end-Cretaceous, which has been attributed to Deccan flood basalt volcanism in India (Barrera, 1997; Huber et al., 2002; Cramer et al., 2009; Keller & Abramovich, 2009; Thibault et al., 2010; Thibault & Gardin, 2010). Immediately after the bolide impact that likely caused the mass extinction at the Cretaceous-Paleogene boundary (K/Pg, e.g., Koutsoukos, 2014), there may have been a short interval of global cooling caused by dust or sulfate particles, global wildfires, severe acid rain and acidification of the oceans (Alegret et al., 2012, Alegret & Thomas, 2012). During the early to mid-Paleocene, global temperatures were similar to slightly lower than in the Maastrichtian (e.g., Zachos et al., 2001), but in the late Paleocene (~59 Ma) a long-term warming trend began, which culminated with the Early Eocene Climatic Optimum (EECO ~52-50 Ma; Zachos et al., 2001, 2008; Cramer et al., 2009). A number of hyperthermals events characterised the late Paleocene through early Eocene, with the Paleocene-Eocene Thermal Maximum (PETM, or Eocene Thermal Maximum 1, ETM1) the most extreme followed by the less severe events ETM2 and ETM3, with latter representing the early part of EECO (Zachos et al., 2008; DeConto et al., 2011, Litter et al., 2014, Lauretano et al., 2015). Temperatures did not reach freezing even in continental interiors (Zachos et al., 2001, 2005, Thomas et al., 2006) at mid-high-latitudes, and global deep waters temperatures were 10°-12°C warmer than today (Zachos et al., 2001, 2008, Cramer et al., 2009). In addition, the ocean circulation was efficient in maintaining higher temperatures, with low temperature gradients from high to low latitudes (Thomas et al., 2000, Huber & Sloan, 2001, Cramer et al., 2009, Huber & Caballero, 2011). The Paleogene continental configuration influenced ocean circulation and sites of deep water formation (e.g., Thomas et al., 2006), and thus ocean thermohaline circulation (e.g., Winguth et al., 2012). The exact time of opening of Drake Passage is controversial, ranging from the late middle Eocene (~41 Ma, Scher & Martin, 2006) to the early Miocene (~20 Ma, Anderson & Delaney, 2005). Opening of the Drake Passage has been speculated to have played an important role in the abrupt cooling starting the late Eocene and culminating in the growth of the Antarctic ice sheet and global cooling at the Eocene-Oligocene boundary (e.g., Kennett, 1977), but recently declining CO₂ levels are seen as more
important factors in Cenozoic cooling (e.g., DeConto & Pollard, 2003, Barker & Thomas, 2004).

The production of the deep-water is a key factor in the ocean circulation, and there are controversial ideas about where deep waters originated in the Paleogene. One hypothesis is that Warm Saline Bottom Water (WSBW) produced in the Tethys Seaway flowed southward in the Equatorial Atlantic and/or into the Indian Ocean along the African margin (Kennett & Stott, 1990; Bice et al., 2000). Another hypothesis is deep water forming in the Southern Ocean flowing northwards into the Atlantic and Indian ocean basins (Thomas et al., 2003). WSBW are not easily produced in ocean circulation models and earth system models, but could have existed as a transient condition during hyperthermal events (Bice, 2000; Huber & Thomas, 2008; Alexander et al., 2015). Thomas (2004) reported a shift in deep water sources from the Southern Ocean to the North Pacific ~65 Ma, and then reverted back to the Southern Ocean ~40 Ma, based on Neodymium isotopes of fish debris. Possibly in the Paleogene the main source of deep waters was generally in the Southern Ocean, with smaller or transient contributions from the subtropical Tethys Seaway (Fig. 6).

The planet started to cool at the beginning of the middle Eocene (~49 Ma), with pronounced cooling of high latitude surface waters. The opening of the Arctic to the world ocean may have been a factor in middle Eocene global cooling (Thomas, 2006; Borrelli et al., 2014). The Middle Eocene Climatic Optimum (~40 Ma) was a short-lived warming during the longer-term middle to late Eocene cooling (Bohaty & Zachos, 2003). The ice-free world shifted to small ice on Antarctica by the late Eocene and rapid growth of the Antarctic ice-sheet in the earliest Oligocene (~33.7 Ma; DeConto & Pollard, 2003; Coxall et al., 2005; DeConto et al., 2008; Katz et al., 2011; Borrelli et al., 2014).

**BIOFACIES AND PALAEOBATHYMETRY**

Five major biofacies (A-E) were based on the benthic foraminiferal assemblages and associated parameters, including percentage of planktic foraminifera (% planktics), lithology, and percentage of radiolarians (% rads). The major biofacies are not composed of the same taxa at all sites due to basin-to-basin differences. The biofacies are primarily distinguished by the agglutinated/calcareous percentage, and the dominant three or four species for each biofacies.

By combining Q-mode cluster analysis and the Correspondence Analysis (CA) it was possible to separate the samples into biofacies and then recognise which taxa were associated with each biofacies. Some taxa are abundant throughout the entire study interval, although they are more abundant in one or two biofacies. *Nuttallides truempyi* is the best example, it is the most common taxon among our samples (present in most samples), and more abundant at the distal DSDP sites (20C, 356). Therefore, this species contributes more to the biofacies of the deepest sites than of the proximal wells.

The biofacies are denoted with letters A to E, based on the agglutinated/calcareous percentage. In some locations (wells SEAL-01, SEAL-02, CAM-03, and DSDP Sites 20C and 356), the biofacies do not occur in one strati-
graphic interval, but in repeated intervals. To differentiate repeated biofacies, a number is assigned, e.g., Biofacies A1. The stratigraphic oldest interval is assigned the higher number, so that Biofacies A2 is older than A1 (Figs 7 and 8). The biofacies are presented by basin and with interpreted palaeobathymetry.

Siliceous radiolarians appeared as major contributors in the upper Paleocene (BA-01/Biofacies D) and lower Eocene (SAN-01/Biofacies A), reaching 40-100%. Note that foraminifera (planktic or benthic) are absent when the sample contains 100% radiolarians.

Biofacies A: The benthic foraminiferal assemblages included in this biofacies are composed of 100% calcareous taxa. At proximal locations, this biofacies occurs in the Eocene and is represented by Paralabamina lunata, Hanzawaia ammonita, Globobulimina sp., Planulina costata, Melonis sp.1, Gaudryina sp., and Gaudryina pyramidata. In the distal locations it occurs from the Maastrichtian through the upper Eocene, and Gyroidinoides globosus, Pullenia coreyi, Nuttallides truempyi, Gaudryina pyramidata, and Gaudryina sp. represent the Maastrichtian through Paleocene assemblage. Gyroidinoides, Oridorsalis umberatus, Gaudryina pyramidata, G. laevigata, Spiroplectammina sp., S. spectabilis, and Haplophragmoides sp.

Biofacies D: The benthic foraminiferal assemblages included in this biofacies contain calcareous and agglutinated taxa at about the same abundance. This biofacies is frequently associated with Biofacies E, and occurs from the Maastrichtian through Eocene in the Brazilian marginal basins. Kaminski & Gradstein (2005) described a “slope marls biofacies” that resembles some of the biofacies D over the Paleocene interval.

Biofacies E: The benthic foraminiferal assemblages included in this biofacies are composed primarily of agglutinated taxa, with the tubular forms (Rhizammina, Bathysiphon, Psammospinonella, and Nothia) diagnostic (~20-40% of benthics), associated with coarse-grained coiled taxa (Haplophragmoides, Ammoboligerina, Anmodiscus, Recurvoides, and Budashevaella). Biofacies E occurs from the Maastrichtian through the Eocene, but it is much more abundant in the Paleocene interval. It occurs exclusively in the Brazilian marginal basins.

We recognise two benthic sub-assemblages within Biofacies E, and coarse-grained coiled taxa and tubular forms dominate in both. The first assemblage is composed exclusively of agglutinated taxa, and occurs mostly in the Maastrichtian-Paleocene of the Pelotas, Campos, and Sergipe-Alagoas basins. It represents the greatest palaeo-water depths of the marginal basins, with the seafloor probably at or below the calcite compensation depth (CCD). The second assemblage has ~25% calcareous taxa including planktic foraminifera (~<60% of total assemblage), but these show clear evidence of dissolution (dissolved and corroded calcareous tests). This assemblage also represents deep water, above the CCD but below the lysocline. It occurs from the Maastrichtian to the Eocene in the Campos, Santos, Muruci, and Sergipe-Alagoas basins.

This tubular agglutinant-rich biofacies was originally described as a “flysch-type biofacies” by Gradstein & Berggren (1981), and later investigated by Kaminski et al. (1988) and Kaminski & Gradstein (2005). The original flysch-type biofacies was associated with tectonically active basins, although some authors recognised it also on the continental margins basins (Gradstein & Berggren, 1981). Gradstein & Berggren (1981) concluded that palaeobathymetry per se was not the key factor controlling their presence, although great depth, below the lysocline or CCD creates favourable conditions (Kaminski et al., 1988,
**Figure 6.** Benthic foraminiferal biofacies distributed by age for all sites. The wells are organised northern and shallower (Sergipe-Alagoas) through southern (Pelotas) and deeper (DSDP Sites 356 and 20C). Nannofossil biozones after Gradstein *et al.* (2012), planktic foraminiferal biozones from Wade *et al.* (2011).
Figure 7. Lithology and biofacies of the study locations from the upper Maastrichtian through Eocene, western South Atlantic and Brazilian marginal basins.
Koutsoukos, 2000, Kaminski & Gradstein, 2005).

