# Benthic foraminifera and Neogene sea level changes in the Pelotas Basin, offshore south Brazil

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## ABSTRACT

The Neogene benthic foraminiferal ecostratigraphy of offshore Pelotas Basin has not yet been researched. The benthic foraminifera were examined in twenty-nine ditch cuttings samples from Well 1-SCS-3B, present water depth 200 m. These samples ranged from the Lower Miocene *Catapsydrax dissimilis* planktonic foraminiferal Zone to the Pliocene *Globigerinoides trilobus fistulosus* Zone. Only ditch cuttings were available, which allowed us to present just broad paleoenvironmental trends within the studied section. Benthic foraminifera indicate deposition mostly between outer neritic to upper bathyal paleodepths. A peak in uvigerinid relative abundance marks a possible flooding surface or condensed section with a high nutrient flux, low diversity (marked by the Shannon Function H), and sluggish circulation within the *Globorotalia mayeri* Zone. This peak is bracketed by high abundances of *Cibicidoides*, which indicate stronger current action than within the condensed section. Biostratigraphic hiatuses within these *Cibicidoides*-rich intervals are concluded not to indicate subaerial exposure, but to reflect current action sufficiently strong to induce either non-deposition or seafloor scouring. A second possible flooding surface occurs at the top of the section, indicated by a decline in *Cibicidoides* associated with upticks in *Sphaeroidina* and *Bolivina* and a dip in H. The top of this younger maximum flood was not encountered, probably occurring above the studied section. That the timing of these floods differs from those recorded elsewhere in the Pelotas Basin implies that they were tectonically induced, perhaps as distal effects associated with the interaction between the South American and Nazca tectonic plates. Future studies with better quality core samples will add detail to this picture; such studies can incorporate eustatic sea-level changes into the model presented.

**Descriptors:** Miocene, Uvigerinidae, Argentine Zoogeographic Province, Pelotas Basin, Florianópolis Platform, maximum flooding surface.

## INTRODUCTION

The Pelotas Basin is situated in south-easternmost Brazil and southeast Uruguay. Zoogeographically, its offshore portion currently straddles the boundary between the West Indian Province and the North Patagonian Subprovince of the Argentine Province at ~30°S (see Boltovskoy et al., 1980, Marengo, 2015). During the Cenozoic, Uruguayan deposition was mostly continental. However, Sprechmann (1978), in an examination of the paleontology of a series of water wells drilled on the Uruguayan coastal plane, found marine fossils in the Chuy 364 borehole (Lat. 33°42'S, Long. 53°26'W), drilled in the southern portion of the Pelotas Basin. His study ushered in a series of examinations of the Pelotas Basin marine

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Neogene. Offshore, however, the basin's marine foraminifera remain poorly known.

Sprechmann (1978) recorded a diverse assemblage of foraminifera (45 taxa, some in open nomenclature), ostracods, mollusks, bryozoans, and fishes all of broadly Miocene age. The assemblages were dominated by *Cibicides aknerianus* (d'Orbigny) and *Cibicides "pseudoungerianus"* (Cushman). Of these, Boltovskoy (1959) found *C. aknerianus* (described initially from the Vienna Basin), to be at present associated with the Malvinas Current, not with sluggish waters farther offshore below the Brazilian Current, which does not reach the seafloor. This species thus indicates that the marine Miocene in borehole Chuy 364 was subject to the intense current action. Sprechmann (1978) recorded *Amphistegina gibbosa*, which is characteristic of warm waters and is currently unknown in the Miocene of Argentina to the south. Based on these *A. gibbosa*, Sprechmann (1978) concluded that the shoreline marine current off northern Brazil reached NE Uruguay during the Miocene. This might also be reflected in his recovery of *Discorbis rosea* (as *Rotorbinella rosea* (d'Orbigny)), which is common to dominant in back-reef sites in the Caribbean Sea (Culver and Buzas, 1982, Wilson and Ramsook, 2007). He did not record any planktonic foraminifera, attesting to the nearshore situation of the Chuy 364 borehole location during Miocene times.

In addition to global, eustatic events, SE South America was during Neogene times subject to a series of transgressions and regressions, of which Sprechmann (1978) found just one. Marengo (2015) suggested that these were tectonically induced and apparently due to interactions between the South American and Nazca tectonic plates, reflecting distal subsidence associated with Andean tectonics. In contrast, Anjos-Zerfass et al. (2013) concluded that a regional unconformity at the Oligocene/Miocene boundary is of eustatic origin, being coincidental with almost global sedimentation that resulted from a climatic event, i.e., the 'Mi–1 glaciation'. They proposed that the other regional Neogene unconformities also correspond to global sea-level falls, and so posited that global eustatic movements controlled the development of regional synthem architecture.

