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Late Paleocene to Initial Eocene Thermal Maximum (IETM) Foraminiferal Biostratigraphy and Paleoecology of the Dahomey Basin, Southwestern Nigeria

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Initial Eocene Thermal Maximum
Biostratigraphy
Paleoecology
Foraminifera
Paleocene
Nigeria

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Foraminiferenbiostratigraphie und Paläoökologie vom späten Paläozän bis zum Initial Eocene Thermal Maximum (IETM) im Dahomey-Becken, südwestliches Nigeria

Zusammenfassung

Aus der Oshosun-Formation des Dahomey-Beckens ließen sich hervorragend erhaltene (glasig durchscheinende Schalen) Foraminiferenassoziationen gewinnen, die eine genaue biostratigraphische Einstufung (planktische Foraminiferenzonen P4b bis P5) erlauben und zum ersten Mal das Aufspüren des Beginns der Carbon Isotope Excursion (CIE) an der Paläozän-Eozängrenze in der Golf-von-Guinea-Region ermöglichen. Basierend auf Faunenzählungen haben wir Häufigkeiten für planktische und benthische Foraminiferen berechnet und Paläowassertiefen, Oberflächenproduktivität, Nährstoffanlieferung und Bodenwassersauerstoffgehalt abgeschätzt. Die Sedimentation begann im mittleren neritischen Bereich, gefolgt von einer Vertiefung des Ablagerungsraumes bis hinunter zur Schelfkante und einer nachfolgenden Verflachungsphase. Die Foraminiferenhäufigkeiten schwanken zwischen 0,05 und 24,35 ind/g für planktische sowie 0,20 und 32,32 ind/g für benthische Taxa. Diese Häufigkeiten sind sehr gering im Vergleich mit ozeanischen Bereichen. Benthische Assoziationen weisen auf eine gut mit Sauerstoff versorgte Zone P4b (dominiert von *Lenticulina-Gyroidinoides)* mit zwischenzeitlichen dysoxischen Phasen *(Bulimina*-dominiert) hin. Ein erster starker Abfall des Bodenwassersauerstoffgehalts zusammen mit leicht erhöhter Nahrungszufuhr ereignete sich während der unteren P4c und hielt bis zum P4/P5-Übergang an, als der Sauerstoffgehalt wieder zunahm. Die Phase unmittelbar bevor dem Beginn des IETM zeichnet sich durch eine starke Dominanz der Produktivitätsanzeiger *(Gavelinella)* und erhöhte Foraminiferenhäufigkeit aus. Die benthische IETM-Assoziation ist durch Dominanz von dysoxischen Gattungen *(Bulimina, Nonionella)* und deutlichen Rückgängen bei planktischen und benthischen Foraminiferenhäufigkeiten gekennzeichnet. Dieses zeigt reduzierte Oberflächenproduktivitäten und dysoxische Bodenwasserbedingungen an und wurde möglicherweise durch reduzierte vertikale Durchmischung und/oder verstärkte Schichtung der Wassersäule verursacht.

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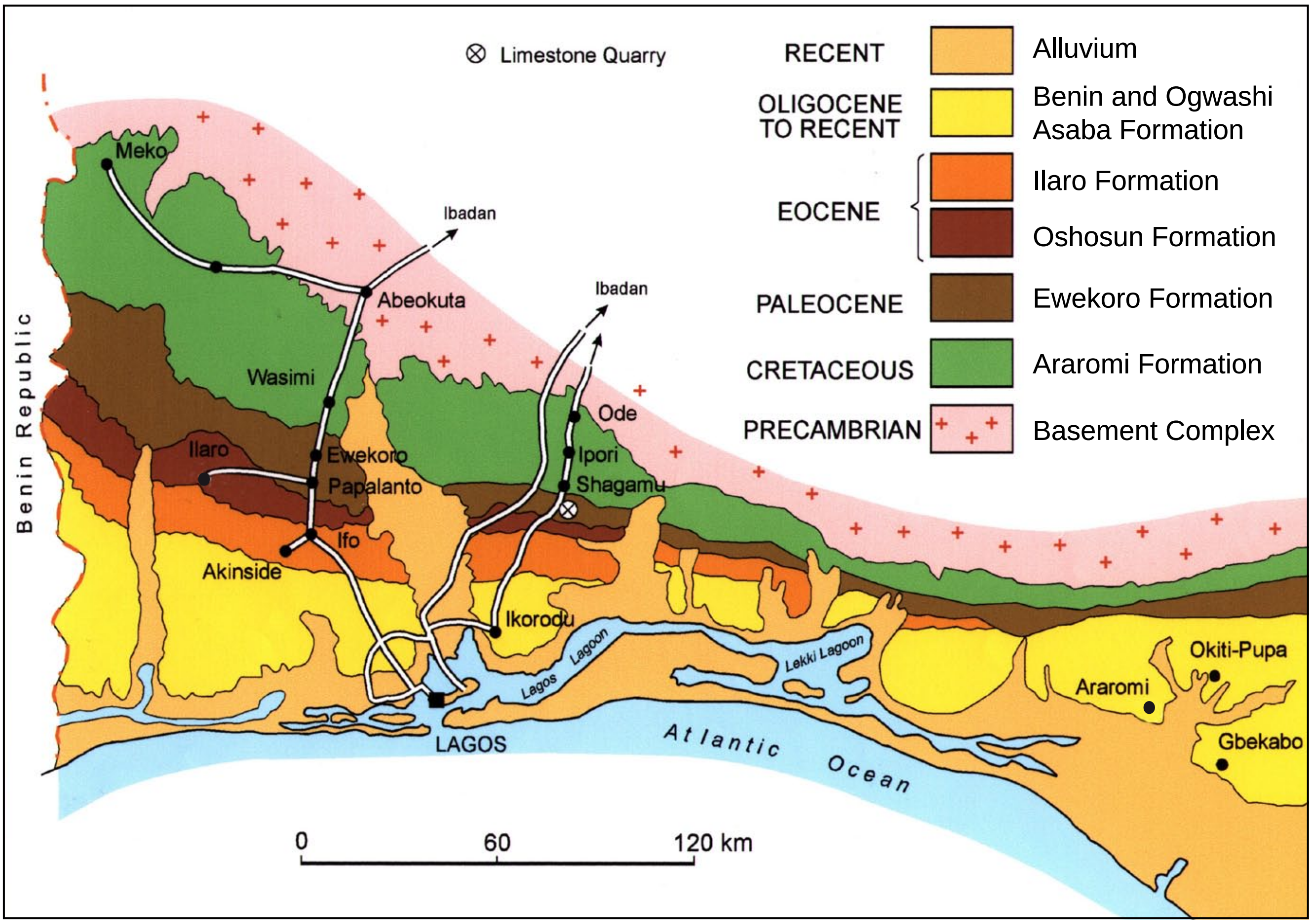
Abstract

