

## 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*, *Psammosiphonella*). This biofacies correlates with the so-called “flyscht-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 microfossil 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-

els at the seafloor, carbon content of the sediments, grain size, current activity, and carbonate corrosivity in pore and bottom waters (e.g., Ingle, 1980, Peterson, 1984, Jorissen *et al.*, 1995, Klitgaard & Sejrup, 1996, Kitazato *et al.*, 2000, Heinz *et al.*, 2001, Murray, 2001, 2006, 2014, Jorissen *et al.*, 2007, Phipps *et al.*, 2010, Nisha & Singh, 2012, Penman *et al.*, 2014). Benthic foraminiferal biofacies have been applied to sequence stratigraphy (Christensen *et al.*, 1995, Liu *et al.*, 1997), and used to define palaeobathymetric models (Pekar & Kominz, 2001). Deep-water benthic foraminiferal studies demonstrate that benthic foraminifera distribution is strongly linked to type and quality of organic matter that reaches the seafloor and bottom current strength, lithology (grain size and mineralogy) and type of substrate, and oxygen levels in the bottom water (Gooday, 1993, 1996, 1999, 2003, Jorissen *et al.*, 1995, Schonfeld, 2002, Fillon, 2003, 2009, Thomas, 2003, Jorissen *et al.*, 2007, Schroder-Adams *et al.*, 2008).

Sea-level fluctuations may have greatly influenced the benthic foraminiferal biofacies distribution in the Maastrichtian 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

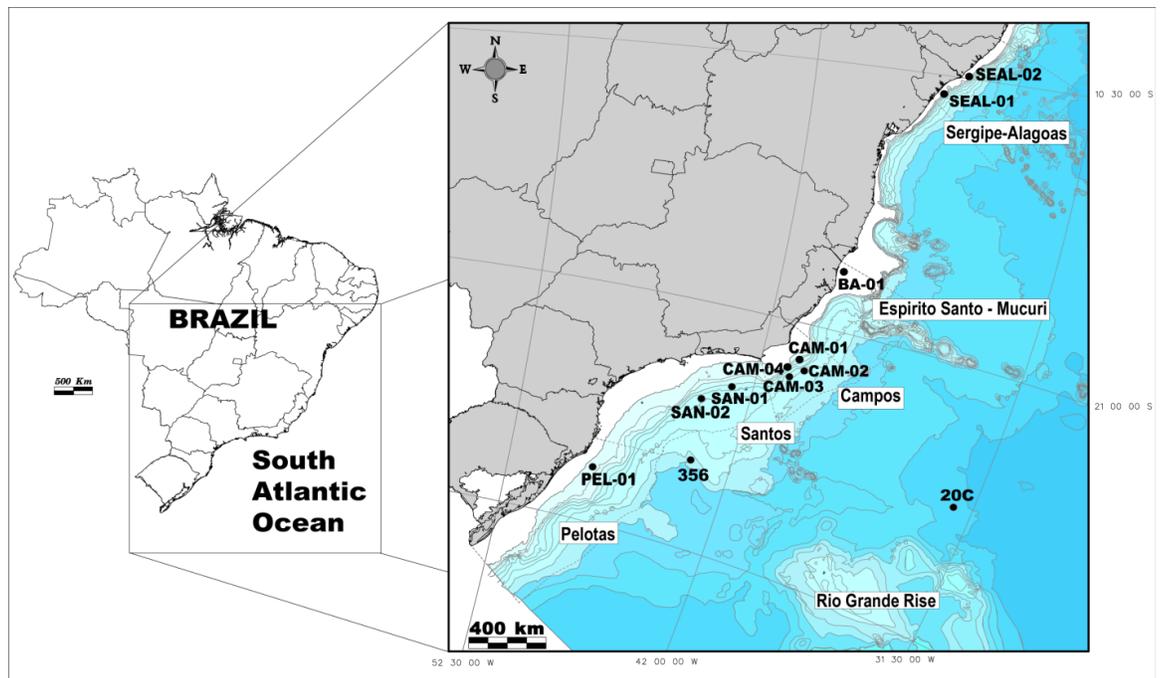
in the marginal basins (Leckie & Olsson, 2003, Miller *et al.*, 2005, Catuneanu, 2006).

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 Maastrichtian-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.

**Table 1.** Present geographic locations and age interval of samples in this study.

Well/Site	Location	Present water depth (m)	Samples	Sample type	Age
20C	Rio Grande Rise	4506	28	core	Paleocene-Eocene
	Sao Paulo				
356	Pupperau - Santos	3203	107	core	Paleocene-Eocene
	Basin				
			15	core	middle to upper Eocene
			40	cuttings	lower Eocene
		151	8	core	lower Eocene
PEL-01	Pelotas Basin		28	cuttings	upper Paleocene
			14	core	lower Paleocene
			9	cuttings	upper Maastrichtian
			13	cuttings	upper Eocene
			14	sidewall	lower Eocene
SAN-01	Santos Basin	1515	16	core	upper Paleocene-lower Eocene
			11	cuttings	upper Maastrichtian
			12	core	upper Maastrichtian
SAN-02	Santos Basin	1733	48	core	lower Eocene
CAM-01	Campos Basin	791	4	core	upper Maastrichtian
CAM-02	Campos Basin	1336	6	sidewall	Paleocene-Eocene
			11	cuttings	upper Eocene
CAM-03	Campos Basin	923	22	core	lower to middle Eocene
			3	cuttings	upper Maastrichtian to lower Paleocene
CAM-04	Campos Basin	S20	42	core	Paleocene-Eocene
			16	cuttings	upper Eocene
BA-01	Mucuri Basin	22	46	core	Paleocene
			31	cuttings	upper Maastrichtian to lower/middle Paleocene
SEAL-01	Sergipe-Alagoas Basin	27	44	cuttings	Eocene
			30	core	Paleocene
			30	cuttings	upper Paleocene-lower Eocene
SEAL-02	Sergipe-Alagoas Basin	24	18	core	Paleocene
			16	cuttings	upper Maastrichtian

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 Paleocology 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

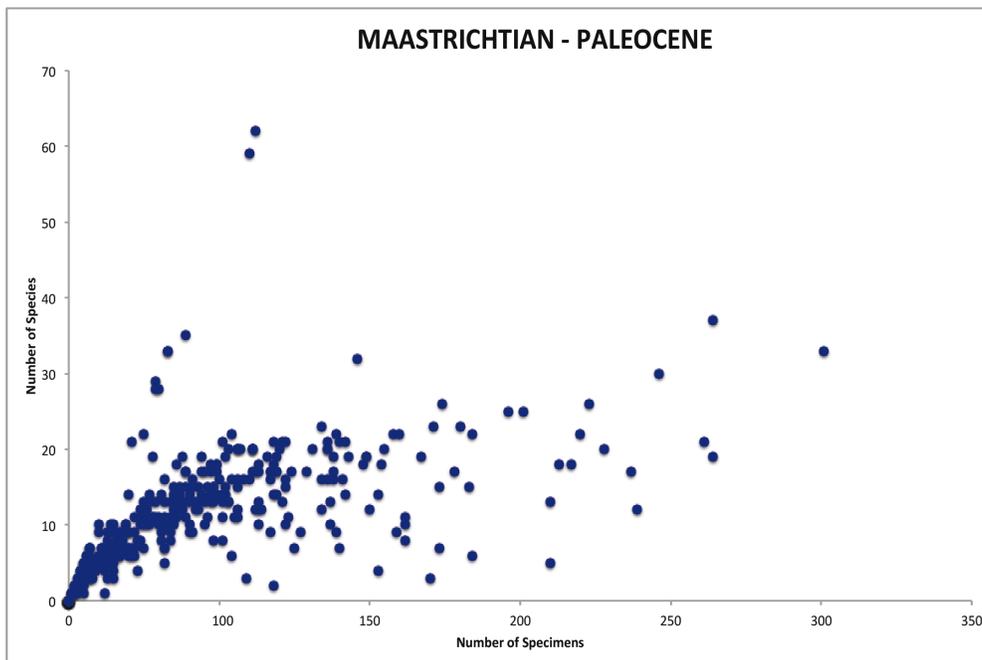
soaked in solution of 40% hydrogen peroxide washed over a 63 $\mu$ m sieve and dried, following standard procedure of the company. These industrial samples were provided in slides, picked. The picking follows the standard company procedure to pick ~300 tests (planktics and benthics).

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.

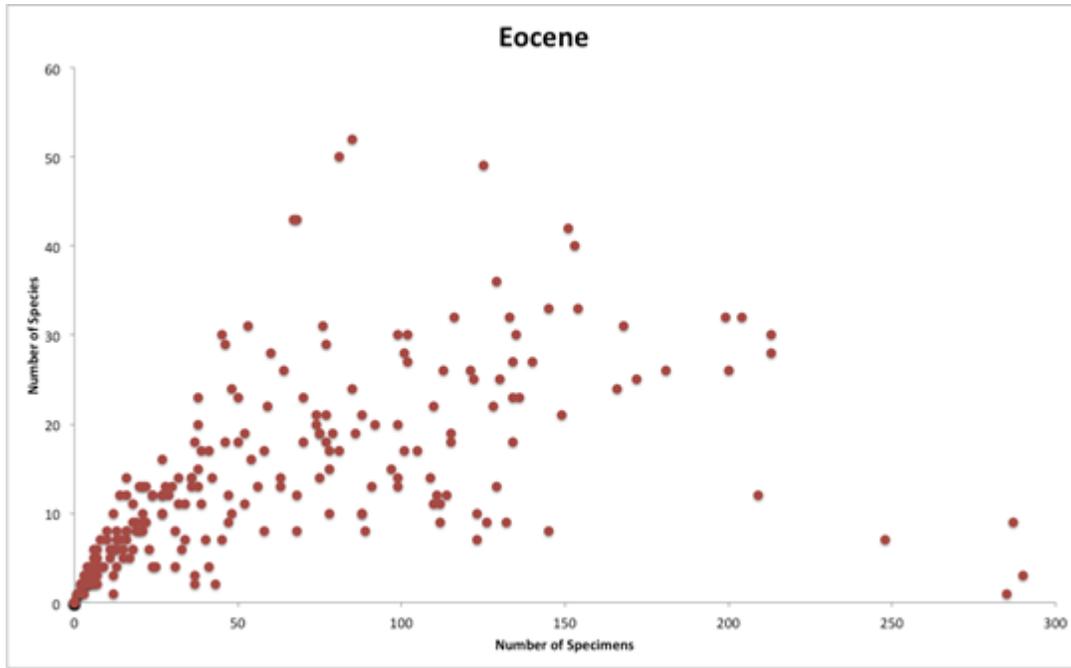
A low number of specimens was also observed in samples from DSDP Sites 20C and 356, even though all benthic foraminifera were picked in each sample, possibly due to the relatively small sample volume (~10 cc). However, Site 20C has a relatively higher number of benthic specimens than Site 356. Despite 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.** 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  $\geq 50$  specimens.



**Figure 3.** Distribution (in percentages) of agglutinated foraminiferal morphogroups in the BR-1 section (circles represent percentages < 1%).

benthic foraminiferal assemblage, and includes the elongate, tubular agglutinant taxa (e.g., *Bathysiphon*, *Psammosiphonella*, *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):

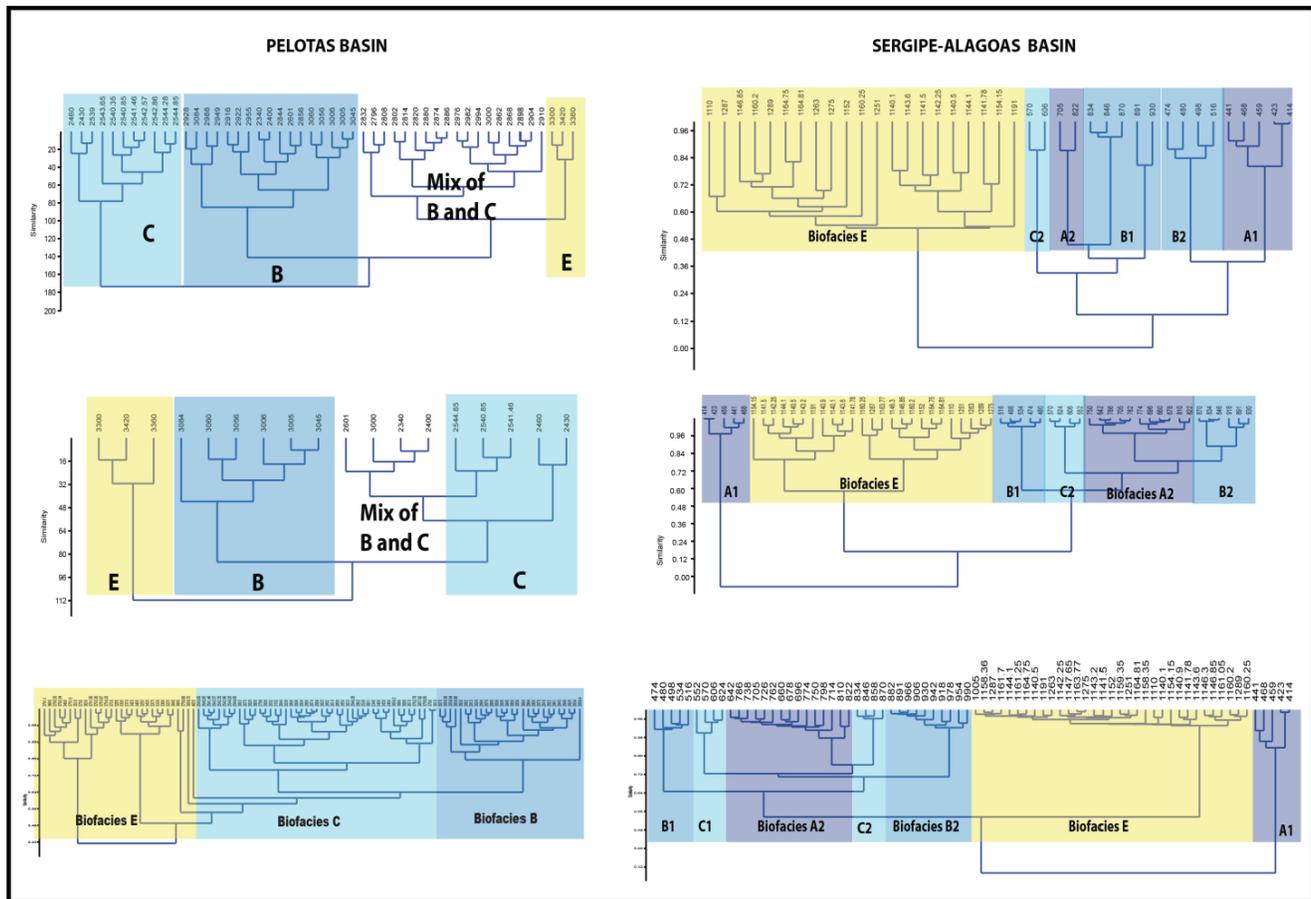
- Neritic: 0 – 200 m inner <30 m
- middle 30 – 100 m
- outer 100 – 200 m
- Bathyal: 200 – 2000 m upper 200 – 600 m
- middle 600 – 1000 m lower 1000 – 2000 m
- Abyssal: >2000 m
- upper 2000 – 3000 m
- lower > 3000 m (below the CCD)

## GEOLOGICAL SETTING

### The Proximal Brazilian Marginal Basins

The Brazilian marginal basins (Pelotas, Santos, Campos, Mucuri, Bahia-Sul, Sergipe-Alagoas and Pernambuco-Paraíba) have a similar formation and evolution that be-

gan 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 fluvio-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,



**Figure 4.** Dendrograms of the Q-mode cluster analysis of the Pelotas (left) and Sergipe-Alagoas (right) basins, using samples with > 35 specimens (top), >100 specimens (middle) and all the samples (bottom). Note that we can observe consistent clusters, shown by yellow (agglutinant-rich) and blue (calcareous-rich) blocks, despite the variable numbers of benthic foraminiferal specimens in the samples.

characterise the post-rift section of the eastern Brazilian margin. During the Albian, marine conditions became established, first represented by carbonates and then by thick siliciclastic sediments, including predominantly shales and sandstones, with shallow platform, coastal fans, and slope and basin turbidites. This siliciclastic sequence consists of transgressive-regressive cycles that characterise the Upper Cretaceous through Pleistocene (Asmus & Baisch, 1983, Milani *et al.*, 2007).

During the Cenozoic, the Mucuri Basin experienced an important magmatic event that 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, Zalan, 2004).

Salt tectonics played an important role in the Cenozoic

evolution of the Brazilian marginal basins (Mohriak *et al.*, 1990, Cainelli & Mohriak, 1999, 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 msbf (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- to 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 CO<sub>2</sub> levels are seen as more

important factors in Cenozoic cooling (e.g., DeConto & Pollard, 2003, Barker & Thomas, 2004).