Sanguinetti (1980), who studied ostracods, suggested that during the Miocene (*Sphenolithus heteromorphus-Discoaster quinqueramus* calcareous nannofossil Zones), within a *Henryhowella evax* ostracod Zone of local extent, the Pelotas Basin was uniformly covered by a sea with maximum depths of ~200 m (outermost neritic to uppermost bathyal). This is within the planktonic foraminiferal *Globorotalia acostaensis* and *Globorotalia humerosa* Zones, N16/N17 (see figure 2 in Bolli et al., 1985).

Carreño et al. (1999) examined the ostracods in onshore boreholes of the Pelotas Basin. Correlation of the ostracod biozones placed maximum transgressive events in the latest Miocene and Pleistocene. Ostracod paleoecology indicates the depositional system to be a barrier-lagoon. Of the transgressions recorded, the oldest (1st T of Carreño et al. (1999)) peaked during calcareous nannofossil Zone NN11, equivalent to the *Globorotalia acostaensis* and *Globorotalia humerosa* Zones, N16/N17.

Malumián and Nánez (2011) reported Atlantic transgressions on the Patagonian Platform, southernmost South America, which they characterized as comprising a passive margin on one of the most extended continental shelves in the world. The Colorado Basin, centered around 40°S, and the Salado Basin, at ca. 37°S, were the most north-easterly basins reported by these authors (see figures 1, 2 in Malumián and Nánez, 2011). They noted three
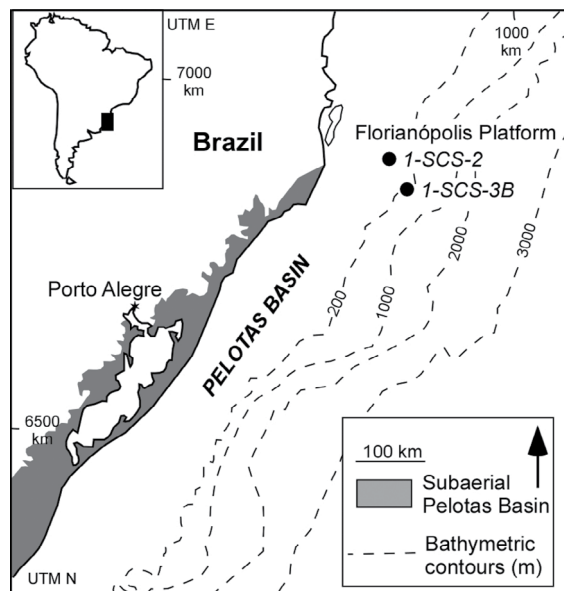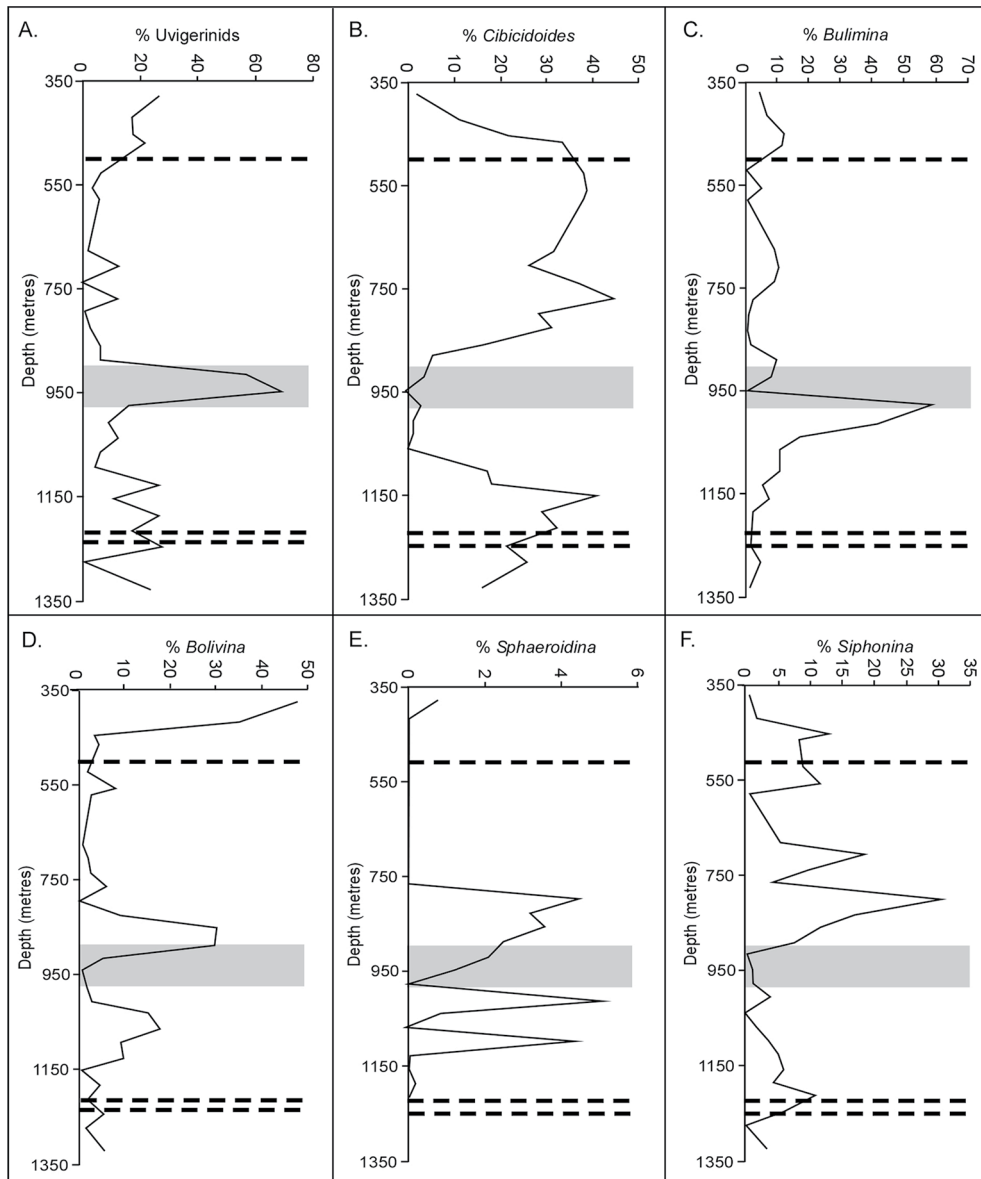