The Oshosun Formation of the Dahomey Basin yielded excellently preserved (glassy) foraminiferal assemblages that allowed for detailed biostratigraphy (planktic foraminiferal zones P4b to P5) and the tracing of the onset of the Carbon Isotope Excursion (CIE) at the Paleocene-Eocene boundary in the Gulf of Guinea region for the first time. Based on assemblage counts, we calculated planktic and benthic foraminiferal abundances and inferred paleo-water depths, surface productivity, nutrient supply and bottom water oxygenation. Sedimentation started in a middle neritic environment, followed by a deepening down to the shelf break and a successive shallowing phase. Foraminiferal abundance varies between 0.05 and 24.35 ind/g for planktic and between 0.20 and 32.32 ind/g for benthic taxa and is very low if compared with oceanic settings. Benthic foraminiferal assemblages indicate a well oxygenized Zone P4b *(Lenticulina-Gyroidinoides* dominated) with intermittent short dysoxic phases *(Bulimina* dominated). A first sharp drop in bottom water oxygenation together with slightly increased food supply occurred during the lower P4c and lasted until the P4/P5 transition when oxygen supply increased. The immediate phase before the IETM onset is characterized by strong dominance of productivity indicators *(Gavelinella)* and increased foraminiferal abundance. The benthic IETM-assemblage shows the dominance of dysoxic *Bulimina* and *Nonionella* and strongly reduced planktic and benthic foraminiferal abundance. This indicates reduced surface productivity and dysoxic bottom water conditions, possibly caused by reduced vertical mixing and/or increased stratification of the water column.