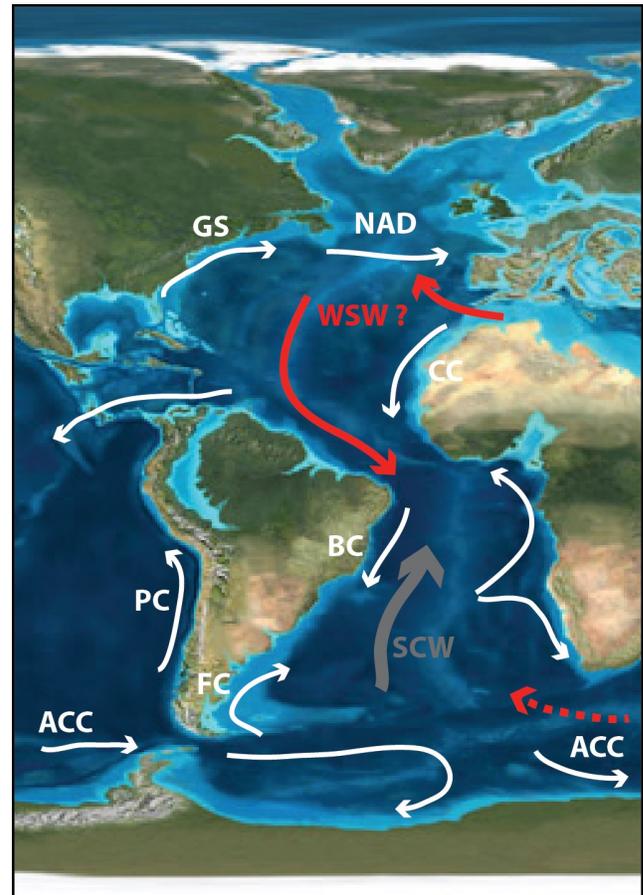
The production of the deep-water is a key factor in the ocean circulation, and there are controversial ideas about where deep waters originated in the Paleogene. One hypothesis is that Warm Saline Bottom Water (WSBW) produced in the Tethys Seaway flowed southward in the Equatorial Atlantic and/or into 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



**Figure 5.** Interpretative Atlantic Ocean circulation during the Paleogene. White arrows: surface water currents, red: intermediate water, grey: deep water. GS – Gulf Stream, NAD – North Atlantic Drift, WSW – Warm Saline Water, BC – Brazil Current, FC – Falkland Current, PC – Peru Current, ACC – proto-Antarctic Circumpolar Current, SCW – Southern Component Water, CC – Canary Current. Physiographic map from Ron Blakey (<https://www2.nau.edu/>). Surface currents from Bice *et al.* (2000), WSW from Bice (2000), SCW from Thomas *et al.* (2003) and Thomas (2004).

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 has greater percentages of shallow-water indicator species, e.g., *Amphistegina*, *Elphidium*, *Quinqueloculina*, *Lenticulina*, and *Nodosaria*, which are usually more poorly preserved (yellowish and oxidised tests) due to downslope transport from the continental shelf. At the more distal locations, this biofacies is composed of bathyal to upper abyssal benthic foraminiferal taxa, e.g., *Cibicidoides*, *Hanzawaia* and *Nuttallides truempyi*. This biofacies occurs mostly in the Eocene interval in the Sergipe-Alagoas, Mucuri, and Santos, basins and at DSDP Sites 356 and 20C.

**Biofacies B:** The benthic foraminiferal assemblages included in this biofacies have up to 10% agglutinated taxa. At the proximal locations, this biofacies occurs in the Eocene and is represented by *Paralabamina lunata*, *Hanzawaia ammophila*, *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 coryelli*, *Nuttallides truempyi*, *Gaudryina pyramidata*, and *Gaudryina* sp. represent the Maastrichtian through Paleocene assemblage. *Nuttallides truempyi*, *Globocassidulina subglobosa*, *Cibicidoides grimsdalei*, *C. havanensis*, *C. praemundulus*, *C. eocaenus*, *Oridorsalis umbonatus*, *Gaudryina pyramidata*, and *G. laevigata* define the Eocene benthic assemblage of the deepest sections at DSDP Sites 356 and 20C.

**Biofacies C:** The benthic foraminiferal assemblages included in this biofacies have 11% to 25% agglutinated taxa. This biofacies occurs in the middle to upper Eocene at the proximal locations, and throughout the Paleocene through Eocene at the distal sites. This biofacies contains species that are diagnostic of the lower bathyal palaeobathymetric zones based on the presence of *Nuttallides truempyi*, *Osangularia mexicana*, *O. velascoensis*, *Cibicidoides*,

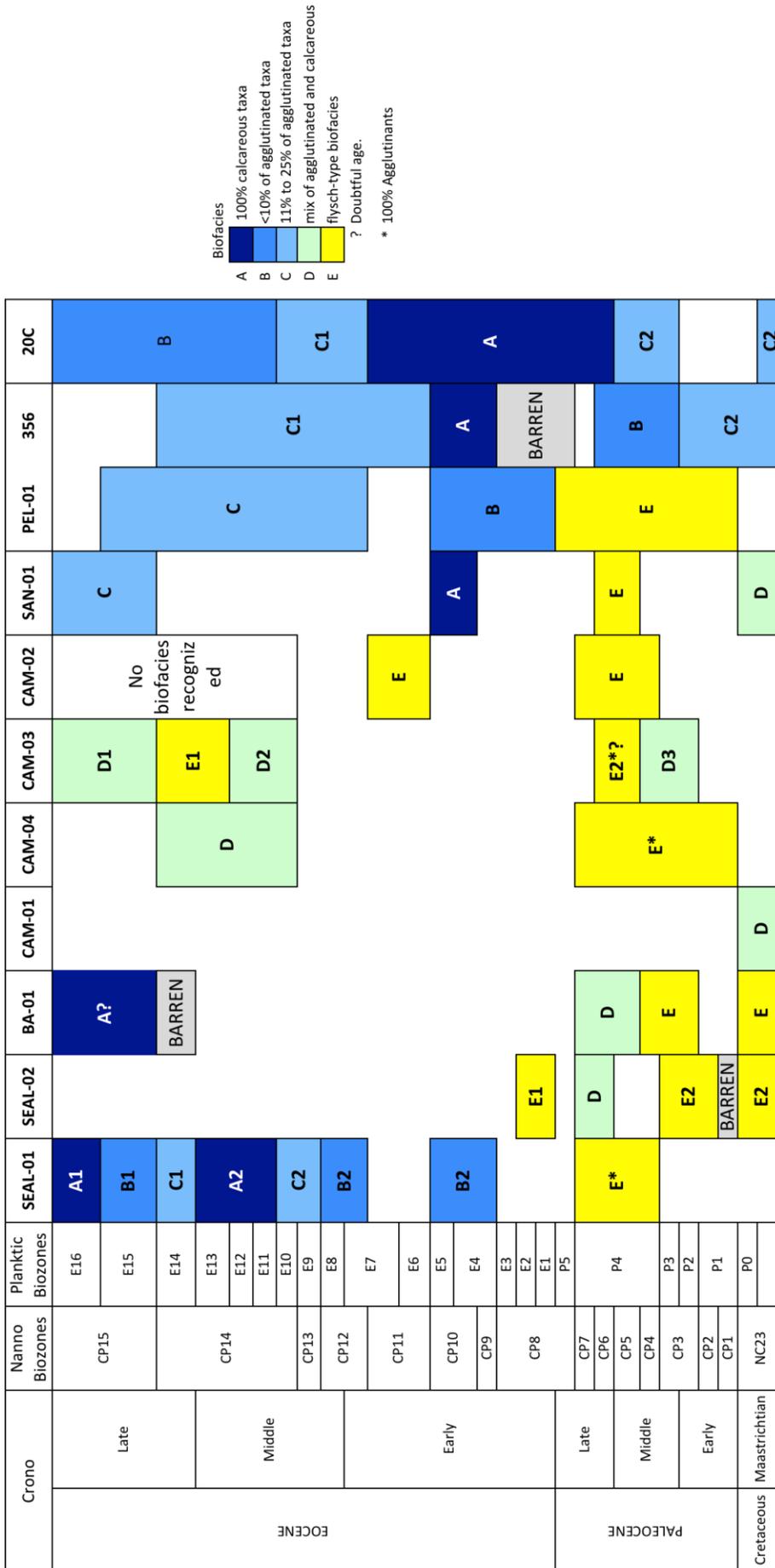
*Gyroidinoides*, *Oridorsalis umbonatus*, *Gaudryina pyramidata*, *G. laevigata*, *Spiroplectammina* sp., *S. spectabilis*, and *Haplophragmoides* sp.

**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*, *Psammosiphonella*, and *Nothia*) diagnostic (~20-40% of benthics), associated with coarse-grained coiled taxa (*Haplophragmoides*, *Ammoglobigerina*, *Ammodiscus*, *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, Mucuri, and Sergipe-Alagoas basins.

This tubular agglutinant-rich biofacies was originally described as a “fysch-type biofacies” by Gradstein & Berggren (1981), and later investigated by Kaminski *et al.* (1988) and Kaminski & Gradstein (2005). The original fysch-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).

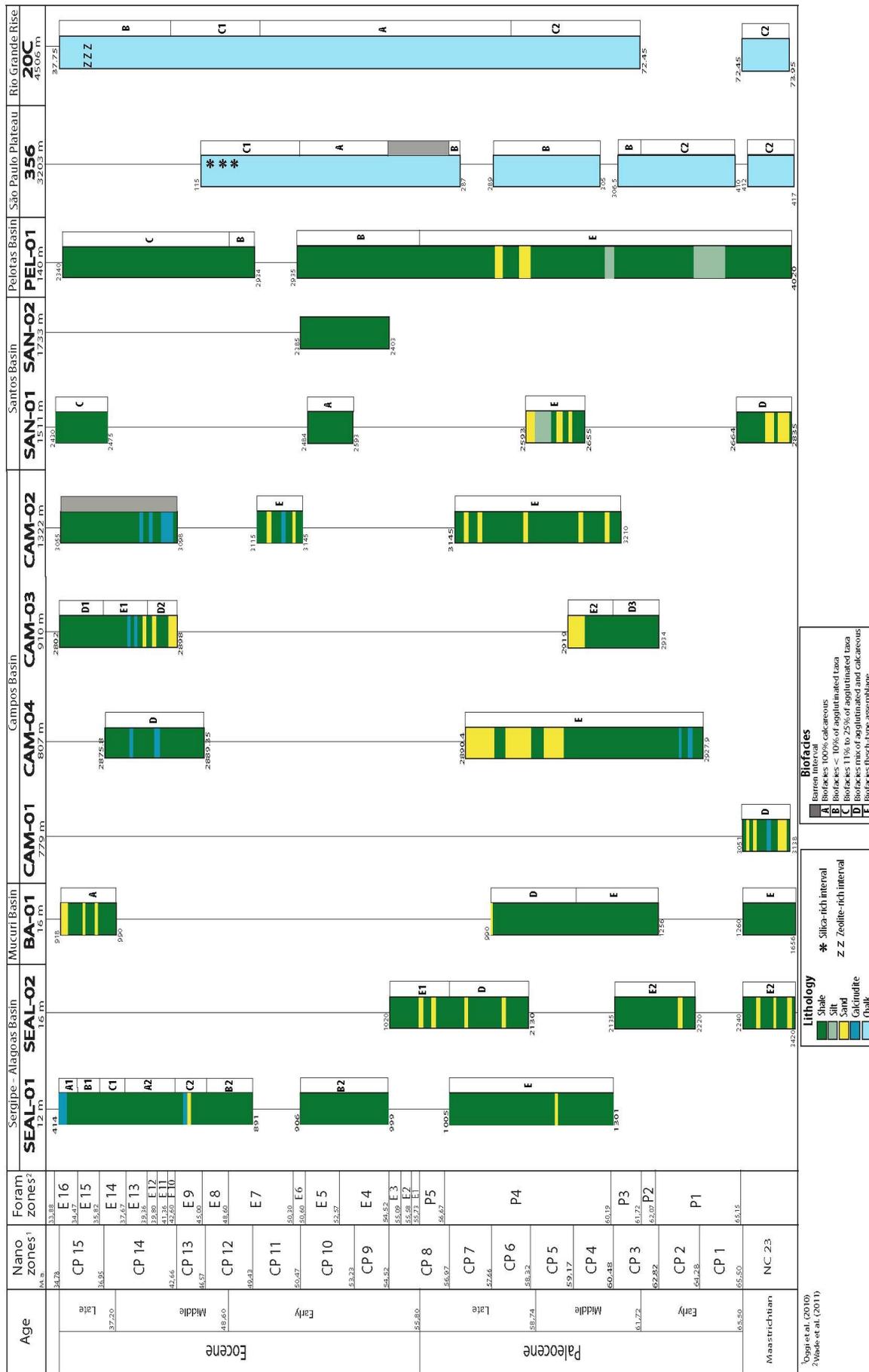


Figure 7. Lithology and biofacies of the study locations from the upper Maastrichtian through Eocene, western South Atlantic and Brazilian marginal basins.

**Table 2.** Key taxa for each biofacies used for the palaeobathymetric ranges.

Biofacies	Key Taxa
A	<i>Elphidium, Amphistegina, Lenticulina, Cibicides</i>
	<i>Cibicoides, Hanzawaia amphilla, Planulina costata, Lenticulina, Nodosaria</i>
B	<i>Amphistegina, Lenticulina, Paralammina lunata, Cibicoides eoacenus, Melonis sp.1</i>
	<i>Planulina costata, Hanzawaia amphilla, Nuttallides truempyi, Gaudryina sp., Cyclammina sp., Paralammina lunata, Cibicoides eoacenus</i>
C	<i>Cibicoides sp., C. praemundulus, Lenticulina sp., Bulimina sp., Gaudryina sp., G. pyramidata, Globocassidulina subglobosa,</i>
D	<i>Rhizammina, Bathysiphon, Psammosiphonella cylindrica, Haplophragmoides, Trochamminoides, Ammodiscus, Recurvoides, Nuttallides truempyi, Cibicoides, Gyroidinoides</i>
E	<i>Rhizammina, Bathysiphon, Psammosiphonella cylindrica, Haplophragmoides, Trochamminoides, Ammodiscus + calcareous taxa (Velasco-type assemblage in the Paleocene, and Barbados-type assemblage in the Eocene)</i>
	<i>Rhizammina, Bathysiphon, Psammosiphonella cylindrica, Haplophragmoides, Trochamminoides, Ammodiscus, Recurvoides</i>

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, *Cibicoides* sp. and *Gyroidinoides* sp. The agglutinated assemblage is dominated by tubular forms (*Rhizammina*, *Bathysiphon*, *Psammosiphonella cylindrica*, *P. discreta*, *Nothia* sp., *Nothia latissima*) and coarse-grained taxa (*Ammodiscus*, *Haplophragmoides*). 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 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 *Paralammina 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.

Main taxa: *Amphistegina* sp., *Paralammina lunata*,

*Nodosaria* sp.

Other taxa: *Cibicides* sp., *Lenticulina* sp., *Anomalinoidea* sp., *Melonis* sp.1. Planktic: 0%.

Palaeobathymetric range: middle to outer neritic.

Age range: late Eocene (CP15\*\*).

## ➤➤ 2 – Biofacies B1

Main taxa: *Paralabamina lunata*, *Melonis* sp.1, *Cibicoides ecoaenus*.

Other taxa: *Amphistegina* sp., *Lenticulina* sp., *Cibicoides 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 pyramidata*

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*, *Anomalinoidea* sp., *Cibicoides* sp., *Nuttallides truempyi*.

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 pyramidata*, *Bulimina* sp.

Other taxa: *Cibicoides* sp., *Globocassidulina subglobosa*, *Gyroidinoides* sp., *Lenticulina* sp., *Uvigerina* sp., *Gaudryina* sp.

Planktic: 50-60% of total assemblage.

Palaeobathymetric range: upper 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 truempyi*, *Cyclammina* sp.

Other taxa: *Gyroidinoides* sp., *Gavelinella* sp., *Gaudryina* sp., *Paralabamina lunata*, *Anomalinoidea* 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 cretaceus*, *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 other 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 stomatus*, *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 beccariformis*, *Saccammina placenta*, *Nuttallides truempyi*.

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-*

na sp. with evidence of transport.

**Main taxa:** *Psammosphaera irregularis*, *Cribrostomoides trinitatis*, *Psammosiphonella cylindrica*, *Haplophragmoides* sp.

**Other taxa:** *Saccamina placenta*, *Nothia* sp., *Recurvoides* sp., *Haplophragmoides stomatus*, *Praebulimina* sp., *Valvulineria* sp., Tubular forms ~20% of benthics.