**Figure 1.** Location of Well 1-SCS-3B, within the Pelotas Basin.

**Figure 2.** The distributions of selected genera or genera groups in the Neogene of Well 1-SCS-3B, Pelotas Basin. A. Uvigerinids (*Uvigerina* + *Trifarina*). B. *Cibicidoides*. C. *Bulimina*. D. *Bolivina*. E. *Sphaeroidina*. F. *Siphonina*. The grey bar outlines the peak in uvigerinids.

transgressions to occur in the Late Oligocene, Early Miocene, and Middle Miocene. The Late Oligocene transgression, represented in the Colorado Basin by the Elvira Formation, was of limited extent, inducing shallow waters with abundant *Buccella* and conspicuous *Discorotalia*. The Early Miocene transgression, the rocks for which have not been named in the Colorado Basin but which might have been coincident with the Laguna Paiva Transgression (TLP) of Marengo (2015), transported the extinct Antarctic genus *Ammoelphidiella* northwards and

saw the development of the modern, low diversity Patagonian coastal assemblage with dominant *Buccella*. The Middle Miocene transgression reported by Malumián and Nánez (2011), represented in the Colorado Basin by the Barranca Final and Belén Formations, covered mainly northern Argentina and maybe the TEP of Marengo (2015). Malumián and Nánez (2011) noted that this Middle Miocene transgression was coeval with a relative climatic optimum. Windhausen (1931) recorded tropical mollusks in the Golfo San Jorge Basin at this time.

*Amphistegina*, though found along the Uruguayan coast during the Middle Miocene, is not recorded in the Argentine Salado Basin, though equatorial microfossil bryozoa (e.g., *Cupuladria canariensis*) are there common in subsurface samples but not in the more austral Colorado Basin. This distribution provides evidence of a clear Middle Miocene thermal gradient (Malumián, 1999).

In contrast to Malumián and Nánez (2011) finding three transgressions on the Patagonian Platform, Marengo (2015) suggested that two major transgressive-regressive cycles affected the Chacoparanense Basin of onshore northern Argentina during the Neogene and that both of these impacted the Pelotas Basin. The deposits of both transgressions are micropaleontologically rich, allowing reliable estimates of their ages and the main environmental changes. The first of these transgressions, known as the Patagoniense on the Patagonian coast, is in northern Argentina called the Laguna Paiva Transgression (TLP). It started during the latest Oligocene (NP25, = *Globorotalia kugleri* Zone, P22) and persisted through the Early Miocene (NN1, = *Globigerinoides primordius* Zone, N4) (Marengo, 2015, figure 2.13). The second transgression, which occurred between the Middle Miocene and the early Late Miocene (NN5 – NN8, = latest *Globigerinatella insueta* to *Globorotalia mayeri* Zones, latest N7 – N14) was referred to by Marengo (2015) as the Entrerriense-Paranense Transgression (TEP).