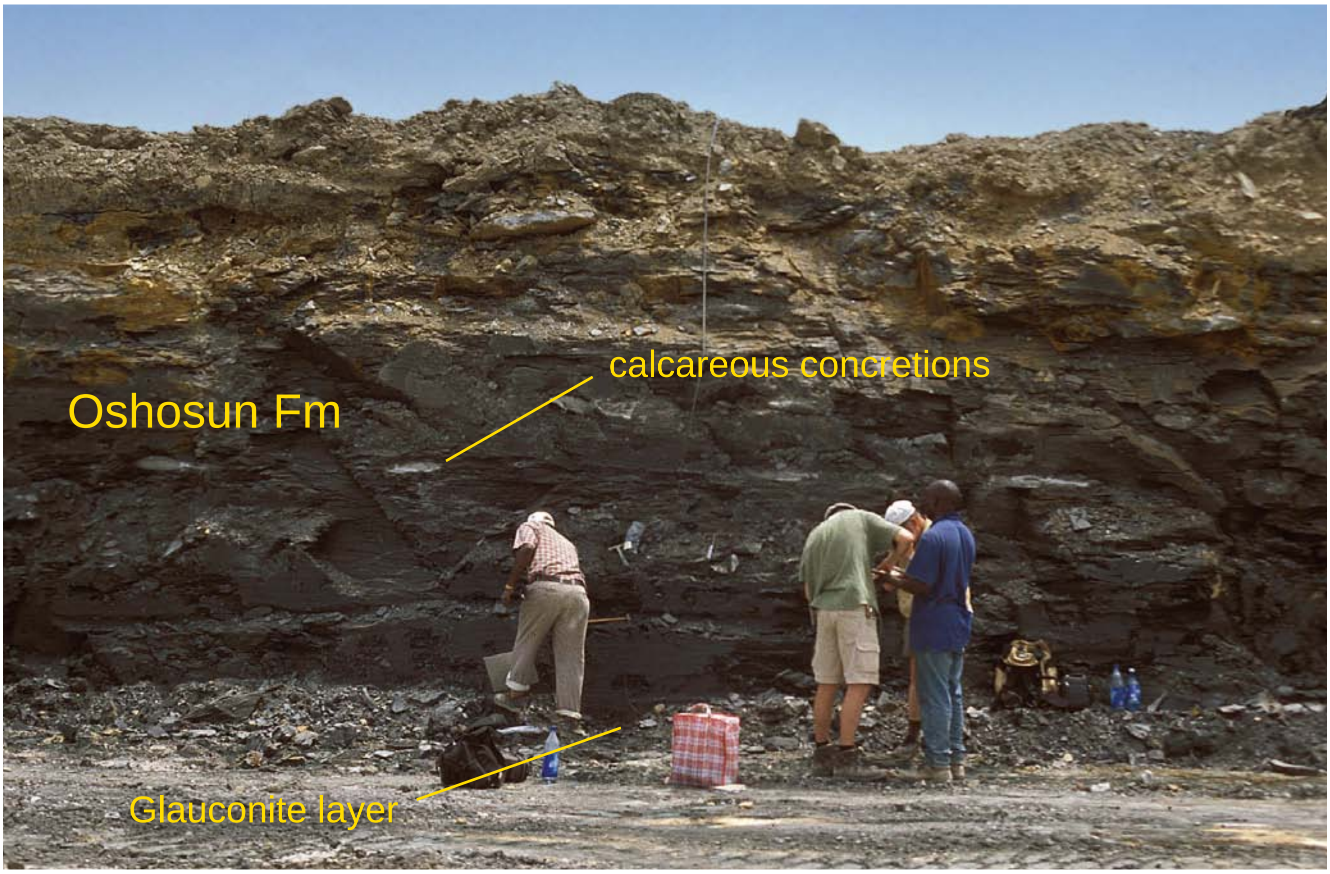
Introduction

The Paleocene-Eocene transition has been of special geoscientific interest in recent years. Paleoceanographic processes that occurred during this time interval include dramatic global warming (IETM or Paleocene–Eocene Thermal Maximum, PETM; e.g., Zachos et al., 2003; Sluijs et al., 2007), intensive black shale deposition (e.g., Speijer & Wagner, 2002; Pearson et al., 2007), and acidification of the ocean (e.g., Zachos et al., 2005). This event is thought to be caused by the rapid release of a large mass of ^{12}C-enriched carbon. As a source for the carbon release, a massive methane hydrate (clathrate) dissociation was suggested by Dickens et al. (1995). Alternatively, circum-Caribbean volcanism has been linked to the recorded environmental changes during the IETM (Bralower et al., 1997). There is growing evidence that the initial Carbon Isotope Excursion (CIE) was geologically instantaneous and was preceded by a brief period of surface water warming (e.g., Thomas et al., 2002; Sluijs et al., 2007). These events had severe impacts on communities on land as well as in the sea, e.g., extinction events and faunal turnovers. In the marine realm, changes of the foraminiferal assemblages were studied in sections from the deep ocean (e.g., Kennet & Stott, 1991; Thomas, 1998; Thomas, 2003) to neritic environments (e.g., Speijer et al., 1996, 1997; Alegret & Ortiz, 2006).

The Dahomey Basin in southwestern Nigeria became increasingly interesting in recent years due to its economic



Text-Fig. 1.
Geological map of the Dahomey embayment (Nigerian part) and location of section (Shagamu limestone quarry).



Text-Fig. 2.
Lower part of the Oshosun Formation exposed in the Shagamu limestone quarry.
People are standing on the underlying limestones of the Ewekoro Formation.

(hydrocarbon) potential. For many decades, most geoscientific research focused on the lithostratigraphy and tectonic framework of the basin and some on hydrocarbon potential. A few studies were dedicated to foraminiferal biostratigraphy and paleoecology. Previous works of Reyment (1966), Adegoke (1969, 1972, 1977), Adegoke et al. (1970, 1980), Petters & Olsson (1979), Petters (1980, 1982, 1983), Nwachukwu et al. (1992), and Adekeye (2005) have only discussed the stratigraphic occurrence and the taxonomy of foraminifera species in the basin. Quantitative analyses of foraminiferal assemblages and modern interpretations are still missing for the region. Several other contributions deal with various fossil groups occurring in rocks of the Paleocene to Eocene Oshosun Formation of southwestern Nigeria or its lateral equivalents. This includes e.g., ostracods (Okosun, 1989; Bio-Lokoto et al., 1998), pollen and spores (Bio-Lokoto et al., 1998; Bankole et al., 2007), dinoflagellates (Bankole et al., 2007) or calcareous nannofossils (Fernandes Alves, 2007).

The studied succession is located in the Shagamu Quarry of the West African Portland Cement Company located at Shagamu, southwestern Nigeria (Text-Fig. 1). Our study is based on the exposed sedimentary record in the quarry with special emphasis on the shales of the Oshosun Formation. The main objective of this contribution is to examine carefully the evidence of the foraminiferal record before and possibly during the IETM (or Paleocene–Eocene Thermal Maximum, PETM) in the basin for the first time. We also attempt to trace the paleoceanographic changes that influenced the region. Several sections were compiled to yield one composite section that spans the Paleocene–Eocene time interval. The lithofacies exposed at Shagamu include calcareous limestones and shales (Ewekoro Formation) overlain by dark grey to light grey shales (Oshosun Formation, Text-Fig. 2) and sandstones of the Ilaro Formation. Detailed descriptions of the lithofacies exposed in the Shagamu Quarry can be found in the works of Okosun (1990), Adekeye (2005), and Adekeye et al. (2005, 2007).