The palaeodepths were based on the major benthic foraminiferal taxa of each biofacies (Table 2). Palaeobathymetric ranges of the key taxa were based on Tjalsma & Lohmann (1983), Van Morkhoven et al. (1986), Kaminski & Gradstein (2005).

In this section, the biofacies are presented by basin, but described for each site. A palaeobathymetric interpretation based on the benthic foraminiferal biofacies is also presented with a tentative palaeobathymetric curve.

**Sergipe-Alagoas Basin**

SEAL-01 and SEAL-02 are today located in very shallow depths (12 m and 16 m, respectively), ~100 km apart (Fig. 1). The biofacies were clearly distinguished by statistical analysis (Figs. 9 and 10).

The flysch-type biofacies E is very common in this basin, occurring in both wells from the upper Maastrichtian through to the lower Eocene, with usually high sedimentation rates (average ~120 m/myr – Figs. 11 and 12).

The Eocene is represented only in SEAL-01, and is predominantly composed of calcareous- rich biofacies A, B and C. There is no linear correlation between the occurrence of the calcareous biofacies and the sedimentation rates, which vary widely from 8 to 96 m/myr (Fig. 11).

**Well SEAL-01.**

Five biofacies were defined for the Paleocene- Eocene (Fig. 9). The Paleocene biofacies are mostly composed by agglutinated benthics (80-100% of benthics), without planktics, represented by **Biofacies E**. The most common calcareous taxa are **Globobulimina sp.**, **Cibicidoides sp.** and **Gyroidinoids sp.** The agglutinated assemblage is dominated by tubular forms (**Rhizammina, Bathysiphon, Psammosiphonella cylindrica, Haplophragmoides, Trochanminoides, Ammodiscus**, **Recuvridae, Nattallides truempi**, **Cibicidoides**, **Gyroidinoids**). This biofacies occurs in a shale interval with intercalated sandy beds.

The Eocene benthic biofacies are dominated by calcareous taxa (80-100% of benthics), and the diversity of species increases from the lower to upper Eocene. The interval is composed mostly by shale with some layers of sand and calcirudite, especially in the top of the interval (upper Eocene) (Fig. 8).

**Biofacies A1**

This biofacies is composed of calcareous taxa only, and occurs in one distinct interval in the upper Eocene. The interval has intercalated calcirudite and shale beds deposited above a thick layer of sandstone (~250m). This benthic foraminiferal assemblage is dominated by the large foraminifera **Amphistegina** sp. (80% to 100% of total assemblage) and other calcareous taxa, which are badly preserved, especially in the samples at the base of interval, where **Paralabamina lunata** is also badly preserved with evidence of dissolution. There are no planktic foraminifera. Ostracodes, echinoid spines, and fragments of corals and bryozoans are present in this interval.

Nodosaria sp.  
Other taxa: Cibicides sp., Lenticulina sp., Anomalinoiudes sp., Melonis sp.1. Planktic: 0%.  
Palaeobathymetric range: middle to lower neritic.  
Age range: late Eocene (CP15**).

>> 2 – Biofacies B1

Main taxa: Paralabamina lunata, Melonis sp.1, Cibicidoides eocaenus.  
Other taxa: Amphistegina sp., Lenticulina sp., Cibicidoides micrus, Globobulimina sp., Nodosaria sp.  
Planktic: 1-8% of total assemblage.  
Palaeobathymetric range: outer neritic.  
Age range: late Eocene (CP15**).

>> Biofacies C1

Main taxa: Bulimina alazanensis, Karrerulina conversa, Gaudryina pyramindata  
Other taxa: Gaudryina sp., Bulimina sp., Cibicides sp., Lenticulina sp., Uvigerina sp.  
Planktic: 5-15% of total assemblage.  
Palaeobathymetric range: outer neritic to upper bathyal.  
Age range: late Eocene (CP14**).

>> Biofacies A2

Main taxa: Globobulimina sp., Neoeponides elevatus, Globocassidulina subglobosa  
Other taxa: Planulina costata, Anomalinoiides sp., Cibicidoides sp., Nuttallides truemysi.  
Planktic: 50-60% of total assemblage.  
Palaeobathymetric range: upper bathyal to middle bathyal.  
Age range: late Eocene (CP14**).

>> Biofacies C2

Main taxa: Planulina costata, Gaudryina pyramindata, Bulimina sp.  
Other taxa: Cibicidoides sp., Globocassidulina subglobosa, Gyroidinoides sp., Lenticulina sp., Uvigerina sp., Gaudryina sp.  
Planktic: 50-60% of total assemblage.  
Palaeobathymetric range: upper bathyal to middle bathyal.  
Age range: middle Eocene (CP13/14**).

>> Biofacies B2

Poorly preserved tests of Amphistegina sp., with tiny reworked planktics and evidence of dissolution on planktic and benthic foraminifera (dissolved and corroded tests) also characterise this biofacies.

Main taxa: Planulina costata, Nuttallides truemysi, Cyclammina sp.  
Other taxa: Gyroidinoides sp., Gavelinella sp., Cibicides sp., Paralabamina lunata, Anomalinoiides sp.  
Planktic: 40-60% of total assemblage.  
Palaeobathymetric range: middle to lower bathyal.  
Age range: early to middle Eocene (CP9/10**, and CP12**, biozone CP11** is missing).

>> Biofacies E

This benthic foraminiferal biofacies is agglutinated taxa only and resembles the flysch-type assemblage (Gradstein & Berggren, 1981, Kaminski & Gradstein, 2005). Agglutinated tubular forms are ~32%.

Main taxa: Rhizammina sp., Haplophragmoides sp., Spiroplectammina navarroana, Psammosiphonella cylindrica  
Other taxa: Ammodiscus cretaeus, Ammoglobigerina sp., Cribrostomoides trinitatensis, Karrerulina conversa, Nothia sp., Nothia latissima, Recurvoides sp., Spiroplectammina sp., Trochamminoides sp.  
Planktic: 0-10% (~1% average) of the total assemblage.  
Palaeobathymetric range: lower abyssal.  
Age range: middle to late Paleocene (CP4 to CP8**, P4/5 to E2*).

Well SEAL-02.

A high percentage of agglutinated taxa is the characteristic feature of the biofacies in this well, although one interval has about the same percentages of agglutinate/calcareous (Biofacies D). The others samples are placed in Biofacies E (agglutinated taxa dominates) (Fig. 10). There is an unconformity in the middle Paleocene (missing nannofossil biozones CP4 and CP5) (Fig. 8).

>> Biofacies E1

Main taxa: Haplophragmoides sp., Ammoglobigerina sp., Nothia robusta.  
Other taxa: Globobulimina sp., Lenticulina sp., Globobulimina ovata, Cribrostomoides sp., Haplophragmoides stomaticus, Recurvoides sp., Psammosiphonella cylindrica.  
Tubular forms 20-30% of the benthics.  
Planktic: 50-60% of total assemblage.  
Palaeobathymetric range: lower bathyal.  
Age range: early Eocene (E1/E2*, CP8**).

>> Biofacies D

Main taxa: Haplophragmoides sp., Stensioeina becariiformis, Saccammina placenta, Nuttallides truemysi.  
Other taxa: Gavelinella sp., Spiroplectammina sp., Globobulimina sp., Lenticulina sp., Nothia sp.  
Planktic: 40-50% of total assemblage.  
Palaeobathymetric range: bathyal.  
Age range: late Paleocene (CP6/7**).

>> Biofacies E2

This biofacies contains Orthokarstenia sp. and Lenticuli-
Main taxa: *Psammosphaera irregularis*, *Cribrostomoides trinitatensis*, *Psammosiphonella cylindrica*, *Haplophragmoides* sp.

Other taxa: *Saccammina placenta*, *Nothia* sp., *Rercurvoides* sp., *Haplophragmoides stomatus*, *Praebulimina* sp., *Vulvulineria* sp., Tubular forms ~20% of benthics.

Planktic: 0-5% total assemblage.

Palaeobathymetric range: lower abyssal.

Age range: late Maastrichtian to late Paleocene (NC23 to CP2/3**).

**Palaeobathymetry of the Sergipe-Alagoas Basin**

The SEAL-01 biofacies sequence shows a progressive shallowing through the Paleocene-Eocene (Figs. 8, 11). We suspect rapid progradation of the margin and shoaling palaeobathymetry is the principle cause of this shallowing upwards trend due to the magnitude of the change, from lower abyssal depths in the Paleocene (Biofacies E), to middle-lower bathyal depths in the lower Eocene (Biofacies B), to neritic depths in the upper Eocene (Biofacies A). Likewise, SEAL-02 records a shallowing-upwards sequence through the Paleocene (Fig. 12) based on the increase in relative abundance of planktic foraminifera from Biofacies E2 in the Maastrichtian and lower Paleocene (0-5% planktics) to Biofacies E1 in the upper Paleocene (50-60% planktics) as the site shoaled above the CCD. The wells are 100 km apart, but both show a similar bathymetric trend in response to progradation along the margin. SEAL-02 is 10 km away from the present present day São Francisco River mouth. There is a hiatus in the Eocene of well SEAL-02, either the depositional conditions were not favorable or the entire interval was eroded.