**Planktic:** 0-5% total assemblage.

**Palaeobathymetric range:** lower abyssal.

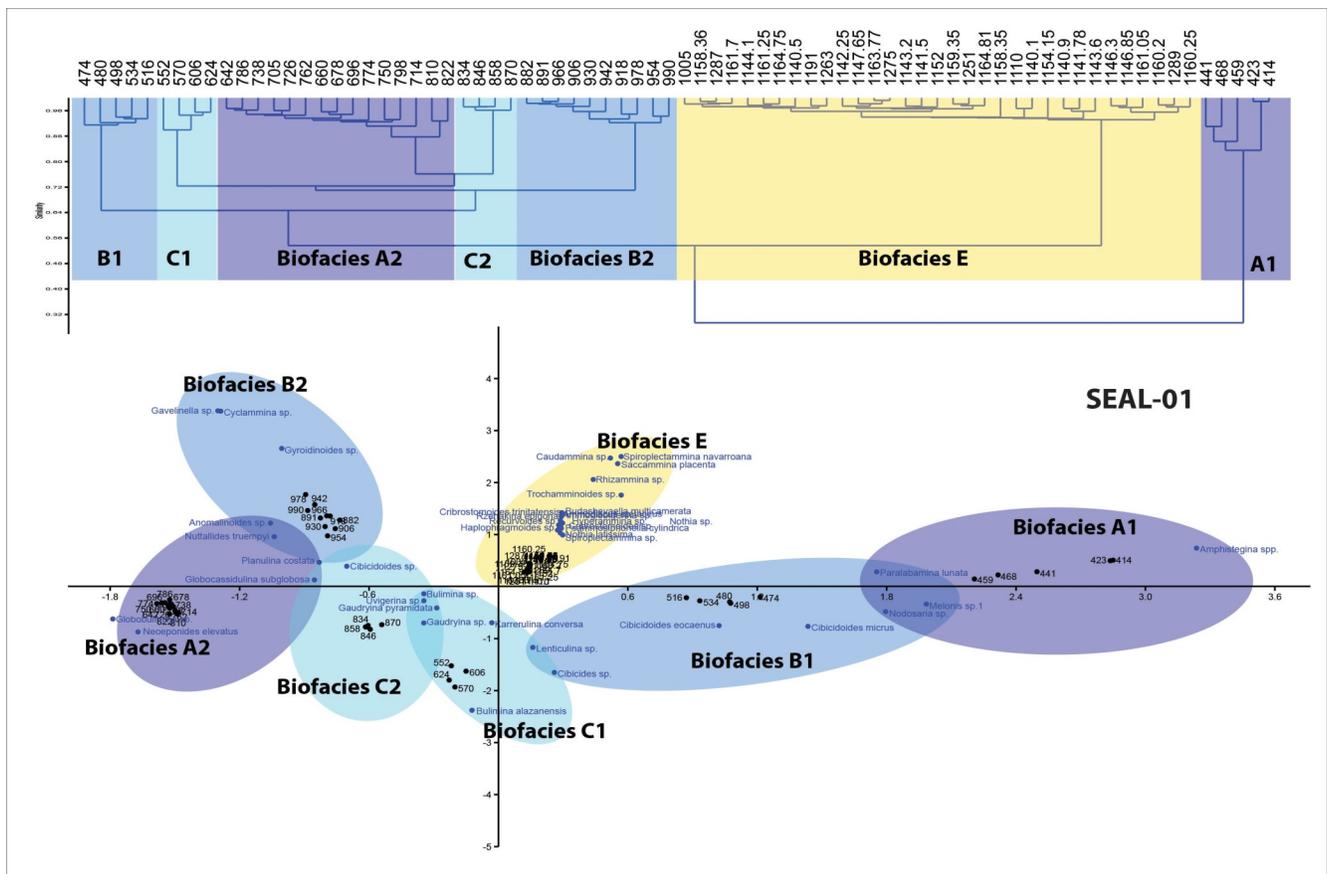
**Age range:** late Maastrichtian to late Paleocene (NC23 to CP2/3\*\*).

### 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.

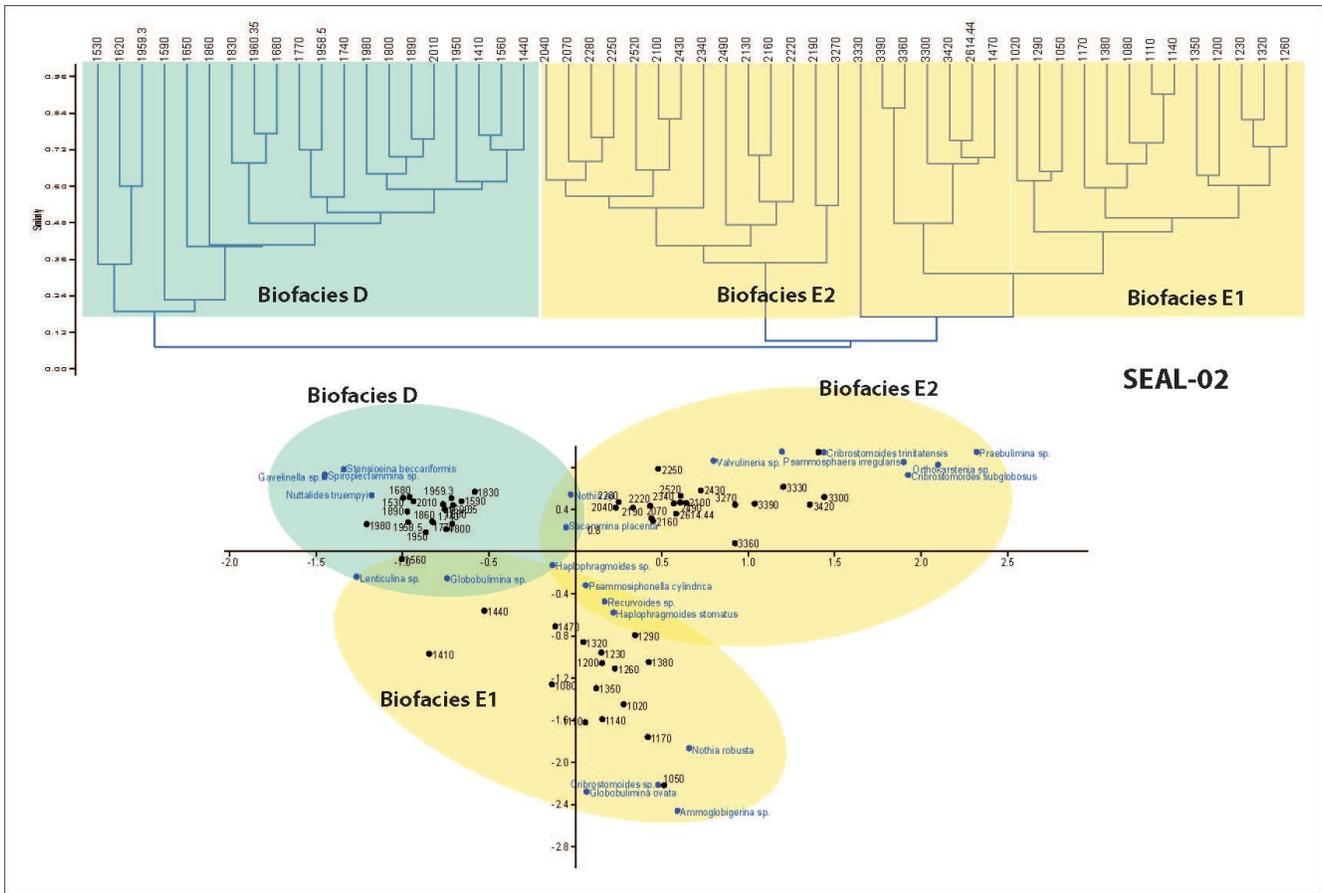


Figure 9. Dendrogram of samples produced by Q-mode cluster analysis and correspondence analysis showing the three major biofacies of the well SEAL-02.

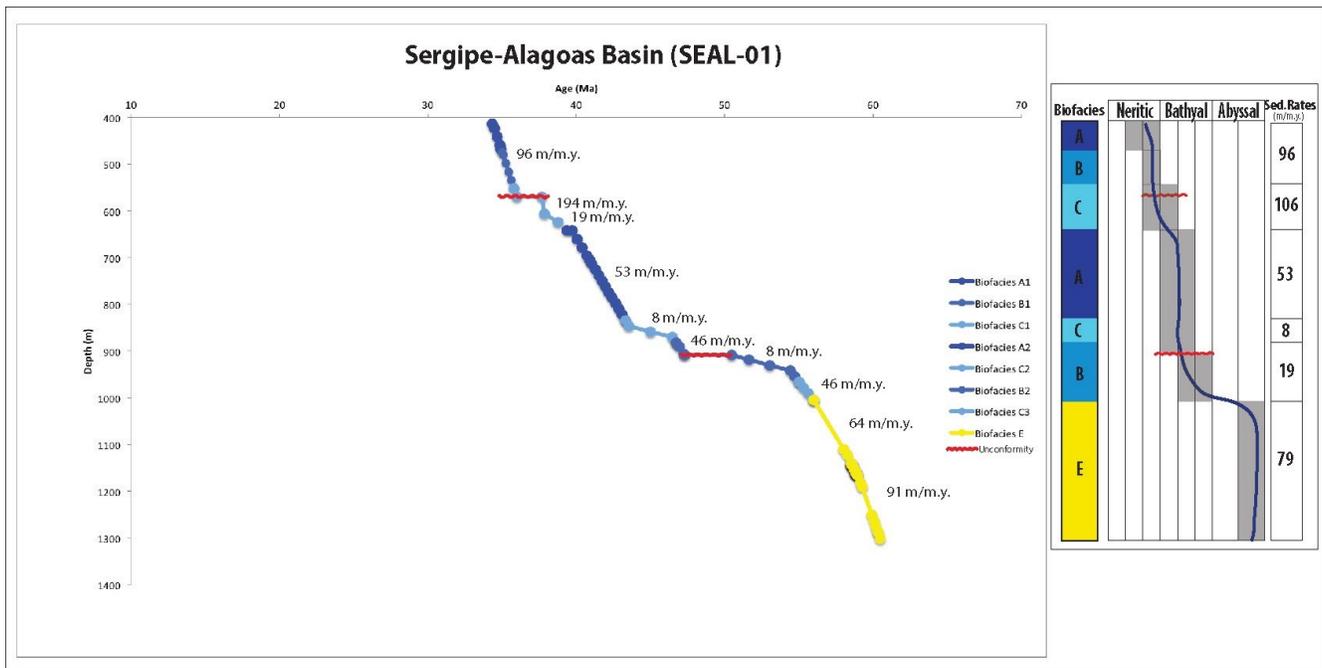
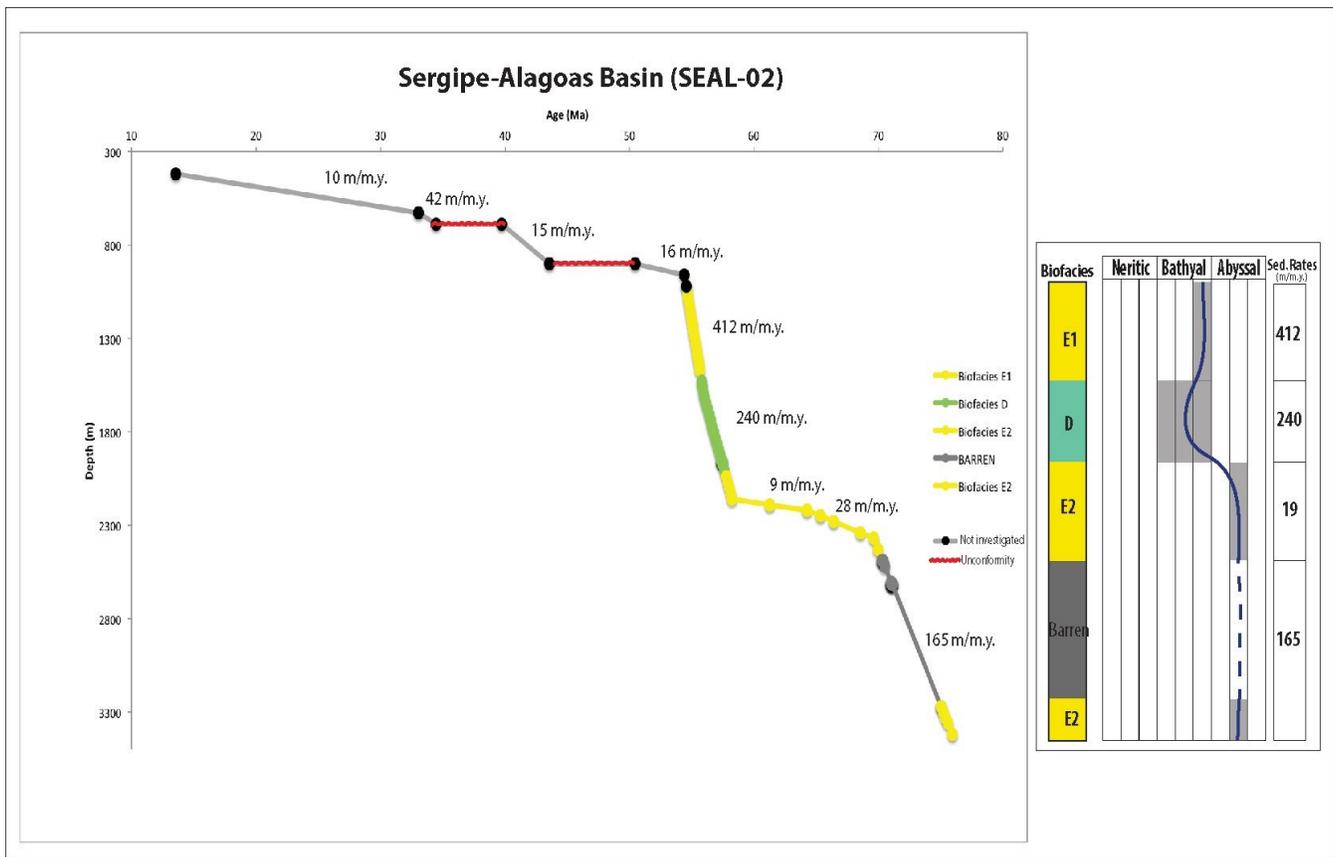


Figure 10. Age vs Depth Model of well SEAL-01, plotted with the benthic foraminiferal biofacies, correlated palaeobathymetric ranges and sedimentation rates.



**Figure 11.** Age vs Depth Model of well SEAL-02 plotted with the benthic foraminiferal biofacies with correlated palaeobathymetric range 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., *Discorbinella bertheloti*,

*Elphidium* sp. (transported from shallower areas)

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

Planktic: 0% of total 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: *Saccamina grzybowskii*, *Nuttallides truempyi*, *Stensioeina beccariiiformis*, *Psammosiphonella cylindrica*.

Other taxa: *Cibicidoides velascoensis*, *Gyroidinoides globosus*, *Gyroidinoides* sp., *Saccamina placenta*, *Glomospira* sp., *Trochamminoides* sp.

Planktic: 30-45% of total assemblage.

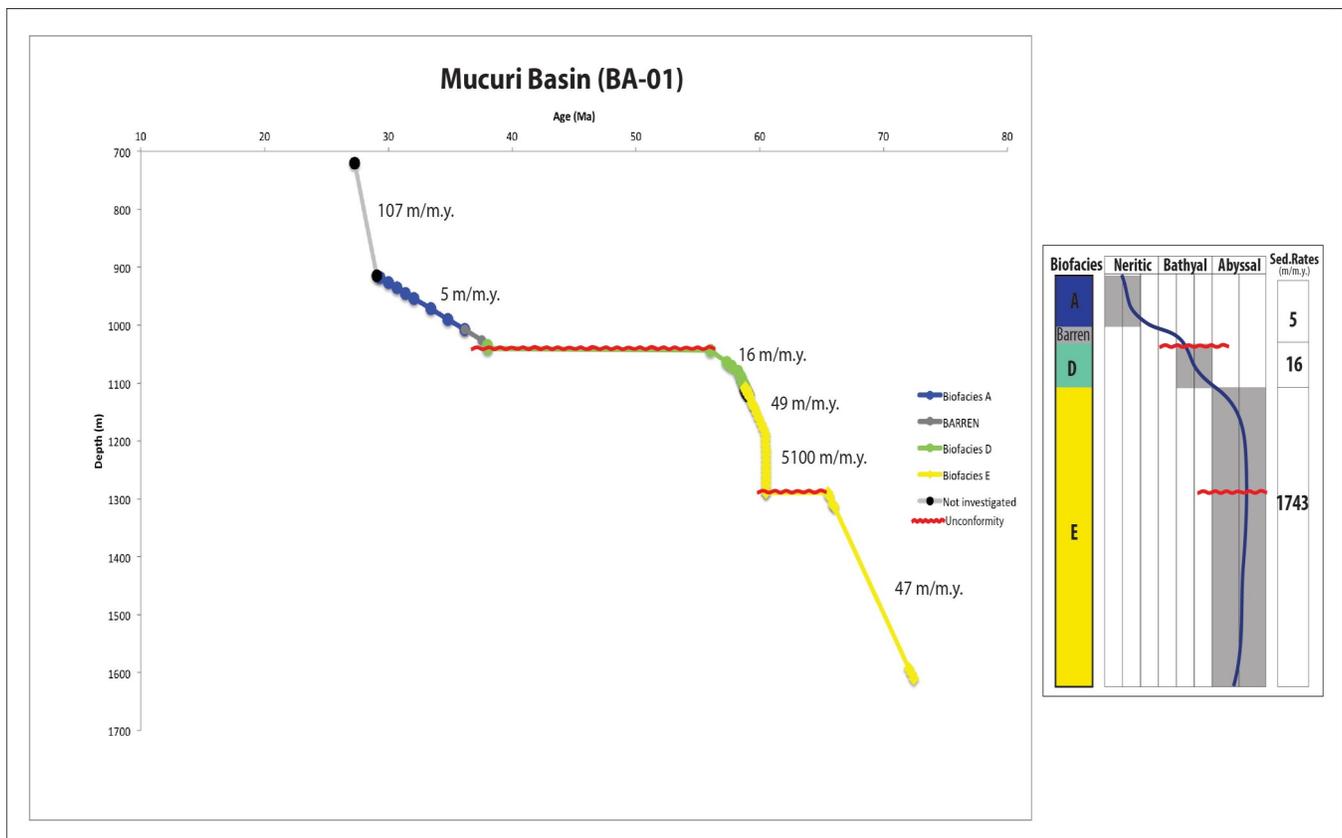
Palaeobathymetric range: middle to lower bathyal.