Material and Methods

During a field trip in March 2003, a continuous section covering all formations exposed in the Shagamu limestone quarry was measured and sampled. Here, we focus on the foraminiferal content of the black shales of the Oshosun Formation (17 samples). 600 g of sediment were disintegrated completely with hydrogen peroxide, washed over a 0.063-mm sieve, and finally air-dried. The residue was split into manageable subsamples (aliquots) and completely picked for foraminifera (Tables 1, 2). Previously picked specimens (for separate diploma thesis) were added and abundances (individuals per gram dry sediment) of complete assemblages were calculated (Tables 3, 4) for further interpretations. Accordingly, Table 3 and 4 contains more occurrences than Tables 1 and 2, in particular among planktic taxa.

Planktic foraminifera

Samples	*split*	*Acarinina* cf. *coalingensis*	*Acarinina* cf. *mckannai*	*Acarinina nitida*	*Acarinina soldadoensis*	*Chiloguembelina crinita*	*Chiloguembelina midwayensis*	*Globanomalina chapmani*	*Globanomalina pseudomenardii*	*Igorina albeari*	*Igorina tadjikistanensis*	*Morozovella acuta*	*Morozovella acutispira*	*Morozovella aequa*	*Morozovella apanthesma*	*Morozovella subbotinae*	*Morozovella velascoensis*	*Parasubbotina varianta*	*Subbotina cancellata*	*Subbotina triangularis*	*Subbotina velascoensis*	Sum planktic taxa
32	1													1								1
31	1													1								1
30	1			1		1																2
29	4				22	3		15		83	31	39		27	38	16				13		287
28	16			8	12	4	3	19	2	75	35	43		135	3	20		16		27	3	405
27	1									2				6	3					1		12
26	8			16	16	5	5	9	9	68	32	18		85	12			5		28	5	313
25	8			81	3	21		15	21	109	45	23		180	21			21		29	7	576
24	4			7	9	1	4	26	10	34	9	8		113	16			20		12	11	280
23	1			33	8	1	4	27	11	99	38	36	6	129	30			13		5	7	447
22	8	2		82	9	4	3	14	11	52	35	22	3	74	6			18		26	5	366
21	4	3		102	12	1		14	4	100	13	35	11	82	9		3	2		14	5	410
20	32	10		94	11	9	17	37	7	146	82	20	12	56	3			63		25	2	594
19	8	9		40	7			9		55	10	51	24	105	12		4			5	2	333
18	8	6		20	7	8		27	16	75	6	19	26	66	5			11		17		309
17	16		22					6	7	94	34	19	40	55	3				2	9		291
16	1	1		18				1		5	5											30

Tables 1 + 2.
Distribution of planktic and benthic foraminifera picked.

Benthic foraminifera

Samples	*split*	*Ammobaculites* cf. *expansus*	*Ammobaculites* sp.	*Bulimina midwayensis*	*Bulimina paleocenica*	*Bulimina thanetensis*	*Cibicidoides succedens*	*?Cibicidoides* sp.	*?Dentalina* sp.	*Epistominella minuta*	*Eponides pseudoelevatus*	*?Eponides* sp.	*Gaudryina* sp.	*Gavelinella pachysuturalis*	*Gyroidinoides* cf. *soldanii*	*Haplophragmoides excavatus*	*Haplophragmoides glabra*	*Haplophragmoides* sp. A	*Haplophragmoides* sp. B	*Lenticulina olokuni*	*Lenticulina pseudomamilligerus*	*Lenticulina* sp.	*Nonionina panamensis*	*Osangularia plummerae*	*?Recurvoides* sp.	*Saccammina* sp.	*Siphogenerinoides eleganta*	*Stilostomella* cf. *midwayensis*	*Stilostomella* cf. *plummerae*	*Tappanina selmensis*	*Textularia* cf. *midwayana*	*Trochammina globigeriniformis*	Sum benthic taxa
32	1										3					31		176					1										211
31	1				2	1										36		9															48
30	1					2					1					60		115		1												2	181
29	4				148	46								30		9		14		3	1		203									1	455
28	16				31	5				1				390		22		10		31	1		28										519
27	1				7									2		7				2			2										20
26	8				206	24					5	2		4		16		5		27	2		40										331
25	8				197	26					2			52	2	7		4		53	1		57	1									402
24	4			1	107	53					6	5		29		8		2		32			53			3							299
23	1				16	13					2			10	2	17		6		153	3		4										226
22	8				88	36								11		12		3		118	3		4	2									277
21	4				12	15	4				1	1		5	9	28		3		191	6												275
20	32			2	439	57		1			4	2		16	27	2		2		38	5		7	1									603
19	8			1	7	2	1								44	121				230	9				2								417
18	8			7	495	86	5		1		2	5		6	21	22				18	2		1		1				1		1		674
17	16		7	20	210	43	3					1	7		36	47		6	5	41		1	1	3	4		1	1					437
16	1	70	32	56	91	34	27		1	2	1	1	362	8	64	103	9	9	24	54	2			12	8				2	1			973