Likewise, SEAL-02 records a shallowing-upwards sequence through the Paleocene (Fig. 12) based on the increase in relative abundance of planktic foraminifera from Biofacies E2 in the Maastrichtian and lower Paleocene (0-5% planktics) to Biofacies E1 in the upper Paleocene (50-60% planktics) as the site shoaled above the CCD. The wells are 100 km apart, but both show a similar bathymetric trend in response to progradation along the margin. SEAL-02 is 10 km away from the present day São Francisco River mouth. There is a hiatus in the Eocene of well SEAL-02, either the depositional conditions were not favourable or the entire interval was eroded.

**Figure 8.** Dendrogram classification of the samples by Q-mode cluster analysis and correspondence analysis, showing the seven major biofacies for well SEAL-01.
Figure 9. Dendrogram of samples produced by Q-mode cluster analysis and correspondence analysis showing the three major biofacies of the well SEAL-02.

Figure 10. Age vs Depth Model of well SEAL-01, plotted with the benthic foraminiferal biofacies, correlated palaeobathymetric ranges and sedimentation rates.
Mucuri Basin

Well BA-01.

The correspondence analysis and the Q-mode cluster analysis discriminated three biofacies for the Paleocene (Fig. 13). No Eocene was recovered in this well due to a major unconformity where the uppermost Paleocene through the lower Oligocene is missing (missing biozones CP8/9 to CP18). However, there is a nearly 100-m thick interval of which the age could not be determined, but could be upper Eocene. This interval corresponds to Biofacies A followed by a barren interval. The barren interval coincides with thick layers of sandstone intercalated with thin layers of shale. The Paleocene is composed mostly of shale (Fig. 8).

**Biofacies A**

This biofacies is characterised by shallow water taxa with evidence of transport (broken, yellowish and oxidised tests). *Quinqueloculina* sp. is poorly preserved.

**Main taxa:** *Cibicidoides* sp., *Discorbinitella bertheloti*, *Elphidium* sp. (transported from shallower areas)

**Other taxa:** *Lenticulina* sp., *Reussoolina* sp., *Quinqueloculina* sp., *Pyrgo* sp., *Nodosaria* sp.

**Planktic:** 0% of total assemblage.

**Palaeobathymetric range:** inner to middle neritic.

**Age range:** No older than late Eocene, based on the presence of *Elphidium* sp. (first occurrence was in the late, Loeblich & Tappan, 1988).

**Biofacies D**

This biofacies has a high percentage of radiolarians (60-80% of total assemblage), present in shales.

**Main taxa:** *Saccammina grzybowski*, *Nuttallides truncumpy*, *Stensioeina beccariiformis*, *Psammosiphonella cylindrica*.

**Other taxa:** *Cibicidoides velascoensis*, *Gyroidoides globosus*, *Gyroidoides* sp., *Saccammina placenta*, *Glomospira* sp., *Trochamminoides* sp.

**Planktic:** 30-45% of total assemblage.

**Palaeobathymetric range:** middle to lower bathyal.

**Age range:** middle to late Paleocene (CP5 to CP7**).

**Biofacies E**

**Main taxa:** *Rhizammina* sp., *Psammosiphonella cylindrica*

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*Figure 11.* Age vs Depth Model of well SEAL-02 plotted with the benthic foraminiferal biofacies with correlated palaeobathymetric range and sedimentation rates
ca, Trochamminodes sp., Haplophragmoides sp.


Planktic: 35-45% of total assemblage.

Palaeobathymetric range: lower bathyal.

Age range: Maastrichtian (NC23**) to early/middle Paleocene (CP3 to CP5**, the nannofossil biozones CP1 and CP2 are not present).

**Palaeobathymetry of the Mucuri Basin.**

The well BA-01 (22 m water depth) is located between the islands of the Abrolhos Coral Reef (Fig. 1). There is a major unconformity between the upper Paleocene Biofacies D and upper Eocene Biofacies A associated with a rapid change in the benthic assemblage suggesting a major change of palaeobathymetric setting, from at least middle bathyal to neritic. The shoaling upwards trend and unconformity also coincide with a major decrease in sedimentation rates, from an average of ~1743 m/yr in the Maastrichtian-Paleocene to 5 m/yr in the upper Eocene (Fig. 14). The observed changes in sedimentation rate may be related to the rising of the volcanic islands of Abrolhos Reef that occurred during the middle/late Paleocene to late Eocene (Szatimati et al., 2000, Zalan, 2004).

The biofacies sequence shows progressive shallowing up from the upper Maastrichtian through to the upper Paleocene. The Maastrichtian-lower Paleocene flysch-type Biofacies E is interpreted as lower bathyal- upper abyssal-type. Biofacies D interval represents middle to lower bathyal palaeodepths. A radiolarian event was recognised in the upper Paleocene (~56-57 Ma – Biofacies D) and is restricted to this basin during this time period.

The upper Eocene Biofacies A is composed mostly of shallow water benthic taxa (Discorbina, Cibicides, and Lenticulina), some of which show evidence of transport.

Figure 12. Dendrogram of samples by Q-mode cluster analysis and correspondence analysis showing the three major biofacies of well BA-01.
(Quinqueloculina, Elphidium). This interval is interpreted as inner to middle neritic. The absence of planktic foraminifera or calcareous nannofossils precluded a precise age determination for this interval. However, the presence of the benthic genus Elphidium (shallow water taxon) suggests that this deposition occurred no later than the late Eocene (Loeblich & Tappan, 1988). The shale deposited above Biofacies A was dated as late Oligocene (Figs. 7, 8).

Campos Basin.

The four wells in this basin (CAM-01, CAM-02, CAM-03, CAM-04 – Fig. 1), cover the Paleocene–Eocene with several unconformities or depositional gaps. These wells all have the high percentages of agglutinated benthic foraminiferal taxa, represented by biofacies D and E. Biofacies E occurs mostly in the Paleocene, whereas Biofacies D occurs commonly in the middle to upper Eocene.

Well CAM-01.

There are only four sidewall samples available from this well, which all are upper Maastrichtian. The samples have a very similar benthic assemblage, and represent biofacies D (mix of calcareous and agglutinated taxa) (Fig. 15). The sidewall samples were positioned in shale intervals between thick sandy intervals.

Biofacies D

Main taxa: Cibicidoides velascoensis, Nuttallides truempyi, Bathysiphon sp., Budashveaella multicamerata. Other taxa: Stenioecina beccariiformis, Gyroidinoides globosus, Cribrastomoides trinitatensis, Caudammina ovula, Ammodiscus glabratu, Cibicidoides hyphalus, Glomospira charoides, G. serpens, Rzehakina epigona, Recurvoides walteri, Gaudryina sp.

Planktic: ~40% of total assemblage.

Palaeobathymetric range: lower bathyal.

Age range: late Maastrichtian (NC23**).

Well CAM-02.

The six sidewall samples available from this well span upper Paleocene through the upper Eocene, with an unconformity from the uppermost Paleocene to lower Eocene (missing nannofossil biozones CP8 to CP10**). The upper, middle and lower Eocene are each represented by a
single sample, and the other three samples are from the Paleocene.

Although the species diversity was very low and preservation of the foraminiferal tests poor, we could recognise one biofacies for the upper Paleocene through lower Eocene (Biofacies E – Fig. 16). The middle to upper Eocene has 90-100% planktics damaged dissolution as well as rare benthic calcareous taxa (Cibicidoides sp., Lenticulina sp.), so we could not recognise a diagnostic biofacies for this interval of the Eocene. The entire study interval consists of shale with thin layers of calcirudite and sandstone (Fig. 8).

**Biofacies E**

Main taxa: Bathysiphon sp., Haplophragmoides sp., Recurvoides sp.

Other taxa: Rhizammina sp., Glomospira serpens, Cribrostomoides subglobosus, Karrerulina conversa, Trochamminoides sp., Subreophax sp. Tubular forms 35% of benthics.

Planktic: 0%.

Palaeobathymetric range: lower abyssal.

Age range: late Paleocene to early Eocene (CP6/7** and CP11**)

**Well CAM-03.**

The correspondence analysis and the Q-mode cluster analysis result in two distinct groups corresponding to two major biofacies which are intercalated (Fig. 17). These biofacies are D (mix of agglutinants and calcareous taxa) and E (flysch-type assemblage). Biofacies D has abundant planktics (>80% of total assemblage). Biofacies E2 contains a true flysch-type benthic assemblage, in which tubular forms dominate (Rhizammina, Bathysiphon, Psammosiphonella discreta, P. cylindrica) associated with coarse-grained agglutinated taxa (Haplophragmoides, Paratrochamminoides, Recurvoides, Trochamminoides). The calcareous benthic and planktic foraminifera are poorly preserved, exhibiting clear evidence of dissolution.

The Paleocene–Eocene interval is composed mostly of shale, with layers of calcirudite in the middle Eocene and a 100m-thick layer of sandstone in the middle Eocene and middle Paleocene. There is a gap from the upper Paleo-
cene through the lower Eocene, probably an erosional hiatus associated to the sand deposition (Fig. 8).