Within the Pelotas Basin, Anjos and Carreño (2004) examined the planktonic foraminifera in Well 1-SCS-3B (Figure 1). They concentrated on the Neogene section. Although they found that the well penetrated Oligocene sediment, there was too much caving of Miocene age material into that Oligocene section, and recrystallization of the in situ Oligocene foraminifera, to allow reliable zonation of it. The Neogene section, between 360 – 1230 m below the seafloor, was assigned by Anjos and Carreño (2004) to planktonic foraminiferal zones using the zonal scheme for tropical and temperate areas of Bolli and Saunders (1985) (see Table 1). Anjos and Carreño (2004) recorded eight zones within this Neogene interval. The ages of the zonal boundaries recognized by these authors were based on the extinction of taxa established by Berggren et al. (1995). Based on the zonal scheme, four hiatuses were observed in the studied sedimentary sequence, situated at the Oligocene-Miocene boundary, in the Early Miocene, at the Early Miocene-Middle Miocene boundary and the Miocene-Pliocene boundary.

Some caving of material was noted throughout the open drill hole of Well 1-SCS-3B. For example, specimens of *Orbulina universa* and *O. suturalis* were recovered from the *Catapsydrax dissimilis* Zone. However, Anjos and Carreño (2004) did not tabulate the number of specimens per species in each sample, so the severity of the caving is unknown. Nor did these authors provide details of casing points. The total recovery of specimens per sample was generally low, ranging between ~10 – 125 (see figure 3 in Anjos and Carreño, 2004), suggesting mostly shallow water conditions. Several intervals in the Neogene section contained what Anjos and Carreño (2004)

**Table 1.** Planktonic foraminiferal biostratigraphy of the Neogene in Well 1-SCS-3B, Pelotas Basin.

| Depth in Well | Zone | Age |
|---|---|---|
| 360 - 510 m | *Globigerinoides trilobus fistulosus* Zone | Lower Pliocene |
| | Hiatus | |
| 510 - 630 m | *Globorotalia margaritae evoluta* Zone | Lower Pliocene |
| 630 - 780 m | *Globorotalia menardii / Globorotalia acostaensis* Zone | Middle to Upper Miocene |
| 780 - 1080 m | *Globorotalia mayeri* Zone | Middle Miocene |
| 1080 - 1200 m | *Globigerinoides ruber* Zone | Middle Miocene |
| | Hiatus | |
| 1200 - 1230 m | *Globorotalia fohsi* Zone | Middle Miocene |
| | Hiatus | |
| 1230 - 1260 m | *Catapsydrax stainforthi* Zone | Lower Miocene |
| 1260 - 1320 m | *Catapsydrax dissimilis* Zone | Lower Miocene |
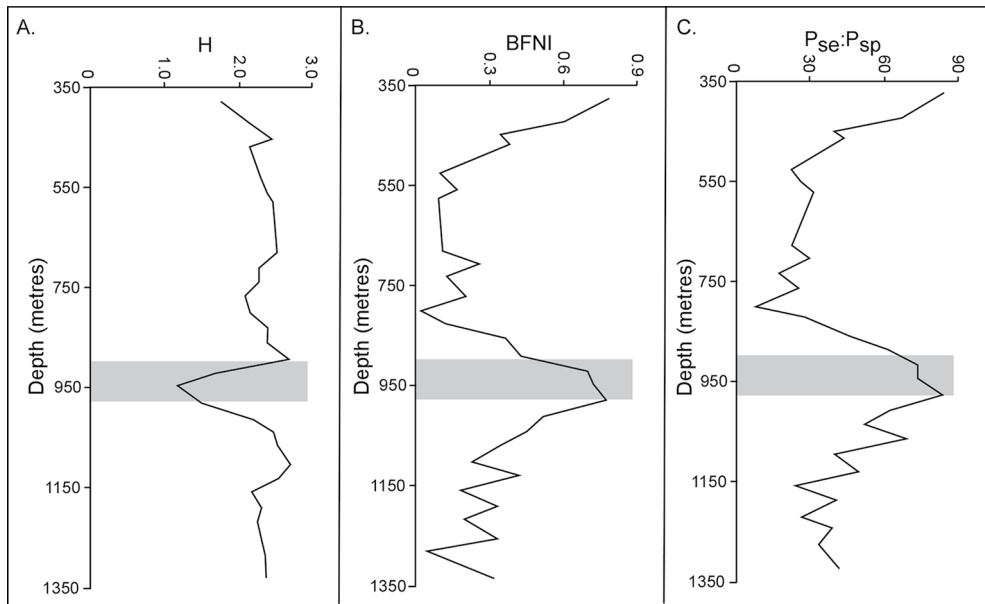
**Figure 3.** Selected measures within the Neogene of Well 1-SCS-3B, Pelotas Basin. A. The Shannon Function, H. B. The nutrient flux indicator BFNI. C. The serial:spiral coiling ratio, Pse:Psp. The grey bar outlines the peak in uvigerinids.