Samples	*Acarinina* cf. *coalingensis*	*Acarinina* cf. *mckannai*	*Acarinina nitida*	*Acarinina soldadoensis*	*Chiloguembelina crinita*	*Chiloguembelina midwayensis*	*Globanomalina chapmani*	*Globanomalina pseudomenardii*	*Igorina albeari*	*Igorina tadjikistanensis*	*Morozovella acuta*	*Morozovella acutispira*	*Morozovella aequa*	*Morozovella apanthesma*	*Morozovella subbotinae*	*Morozovella velascoensis*	*Parasubbotina varianta*	*Subbotina cancellata*	*Subbotina triangularis*	*Subbotina velascoensis*	Sum planktic taxa
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,002
31	0	0	0	0	0	0	0	0	0	0	0	0	0,002	0	0	0	0	0	0	0	0,002
30	0	0	0,002	0	0,002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,003
29	0	0	0,032	0,158	0,022	0	0,1	0	0,168	0,21	0,298	0	0,228	0,253	0,107	0	0	0	0,09	0	1,668
28	0	0	0,26	0,362	0,11	0,08	0,512	0,057	0,155	0,933	1,213	0	3,718	0,08	0,538	0	0,427	0	0,732	0,108	9,285
27	0	0	0,005	0,007	0,002	0,003	0,002	0	0,042	0,002	0,04	0	0,095	0,005	0	0	0	0	0,013	0	0,217
26	0	0	0,237	0,267	0,068	0,068	0,122	0,12	0,175	0,453	0,295	0	1,225	0,16	0	0	0,067	0	0,398	0,067	3,733
25	0	0	1,115	0,058	0,282	0	0,222	0,282	0,205	0,6	0,338	0	2,438	0,298	0	0,007	0,28	0,002	0,405	0,093	6,653
24	0	0	0,057	0,067	0,007	0,027	0,173	0,067	0,057	0,06	0,065	0	0,753	0,107	0	0	0,133	0	0,08	0,073	1,725
23	0	0	0,068	0,018	0,005	0,007	0,055	0,042	0,178	0,063	0,118	0,022	0,25	0,088	0	0,003	0,022	0	0,03	0,012	0,982
22	0,027	0	1,052	0,137	0,053	0,045	0,19	0,147	0,087	0,492	0,33	0,04	1,013	0,087	0	0	0,24	0	0,357	0,067	4,362
21	0,02	0	0,703	0,122	0,007	0,002	0,093	0,028	0,167	0,087	0,302	0,073	0,57	0,073	0	0,02	0,013	0,002	0,093	0,033	2,408
20	0,533	0	5,037	0,638	0,48	0,912	1,98	0,377	0,243	4,405	1,113	0,64	3,003	0,163	0	0	3,363	0,025	1,333	0,107	24,35
19	0,12	0	0,562	0,12	0	0	0,125	0	0,145	0,152	0,728	0,32	1,483	0,18	0	0,053	0	0	0,07	0,027	4,085
18	0,08	0	0,295	0,11	0,107	0	0,373	0,213	0,222	0,088	0,307	0,357	0,97	0,067	0	0	0,147	0	0,235	0	3,57
17	0	0,587	0,052	0,003	0	0	0,162	0,187	0,197	1,002	0,572	1,09	1,538	0,085	0	0,003	0,003	0,053	0,24	0	5,773
16	0,002	0	0,032	0	0	0	0,002	0	0,01	0,008	0	0	0	0	0	0	0	0	0	0,002	0,055

Table 3.
Abundances (ind/g) of planktic foraminifera.

We followed the taxonomic concepts of Olsson et al. (1999; for planktic foraminifera) and of Reyment (1966), Petters (1979, 1982), Tjalsma & Lohmann (1983), Revets (1996), Speijer et al. (1996; for benthic foraminifera). A complete list of all identified taxa is provided in Appendix A.

The calcareous foraminiferal shells are glassy (only in sample SH 16 some shells show a milky appearance) and in some cases are filled with pyrite, in particular Buliminids. This excellent preservation of the foraminiferal assemblages indicates the complete absence of diagenetic alteration of the assemblages and allows for very reliable stable isotope measurements.

Stable carbon isotope measurements on organic matter were made for bulk rock samples at NIOZ, Netherlands. For three selected foraminiferal taxa (benthic: *Bulimina paleocenica*, planktic: *Morozovella acuta* and *Acarinina* spp.), δ^{13}Ccarb values were measured at Leibniz Laboratory in Kiel, Germany (Table 5). Standard sample processing was applied at both institutions.

Results

The samples yielded a number of planktic foraminiferal species (Text-Fig. 3) that were used for stratigraphic classification of the rocks and for paleoecological interpretations. Based on their occurrences, we were able to apply a planktic foraminiferal zonation as a time frame that was further refined by δ^{13}C records (Text-Fig. 4). The distribution of benthic taxa (Text-Fig. 5) is mainly used for paleoecological interpretations. The combination of planktic and benthic assemblage counts gives good insights into the paleoceanographic processes that governed its distribution in the Gulf of Guinea during the investigated time interval.

Stratigraphy

Several lines of evidence were followed in order to achieve maximum stratigraphic precision and age control. These lines are 1) biostratigraphy based on planktic foraminifera and stable carbon isotope stratigraphy based on 2) δ^{13}C values of organic matter from bulk rock samples, and 3) δ^{13}C values of calcareous matter from selected planktic and benthic foraminifera species.

The Paleocene-Eocene boundary is defined by the onset of a pronounced negative carbon isotope excursion (CIE, see e.g., Luterbacher et al., 2004). The boundary itself falls within planktic foraminifera Zone P5 (Olsson et al., 1999; Berggren & Pearson, 2006) and can't be traced by the exclusive study of planktic foraminifera.