≫ **Biofacies D1**

Main taxa: Cibicidoides havanensis, Recurvoides sp., Cibicidoides sp.
Other taxa: Anomalinoidea sp., C. eocaenus, C. mexicanus, Gyroidinoidea sp., Hanzawaia ammophila, Oriddorsalis umbonatus, Dorothia sp, Glomospira sp., Pseudomosphonella discreta, P. cylindrica, Recurvoides sp., Paratrochamminoides sp.
Planktic: 80-90% of total assemblage.
Paleobathymetric range: lower bathyal.
Age range: late Eocene (CP15**).

≫ **Biofacies D2**

Main taxa: Cibicidoides sp., Lenticulina sp., Bathysiphon sp.
Other taxa: Gyroidinoidea sp., Globocassidulina subglobosa, Dorothia sp., Haplophragmoides sp.
Planktic: 90% of total assemblage.
Paleobathymetric range: middle to lower bathyal.
Age range: middle Eocene (CP14**).

≫ **Biofacies E1**

Main taxa: Bathysipphon sp., Psammosphaera fusca, Rhizammina sp.
Planktic: ~70% of total assemblage.
Paleobathymetric range: lower bathyal/upper abyssal.
Age range: middle Eocene (CP15**).

≫ **Biofacies E2**

Main taxa: Bathysipphon sp., Kalamopsis grzybowski, Psammosiphonella cylindrica, Rhizammina sp.
Planktic: 0%.
Palaeobathymetric range: lower abyssal.
Age range: Paleocene (?).

**Biofacies D3**

Main Taxa: *Gyroidinoides* sp., *Nuttallides truempi*, *Caudammina ovula*
Other taxa: *Alabamina midwayensis*, *Anomalinoides* sp., *Cibicidoides* sp., *Guttulina trigonula*, *Glomospira charoides*, *Eggerella* sp., *Marssonella* sp., *Textularia* sp.
Planktic: 70-80% of total assemblage.
Palaeobathymetric range: lower bathyal.
Age range: early Paleocene (P3*, CP3/4**).

**Well CAM-04.**

Q-mode cluster and correspondence analyses classified the interval into two biofacies, one for the middle Eocene and other for the Paleocene (Fig. 18).

The lower Eocene is missing probably related to erosion associated with sandstone deposited above. The middle Eocene biofacies was deposited in a shelf interval with layers of calcirudite, whereas the Paleocene is characterised by sandstone with layers of shale. The upper Paleocene benthic foraminiferal assemblage corresponds to the flysch-type biofacies, whereas the middle Eocene has a mix of agglutinated and calcareous taxa. Planktic and calcareous benthic foraminifera are poorly preserved, especially in Biofacies E. In Biofacies D, planktic and calcareous benthic foraminifera show evidence of dissolution.

**Biofacies D**

Main taxa: *Cibicidoides eocaenus*, *Globocassidulina subglobosa*, *Dorothyia* sp., *Gaudryina* sp., *Gaudryina pyramidata*.
Other taxa: *Cibicidoides* sp., *Gyroidinoides* sp., *Hanzawaia ammophila*, *Oridorsalis umbonatus*, *Eggerella* sp.
Planktic: ~80% of total assemblage (very poorly preserved).
Palaeobathymetric range: middle bathyal.
Age range: middle Eocene (CP13/14**).

**Biofacies E**

Main taxa: *Rhizammina* sp., *Psammosiphonella cylindri-
ca, Kalamopsis grzybowskii, Bathysiphon sp. Tubular forms are ~60% of the benthics. Other taxa: Ammodiscus latus, A. glabratoides, Cribriformis trinitatensis, Globosiria charoides, Haplophragmoides sp., Saccammina placenta, Cibicides velascoensis, Karrerulina conversa, Stenosoeina beccariiformis, Nutallides truempyi, Gyroidinoides globosus, Notitia sp., Recurvoodles sp., Planktic: 0%. Palaeobathymetric range: lower abyssal. Age range: Paleocene (CP1/7**).

Palaeobathymetry of the Campos Basin.

Four major depositional sequences identified in the Paleocene-Eocene interval of the Campos Basin: lower Paleocene (biozones CP1 to CP3), lower to upper Paleocene (biozones CP4 to CP6), middle Eocene (biozones CP12 to CP13) and middle to upper Eocene (nanno biozones CP14 to CP15) (Becker et al., 2000). The lower Eocene is poorly represented (CAM-01, CAM-02, CAM-03 and CAM-04 shows a relatively lower sedimentation rate (0.26 to 13m/myr) for the upper Maastrichtian to the middle Eocene (Figs 19 to 22), significantly increased for the upper Eocene (12 to 35 m/myr). The low sedimentation rate (when compared with other Brazilian marginal basins) could be one of the factors contributing to the establishment of the flysch-type biofacies. The tubular forms are mainly suspension-feeders and have been reported as inhabit tranquil bathyal and abyssal regions with low sedimentation rates and organic matter flux (Jones & Charnock, 1985, Kaminski & Gradstein, 2005).

Biofacies E occurs mainly in the Paleocene of the Brazilian marginal basins, at palaeobathymetric range from lower abyssal through lower bathyal zones, close to, or below the CCD. Relatively high sea-level in the Paleocene is indicated by sedimentological and stratigraphic evidences.
Figure 18. Age vs Depth Model of well CAM-01, with benthic foraminiferal biofacies, palaeobathymetric range, and sedimentation rates.

Figure 19. Age vs Depth Model of well CAM-02, with benthic foraminiferal biofacies with palaeobathymetric ranges, and sedimentation rates.
The lower Cenozoic depositional sequences cover the topography of the Cretaceous seafloor, controlled by salt tectonics and turbidite deposition. As the sea level rose, the CCD could have been elevated CCD during the Paleocene and early Eocene. Biofacies D was more common in the middle to upper Eocene, representing shoaling to lower to middle bathyal depth.

**Santos Basin.**

**Well SAN-01.**

The Santos Basin is represented by two wells (SAN-01 and SAN-02), ~500km apart (Fig. 1). Biofacies were recognised in only one, SAN-01, due to poor preser-
vation of the benthic and planktic foraminifera in SAN-02.

The Paleocene-Eocene recovered in SAN-01 has at least three major unconformities associated with the turbidite deposition on the slope: lower to middle Paleocene (nannofossil biozones CP1 to CP4), upper Paleocene to lower Eocene (nannofossil biozones CP6 to CP9), and middle to upper Eocene (nannofossil biozones CP11 to CP14) (Fig. 8). Despite the presence of these depositional gaps, it was possible to recognize four distinct biofacies of benthic foraminifera (Fig. 23), which are distinct for each time slice from Maastrichtian through upper Eocene.

⋙ Biofacies A

Main taxa: Hanzawaia ammophila, Stainforthia sp., Pullenia sp.
Other taxa: Nuttallides truempyi, Gavelinella sp., Globobulimina sp., Oridorsalis umbonatus and radiolarian (40-100% of total assemblage).
Planktics: 50-60% of total assemblage.
Palaeobathymetric range: middle to lower bathyal.
Age range: early Eocene (CP10**).

⋙ Biofacies C

Main taxa: Nuttallides truempyi, Oridorsalis umbonatus, Globocassidulina subglobosa.
Other taxa: Osangularia mexicana, Cibicidoides sp., Dorothia beloides, Eggerelina brevis, Hanzawaia ammophila.
Planktics: 50% of total assemblage.
Palaeobathymetric range: lower bathyal.
Age range: late Eocene (CP15**).

⋙ Biofacies E

This biofacies is dominated by agglutinated taxa, but calcareous benthic foraminifera are present in some samples. The agglutinated taxa have high percentage of tubular forms (Rhizammina, Bathysiphon, Psammosiphonella cylindrica) reaching 70% of benthics in some samples, but the average is ~40%.

Main taxa: Psammosiphonella cylindrica, Rhizammina sp., Spiroplectammina jarvisi.
Other taxa: A. glabratum, A. latus, Haplophragmoides sp., Karrerulina conversa, Psammosphaera fusca, Haplophragmoides suborbicularis, Cribrostomoides tridi-

Figure 22. Dendrogram of samples by Q-mode cluster and correspondence analysis showing the four major biofacies in well SAN-01.
**Biofacies D**

This biofacies is mostly composed of calcareous taxa, but some samples agglutinated taxa (30-40% of benthics). The agglutinated taxa have a significant percentage of tubular forms (20-30% of agglutinants).

**Main taxa:** Psammosiphonella cylindrica, Globobulimina sp., Gyroidinoides globosus

**Other taxa:** Stensioeina beccariiformis, Gavelinella sp., Bulimina sp., Ammodiscus pennyi, Caudammina excelsa, Haplophragmoides eggeri, Bathysiphon sp., Nuttallides truempyi.

**Planktics:** 45-60% of total assemblage.

**Palaeobathymetric range:** middle to lower bathyal.

**Age range:** late Maastrichtian (NC23**).

**Well SAN-02.**

Well SAN-02 recovered the lower Eocene (CP9/10**), but we were unable to recognise any foraminiferal biofacies. The interval is mostly dominated by radiolarians (60% to 100% of total assemblage), and the rare planktic and calcareous benthic foraminifera recovered were severely affected by dissolution. The agglutinants are very rare and are not diagnostic of any biofacies (Saccammina, Caudammina, Haplophragmoides).