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

#### »» Biofacies E

Main taxa: *Rhizammina* sp., *Psammosiphonella cylindri-*





**Figure 13.** Age vs Depth Model of well BA-01 plotted with benthic foraminiferal biofacies with palaeobathymetric ranges and sedimentation rates.

(*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 layers.

### » Biofacies D

Main taxa: *Cibicoides velascoensis*, *Nuttallides truempyi*, *Bathysiphon* sp., *Budashevaella multicamerata*.

Other taxa: *Stensioeina beccariiformis*, *Gyroidinoides globosus*, *Cribrostomoides trinitatensis*, *Caudamina ovula*, *Ammodiscus glabratus*, *Cibicoides hyphalus*, *Glomospira charoides*, *G. serpens*, *Rzehakina epigona*, *Recurvoides walteri*, *Gaudryina* sp.

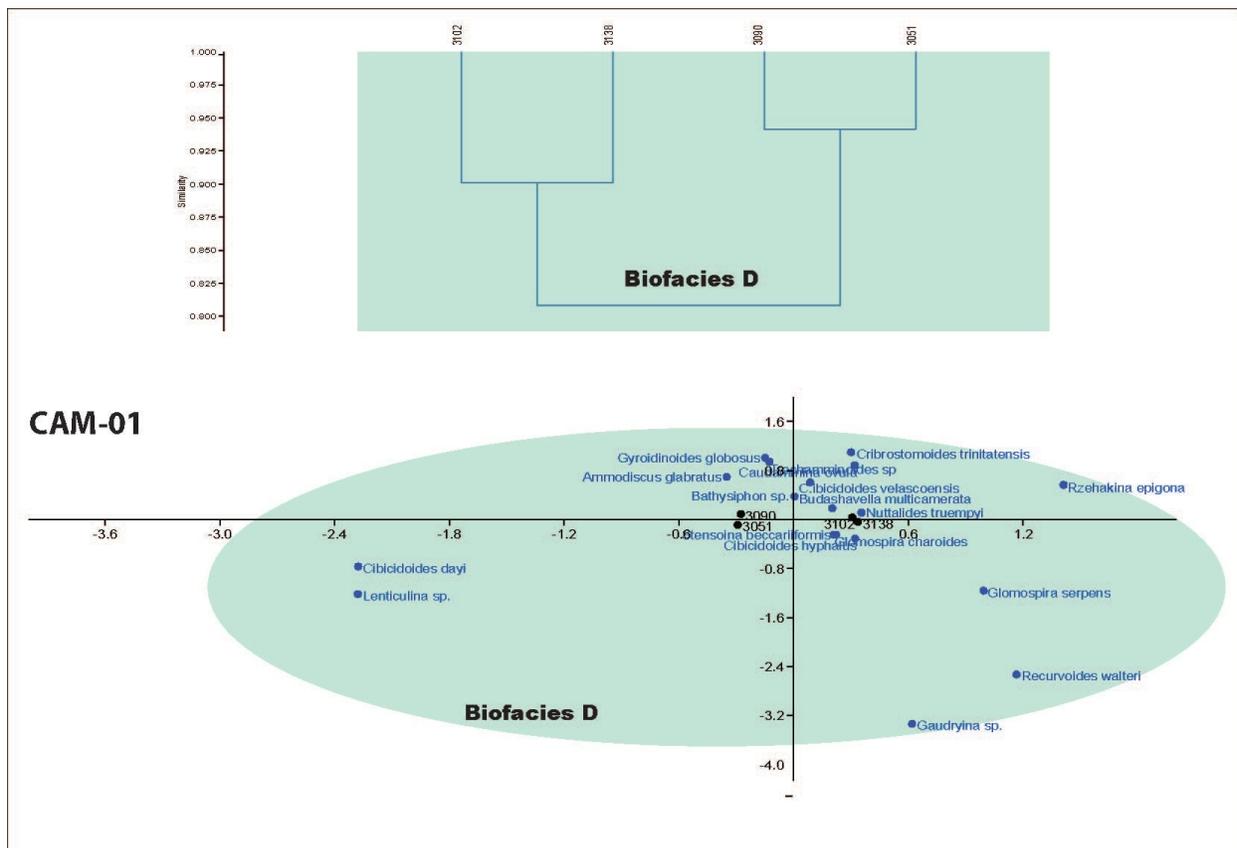
Planktic: ~40% of total assemblage.

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



**Figure 14.** Dendrogram of the samples produced by Q-mode cluster analysis and correspondence analysis showing the major biofacies in well CAM-01.

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 by dissolution as well as rare benthic calcareous taxa (*Cibicidoides* sp., *Lenticulina* sp.), so that 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%.

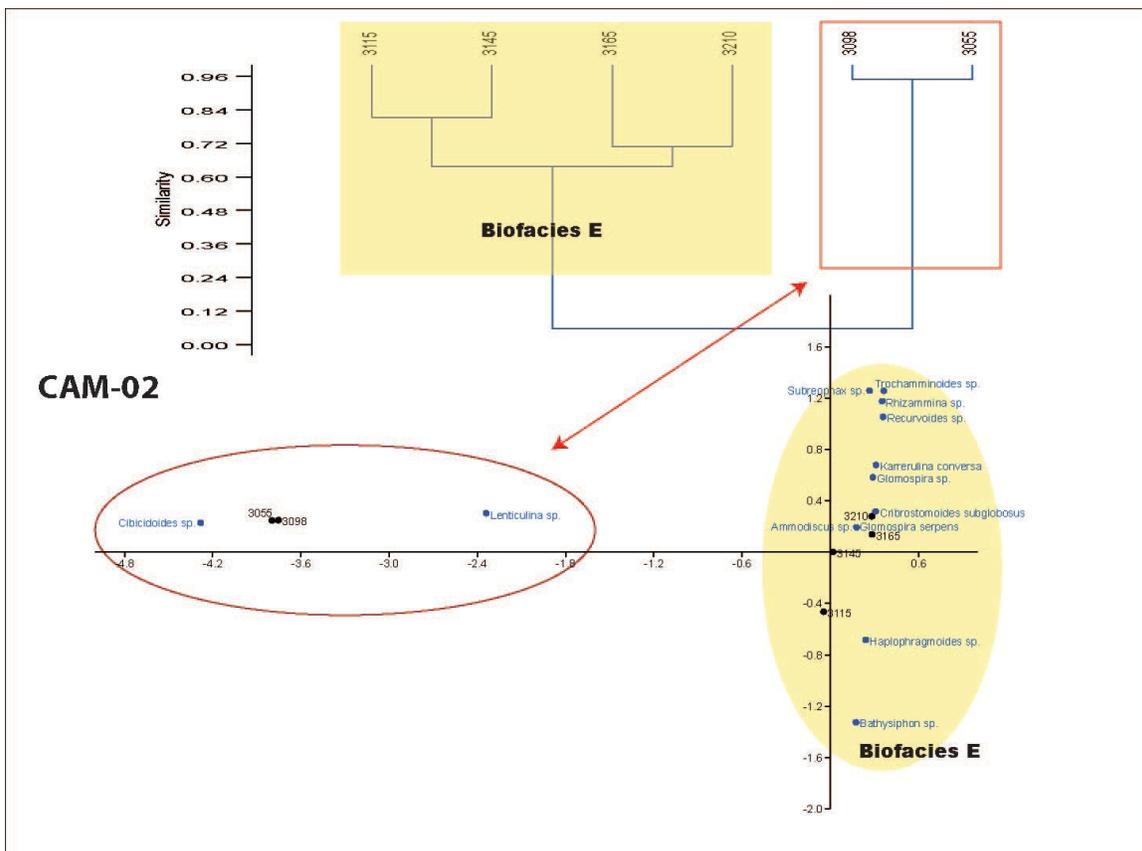
Palaeobathymetric range: lower abyssal.

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-



**Figure 15.** Dendrogram of the samples by Q-mode cluster analysis and correspondence analysis (CA) showing the major biofacies and the interval with poor recovery of the well CAM-02.

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*, *Oridorsalis umbonatus*, *Dorothia* sp., *Glomospira* sp., *Psammosiphonella discreta*, *P. cylindrica*, *Recurvoides* sp., *Paratrochamminoides* sp.

Planktic: 80-90% of total assemblage.

Palaeobathymetric range: lower bathyal.

Age range: late Eocene (CP15\*\*).

#### »» Biofacies E1

Main Taxa: *Bathysiphon* sp., *Psammosphaera fusca*, *Rhizammina* sp.

Other taxa: *Cyclammina placenta*, *Haplophragmoides* sp., *H. contortus*, *H. walteri*, *H. porrectus*, *Recurvoides* sp., *R. anormis*, *R. contortus*, *Cribrostomoides subglobosus*, *Kalamopsis grybowskii*, *Karrerulina conversa*, *Paratrochamminoides* sp., *Ammodiscus cretaceus*, *A. latus*, *Saccammina placenta*, *Cibicidoides* sp., and *Gy-*

*roidinoidea* sp. Tubular forms ~30% of benthics.

Planktic: ~70% of total assemblage.

Palaeobathymetric range: lower bathyal/upper abyssal.

Age range: middle Eocene (CP14\*\*).

#### »» 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.

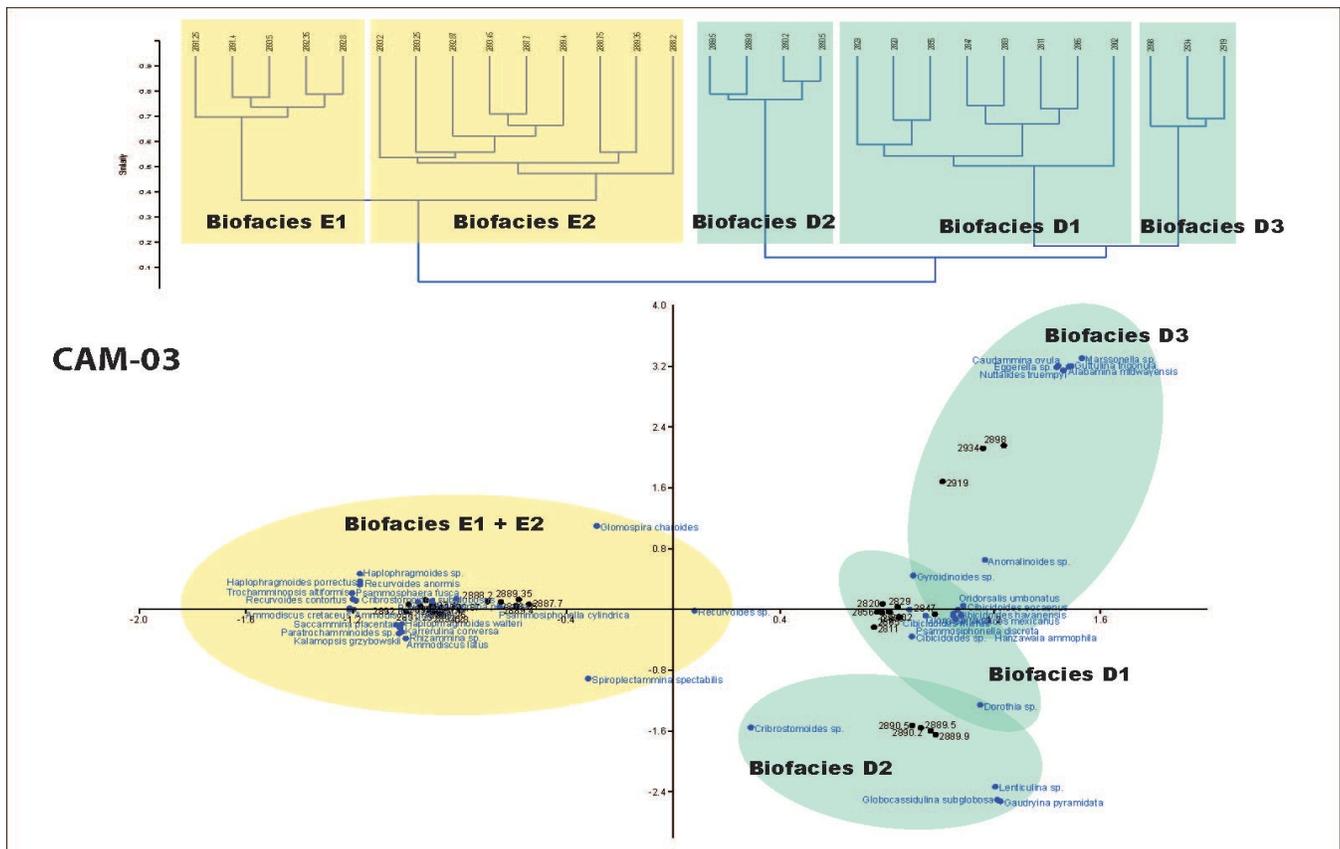
Palaeobathymetric range: middle to lower bathyal.

Age range: middle Eocene (CP14\*\*).

#### »» Biofacies E2

Main taxa: *Bathysiphon* sp., *Kalamopsis grybowskii*, *Psammosiphonella cylindrica*, *Rhizammina* sp.

Other taxa: *Ammodiscus glabratus*, *A. cretaceus*, *A. latus*, *Cribrostomoides subglobosus*, *Cyclammina placenta*, *Glomospira charoides*, *Haplophragmoides* sp., *H. stomatus*, *H. porrectus*, *H. walteri*, *Karrerulina conversa*, *Paratrochamminoides* sp., *Recurvoides* sp., *R. anormis*, *R. contortus*, *Trochamminoides altiformis*, *Spiroplectamina spectabilis*. Tubular forms 40-60% of benthics.



**Figure 16.** Dendrogram of the samples by Q-mode cluster analysis and correspondence analysis showing the five major biofacies in well CAM-03.

Planktic: 0%.

Palaeobathymetric range: lower abyssal.

Age range: Paleocene (?).

### »» Biofacies D3

Main Taxa: *Gyroidinoides* sp., *Nuttallides truempyi*, *Caudammina ovula*

Other taxa: *Alabamina midwayensis*, *Anomalinoidea* 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 shale interval with layers of calcirudite, whereas the Paleocene is character-

ised 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 eoceanus*, *Globocassidulina subglobosa*, *Dorothia* sp., *Gaudryina* sp., *Gaudryina pyramidata*.

Other taxa: *Cibicidoides* sp., *Gyroidinoides* sp., *Hanzawaia ammophila*, *Oridorsalis umbonatus*, *Eggerella* sp.