Biostratigraphy

Three planktic foraminiferal zones according to the definitions and range charts published in Olsson et al. (1999) and Berggren & Pearson (2006) were recognized (Text-Fig. 4). Zone P4b covers the lower part of the exposed

Samples	*Ammobaculites cf. expansus*	*Ammobaculites sp.*	*Bulimina midwayensis*	*Bulimina paleocenica*	*Bulimina thanetensis*	*Cibicidoides succedens*	*?Cibicidoides* sp.	*?Dentalina* sp.	*Epistominella minuta*	*Eponides pseudoelevatus*	*?Eponides* sp.	*Gaudryina* sp.	*Gavelinella pachysuturalis*	*Gyroidinoides cf. soldanii*	*Haplophragmoides excavatus*	*Haplophragmoides glabra*	*Haplophragmoides* sp. A
32	0	0	0	0	0	0	0	0	0	0,005	0	0	0	0	0,052	0	0,293
31	0	0	0	0,003	0,002	0	0	0	0	0	0	0	0	0	0,06	0	0,015
30	0	0	0	0	0,003	0	0	0	0	0,002	0	0	0	0	0,1	0	0,192
29	0	0	0	1,182	0,325	0	0	0	0	0	0	0	0,208	0	0,06	0	0,093
28	0	0	0	0,993	0,133	0	0	0	0,027	0	0	0	10,48	0	0,482	0	0,267
27	0	0	0	0,015	0,002	0	0	0	0	0	0	0	0,017	0	0,022	0	0
26	0	0	0	2,92	0,323	0	0	0	0	0,067	0,027	0	0,053	0	0,23	0	0,067
25	0	0	0	2,868	0,39	0	0	0	0	0,027	0	0	0,693	0,027	0,082	0	0,053
24	0	0	0,007	0,88	0,353	0	0	0	0	0,04	0,033	0	0,193	0	0,04	0	0,013
23	0	0	0	0,102	0,025	0	0	0	0	0,003	0	0	0,017	0,003	0,025	0	0,01
22	0	0	0	1,407	0,513	0	0	0	0	0,002	0	0	0,147	0	0,147	0	0,04
21	0	0	0	0,202	0,1	0,027	0	0	0	0,007	0,007	0	0,033	0,06	0,21	0	0,02
20	0	0	0,107	23,6	3,052	0	0,053	0	0	0,213	0,107	0	0,853	1,448	0	0	0,107
19	0	0	0,013	0,123	0,028	0,013	0	0	0	0	0	0	0	0,587	2,973	0	0,003
18	0	0	0,093	6,943	1,2	0,067	0	0,013	0	0,027	0,067	0	0,082	0,287	0,302	0	0
17	0	0,187	0,533	5,852	1,167	0,08	0	0	0	0	0,027	0,187	0,002	0,96	1,255	0	0,168
16	0,117	0,053	0,097	0,167	0,07	0,047	0	0,002	0,003	0,002	0,002	0,725	0,013	0,12	0,175	0,015	0,015

Oshosun Formation. The lower boundary to Zone P4c is defined by the first occurrence of *Acarinina soldadoensis*. Specimens assigned to this species occur however near the base of the investigated section. Furthermore, the extinction level of *Morozovella acutispira* is shortly after the P4b/P4c boundary. Therefore, we located this boundary at Shagamu below the last occurrence of *M. acutispira*, i.e., between samples SH 22 and SH 23 (Text-Fig. 4). Zone P5 is defined as the interval between the last appearance datum (LAD) of *Globanomalina pseudomenardii* and the LAD of *Morozovella velascoensis*. In addition to this, the first appearance of *Morozovella subbotinae* is at the base of Zone P5. At Shagamu, *G. pseudomenardii* and *M. subbotinae* occur both in sample SH 28 and the occurrence of *G. pseudomenardii* became incomplete in its upper range. Therefore, we assume the P4/P5 boundary to be below the first occurrence of *M. subbotinae*, i.e., around sample SH 27.

	δ^{13}Ccalc						δ^{13}Corg
sample	*B .paleocenica*	error	*Acarinina* spp.	error	*M. acuta*	error	bulk rock
32							-26,0
31							-26,3
30							-26,2
29	-4.003	0.018	1.822	0.013	2.079	0.015	-25,7
28	-1.973	0.015	2.99	0.009	3.291	0.124	-25,2
27			3.444	0.043			-25,0
26	-1.937	0.009	3.222	0.01	4.053	0.01	-25,1
25	-1.616	0.017	3.671	0.03	3.87	0.075	-25,1
24	-1.643	0.009	3.087	0.027	3.443	0.058	-25,1
23	-1.943	0.019	2.977	0.194	3.488	0.017	-25,4
22	-2.098	0.012	3.157	0.021	3.679	0.023	-25,1
21	-2.124	0.013	3.160	0.009	3.881	0.019	-25,2
20	-2.022	0.016	2.971	0.08	4.273	0.014	-25,1
19			3.44	0.035	4.002	0.014	-24,7
18	-1.389	0.084	3.322	0.043	3.719	0.017	-24,3
17	-1.159	0.029	3.28	0.007	3.676	0.012	-25,2
16							-25,4

Table 5.
Stable carbon isotope ratios of selected foraminiferal taxa (δ^{13}Ccarb) and of bulk rock samples (δ^{13}Corg).