**Palaeobathymetry of the Santos Basin.**

The biofacies in well SAN-01 represent a sequence from the middle to lower bathyal in the upper Maastrichtian (Biofacies D), to lower bathyal to upper abyssal in the upper Paleocene (Biofacies E), middle to lower bathyal in the lower Eocene (Biofacies A) and lower bathyal in the upper Eocene (Biofacies C) (Fig. 24). The Paleocene interval is very thin, corresponding to ~40-m thick silt-sand layer. Biofacies E (upper Paleocene) occurs in the transition from a ~34-m thick silt interval to a coarse sandy interval (Fig. 8).

**Pelotas Basin.**

**Well PEL-01.**

The Pelotas Basin is represented by well PEL-01, and samples cover the Maastrichtian through upper Eocene (biozones NC23 to CP15). There is a major unconformity in the lower Eocene (missing biozone CP11). Preservation of the benthic foraminifera in this well is among the best.

![Figure 23. Age vs Depth Model of well SAN-01, with benthic foraminiferal biofacies, palaeobathymetric ranges, and sedimentation rates.](image-url)
of industry wells examined in this study.

>>> Biofacies C

Main Taxa: Anomalinoioides garzaensis, Bulimina alazanensis, Gaudryina pyramidata, Cibicides eocaenus, C. praemundulis. Other taxa: Anomalinoioides sp., Bulimina sp., Bulimina midwayensis, B. alazanensis, Neopontides elevatus, N. byramensis, Globobulimina sp., Nutallinella sp.1, Planulina costata, Prebulimina sp., Siphonina sp., Uvigerina sp., Clavulinoides sp., Gaudryina sp., Haplophragmoides sp., Reticuloplagium auctidorsatum, R. amphilica. Planktic: 0-10% of total assemblage (planktics very tiny or poorly preserved in this biofacies interval) Palaeobathymetric range: middle bathyal. Age range: early (E6* - CP11/12**) through late Eocene (E15* - CP15**).

>>> Biofacies B


>>> Biofacies E

Main taxa: Bathysiphon sp., Haplophragmoides sp., Gaudryina pyramidata, Cyclammina placenta. Other taxa: Bolivinopsis spectabilis, Budahevaella multicamerata, Cribrostomoides subglobosus, Gaudryina sp., G. laevigata, Hormosina sp., Marssonella sp., Marssonella trochoidea, Psammosiphonella cylindrica, Saccammina placenta. Tubular forms 10 to 25% of benthics. Planktic: 0%. Palaeobathymetric range: lower abyssal. Age range: Maastrichtian (P0* - NC23**) through late Paleocene (P4/P5* - CP7/8**).

Palaeobathymetry of the Pelotas Basin.

The age vs depth model demonstrates that this location experienced nearly continuous sedimentation with alternating intervals of higher and lower sedimentation rates (Fig. 26). Correa (2004) reported an average of 53 m/ myr sedimentation rate for the Maastrichtian through the upper Eocene. The Maastrichtian–Paleocene is dominated by the Biofacies E, with abyssal palaeodepths. During the Eocene, the bottom water conditions changed as the basin shoaled, creating a more favorable environment for calcareous benthic taxa. Biofacies B characterises the lower Eocene with palaeodepth of middle to lower bathyal. Biofacies C dominates the middle and upper Eocene with middle bathyal palaeodepths. Overall, the basin records a shallow upwards trend, as observed in the other marginal basins, due primarily to the progradation of the continental margin and shoaling of the slope during the Paleocene–Eocene.

Planktic foraminifera are rare to absent throughout the entire interval, with percentages up to 25%. The preservation is poor and tiny specimens are the most common suggesting depths below the foraminiferal lysocline (Berger, 1970, 1973, Berger et al., 1982, Kucera et al., 1997, Waśkowska-Oliwa, 2005).

Abyssal Basin.

DSDP Site 356, on the São Paulo Plateau, and DSDP Site 20C on the Brazil Basin abyssal plain represent the most distal locations included in this study and provide a contrast with the deep-water settings of the Brazilian continental margin. The Paleocene–Eocene was recovered at both sites, but Hole 20C upper Maastrichtian through upper Eocene. The preservation of the microfossils continuity of these cores provides a valuable comparison with assemblages from the Brazilian marginal basins, which were highly affected by turbidites, downslope debris and carbonate dissolution.

Site 356 – São Paulo Plateau.

Q-mode cluster analysis and correspondence analysis classified four major calcareous-rich biofacies (Fig. 27). The Paleocene – Eocene is mostly composed of chalk with more abundant biogenic silica in the middle Eocene, where radiolarians increased in abundance. A barren interval corresponds to the lower Eocene (E3*, CP8**) (Figs 7, 8).

>>> Biofacies C1

This biofacies occurs in the continuous record from lower through middle Eocene and occurs in the silica-rich interval, especially in the middle Eocene. The benthic foraminiferal assemblage is mostly composed of calcareous taxa, but some agglutinated taxa are present. The radiolarians are very abundant in this biofacies, reaching 60% in some samples (average 30-40% of total assemblage).

Main taxa: Nutallides truempyi, Osangularia mexicana,
Figure 24. Dendrogram of samples by Q-mode cluster and correspondence analysis, showing the three major biofacies in well PEL-01.

Figure 25. Age vs Depth Model of well PEL-01, with benthic foraminiferal biofacies, palaeobathymetric ranges, and sedimentation rates.
Gyrodinoides subangulatus, Stilostomella sp., Gaudryina sp.

Other taxa: Oridorsalis umbonatus, Bulimina taxamensis, B. trinitatensis, Karreriella subglobula, Spiroplectammina spectabilis, Haplophragmoides sp., Pullenia eocenea.

Planktic: 93-99% of total assemblage.

Palaeobathymetric range: lower bathyal to upper abyssal.

Age range: early (E6*, CP11**) to middle Eocene (E12*, CP14**).

Biofacies A

This biofacies occurs above the barren Paleocene/Eocene boundary interval and is characterised by a benthic foraminiferal assemblage of exclusively calcareous taxa, along with radiolarians ~10% of total assemblage.

Main taxa: Cibicidoides subspiratus, Globocassidulina subglobosa, Hanzawaia annophila.


Planktic: 80-98% of total assemblage.

Palaeobathymetric range: lower bathyal.

Age range: early Eocene (E4/5*, CP9/10**).

Biofacies B

This biofacies has the lowest species richness at this site and occurs below the barren Paleocene/Eocene boundary interval.

Main taxa: Gyroidinoides globosus, Pullenia corryelli, Anomalinoidea sp.

Other taxa: Gavelinella sp., Osangularia sp., Pullenia sp., Gaudryina sp., Gaudryina pyramidata, Nuttallides truempyi.

Planktic: 50-80% of total assemblage.

Palaeobathymetric range: middle to lower bathyal.

Age range: middle (P3*, CP3/4**) to late Paleocene (P4*, CP5/6**).

Biofacies C2

This biofacies occurs from upper Maastrichtian through upper Paleocene, and correlates with the ‘Velasco-type’ assemblage described by Berggren & Aubert (1975). This biofacies comprises the pre-PETM benthic foraminiferal assemblage.

Figure 26. Dendrogram of samples by Q-mode cluster analysis and correspondence analysis, showing the four major biofacies in Site 356.
Main taxa: Nuttallides truempyi, Stensioeina beccariiformis, Neoeponides hillebrandti, Gaudryina pyramidalita


Planktic: 70-90% of total assemblage.

Palaeobathymetric range: middle to lower bathyal.

Age range: late Maastrichtian (NC23**) through late Paleocene (P3*, CP3**)

Site 20C – Brazilian Basin.

The Q-mode cluster analysis and correspondence analysis discriminates four major biofacies (A, B, C1, C2), which are intercalated through the upper Maastrichtian- Eocene interval (Fig. 28). This interval is composed of chalk and calcareous ooze with some zeolite-rich layers in the middle Eocene. Biofacies C2 correlates with the Velasco-type assemblage described by Berggren & Aubert (1975).

〉 Biofacies B

Main taxa: Nuttallides truempyi, Globocassidulina subglobosa, Cibicidoides grimsdalei, C. havanensis, Oridorsalis umbonatus.

Other taxa: Cibicidoides eocaenus, C. praeacuta, Alabamina dissonata, Aragonia aragonensis, Bolivina huneri, Buliminella grata, Plectofrondicularia lirata, Siphonodorsalis sp., Stilostomella aculeata, S. spinosa, Gaudryina pyramidalita, G. laevigata, Dorothea sp.

Planktic: <20% of total assemblage

Palaeobathymetric range: lower bathyal to upper abyssal.

Age range: middle to late Eocene (E10* to E16*).

〉 Biofacies C1

Main taxa: Nuttallides truempyi, Oridorsalis umbonatus, Gaudryina pyramidalita, Globocassidulina subglobosa.


Planktic: 60-80% of total assemblage.

Palaeobathymetric range: lower bathyal.

Age range: early to middle Eocene (E7* to E10*).