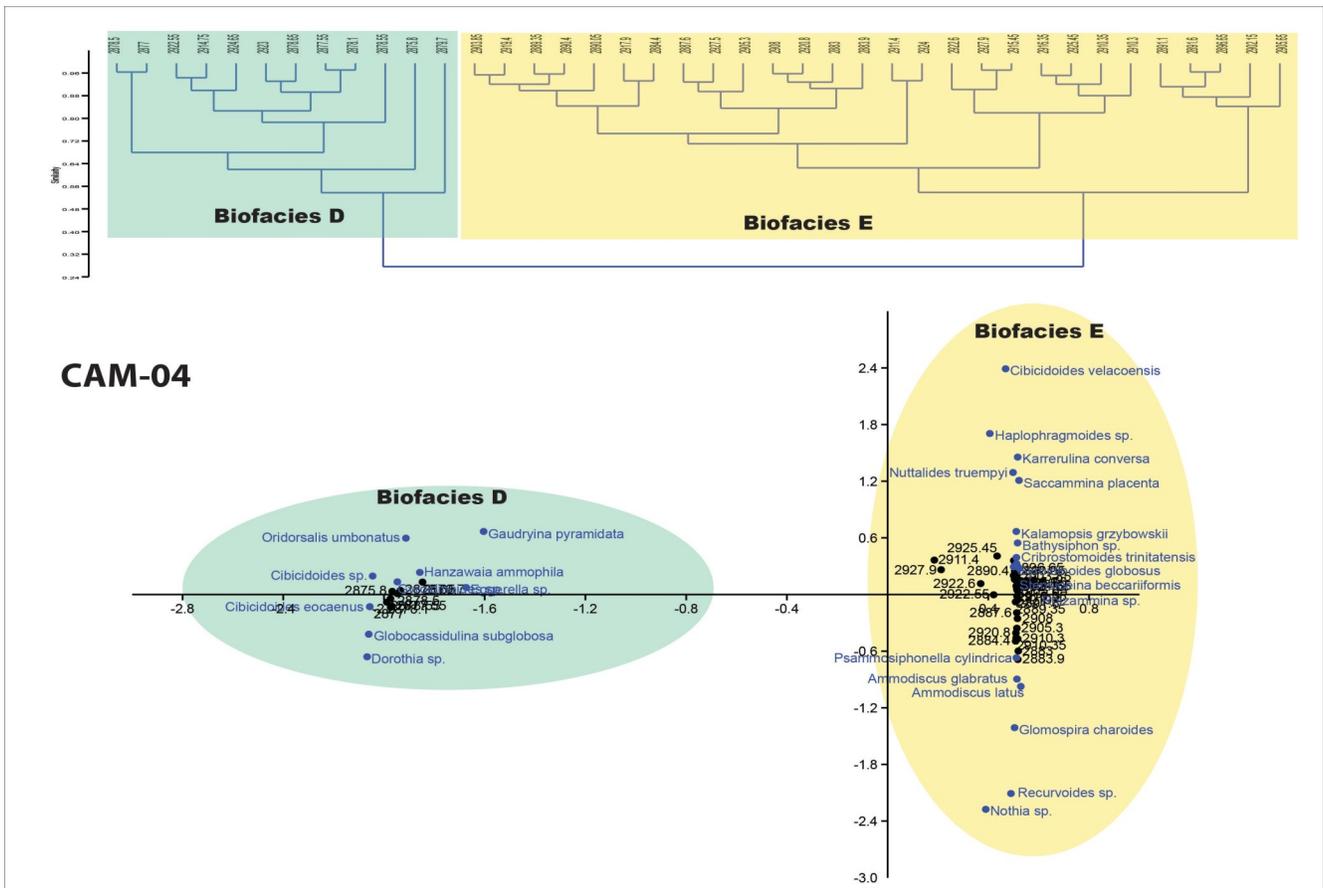
Planktic: ~80% of total assemblage (very poorly preserved).

Palaeobathymetric range: middle bathyal.

Age range: middle Eocene (CP13/14\*\*).

### »» Biofacies E

Main taxa: *Rhizammina* sp., *Psammosiphonella cylindri-*



**Figure 17:** Dendrogram of samples by Q-mode cluster and correspondence analysis, showing the two major biofacies in well CAM-04.

*ca.*, *Kalamopsis grzybowskii*, *Bathysiphon* sp. Tubular forms are ~60% of the benthics.

Other taxa: *Ammodiscus latus*, *A. glabratus*, *Cribratomoides trinitatensis*, *Glomospira charoides*, *Haplophragmoides* sp., *Saccamina placenta*, *Cibicoides velacoensis*, *Karrerulina conversa*, *Stenioeina beccariiformis*, *Nuttallides truempyi*, *Gyroidinoides globosus*, *Nothia* sp., *Recurvoides* 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, CAM-04 – Fig. 8). This near-absence of lower Eocene deposits may be related to tectonic reactivation in the source area (Serra do Mar Mountains) inland, leading to

increased mass wasting and downslope transport (Almeida & Carneiro, 1998, Modica & Brush, 2004). Becker *et al.* (2000) reported an unconformity between the middle Eocene and Paleocene.

The age model for wells CAM-01, CAM-02, CAM-03 and CAM-04 shows a relatively low 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

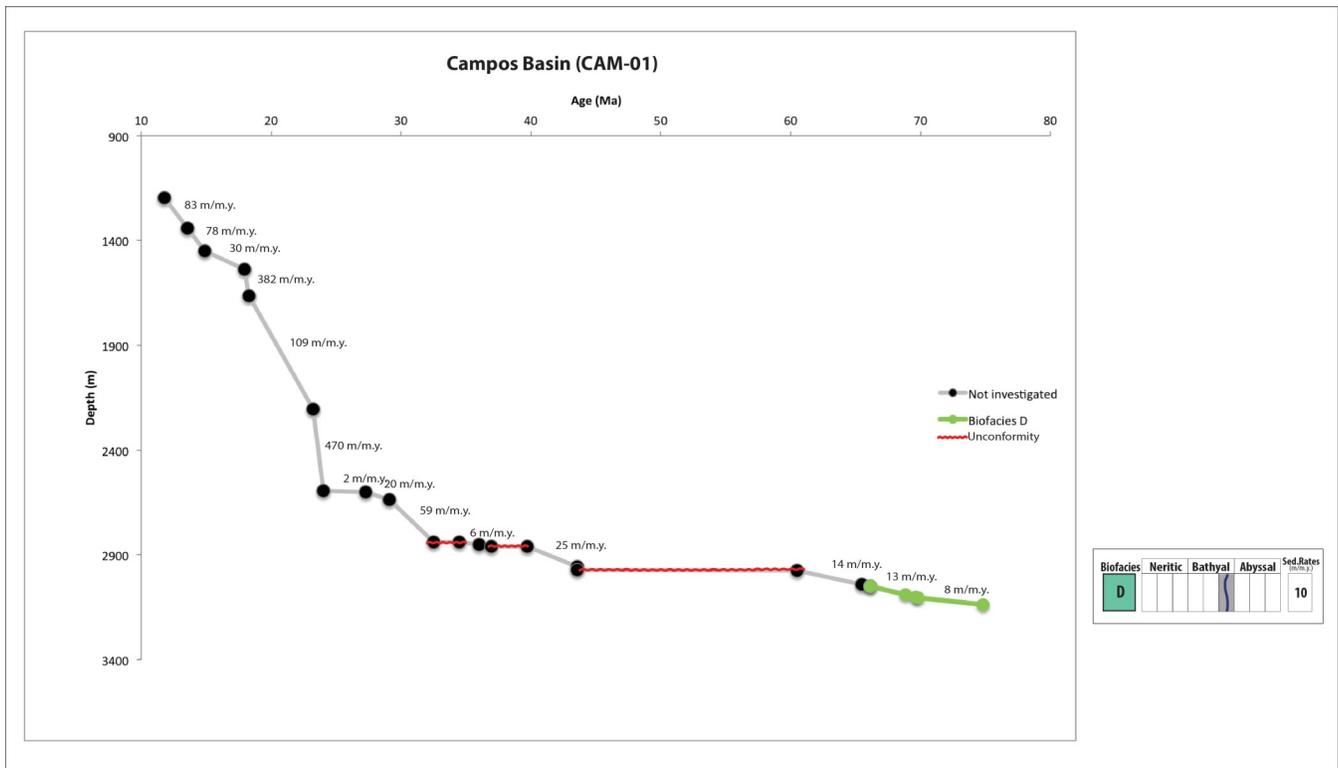


Figure 18. Age vs Depth Model of well CAM-01, with benthic foraminiferal biofacies, palaeobathymetric range, and sedimentation rates.

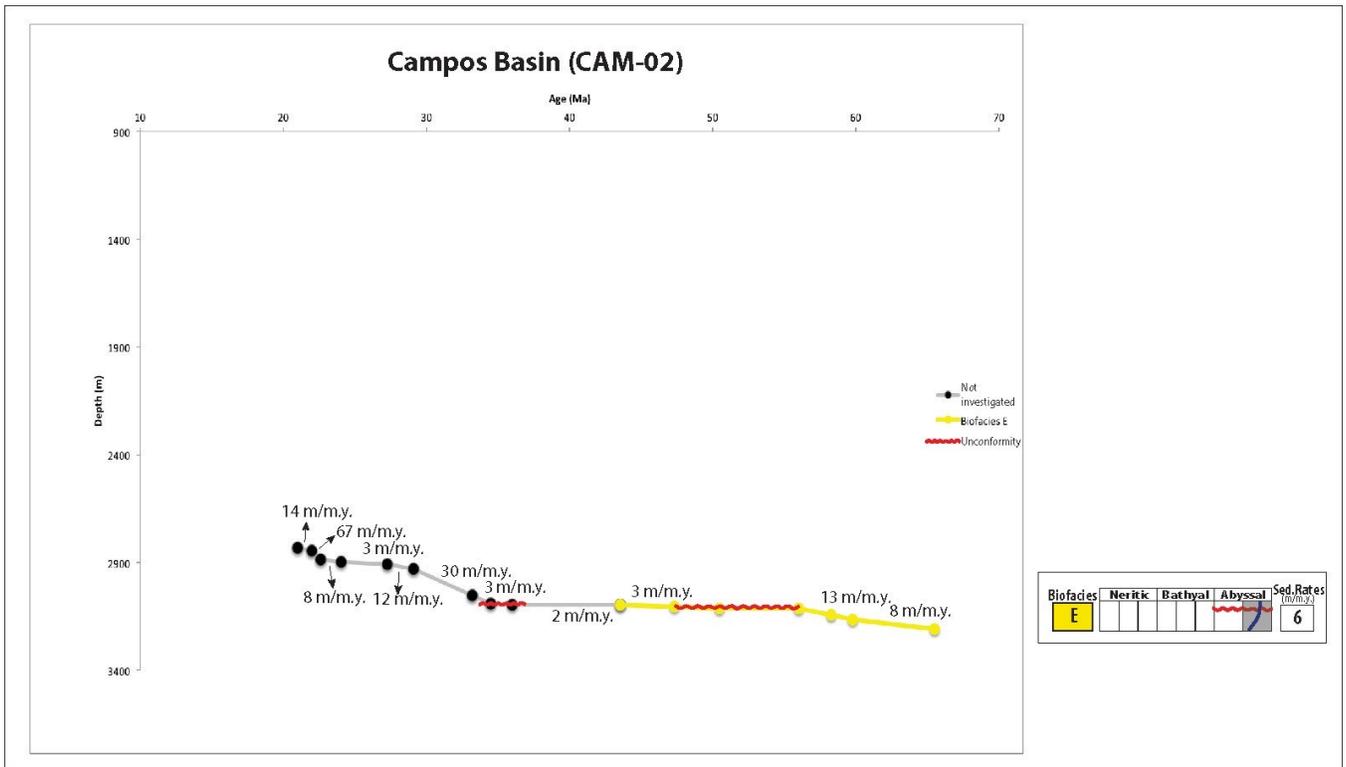


Figure 19. Age vs Depth Model of well CAM-02, with benthic foraminiferal biofacies with palaeobathymetric ranges, and sedimentation rates.

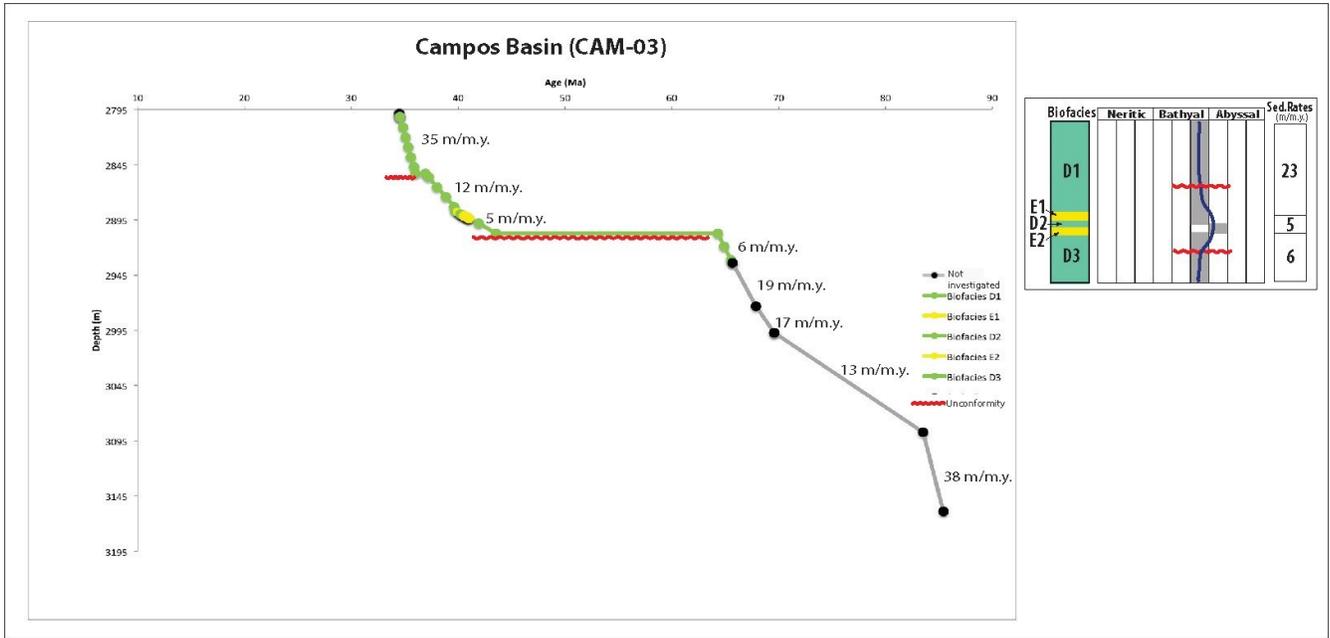


Figure 20. Age vs Depth Model of well CAM-03, with benthic foraminiferal biofacies with palaeobathymetric ranges, and sedimentation rates.

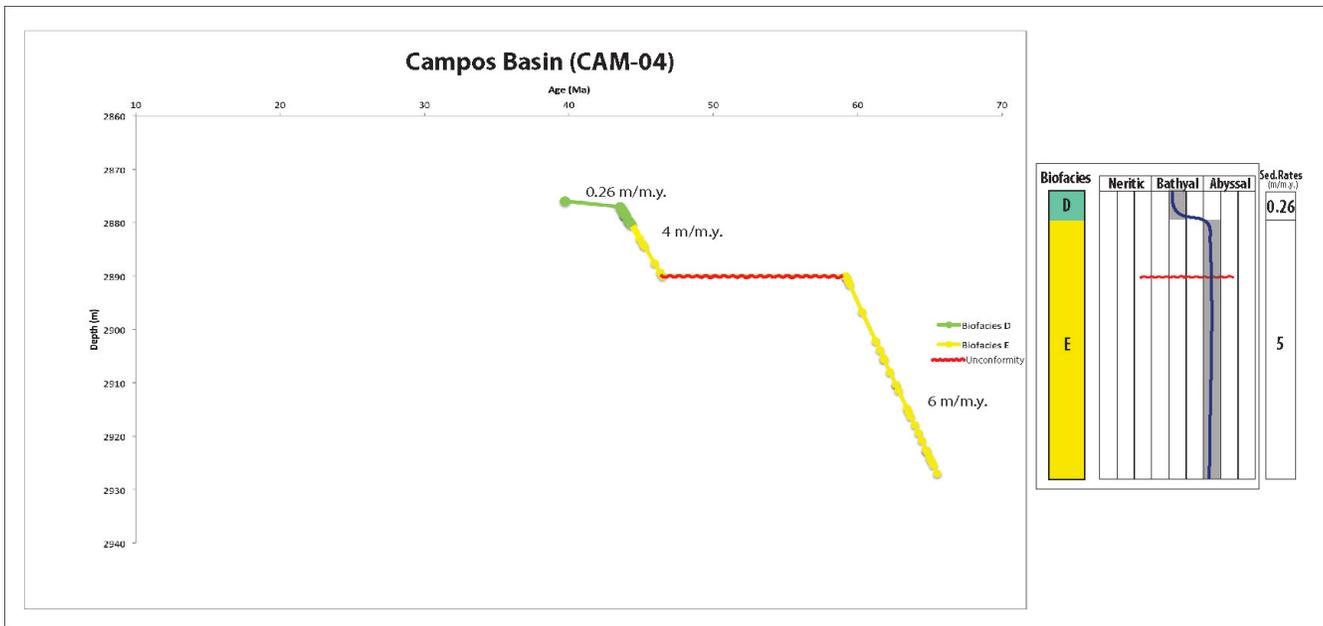


Figure 21. Age vs Depth Model of well CAM-04, with benthic foraminiferal biofacies with palaeobathymetric ranges, and sedimentation rates.

(Becker *et al.*, 2000). The lower Cenozoic depositional sequences cover the topography of the Cretaceous sea-floor, 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 recognise four distinct biofacies of benthic foraminifera (Fig. 23), which are distinct for each time slice from Maastrichtian through upper Eocene.