Stable Carbon Isotope Stratigraphy

The onset of the CIE at the Paleocene-Eocene boundary is well expressed in the four δ^{13}C curves shown in Text-Fig. 4. Due to the strong weathering that decalcified the upper part of the investigated section, the main part of the CIE can only be demonstrated for the organic matter. However, this curve shows the CIE to be present at Shagamu and allows, in combination with the strong negative shifts within the planktic and benthic calcareous records, the exact fixation of the Paleocene-Eocene boundary.

Paleoecology

Foraminiferal Abundance

The foraminiferal abundance (Text-Fig. 6, Tables 3, 4), i.e., individuals per gram dry sediment, varies strongly between 0.05 and 24.35 ind/g for planktic and between

Haplophragmoides sp. B	*Lenticulina olokuni*	*Lenticulina pseudomamilligera*	*Lenticulina* sp.	*Nonionina panamensis*	*Osangularia plummerae*	*?Recurvoides* sp.	*Saccammina* sp.	*Siphogenerinoides eleganta*	*Stilostomella* cf. *midwayensis*	*Stilostomella* cf. *plummerae*	*Tappanina selmensis*	*Textularia* cf. *midwayana*	*Trochammina globigeriniformis*	Sum benthic taxa
0	0,002	0	0	0,002	0	0	0	0	0	0	0	0	0	0,353
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,08
0	0,008	0	0	0	0	0	0	0	0	0	0	0	0,003	0,308
0	0,023	0,007	0	1,458	0	0	0	0	0	0	0	0	0,007	3,363
0	0,928	0,028	0	0,752	0	0	0	0	0	0	0	0	0	14,085
0	0,133	0,002	0	0,008	0	0	0	0	0	0	0	0	0	0,198
0	0,432	0,038	0	0,537	0	0	0	0	0	0	0	0	0	4,693
0	0,783	0,013	0	0,78	0,013	0	0	0	0	0	0	0	0	5,73
0	0,23	0	0	0,353	0	0	0,02	0	0	0	0	0	0	2,163
0	0,452	0,007	0	0,007	0	0	0	0	0	0	0	0	0	0,65
0	1,675	0,042	0	0,053	0,027	0	0	0	0	0	0	0	0	4,052
0	1,43	0,045	0	0	0	0	0	0	0	0	0	0	0	2,14
0	2,09	0,267	0	0,373	0,053	0	0	0	0	0	0	0	0	32,32
0	3,283	0,125	0	0	0	0,027	0	0	0	0	0	0	0	7,177
0	0,285	0,032	0	0,013	0	0,013	0	0	0	0,013	0	0,013	0	9,45
0,133	1,195	0,005	0,027	0,027	0,08	0,107	0	0,027	0,027	0	0	0	0	12,04
0,040	0,153	0,048	0	0	0,02	0,013	0	0	0	0,003	0,002	0	0,002	1,903

Table 4.
Abundances (ind/g) of benthic foraminifera.

0.20 and 32.32 ind/g for benthic taxa. The highly similar curves show unidirectional, coeval fluctuations. This indicates strong dependence of both groups from the same basic source of food, i.e., primary surface productivity. Abundances of planktic and benthic foraminifera can be used to estimate changes in surface (paleo-) productivity as foraminifera depend either on prey living in the surface layer (planktic species; e.g., Hemleben et al., 1989) or on organic rain that reaches the seafloor (benthic species; e.g., van der Zwaan et al., 1999; Gooday, 2003). Phases of high abundances in foraminifera are therefore interpreted as periods of increased surface productivity. Foraminiferal abundance at Shagamu is very low if compared with oceanic settings in the Southern Ocean (Thomas, 2003).

Percentage Planktic Foraminifera and Paleo-Water Depth

Paleo-water depth can be estimated by using ratios of planktic to benthic foraminifera (or percent planktic foraminifera). Proportions of planktic foraminifera vary between 3 and 60 %. The succession (Text-Fig. 6) shows a gradual increase in percentages from the base of the section to the lower part of Zone P4c (max.) and a gradual decrease afterwards towards the IETM (33 %). Interpreted as influenced by paleo-water depth only and compared with modern environments (e.g., van der Zwaan et al., 1990), this would indicate an increase in depth from less than 50 m to ca 300 m and a decrease afterwards to ca 120 m. In other words, sedimentation started in a middle neritic environment, followed by a deepening down to the shelf break and a successive shallowing phase.

High proportions of agglutinated taxa seem to represent shallower environments (Text-Fig. 6) or reduced paleo-productivity as this ratio correlates negatively with foraminiferal abundance.