called 'oxidized' tests. These intervals were mainly concentrated above 855 m depth. There was also an interval with fragmentary planktonic foraminiferal tests at ~1245 m depth. Anjos-Zerfass et al. (2014) suggested that concentrations of oxidized tests may be related to regressive events that promoted the reworking of the Miocene deposits in the Pelotas Basis by exposing areas of the Florianópolis Platform. Oxidized tests in Well 1-SCS-3B are found mainly in the late *Globorotalia mayeri* Zone and younger. The TLP was not recorded by Anjos and Carreño (2004), but rocks representing this transgression may be found within the unstudied Oligocene interval. Some other transgressions, perhaps reflecting the greater depth at 1-SCS-3B, were apparently recorded by Anjos and Carreño (2004). The maximum flood recorded in 1-SCS-3B coincides with the TEP. The transgression at the very top of the studied interval in 1-SCS-3B is apparently associated with 1st T of Carreño et al. (1999). The authors were unable to infer the causes of the hiatuses but hypothesized that they were associated with transgressive events. They suggested that an analysis of benthic foraminifera might test this hypothesis. Such an analysis is presented in this paper.

The onshore wells studied by Carreño et al. (1999), with their maximum transgressive events in the latest Miocene and Pleistocene, lay somewhat west of Well 1-SCS-3B. Anjos and Carreño (2004) did not study the Pleistocene in Well 1-SCS-3B. Nor is it examined here. However, the 1st T of Carreño et al. (1999), which reached its maximum in the *Globorotalia acostaensis* and *Globorotalia humerosa* Zones, occurs within the single most extensive interval of deposition found by Anjos and Carreño (2004), these Zones specifically being within the 630 – 780 m interval in Well 1-SCS-3B.

Coimbra et al. (2009) expanded on Anjos and Carreño 's (2004) study of the biostratigraphy and paleoceanographical significance of the Neogene planktonic foraminifera from the Pelotas Basin, southernmost Brazil. Coimbra et al. (2009) examined the assemblages in 1-SCS-2 drill-hole of Pelotas Basin, ~70 km NW of 1-SCS-3B. In 1-SCS-2, they recognized the *Catapsydrax dissimilis, Catapsydrax stainforthi, Globorotalia fohsi robusta, Globorotalia mayeri, Globorotalia margaritae evoluta* and *Globigerinoides trilobus fistulosus* Miocene and Pliocene zones. There are thus four important hiatuses, though they do not precisely correlate with those in Well 1-SCS-3B. The Miocene planktonic foraminifera constitute a tropical/sub-tropical assemblage. In contrast, the Pliocene yielded scarce species associated with subantarctic water masses, suggesting that the Malvinas Current had reached the area by then, but it was not a

controlling factor concerning paleoenvironmental conditions.

Anjos-Zerfass et al. (2014) used strontium isotope ratios to identify hiatuses in the Oligocene and Miocene of the Pelotas Basin. Most of these were related to unconformities and coincided with those hiatuses identified by Anjos and Carreño (2004). However, Anjos-Zerfass et al. (2014) concluded that a hiatus in the early–late Oligocene hiatus reflected a maximum flooding surface. No such condensed sections were noted in the Miocene sections examined by Anjos-Zerfass et al. (2014).

Here we examine the timing of maximum transgressions (maximum floods) in the offshore Pelotas Basin. To do so, we use benthic foraminifera in Well 1-SCS-3B, drilled on the Florianópolis Platform, Pelotas Basin, in the State of Santa Catarina, Brazil (28º29'34.18" S, 47º29'10.8" W; present water depth ~200 m).