### » 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 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.

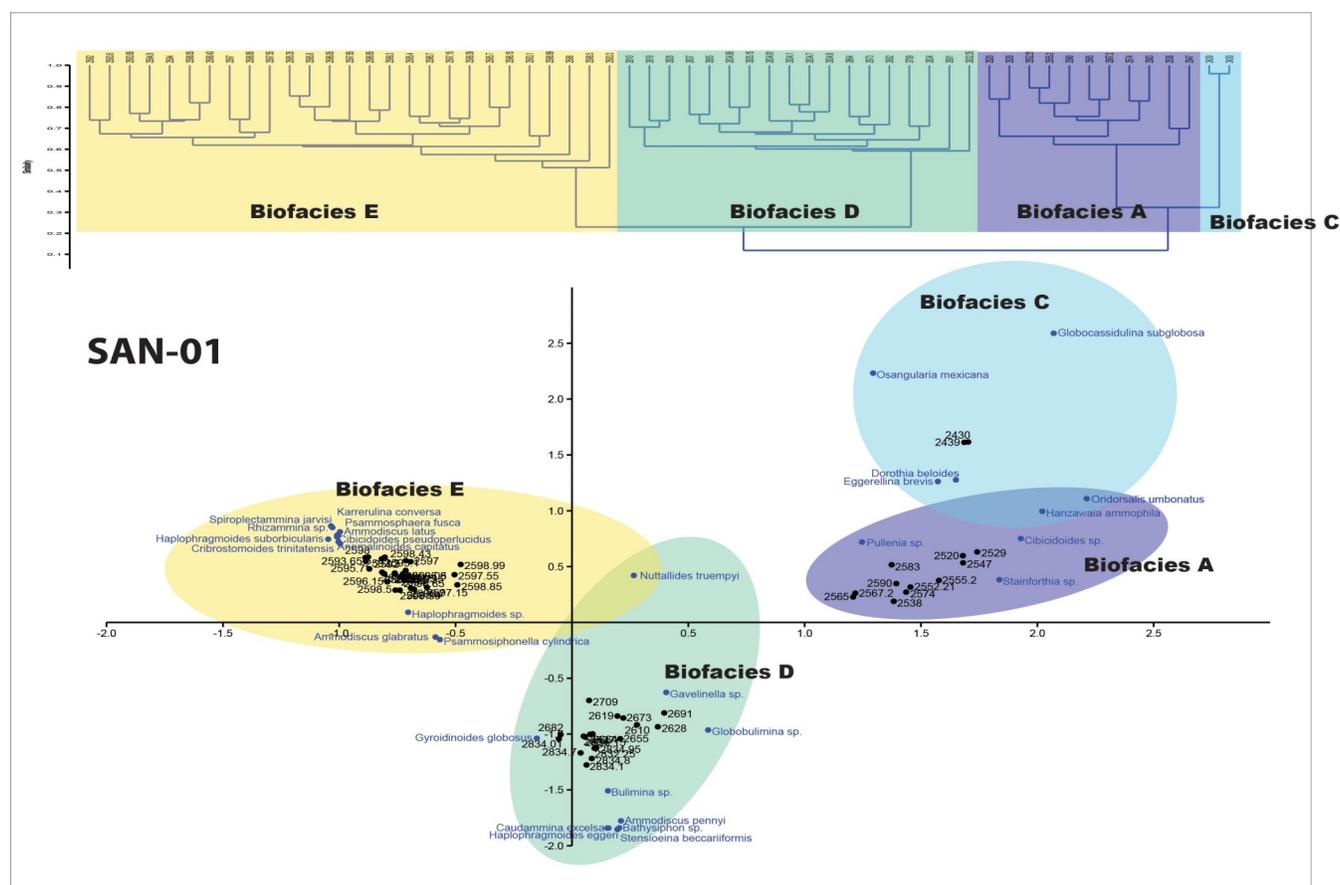
Age range: early Eocene (CP10\*\*).

### » Biofacies 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. glabratus*, *A. latus*, *Haplophragmoides* sp., *Karrerulina conversa*, *Psammosphaera fusca*, *Haplophragmoides suborbicularis*, *Cribrostomoides trinitensis*.



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

*tatensis*, *Nuttallides truempyi*, *Gavelinella* sp., *G. globosus*, *Cibicidoides pseudoperlucidus*, *Anomalinoidea capitatus*.

**Planktics:** 40-50% of total assemblage, but poorly preserved.

**Palaeobathymetric range:** lower bathyal to upper abyssal.

**Age range:** late Paleocene (P4\*, CP5/6\*\*).

» **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 beccariiiformis*, *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 (*Saccamina*, *Caudammina*, *Haplophragmoides*).

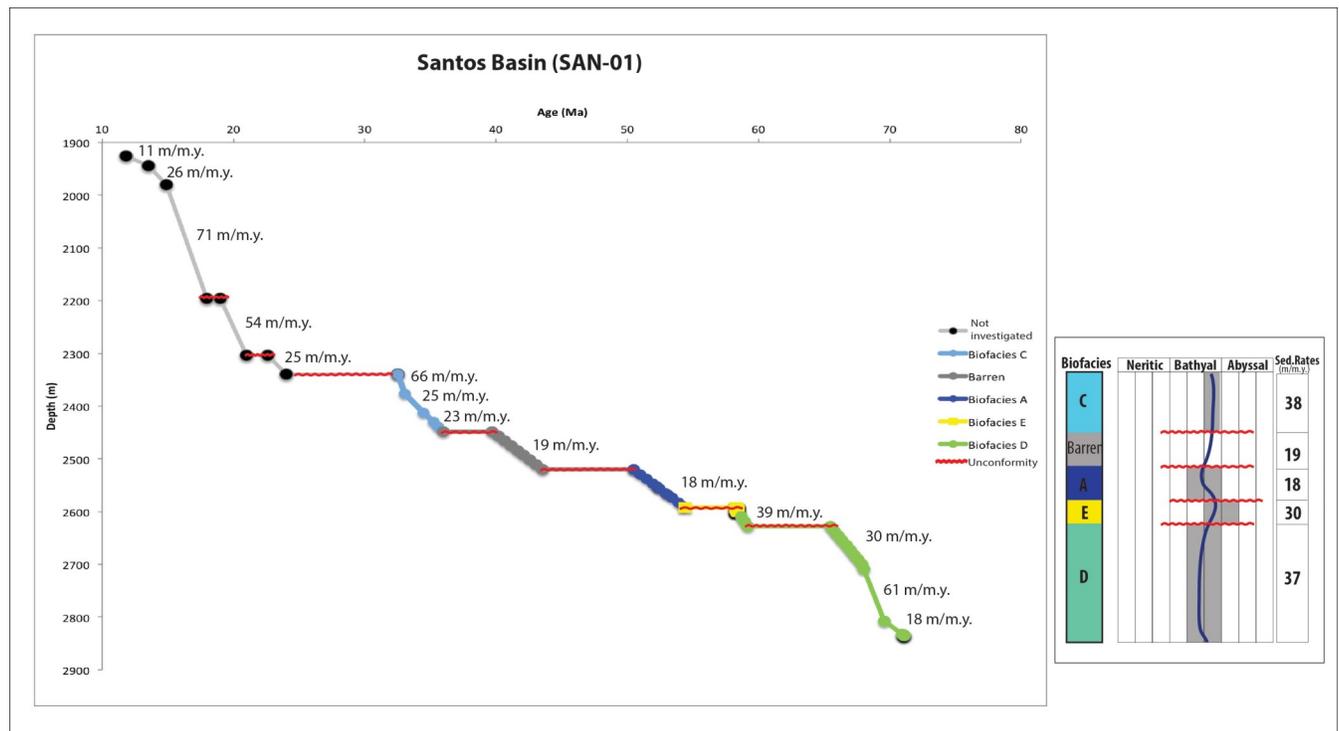
**Palaeobathymetry of the Santos Basin.**

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.

of industry wells examined in this study.

### »» Biofacies C

Main Taxa: *Anomalinoidea garzaensis*, *Bulimina alazanensis*, *Gaudryina pyramidata*, *Cibicidoides eocaenus*, *C. praemundulus*.

Other taxa: *Anomalinoidea* sp., *Bulimina* sp., *Bulimina midwayensis*, *B. alazanensis*, *Neoeponides elevatus*, *N. byramensis*, *Globobulimina* sp., *Nuttallinella* sp.1, *Planulina costata*, *Praebulimina* sp., *Siphonina* sp., *Uvigerina* sp., *Cribrostomoides* sp., *Clavulinoidea* sp., *Gaudryina* sp., *Haplophragmoides* sp., *Reticulophragmium acutidorsatum*, *R. amplectens*.

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

Main taxa: *Cibicidoides eocaenus*, *Paralabamina lunata*, *Hanzawaia ammophila*.

Other taxa: *Alabamina dissonata*, *Cibicidoides* sp., *Gyrogonoides subangulatus*, *Nuttallides truempyi*, *Pullenia* sp., *Gaudryina* sp., *Anomalinoidea* sp., *Globobulimina* sp., *Spiroplectammina* sp.

Planktic: 0 to 25% (rarely occurring, tiny planktics).

Palaeobathymetric range: middle to lower bathyal.

Age range: late Paleocene (P5\* – CP8\*\*) through early Eocene (E6/7\* – CP11/12\*\*).

### »» Biofacies E

Main taxa: *Bathysiphon* sp., *Haplophragmoides* sp., *Gaudryina pyramidata*, *Cyclammmina placenta*.

Other taxa: *Bolivinopsis spectabilis*, *Budashevaella multicamerata*, *Cribrostomoides subglobosus*, *Gaudryina* sp., *G. laevigata*, *Hormosina* sp., *Marssonella* sp., *Marssonella trochoides*, *Psamosiphonella 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 shallowing 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 covers upper Maastrichtian through upper Eocene. The preservation of the microfossils and continuity of these cores provides a valuable comparison with assemblages from the Brazilian marginal basins, which were highly affected by turbidites, downslope debris flows 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: *Nuttallides truempyi*, *Osangularia mexicana*,

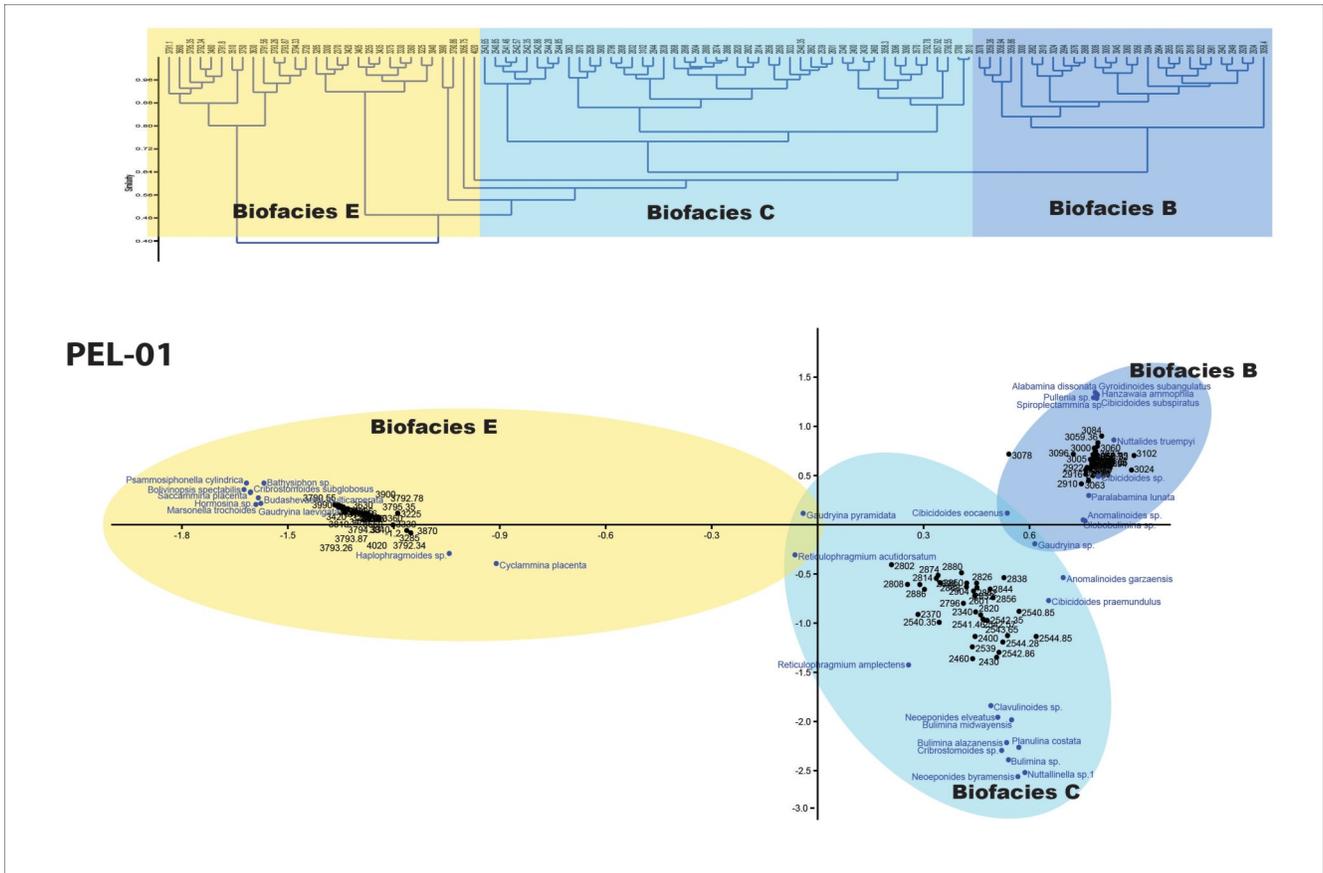


Figure 24. Dendrogram of samples by Q-mode cluster and correspondence analysis, showing the three major biofacies in well PEL-01.

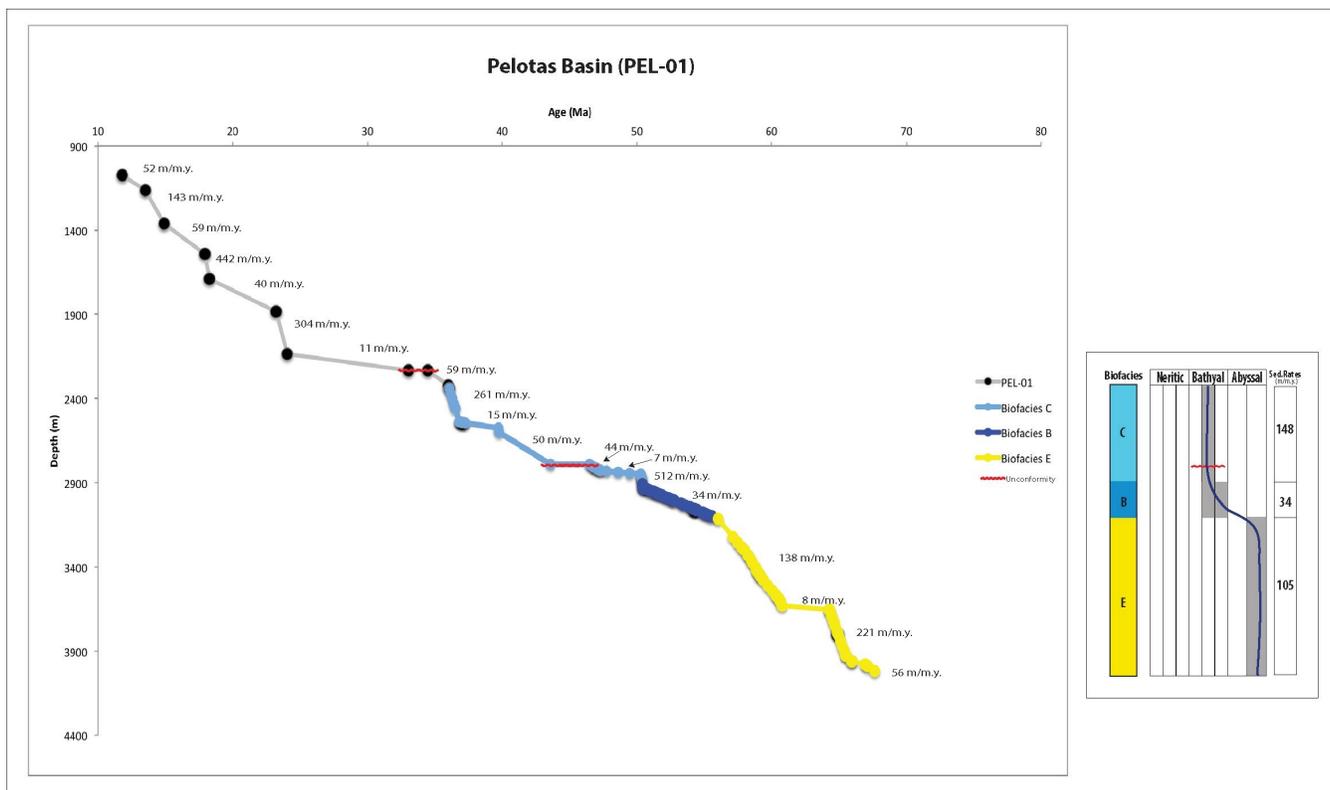


Figure 25. Age vs Depth Model of well PEL-01, with benthic foraminiferal biofacies, palaeobathymetric ranges, and sedimentation rates.

*Gyrodinoides subangulatus*, *Stilostomella* sp., *Gaudryina* sp.

Other taxa: *Oridorsalis umbonatus*, *Bulimina tuxpamensis*, *B. trinitatensis*, *Karrerella subglabra*, *Spiroplectamina spectabilis*, *Haplophragmoides* sp., *Pullenia eocenica*.

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 ammophila*.

Other taxa: *Alabamina dissonata*, *Anomalinoidea capitatus*, *B. semicostata*, *B. trinitatensis*, *Cibicidoides* sp., *Gyrodinoides* sp., *G. subangulatus*, *Oridorsalis umbonatus*, *Stilostomella* sp., *Nuttallides truempyi*.