〉 Biofacies A

Main taxa: Nuttallides truempyi, Anomalinoideas praeacusta, Oridorsalis umbonatus.

Other taxa: Neoeponides hillebrandti, Cibicidoides hyphalus, Anomalinoideas praeacusta, Aragonia velascoensis, Buliminella grata, Cibicidoides velascoensis, Pullenina coryelli, Dorothea trochoides, Gaudryina pyramidalita, G. laevigata, Tritaxia sp., Spirulpectammina sp., Osangularia velascoensis.

Planktic: ~70% of total assemblage.

Palaeobathymetric range: lower bathyal.

Age range: late Maastrichtian to early Eocene (P4* to E7*).

〉 Biofacies C2

Main taxa: Nuttallides truempyi, Gyroidinoideas globosus, Stensioeina beccariiformis, Oridorsalis umbonatus.

Other taxa: Neoeponides hillebrandti, Cibicidoides hyphalus, Anomalinoideas praeacusta, Aragonia velascoensis, Buliminella grata, Cibicidoides velascoensis, Pullenina coryelli, Dorothea trochoides, Gaudryina pyramidalita, G. laevigata, Tritaxia sp., Spirulpectammina sp., Osangularia velascoensis.

Planktic: ~70% of total assemblage.

Palaeobathymetric range: lower bathyal.

Age range: late Maastrichtian to late Paleocene (NC23** to P4*).

Palaeobathymetry.

The agglutinated taxa that dominated biofacies D and E on the Brazilian margin are absent, probably because siliciclastic input could not reach this distal area with lower sedimentation rates (Figs 29 and 30). The palaeobathymetric range of both sites varies from the lower to middle bathyal in the Paleocene to abyssal to lower bathyal in the upper Eocene. Calcareous dominated biofacies (A, B and C) occur in both sites from upper Maastrichtian through upper Eocene.

BIOFACIES DISTRIBUTION IN THE WESTERN SOUTH ATLANTIC

Benthic foraminiferal biofacies reflect the environmental conditions in which the benthic foraminiferal assemblages lived, and biofacies distribution maps (Fig. 31) show the distribution and evolution of the biofacies from the late Maastrichtian through the late Eocene in the western South Atlantic.

In the late Maastrichtian sea-level was higher than at present (Miller et al., 2005, Kominz et al., 2008), and during this time the western South Atlantic was characterised by three benthic foraminiferal biofacies: Biofacies D and E on the Brazilian continental margin, Biofacies C at the distal DSDP sites (Fig. 31), dominated by calcareous taxa (Nuttallides truempyi, Stensioeina beccariiformis,
Figure 27. Dendrogram of samples by Q-mode cluster and correspondence analysis showing the four major biofacies recognised for the Site 20C.

Figure 28. Age vs Depth Model of the DSDP Site 356 with benthic foraminiferal biofacies, palaeobathymetric ranges, and sedimentation rates.
*Neoeponides hillebrandti*, with the agglutinant *Gaudryina pyramidata* and *Gaudryina* sp. (Biofacies C).

The northern and southern basins (Sergipe-Alagoas, Mucuri and Pelotas) were dominated by Biofacies E, although the presence of 35-45% planktic foraminifera in the Mururi Basin assemblages suggests that this location was above the CCD, while the Sergipe-Alagoas and Pelotas basins were below the CCD (no calcareous benthics or planktics). This flysch-type assemblage occurred since the late Coniacian in the Sergipe-Alagoas (Koutsoukos, 2000). The Campos and Santos basins were populated by Biofacies D during the Maastrichtian and early Paleocene. There may be a weak correlation between biofacies and the sedimentation rate. For example, there is a tendency for Biofacies E to be associated with higher sedimentation rates, except in the Campos Basin (Fig. 31), whereas Biofacies D is associated with low sedimentation rates in Campos and Santos basins.

In the early and middle Paleocene, sea level was relatively lower than the late Cretaceous (Komintz *et al.*, 2008), and siliciclastic input increased in the marginal basins, which may have favored the establishment of agglutinated-dominated Biofacies E across all marginal basins, while calcareous taxa dominated at the distal sites (Biofacies B and C) (Fig. 31). Biofacies E is generally associated with higher sedimentation rates (Fig. 31), as in the Maastrichtian, except in the Campos Basin, which shows the lowest sedimentation rates of the Brazilian marginal basins. Biofacies B dominated at DSDP Site 356, and Biofacies C remained dominant at Site 20C in the early and middle Paleocene. Both biofacies contain a Velasco-type calcareous assemblage (e.g., *Nuttallides truempyi*, *Stensioeina beccariiformis*, *Pullenia* coryelli, *Cibicidoides hyphalus*, *C. velascoensis*, *Osangularia velascoensis* and *Gyroidinoides globosus* (Berggren & Aubert, 1975), differing only in the foraminiferal percentages (*Gaudryina* sp., *G. laevigata*, *G. pyramidata*, *Karreriella cubensis*).

The period between the late Maastrichtian through middle Paleocene appears to have relatively been stable environmentally, without abrupt or large changes in the benthic foraminiferal biofacies of the western South Atlantic region. There was no abrupt sea level change within this period (Haq *et al.*, 1987, Zachos *et al.*, 2001; Komintz *et al.*, 2008). The dominance of epifaunal benthic foraminifera suggests generally oligotrophic conditions during this time in the western South Atlantic.

During the late Paleocene Biofacies E dominated in the southern Brazilian marginal basins (Pelotas, Campos and Santos, Fig. 31). The occurrence and expansion of Biofacies E could be associated to the interplay of two factors that are closely related: the Serra do Mar uplift and a sea
level fall. The Serra do Mar Mountains uplift occurred from the Late Cretaceous to the Paleocene (Almeida & Carneiro, 1998, Cobbold et al., 2001, Modica & Brush, 2004). Erosion of these mountains introduced a large volume of clastic sediment to the Santos and Pelotas basins, through the Paraiba do Sul drainage system that was fairly well developed in the late Paleocene (Cobbold et al., 2001, Modica & Brush, 2004). In addition, global eustatic sea level fall caused by global tectonics (Haq et al., 1987, Koniz et al., 2008), exposed outer shelf sediments of the marginal basins that were redeposited basinward. This erosional event caused canyon cutting as recognised in seismic data from the Campos, Santos and Sergipe-Alagoas basins (Cainelli, 1992, Becker et al., 2000, Cobbold et al., 2001, Modica & Brush, 2004).

During the late Paleocene, Biofacies D occurred in the Mucuri Basin and in one of the wells of the Sergipe-Alagoas Basin (Fig. 31). In the latter Basin, each well exhibits a distinct biofacies: SEAL-01 has Biofacies E in the upper Paleocene, while 100 km away SEAL-02 has Biofacies D. The main reason for this difference may be the presence of the São Francisco River since the Campanian (Koutsoukos, personal comm. 2015). The terrigenous input from this river is enriched in refractory organic matter that could serve as food for the benthic foraminiferal community (Jorissen et al., 1995, 2007, Gooday & Rathburn, 1999). In addition, the increase in organic matter flux to the seafloor due to higher productivity along the Brazilian margin could have increased the CO2 due to degradation of both terrestrial and marine organic matter, possibly causing shoaling of the CCD (Berger, 1970). At the distal sites, there is no change in biofacies for Site 356 (Biofacies B, Fig. 31), but Site 20C changed from Biofacies C in the lower-middle Paleocene to Biofacies A in the upper Paleocene, probably due to the continued marginal subsidence.

Eocene fluctuations of the sea level, especially around the late Paleocene/early Eocene transition, could be the main reason for the development of several erosional unconformities, particularly in the Campos, Santos and Sergipe-Alagoas basins (Fig. 8).

The major benthic extinction event (BEE) coincided with the Paleocene-Eocene boundary and the Paleocene-Eocene Thermal Maximum (e.g., Tjalsma & Lohmann, 1983, Thomas, 1989, 1990, 1998, 2003, 2007, Thomas & Shackleton, 1996, Thomas et al., 2000, Alegret & Thomas, 2001, Kaiho et al., 2006, Luciani et al., 2007, Takeda & Kaiho, 2007, Stassen et al., 2012). The BEE was recognised in the Brazilian marginal basins and at the DSDP Sites. In general, the BEE affected the calcareous taxa more than agglutinates and; calcareous taxa are more abundant at the distal Sites 356 and 20C than along the Brazilian margin during the late Paleocene. The Paleocene-Eocene boundary coincided with the abrupt change of agglutinates-dominance in the Paleocene to calcareous-dominant in the Eocene of the Brazilian marginal basins (Fig. 31). This abrupt change in biofacies is closely related to the large input of sediments that forced the margin to prograde and the bathymetry in the basins to shoal (Cainelli, 1992, Becker et al., 2000, Cobbold et al., 2001, Modica & Brush, 2004).

During the early Eocene, biofacies A and B dominated in most basins as the margin prograded and the slope shoaled. At this time, the sediment supply generally decreased and the shallower basins were no longer favorable for the agglutinates assemblage. Biofacies E was restricted to the deep Campos Basin and one well in the Sergipe-Alagoas Basin (SEAL-02) (Fig. 31). Biofacies A occurs in the lower Eocene of the Santos Basin and at DSDP Sites 356 and 20C, suggesting a relatively uniform widespread deep-sea environment.