## MATERIALS AND METHODS

In this study, we use the samples of well cuttings from Well 1-SCS-3B studied for planktonic foraminifera by Anjos and Carreño (2004). As noted by Loboziak et al. (2005) and Jones (2014), of all types of samples recovered from wells, cuttings are the least desirable, caving of material from higher in the well into lower sections causing problems of stratigraphic mixing. Olson and Thompson (2005) recorded that not only do drilling fluids obscure and dilute the true sample volumes of well-cutting samples, but those drilling-fluid additives may also damage microfossils fossils by chemical reactions. Unfortunately, for Well 1-SCS-3B, cuttings are the only available source of micropaleontological data. Nevertheless, they can provide valuable data. Orndorff and Culver (1998) studied the Early Miocene age upper part of the Anahuac Formation of Louisiana, USA, using 109 rotary cuttings samples, each representing a ca. 10 m interval. Despite potential problems from caving, they were able to identify a general up-well shallowing trend punctuated by some possible flooding surfaces. However, as is the case with Well 1-SCS-3B, the lack of magnetostratigraphic and seismic control precluded the identification of sequence boundaries and correlation of maximum flooding surfaces with sea-level cycle charts. Here we concentrate on identifying possible maximum flooding surfaces in the

earlier Neogene of Well 1-SCS-3B and placing them within the biostratigraphic scheme of Anjos and Carreño (2004).

Given the damage from drilling (breakage) and drilling fluids (dissolution), we were able to identify only to genus level, despite the availability of local taxonomic papers (Marengo, 2015, Finger, 2013, Sprechmann, 1978). Dissolution had affected, for example, the surfaces of *Lenticulina* spp., rendering them opaque (cf. Murray, 1967) and making it challenging to identify species with confidence. This was especially so in the oxidized parts of the section. Pekar et al. (2001) found that, in Oligocene of the North American Atlantic passive margin, condensed sections and flooding surfaces are characterized by the peak abundance of uvigerinids, which led to a decrease in biodiversity. We use peaks of *Uvigerina* + *Trifarina* to identify such possible flooding surfaces, and measure diversity using the Shannon function H ( = $-\Sigma p_i \times \ln(p_i)$, in which $p_i$ is the proportional abundance of the *i*th genus). For details of H, see Hayek and Buzas (2013).

We use the benthic foraminiferal high productivity index (BFNI) of Martins et al. (2007) as a proxy for the organic carbon flux, where the BFNI is the sum of the proportions of *Bolivina, Bulimina*, and *Uvigerina*. The percentage of the benthic assemblage as serial tests (defined as $P_{se:sp} = N_{se}/(N_{se} + N_{sp}) \times 100$, in which $N_{se}$ and $N_{sp}$ are the numbers of serial and spiral [= planispiral + trochospiral] tests respectively), has been used as a potential indicator of diminished ventilation (Murray, 2006) and as an indicator of the redox state of the sediments (Tetard et al., 2017). Here we examine the pattern of $P_{se:sp}$ through our Neogene section in Well 1-SCS-3B. All calculations were made using the PAST paleontological freeware of Hammer et al. (2001), version 4.01.

## RESULTS

A total of 7942 benthic foraminiferal specimens were recovered from the samples. These were placed in 89 taxa (primarily genera), of which 39 were rare, being represented by < 4 specimens, and 21 were singletons. Indeterminate agglutinated taxa comprised 52 specimens only (0.6% of total recovery), while indeterminate uniserial chambers formed only 69 specimens (0.9%). Total recovery was dominated by *Cibicidoides* (23.9%; principally, *C.* cf. *coryelli* [~12%

of total recovery] and *C. pachyderma* [~9%]) with lesser *Uvigerina* (15.6%; especially *U. parvula*) (Figure 2). Genera forming >5% of the total recovery each were: *Bulimina* (7.6%; primarily *B. striata mexicana*), *Siphonina* (7.5%; *S. tenuicarinata* only), *Bolivina* (7.4%) and *Lenticulina* (6.5%). Of the total recovery, 4759 specimens (59.9%) had spiral (trochospiral and planispiral) morphologies, including such globose genera as *Globocassidulina* and *Sphaeroidina*. A further 3120 specimens (39.3%) had serial (elongate) morphologies. The small remainder was either unilocular genera or indeterminate agglutinants.

Uvigerinids ranged from 0–69% of each sample ($\overline{x}$ = 15.8%), with a pronounced peak in relative abundance between 900–945 m depth (Figure 2A). The Shannon function ranged from H = 1.19–2.71 ($\overline{x}$ = 2.23, s.d. = 0.33), with particularly low values between 900–975 m depth (which encompasses the section with peak uvigerinids), and at the top of the studied section at 360–375 m depth (Figure 3A). The correlation between the transformed proportions of total uvigerinids [ln(x + 1)] and H was both significant and negative (r = –0.664, *p* < .0001, n = 29).