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: *Gyrodinoides globosus*, *Pullenia coryelli*, *Anomalinoidea* sp.

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

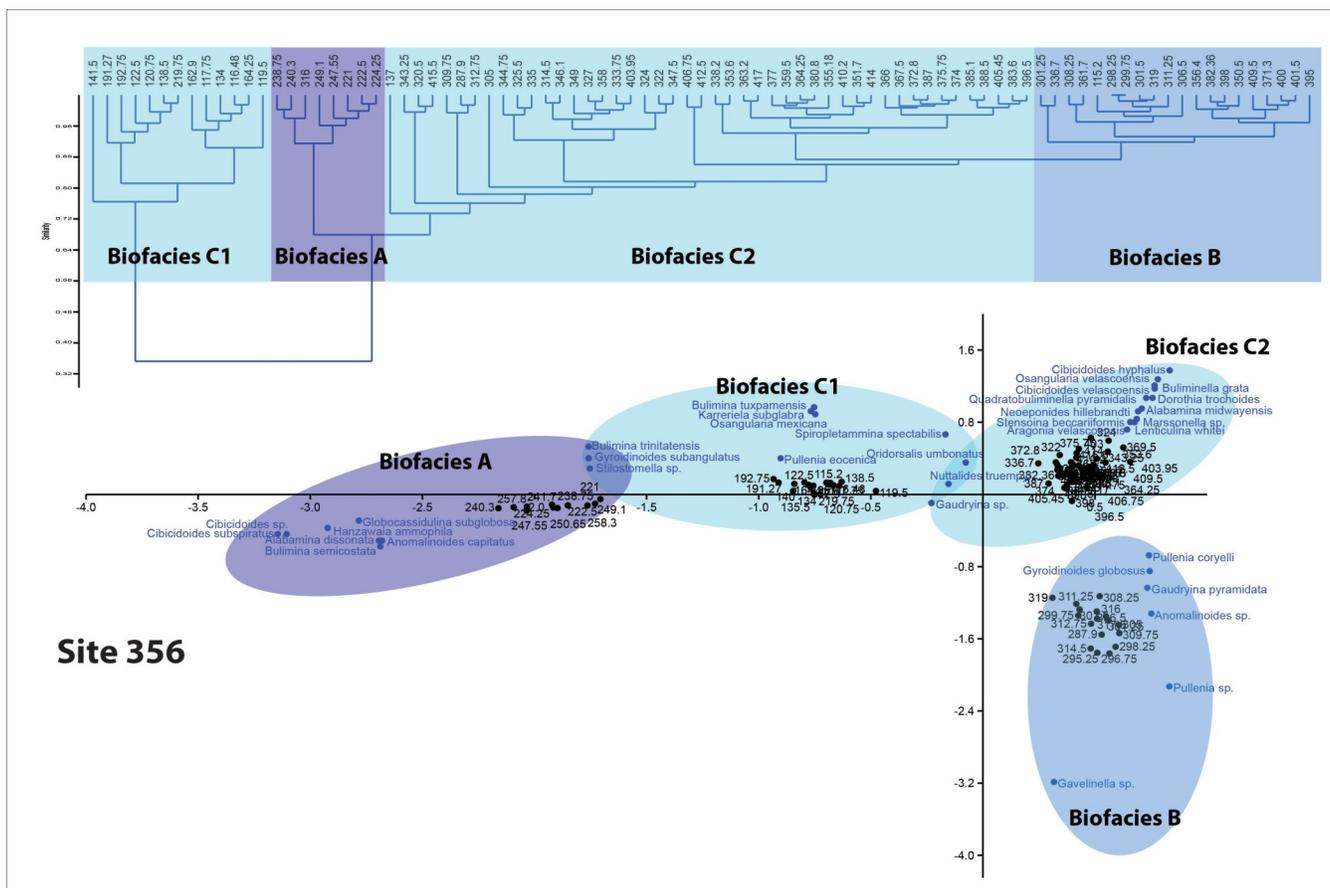
Planktic: 50-80% of total assemblage.

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 beccariiiformis*, *Neoeponides hillebrandti*, *Gaudryina pyramidata*

Other taxa: *Alabamina midwayensis*, *Aragonia velascoensis*, *Anomalinoidea* sp., *Bulimina* sp., *B. trinitatis*, *Buliminella grata*, *Cibicidoides hyphalus*, *C. velascoensis*, *Gavelinella* sp., *Guttulina trigonula*, *Gyroidinoidea*, *G. globosus*, *Lenticulina whitei*, *Osangularia velascoensis*, *Oridorsalis umbonatus*, *Oridorsalis* sp., *Pullenia coryelli*, *Quadratobuliminella pyramidalis*, *Pyramidina* sp., *Dorothia trochoides*, *Clavulinoides* sp., *Marssonella*, *Spiroplectammina spectabilis*.

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*, *Cibicidoides havanensis*, *Oridorsalis umbonatus*.

Other taxa: *Cibicidoides eocaenus*, *C. praemundulus*, *Alabamina dissonata*, *Aragonia aragonensis*, *Bolivina huneri*, *Buliminella grata*, *Plectofrondicularia lirata*, *Siphonodosaria* sp., *Stilostomella aculeata*, *S. spinosa*, *Gaudryina pyramidata*, *G. laevigata*, *Dorothia* 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 pyramidata*, *Globocassidulina subglobosa*.

Other taxa: *Alabamina dissonata*, *Anomalinoidea welleri*, *Aragonia aragonensis*, *Bulimina semicostata*, *Bulimina tuxpamensis*, *Cibicidoides eocaenus*, *Cibicidoides grimsdalei*, *C. havanensis*, *C. micrus*, *C. mexicanus*, *Gyroidinoidea beisseli*, *G. subangulatus*, *Hanzawata ammophila*, *Karrerella cubensis*, *Gaudryina laevigata*.

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*, *Anomalinoidea praeacuta*, *Oridorsalis umbonatus*.

Other taxa: *Abyssamina poagi*, *A. quadrata*, *Alabamina midwayensis*, *Anomalinoidea capitatus*, *Aragonia velascoensis*, *Nodosaria velascoensis*.

Planktic: ~70% of total assemblage.

Palaeobathymetric range: lower bathyal.

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

#### »» Biofacies C2

Main taxa: *Nuttallides truempyi*, *Gyroidinoidea globosus*, *Stensioeina beccariiiformis*, *Oridorsalis umbonatus*.

Other taxa: *Neoeponides hillebrandti*, *Cibicidoides hyphalus*, *Anomalinoidea praeacuta*, *Aragonia velascoensis*, *Buliminella grata*, *Cibicidoides velascoensis*, *Pullenia coryelli*, *Dorothia trochoides*, *Gaudryina pyramidata*, *G. laevigata*, *Tritaxia* sp., *Spiroplectammina* sp., *Osangularia velascoensis*.

Planktic: ~70% of total assemblage.

Palaeobathymetric range: middle to 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 beccariiiformis*,

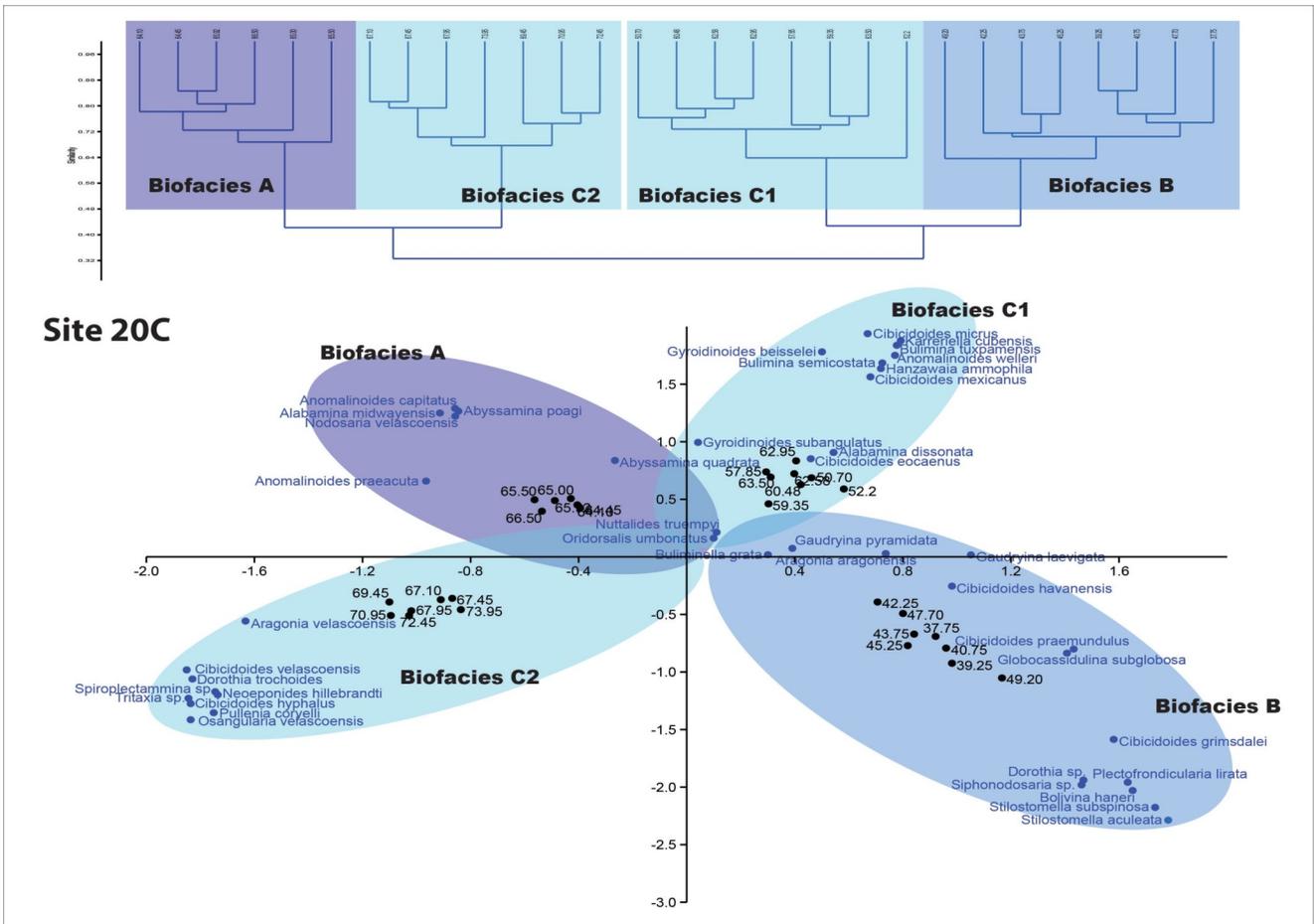


Figure 27. Dendrogram of samples by Q-mode cluster and correspondence analysis showing the four major biofacies recognised for the Site 20C.

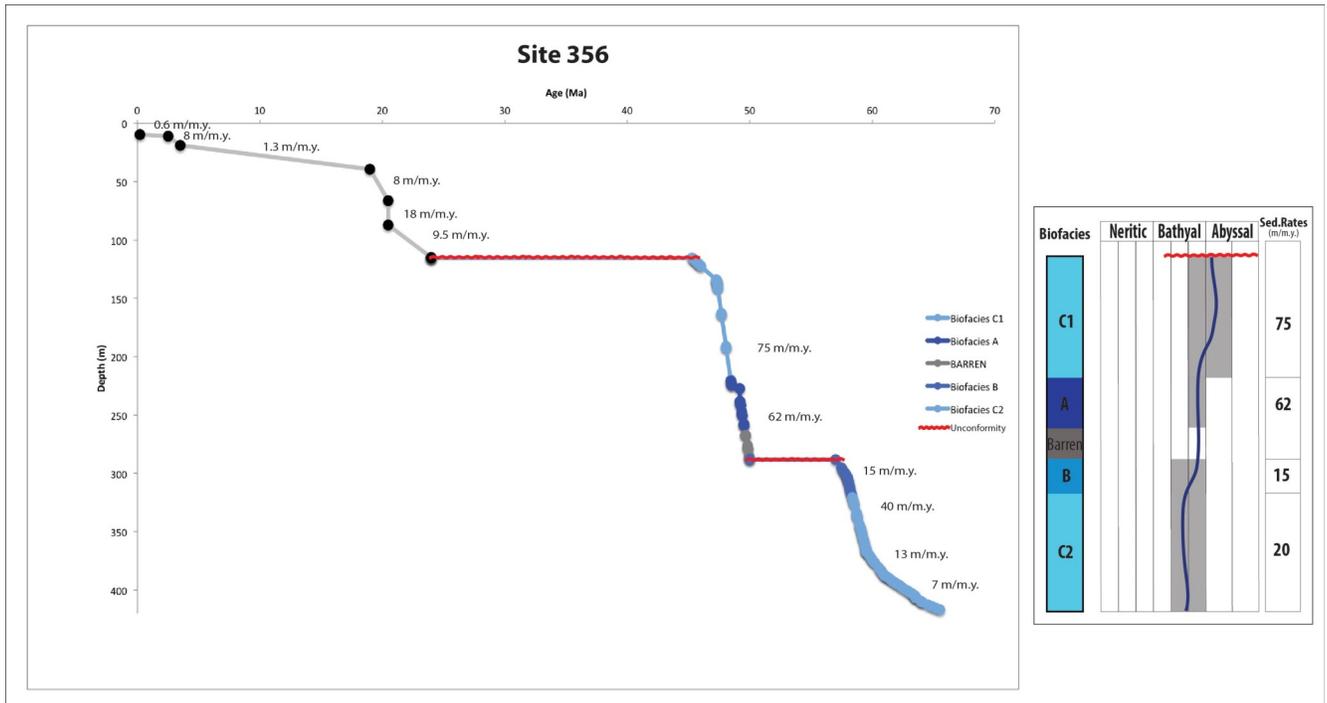
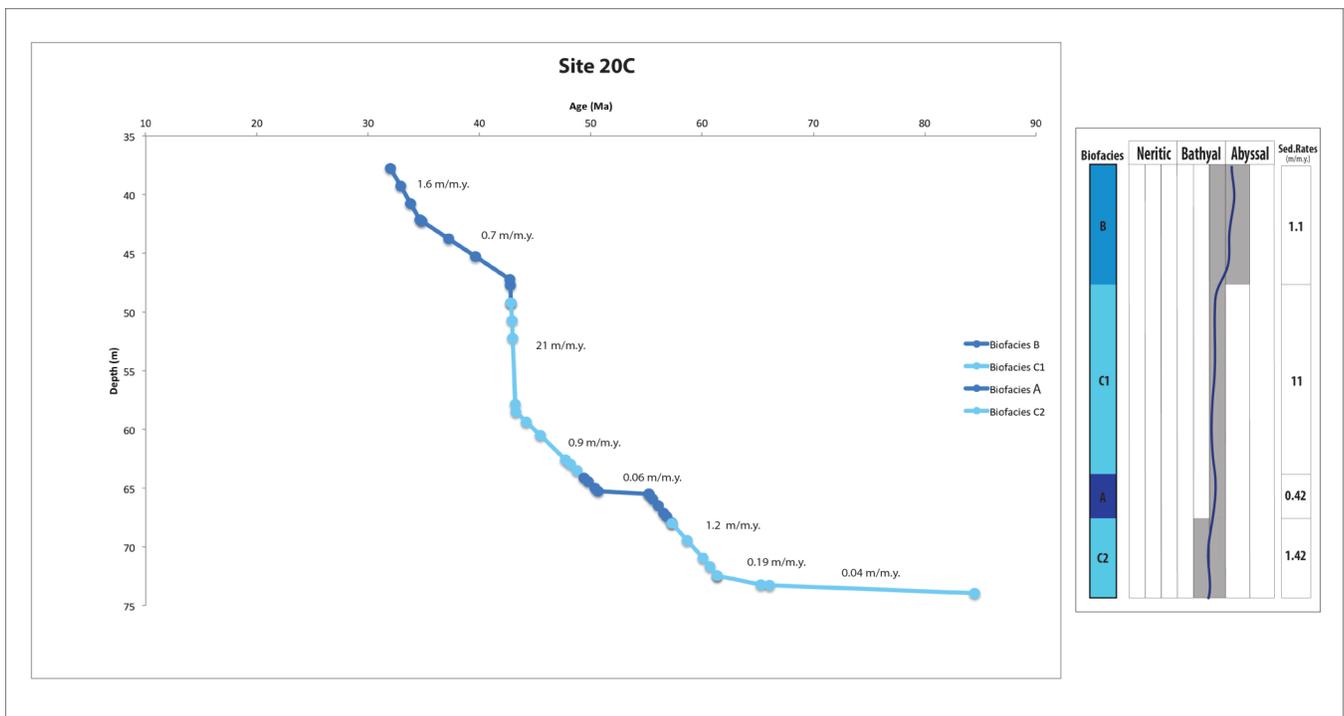


Figure 28. Age vs Depth Model of the DSDP Site 356 with benthic foraminiferal biofacies, palaeobathymetric ranges, and sedimentation rates.