Campos Basin had a very different depositional Eocene history compared with the Santos and Pelotas basins due to a relatively low sediment supply. The Paraiba do Sul River may have shifted its drainage system from the Santos to the Campos basin in the late Eocene/Oligocene, at which time the margin prograded (Cobbold et al., 2001, Modica & Brush 2004). However, the presence of Biofacies D in the middle to upper Eocene suggests that the strong deltaic influence could have begun in the middle Eocene.

Calcareous biofacies dominated all basins in the middle and upper Eocene, with the exception of the Campos Basin, where Biofacies D and E persisted through the Eocene (Fig. 31). Progradation and shoaling in the Sergipe-Alagoas and Mucuri basins established the neritic conditions represented by Biofacies A (Elphidium, Amphistegina, Nodosaria, Discorbinella bertheloti, Cibicides, Paralabammina lunata) by the late Eocene. By contrast, the Pelotas and Santos basins and Site 356 were colonised by Biofacies C, interpreted as bathyal/upper abyssal assemblages. Site 20C was populated by Biofacies B, interpreted as a lower bathyal/upper abyssal assemblage.
Figure 30. The sequence of maps shows the evolution of the benthic foraminiferal biofacies from the late Maastrichtian through the late Eocene of the western South Atlantic. Two sea level records (Haq et al., 1987; Kominz et al., 2008) indicate highest levels in the late Maastrichtian and early- to mid-Eocene, with generally falling sea level during the middle and late Eocene. Notice the development and dominance and retreat of the flysch-type biofacies (yellow) in the Brazilian marginal basins during this time.
Figure 32. Benthic foraminiferal biofacies distribution in the Paleogene of the western South Atlantic. Brazilian marginal wells are displayed from north (SEAL-01) to south (PEL-01) and the distal DSDP Sites 356 and 20C. BEE: Benthic Extinction Event.
FLYSCH-TYPE BIOFACIES E – DISTRIBUTION AND SIGNIFICANCE

Biofacies E is interpreted as a flysch-type biofacies, extremely widespread in the Maastrichtian-Paleocene across the Brazilian marginal basins (Fig. 32). The flysch-type benthic foraminiferal biofacies has been previously reported in the Cretaceous–Paleogene of numerous locations (Table 3). The term flysch-type assemblage was first introduced by Bouwer (1965) referring to benthic foraminiferal assemblages dominated by single-chambered and uniseri-al, multi-chambered agglutinated taxa. This assemblage was first associated with flysch facies of the Alpine-Carpathian belt, but later found in turbidite sequences with high terrigenous input (Gradstein & Berggren, 1981, Wrinkler, 1984).

The agglutinated-rich biofacies occurs across a wide range of water depths and its distribution is likely related to variety environmental factors rather than to water depth per se. These environmental factors include the organic flux to the seafloor, the depth of the lysocline and CCD, the nature of substrate, deep water oxygen levels, and the presence of contour or turbidity currents (Kaminski & Gradstein, 2005). The dominance of agglutinated foraminifera below the CCD depends on their ability to secrete organic, rather than calcareous cement, so the location of the CCD has a decisive influence on the relative abundance of agglutinated foraminiferal assemblages (Gooday, 1990).

The influx of terrigenous sediments probably had a significant impact on the benthic community in our study area (Alegret & Thomas, 2001). Downslope gravitational processes delivered clastic sediment from the outer continental shelf to the slope and rise increasing the availability of siliciclastic grains for use by agglutinated benthic foraminifera (Kaminski et al., 1988). The uplift of the Serra do Mar Mountains associated with local tectonic reactivations related to the opening of the South Atlantic from Cretaceous through Paleogene time provided an abundant terrigenous sediment supply to the marginal basins, especially the Santos and Pelotas basins (Almeida & Carneiro, 1998, Modica & Brush, 2004).

Continental slopes experience elevated productivity and can have strong gradients in organic flux, which may be influenced by occurrence of oxygen minimum zones (OMZ) and deep boundary currents. Hess & Kuhnt (1996) investigated a possible analog to the flysch-type assemblage from the South China Sea, and demonstrated that this assemblage is composed of taxa with organic cement. These taxa survive and flourish on low-energy, fine-grained and organic-rich terrigenous substrates formed under stratified water masses, with moderate to high Corg and lower CaCO₃ productivity. Kaminski & Gradstein (2005) concluded that this ecological condition frequently occurs in relatively small, silled basins such as the South China Sea where an OMZ develops in mid-water settings. The deep-sea agglutinated assemblage appears to be strongly related to the organic carbon flux (Hess & Kuhnt, 1996, Kaminski & Gradstein, 2005).

In the western South Atlantic, the flysch-type biofacies is represented by two types of Biofacies E: one associated with calcareous taxa and planktic percentages 40% to 60%, and the other with very low planktic percentages (0% to 10%) and no calcareous benthic taxa (Table 4). These two types of Biofacies E have distinct environmental interpretations, thus palaeobathymetric zones.

Biofacies E with rare to very low planktic foraminifera and calcareous benthic taxa is interpreted as lower abyssal, deposited in a carbonate free environment, thus below the calcite compensation depth (CCD). This interpretation is supported by the presence of lithofacies of shale with sandy intervals, interpreted to be distal turbidites. This Biofacies E occurs in shale intervals the Pelotas, Campos, and Sergipe-Alagoas, suggesting that these basins were located in very deep-waters (>3000 m) during the Maastrichtian and Paleocene, and for the Campos Basin, extending into the Eocene. This Biofacies E is similar to the abyssal agglutinated assemblage described from the Indian Ocean (Krasheninnikov, 1974), Falkland Outer Basin (DSDP Site 328, Tjalsma, 1977), Pacific and Atlantic oceans (Gradstein & Berggren, 1981), North Sea (Jones, 1988), and Iberian Abyssal Plain and Celebes Sea (Kuhnt & Urquhart, 2001, Kaminski & Gradstein, 2005). These locations have in common the great percentage of tubular forms (Bathysiphon, Rhizammina, Nothia, Psammo-siphonella) associated with other agglutinated taxa (Haplophragmoides, Recurvoides, Ammodiscus, Bolivinopsis, Saccammina, Trochammina, Trochamminoides, Rzezhakina, Spiroplectammina, Glomospira).

The second type of Biofacies E is interpreted as lower bathyal to upper abyssal and occurs in the Paleocene of the Sergipe-Alagoas, Santos, and Mucuri basins, and Paleocene through upper Eocene of the Campos Basin. This Biofacies E occurs associated with calcareous taxa typical of the Velasco-type assemblage in the Paleocene (Nuttallides truempyi, Stensioeina beccariiformis, Gya-
### Table 3. Flysch-type benthic foraminifera assemblages from Cretaceous through Paleogene.

<table>
<thead>
<tr>
<th>Age</th>
<th>Paleodepth</th>
<th>Location</th>
<th>Assemblage</th>
<th>Source</th>
</tr>
</thead>
<tbody>
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<td>Late Cretaceous</td>
<td>Abyssal (below CCD)</td>
<td>several</td>
<td>Bathysiphon, Haplophragmoides, Trochammina, Ammodiscus pennis, Silicosigmoilina, Haplophragmoida, Millioids and Legnids</td>
<td>Brower (1965)</td>
</tr>
<tr>
<td>Paleocene-middle</td>
<td>Bathyal</td>
<td>Indo-Pacific and Atlantic Oceans</td>
<td>upper Cretaceous: Haplophragmoides, Recurvoides, Paratrochamminoides, Haplophragmnia, Solinovinosps, Pseudobolivina, Trochammina, Verneulina, Uvigerinammina, Ammodiscus, Glomospirella, Glomospirella, Saccammina, Pelosina, Hyperammina</td>
<td>Israelky (1951)</td>
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<tr>
<td>Eocene</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cretaceous (Albin to Maastrichtian)</td>
<td>Site 356 - middle bathyal (500 to 1500m) Albin and lower bathyal (1500 to 2500m) for the Santonian to Maastrichtian</td>
<td>Site 356, 357, 358 (western South Atlantic)</td>
<td>Agglutinated species dissolution resistant: Haplophragmoides, Paratrochamminoides, Recurvoides and Saccammina, Ammodiscus, Glomospira, Hyperammina.</td>
<td>Sliter (1977)</td>
</tr>
<tr>
<td>late Paleocene-early Eocene</td>
<td>Abyssal (below CCD)</td>
<td>Site 328 (Falkland Outer Basin)</td>
<td>Cyclammina, Ammodiscus, Glomospira, Bovinopsis, Trochammina, Cribrastomoides, Haplophragmoides + Osangularia pteromphalia Oridorsalis ecuadorensis, Natallidites truempiy, Cibicidoides sp., siphonodarssariids and stiostomellids</td>
<td>Tjalsma (1977)</td>
</tr>
<tr>
<td>Maestrichtian-Paleogene</td>
<td>wide range (200-4000m)</td>
<td>Labrador and North Seas</td>
<td>Locus typicus - Alpine-Carpatian flysch belt (dominated by single chambered and uniserial taxa): Rhabdammina, Bathysiphon, Ammodiscus, Lituotuba, Resphax, Hormosina, Rzehakina. Biserial and ? multiserial (Spiroplectammina, Textularia, Gaudryina, Dorothisa, Gaudryina) and more complex trochoids (Trochammina, Recurvoides, Trochamminoides, Cribrastomoides, Haplophragmoides, Cyclammina) are generally less common</td>
<td>Gradstein &amp; Berggren (1981)</td>
</tr>
<tr>
<td>Late Maestrichtian to Eocene</td>
<td>bathyal to abyssal</td>
<td>Garn ieg-Schlieren flysch</td>
<td>Uvigerinammina, Dorothisa, Verneulina, Plectina. Turbidity, calcaraceous (P+B) foraminifera with debris of algae, bryozoans, etc. Rhabdammina-type assemblage not well developed and less individualized, repopulation on the finest pelitic interval (mud clays). In turbiditic shales a poorer association of &quot;diluted&quot; calcaraceous and arenaceous agglutinated faunas was reported, indicating their reworked nature. Hemipelagic sequences - generally carbonate-free with well developed Rhabdammina-type assemblage that compare with Cretaceous-Paleogene abyssal assemblages below CCD</td>
<td>Wrinkler (1984)</td>
</tr>
</tbody>
</table>
**Table 3.** Flysch-type benthic foraminiferal assemblages from Cretaceous through Paleogene.