Among the remaining genera, *Cibicidoides* showed peaks in relative abundance both above and below the peak in uvigerinids but also showed a marked decline in percentage abundance towards the top of the section (Figure 2B). *Cibicidoides pachyderma* (1080–1235 m depth) was most abundant in the lower part of the studied section, and *C.* cf. *coryelli* in the upper part (360–855 m depth). There was a significant correlation between the transformed proportions of the assemblages as *Cibicidoides* and uvigerinids (r = –0.493, *p* = .007, n = 29). A peak in *Bulimina* (48.4–58.6% per sample) occurred immediately below the peak in uvigerinids, at 960–1005 m depth (Figure 2C), while *Bolivina* peaked both above and below the peak in uvigerinids, and towards the top of the section (Figure 2D). *Sphaeroidina* (represented by *S. bulloides*), showed a remarkable distribution, though forming at most only ~5% of any sample. It occurred principally between 780–1110 m depth, with a minimal increase also in the uppermost sample (Figure 2E). *Siphonina* (represented by *S. tenuicarinata*) increased in abundance from ~0.5–30% per sample between 900–780 m depth, immediately above the peak in uvigerinids (Figure 2F).

The BFNI ranged from 0.024–0.779 ($\overline{x}$ = 0.331, s.d. = 0.216) (Figure 3B). The graphical analysis showed that the values were approximately normally distributed with no outliers. The values reached a maximum between 900–975 m depth, coincident with the peak in uvigerinids, and at the top of the studied section between 360–420 m. The percentage serial specimens ($P_{se:sp}$) ranged between 8.9–83.8% ($\overline{x}$ = 43.7%, s.d. = 20.4). The wide range in the percentage of serial specimens reflected the abundance of serial genera not included in the calculation of the BFNI. As with the BFNI, values showed maxima between 900–975 m and 360–420 m, but with a peak also at 1050–1065 m (Figure 3C). The correlation between suitably transformed values of the BFNI and $P_{se:sp}$ was thus strongly significant (r = 0.936, *p* < .00001, n = 29).

## DISCUSSION

Anjos and Carreño (2004) noted the occurrence of some caving of planktonic foraminifera within Well 1-SCS-3B. They did not quantify its extent; they aimed to correlate the Neogene succession with the zonal scheme of Bolli and Saunders (1985) using stratigraphic tops of planktonic foraminiferal species. No extraction and deletion of caved benthic foraminiferal specimens are possible within our dataset, many of the species found in Well 1-SCS-3B ranging biostratigraphically throughout the entire Neogene (Bolli et al., 1994, van Morkhoven et al., 1986, Holbourn et al., 2013). Thus, we record only the broadest of Neogene benthic foraminiferal trends and events in the studied sedimentary record. A peak in the abundance of uvigerinids was noted between 900–945 m depth within the well. The more-or-less distinct occurrences of *Cibicidoides* cf. *coryelli* above this peak and *C. pachyderma* below allow us to be confident that caving has not distorted benthic foraminiferal signals in the studied samples. The second interval of low H occurred at the top of the section examined.

Some remarks can be made regarding paleodepth using depth ranges provided by van Morkhoven et al. (1986) and Holbourn et al. (2013). *Cibicidoides pachyderma*, which has its maximum abundance near the base of the studied section, is considered an upper bathyal species (Holbourn et al., 2013) primarily though it has been recorded over a more extensive depth range (van Morkhoven et al., 1986). *Uvigerina*

*parvula* was initially described from upper bathyal depths (309 m) and was noted by Cushman (1923) to be most abundant at such depths. *Sphaeroidina bulloides*, the high abundances of which occurred above and below the peak in uvigerinids, is a neritic to abyssal species. However, *Siphonina tenuicarinata*, which had its maximum abundance above the uvigerinids peak, is an outer neritic to the middle bathyal taxon. We conclude that the studied Neogene section in Well 1-SCS-3B was deposited between the outer neritic and upper bathyal paleodepths. Inner neritic *Amphistegina* and *Discorbis rosea*, recorded in the onshore Pelotas Basin by Sprechmann (1978), were not found in the analyzed samples.

The uvigerinid peak at 900–945 m marks a possible flooding surface or condensed section within the *Globorotalia mayeri* Zone. This peak is associated with low values of the Shannon Function H and peaks in the BFNI and $P_{se: sp}$. This is coincident with the latest EPT of Marengo (2015). However, it is challenging to discern the entire EPT in Well 1-SCS-3B, as its commencement during the *Globigerinatella insueta* Zone coincides with a hiatus in the well. The BFNI maximum reflects the association of uvigerinids with a high nutrient flux (Altenbach et al., 1999; Wilson and Hayek, 2017), *Uvigerina* spp. preferring a continuous flux of organic matter (Nomaki et al., 2006). The decline in *Cibicidoides* towards the top of the section, coupled with (1) increases in the relative abundances of *Sphaeroidina* and *Bolivina* in the uppermost two samples, (2) an associated decrease in H, and (3) peaks in the BFNI and $P_{se: sp}$, mark some degree of transgression during the Lower Pliocene *Globigerinoides trilobus fistulosus* Zone, perhaps leading towards a younger possible flooding surface.