**Figure 29.** Age vs Depth Model of the DSDP Site 20C with benthic foraminiferal biofacies, palaeobathymetric ranges, and sedimentation rates.

*Neoponides 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 (Kominz *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 Maastrichti-

an, 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 beccariiiformis*, *Pullenia coryelli*, *Cibicidoides hyphalus*, *C. velascoensis*, *Osangularia velascoensis* and *Gyroidinoides globosus* (Berggren & Aubert, 1975), differing only in the agglutinated 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; Kominz *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 Paraíba 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, Kominz *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 CO<sub>2</sub> 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).

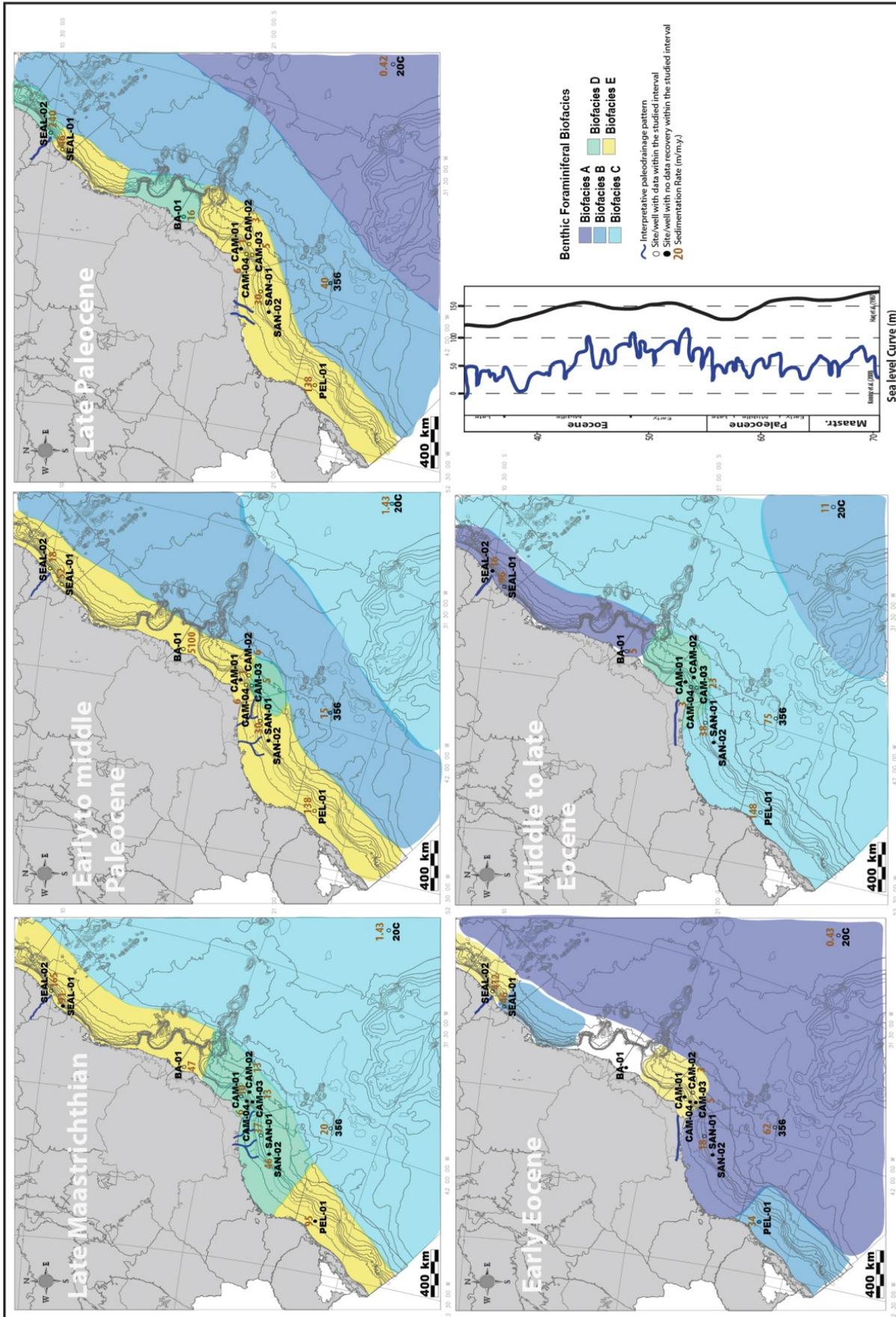
The major benthic extinction event (BEE) coincided with the Paleocene-Eocene boundary and the Paleocene-Eocene Thermal Maximum (e.g., Tjalsma & Lohmann, 1983, Thomas, 1989, 1990, 1998, 2003, 2007, Thomas & Shackleton, 1996, Thomas *et al.*, 2000, Alegret & Thom-

as, 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 agglutinant taxa 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 agglutinant-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).

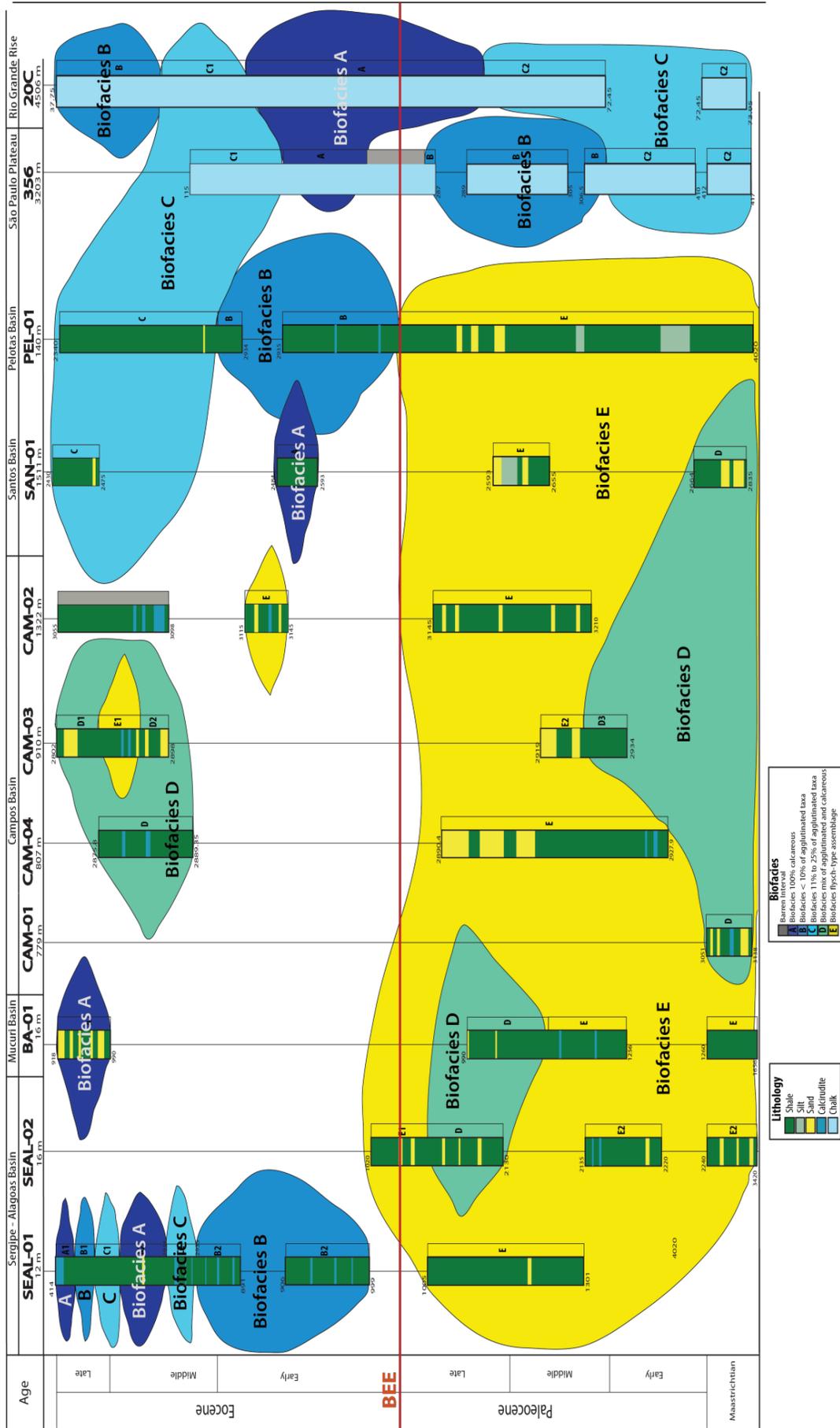
During the **early Eocene**, biofacies A and B dominated in most basins as the margin prograded and the slope shoaled. At this time, the sediment supply generally decreased and the shallower basins were no longer favorable for the agglutinant assemblage. Biofacies E was restricted to the deep Campos 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 Paraíba 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*, *Paralabamina 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 uniserial, 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 CaCO<sub>3</sub> 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*, *Psammosiphonella*) associated with other agglutinated taxa (*Haplophragmoides*, *Recurvoides*, *Ammodiscus*, *Bolivinosia*, *Saccamina*, *Trochammina*, *Trochamminoides*, *Rzehakina*, *Spirolectammina*, *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 beccariiiformis*, *Gy-*

Table 3. Flysch-type benthic foraminifera assemblages from Cretaceous through Paleogene.

Age	Paleodepth	Location	Assemblage	Source
Late Cretaceous Paleogene	Abyssal (below CCD)	several	<i>Rhabdammina</i> -fauna	Brower (1965) 1
Paleocene-middle Eocene	Bathyal	Lodo Fm - Central CA	<i>Bathysiphon</i> , <i>Haplophragmoides</i> , <i>Trochammina</i> , <i>Ammodiscus pennyi</i> , <i>Silicosigmoilina</i> , <i>Rhabdammina</i> , <i>Milliolids</i> and <i>Lagenids</i>	Israelsky (1951)
upper Cretaceous	Abyssal	Indian Ocean (Site 260) and Argo Abyssal Plain (Site 261)	upper Cretaceous: <i>Haplophragmoides</i> , <i>Recurvooides</i> , <i>Paratrochamminoides</i> , <i>Haplophragmium</i> , <i>Solivinopsis</i> , <i>Pseudobolivina</i> , <i>Trochammina</i> , <i>Karreriella</i> , <i>Plectina</i> , <i>Dorothia</i> , <i>Plectorecurvooides</i> , <i>Verneuilina</i> , <i>Uvigerinammina</i> , <i>Ammodiscus</i> , <i>Glomospira</i> , <i>Glomospirella</i> , <i>Saccammina</i> , <i>Pelosina</i> , <i>Hyperammina</i>	Krashennnikov (1974)
Cretaceous (Albin to Maastrichtian)	Site 356 - middle bathyal (500 to 1500m) Albin and lower bathyal (1500 to 2500m) for the Santonian to Maastrichtian) Site 357 - middle to lower bathyal in the Santonian and lower bathyal in the Campanian and Maastrichtian	sites 355, 356, 357, 358 (western South Atlantic)	Agglutinated species dissolution resistant: <i>Haplophragmoides</i> , <i>Paratrochamminoides</i> , <i>Recurvooides</i> and <i>Saccammina</i> , <i>Ammodiscus</i> , <i>Glomospira</i> , <i>Hyperammina</i> . Non-resistant: <i>Tritaxia</i> <i>aspera</i> , <i>Dorothia oxycona</i> , <i>D. buletta</i> , <i>Gaudryina</i> <i>laevigata</i> , <i>G. franki</i> , <i>Spiroplectammina dentata</i> .	Sliter (1977)
upper Cretaceous- lowe Eocene	Abyssal (below CCD)	Site 328 (Falkland Outer Basin)	<i>Ammodiscus cretaceus</i> , <i>Glomospira charoides</i> , <i>G.</i> <i>gordiais</i> , <i>Rzehakina epigona</i> , <i>Haplophragmoides</i> sp., <i>H. excavata</i> . <i>Nodelum velascoense</i> , <i>Bathysiphon</i> sp., <i>Saccammina complanata</i> , <i>Hormosina ovulum</i> , <i>Uvigerinammina</i> sp., <i>Paratrochamminoides</i> sp.	Tjalsma (1977)
late Paleocene-early Eocene	Bathyal	Site 112 (North Atlantic)	<i>Cyclammina</i> , <i>Glomospira</i> , <i>Ammodiscus</i> , <i>Bo-</i> <i>livinopsis</i> , <i>Rhabdammina</i> , <i>Cribrostomoides</i> , <i>Haplophragmoides</i> + <i>Osangularia pteromphalia</i> <i>Oridorsalis ecuadorensis</i> , <i>Nuttallides truempyi</i> , <i>Cibicoides</i> sp., siphonodosariids and stilostomellids	Berggren (1972)
Maestrichtian- Paleogene	wide range (200-4000m)	Labrador and North Seas	<b>Locus typicus</b> - Alpine-Carpatian flysch belt (dominated by single chambered and uniserial taxa): <i>Rhabdammina</i> , <i>Bathysiphon</i> , <i>Ammodiscus</i> , <i>Lituotuba</i> , <i>Reophax</i> , <i>Hormosina</i> , <i>Rzehakina</i> . Biserial and ? multiserial ( <i>Spiroplectammina</i> , <i>Textularia</i> , <i>Gaudryina</i> , <i>Dorothia</i> , <i>Gaudryina</i> ) and more complex trochoids ( <i>Trochammina</i> , <i>Recurvooides</i> , <i>Trochamminoides</i> , <i>Cribrostomoides</i> , <i>Haplophragmoides</i> , <i>Cyclammina</i> ) are generally less common	
Maestrichtian- Paleogene	2500-3500m	Pacific and Atlantic Oceans	<b>Type A</b> - robust and relatively coarse-grained taxa, high diversity (compared with B): <i>Rhizammina</i> , <i>Bathysiphon/Rhabdammina</i> , <i>Ammodiscus</i> , <i>Glomospira</i> , <i>Hormosina</i> , <i>Reophax</i> , <i>Kalamopsis</i> , <i>Rzehakina</i> . <i>Haplophragmoides</i> , <i>Trochamminoides</i> , <i>Recurvooides</i> , <i>Paratrochamminoides</i> , <i>Cyclammina</i> , <i>Trochammina</i> , <i>Spiroplectartunina</i> , <i>Dorothia</i> ,	Gradstein & Berggren (1981)
Middle to late Cretaceous	4000m	Indo-Pacific and Atlantic Oceans	<b>Type B</b> - small size and thin, smooth wall benthic aggl taxa: <i>Hyperammina</i> , <i>Saccammina</i> , <i>Pilulina</i> , <i>Glomospira</i> , <i>Glomospirella</i> . <i>Hormosina</i> , <i>Haplophragmoides</i> , <i>Paratrochamminoides</i> , <i>Recurvooides</i> , <i>Haplophragmium</i> , <i>Trochammina</i> , <i>Praecystammina</i> , <i>Labrospira</i> , <i>Plectorecurvooides</i> , <i>Bolivinopsis</i> , <i>Pseudobolivina</i> ,	
Late Maastrichtian to Eocene	bathyal to abyssal	Gum igei-Schlieren flysch	<i>Uvigerinammina</i> , <i>Dorothia</i> , <i>Verneuilina</i> , <i>Plectina</i> . <b>Turbiditic sequences</b> - calcareous (P+B) foraminifera with debris of algae, bryozoans, etc. <i>Rhabdammina</i> -type assem- blage not well developed and less individualized, repopulation on the finest pelitic interval (mud clouds). In turbiditic shales a poorer association of "diluted" calcareous and arenaceous agglutinated faunas was reported, indicating their reworked nature. <b>Hemipelagic sequences</b> - generally carbonate-free with well developed <i>Rhabdammina</i> -type assemblage that compare with Cretaceous-Paleogene abyssal assemblages below CCD	Wrinkler (1984)
Late Paleocene	bathyal-abyssal	North Sea	<b>Flysch-type assemblage</b> : tubular forms dominate, <i>Trochammina</i> , <i>Haplophragmoides</i> , <i>Spiroplectammina</i> . Calcareous are absent or rare. Radiolarians in some samples. Jones (1988) split the tubular forms into 4 groups correlated to modern genera.	Jones (1988)

**Table 3.** Flysch-type benthic foraminifera assemblages from Cretaceous through Paleogene.

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

*roidinoides globosus*, *Osangularia velascoensis*, *Cibicoides hyphalus*, *C. velascoensis*; Berggren & Aubert, 1975), and with taxa typical of the Barbados-type assemblage in the Eocene (*Cibicoides eoceanus*, *Nuttallides truempyi*, *Osangularia mexicana*, *Hanzawaia ammophila*, *Planulina costata*, *Globocassidulina subglobosa*; Wood *et al.*, 1985, Van Markoven *et al.*, 1986, Berggren & 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 nannofossils 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

material arriving in the Paleocene from the Paraíba do Sul drainage system (Cobbald *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 differs 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 fluvio-deltaic 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 deep-sea 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 Paraíba do Sul River, reported to have been well established by the late Eocene/Oligocene interval (Cobbald *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 calcareous taxa. The Mucuri Basin was greatly influenced by the Abrolhos volcanism in the middle to late Eocene.

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