<table>
<thead>
<tr>
<th>Biofacies</th>
<th>Age</th>
<th>Lithology</th>
<th>Paleobathymetric range</th>
<th>Key Taxa</th>
<th>Planktics (%)</th>
<th>Basins</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Maastrichtian to upper Eocene</td>
<td>shale intervals with medium to coarse sand layers (&gt;5m of thickness)</td>
<td>lower bathyal to upper abyssal</td>
<td><em>Rhizammina, Bathysiphon, Psammosiphonella cylindrica, Haplophragmoides, Trochamminoides, Ammodiscus</em> + calcareous taxa (Velasco-type assemblage in the Paleocene, and Barbados-type assemblage in the Eocene)</td>
<td>40-60</td>
<td>Sergipe-Alagoas, Mucuri, Campos, Santos</td>
</tr>
<tr>
<td>E</td>
<td>Maastrichtian to upper Paleocene</td>
<td>lower abyssal (below CCD)</td>
<td><em>Rhizammina, Bathysiphon, Psammosiphonella cylindrica, Haplophragmoides, Trochamminoides, Ammodiscus, Recurvoides</em></td>
<td>0-10</td>
<td>Pelotas, Campos, Sergipe-Alagoas</td>
<td></td>
</tr>
</tbody>
</table>

*roidinoides globosus, Osangularia velascoensis, Cibicidoides hyphalus, C. velascoensis; Berggren & Aubert, 1975*, and with taxa typical of the Barbados-type assemblage in the Eocene (*Cibicidoides eocaenus, Nuttalildes truempyi, Osangularia mexicana, Hanzawaia ammophila, Planulina costata, Globocassidulina subglobosa; Wood et al., 1985, Van Markoven et al., 1986, Miller, 1989, Bolli et al., 1994*).

In summary, Biofacies E represents a deep- water biofacies deposited near or below the CCD in siliciclastic settings, such as deep tectonically active basins and lower continental slopes and rises. In addition, the 100% agglutinated Biofacies E has stratigraphic importance as cosmopolitan deep water agglutinated foraminifera (DWAF) with organic cement (*Bathysiphon, Recurvoides, Ammodiscus, Glomospira, Rhizammina*) that allows correlation of sedimentary sequences deposited below the CCD, where planktic foraminifera or calcareous nanofossils are not preserved (Gradstein & Berggren, 1981, Kuhnt & Urquhart, 2001, Kaminski & Gradstein, 2005).

**SUMMARY AND CONCLUSIONS**

The Maastrichtian to Eocene benthic foraminiferal biofacies recognised in the Brazilian marginal basins and DSDP Sites 20C and 356 reflects the long-term environmental changes associated with progradation of the continental margin, as well as sea level and climatic fluctuations. Relatively stable sea level and generally cooler conditions in the Paleocene gave way to rising sea level and global warmth culminating in the Early Eocene Climatic Optimum before a long-term cooling trend and falling sea level during the middle and late Eocene. These general trends in climate and sea level are recorded in the evolution of the Maastrichtian-Eocene benthic foraminiferal biofacies of the Brazilian marginal basins. The following observations are summarised in Figure 33.

In general, two distinct biofacies regions are recognised. The proximal region is represented by the Brazilian marginal basins, from North to South: Sergipe-Alagoas, Mucuri, Santos, and Pelotas basins (Fig. 33). DSDP Sites 356 and 20C were at greater palaeo-water depths and more distal to the continental margin of Brazil, and the locations did not receive significant siliciclastic input. Both regions experienced environmental change as recorded by benthic foraminiferal biofacies, which can be divided into three major intervals: the Maastrichtian to late Paleocene, the early Eocene, and the middle to late Eocene.

The Maastrichtian to middle Paleocene is represented by Biofacies E in the Sergipe- Alagoas, Mucuri, and Pelotas basins, Biofacies D in the Campos and Santos basins, and Biofacies C at DSDP Sites 356 and 20C. The sedimentation rates decreased drastically from proximal to distal regions. Campos Basin is the only basin with low sedimentation rates (−6 m/myr) as compared to the Santos (30 m/myr) and Pelotas (105 m/myr) basins. The global sea level high-stand during this time was associated with the uplift of the Serra do Mar. The increased delivery of siliciclastic sediments and terrestrial organic matter in the marginal basins may be the most important cause of the establishment of the flysch-type benthic assemblage in the Paleocene in the marginal basins.

During the late Paleocene, sea level fell and Biofacies E extended into the most proximal and intermediate regions of the Sergipe-Alagoas, Mucuri, Campos, Santos, and Pelotas basins. The uplift and subsequent erosional processes that acted on the Serra do Mar Mountains were responsible for a marked increase in the siliciclastic input in Campos, Santos, and Pelotas basins, causing the margin to prograde (Almeida & Carneiro, 1998, Cobbold et al., 2001, Modica & Brush, 2004). The Santos Basin was by far the most affected by the large volume of terrigenous...
Upper Maastrichtian – Eocene benthic foraminiferal biofacies of the Brazilian margin

material arriving in the Paleocene from the Paraiba do Sul drainage system (Cobbold et al., 2001, Modica & Brush, 2004). The combination of relatively low sea-level and the uplift of the Serra do Mar in the late Paleocene provided the source for the coarse-grained agglutinated, and the establishment of the flysch-type Biofacies E. Biofacies E in the Campos and Sergipe-Alagoas basins was composed exclusively of agglutinated taxa, suggesting that Biofacies E was established under carbonate unsaturated water, below the CCD along the marginal basins (Gradstein & Berggren, 1981, Kaminski et al., 1988, Kaminski et al., 1989, Kuhnt et al., 1989, Kuhnt & Collins, 1996).

The distal Sites 356 and 20C were dominated by Biofacies C and B, and C and A, respectively, during the late Maastrichtian through late Paleocene. The Paleocene/Eocene boundary is marked by the global benthic extinction event (BEE) (Thomas, 1990, 1998, 2003, 2007, Tjalsma & Lohmann, 1983, Zachos et al., 1993, 2001, 2005, Thomas et al., 2000, Lourens et al., 2005, Stassen et al., 2012a,b), recognised at Sites 20C and 356. In the marginal basins, the BEE affected preferentially the calcareous taxa (extinction ~35% and 16%, respectively), although at other locations agglutinant taxa were also strongly affected (Thomas, 1998). In the proximal basins, Biofacies E dominated. The early Eocene seems to have been a special period in the western South Atlantic. The benthic foraminiferal assemblage showed a progressive recovery, with origination of new species, especially in the deepest sites. The origination rates differ from the proximal (marginal basins) to distal (DSDP sites) regions, accounting for ~25% and 47% respectively.

After the Paleocene/Eocene boundary Biofacies E was restricted to the Sergipe-Alagoas and Campos basins, possibly related to fluviodeltaic siliciclastic input (São Francisco and Paraíba do Sul rivers, respectively). The middle to lower bathyal Pelotas Basin was dominated by Biofacies B, Santos Basin and DSDP Sites 356 and 20C were populated by the Biofacies A, suggesting an expansion of a deep-sea environment into the Santos Basin, which was at middle to lower bathyal depths during the early Eocene.

The middle to late Eocene was dominated by calcareous dominated deepsea biofacies in the Pelotas and Santos basins, and at distal DSDP Sites 356 and 20C, and the agglutinated taxa persisted in the Campos Basin (Biofacies D and E). The disappearance of Biofacies E in the middle to late Eocene was coeval with the decrease in siliciclastic input from the Serra do Mar Mountains. The fluvial sediments are restricted to the deeply incised Paraiba do Sul River, reported to have been well established by the late Eocene/Oligocene interval (Cobbold et al., 2001, Modica & Brush, 2004). The more proximal Mucuri and Sergipe-Alagoas basins were at middle to upper bathyal water depths and contain Biofacies A, dominated by shallow water carbonate taxa. The Mucuri Basin was greatly influenced by the Abrolhos volcanism in the middle to late Eocene.

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