This latter maximum flood is somewhat younger than the 1st T of Carreño et al. (1999), which attained maximum transgression during the *Globorotalia acostaensis* and *Globorotalia humerosa* Zones. This indicates that times of maximum flooding varied throughout the Pelotas Basin. This may, in turn, indicate that the maximum floods detected at different sites within the basin reflect not global eustatic events, but tectonic interactions between the Nazca and South American plates affecting different parts of the basin at different times. The shallower, *Cibicidoides*-rich interval above the uvigerinids peak, might reflect the filling of accommodation with sediment.

Of the three hiatuses found by Anjos and Carreño (2004), the one at 510 m depth occurred above the uvigerinid peak, while the two at 1200 m and 1230 m are situated below that peak. All the hiatuses are associated with abundant *Cibicidoides*. Anjos-Zerfass et al. (2014) suggested that areas of the Pelotas Basin may, by the lifting of the Florianópolis Platform, have been exposed during regressive events. However, this appears unlikely given the ecology of *Cibicidoides*. Schoenfeld (2002) noted that *Cibicidoides* spp. in the Gulf of Cadiz live on elevated substrates subject to the current enhanced action. The distribution of *Cibicidoides* throughout the sedimentary section in Well 1-SCS-3B indicates that bottom current strength varied over time, it being depressed around the peak in uvigerinids and at the top of the section. Such stagnation is expected at times of maximum transgression (Catuneanu et al., 2011). Elsewhere, the distribution of *Cibicidoides* suggests current action was enhanced and that conditions were somewhat oligotrophic. It is possible that current action became strong enough to cause non-deposition or to erode bottom sediment, leading to the development of the hiatuses. Similar causes have been invoked for hiatuses in the Miocene deep-sea that coincided with cooling (Barron and Keller, 1982). The reason for the intervals with oxidized foraminiferal tests in Pelotas Basin is unclear. However, we note that such tests are currently widespread on continental shelves around the world (Emery, 1968) and are relict, having been deposited during an early Holocene transgression (Wilson, 2010). Further work, using better quality samples, seismic sections, and well logs, is needed to assess the sequence stratigraphic significance of the oxidized intervals in 1-SCS-3B and elsewhere in the Pelotas Basin.

## CONCLUSIONS

Benthic foraminifera of the Pelotas Basin Neogene have previously been studied using onshore wells, and *Amphistegina* sp. and *Discorbis rosea* reflect how these sections were deposited nearshore. Those in ditch cuttings from the offshore Well 1-SCS-3B, however, reflect deposition at outer neritic to upper bathyal paleodepths with moderate to intense current action, as indicated by the abundance of the genus *Cibicidoides*. Hiatuses in the Well, which coincide with abundant *Cibicidoides*, are concluded to have resulted from either non-deposition

or erosion due to current scouring. A significant peak in uvigerinids within the *Globorotalia mayeri* Zone marks a possible flooding surface or condensed section with possible stagnant bottom water and high nutrient flux. Within the Lower Pliocene *Globigerinoides trilobus fistulosus* Zone, there occurs a decline in *Cibicidoides* coupled with higher relative abundances in *Sphaeroidina* and *Bolivina*, an associated decrease in the Shannon Function H, and an increase in nutrient flux. This is concluded to mark some degree of transgression during this time, perhaps leading towards a younger possible flooding surface.

The timing of maximum flooding identified in Well 1-SCS-3B differs from that found elsewhere in Pelotas Basin. We conclude that the maximum floods were therefore not eustatically induced, though examining core samples from future wells will undoubtedly recover such a signal. The broader trends recorded here instead indicate that the Pelotas Basin had a complex tectonic evolution, with the timing of subsidence differing from one place to another. We suggest that this subsidence was a distal response to plate tectonic interactions between the South American and Nazca Plates.

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## AUTHOR CONTRIBUTIONS

B.W.: Data curation, investigation, methodology, visualisation, writing (original draft), writing (review and editing).

J.C.C: Project administration, resources, conceptualization, data curation, visualization, writing (review and editing).

L.C.H.: Methodology, formal analysis, investigation, writing (original draft), writing (review and editing).

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