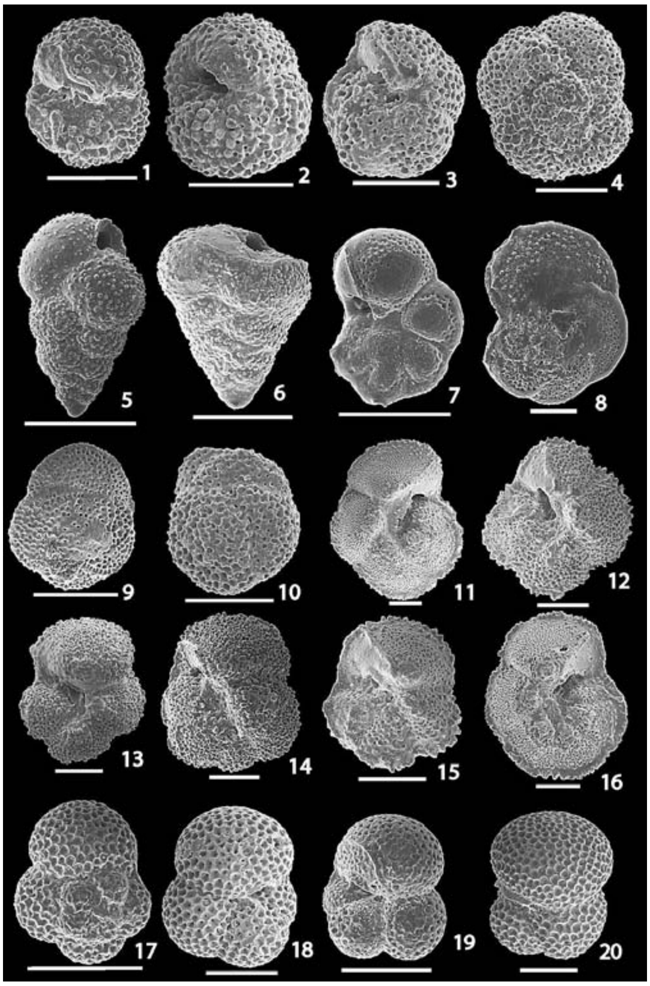
Foraminiferal Habitats

Planktic Foraminifera

Luciani et al. (2007, with further references therein) gave an overview on life strategies with depth rankings of late Paleocene to early Eocene planktic foraminifera that was based on latitudinal distribution, environmental inferences, and stable isotope data. From shallow to deep habitats, genera occurring at Shagamu are *Morozovella* (upper mixed layer), *Igorina, Acarinina* (lower mixed layer), *Chiloguembelina* (around thermocline), *Subbotina, Parasubbotina*, and *Globanomalina* (below thermocline). The deepest dwelling taxa (*Globorotaloides, Planorotalites*) do not occur at Shagamu. The deepest dwelling taxa at Shagamu (*Globanomalina, Subbotina, Parasubbotina, Chiloguembelina*) are either very rare or do not occur in the lowermost samples, when the paleo-water depth was still too shallow. Close to the IETM, these taxa became rare to absent again. This may be because of again reduced water depth (see above), or because of a risen oxygen minimum zone related to the carbon release connected with the IETM.

Benthic Foraminifera

We distinguished between infaunal (dysoxic indicators) and epifaunal (oxic indicators) bottom dwellers among benthic foraminifera (Text-Fig. 6, right column) in order to estimate the oxygen level at the seafloor during the time



Text-Fig. 3.
Stratigraphically important planktic Foraminifera.
1: *Acarinina* cf. *coalingensis*, sample SH 19;
2: *Acarinina nitida*, sample SH 17;
3: *Acarinina* cf. *mckannai*, sample SH 17;
4: *Acarinina soldadoensis*, sample SH 21;
5: *Chiloguembelina crinita*, sample SH 25;
6: *Chiloguembelina midwayensis*, sample SH 28;
7: *Globanomalina chapmani*, sample SH 25;
8: *Globanomalina pseudomenardii*, sample SH 25;
9: *Igorina albeari*, sample SH 28;
10: *Igorina tadjikistanensis*, sample SH 25;
11: *Morozovella acuta*, sample SH 25;
12: *Morozovella acutispira*, sample SH 18;
13: *Morozovella aequa*, sample SH 25;
14: *Morozovella apanthesma*, sample SH 25;
15: *Morozovella subbotinae*, sample SH 29;
16: *Morozovella velascoensis*, sample SH 25;
17: *Parasubbotina varianta*, sample SH 25;
18: *Subbotina cancellata*, sample SH 17;
19: *Subbotina triangularis*, sample SH 25;
20: *Subbotina velascoensis*, sample SH 25.
Length of scale bars: 0.1 mm.

of deposition. We largely applied the morphological concept of Kaiho (1994). However, we did not further subdivide between fully and semi-infaunal taxa (suboxic indicators) because Kaiho's concept is based on modern faunas and morphogroups. Infaunal taxa include all agglutinated genera *(Ammobaculites, Gaudryina, Haplophragmoides*, ?*Recurvoides, Saccammina, Textularia, Trochammina)* and the calcareous genera *Bulimina*, ?*Dentalina*, *Nonionella, Siphogenerinoides, Stilostomella*, and *Tappanina*. Epifaunal taxa are *Cibicidoides, Epistomella, Eponides, Gavelinella, Gyroidinoides, Lenticulina,* and *Osangularia. Lenticulina* and *Gyroidinoides* were attributed to the intermediate suboxic indicators by Kaiho (1994) but were classified as oxic indicators according to their large size (Lenticulina) or prominent distribution pattern *(Gyroidinoides*, Text-Fig. 7).

The infaunal/epifaunal record at Shagamu (Text-Fig. 6, right column) indicates two periods with higher proportions of epifaunal taxa, i.e., such with a higher degree of bottom water ventilation. The first one was around the P4b to P4c transition (up to 75 % epifaunal elements), the second was shortly before the onset of the IETM, during basal P5 (max 81 % epifauna). During the other periods, the infaunal taxa dominate with high proportions, often more than 80 %. The maximum content of infaunal taxa (93 %) was reached during the IETM-onset.

Indicative Benthic Genera and Paleoceanographic Events

Paleoecologic interpretations of Paleogene benthic foraminiferal assemblages can be made on the base of comparisons with distribution patterns of recent (preferably living) faunas and morphogroups (e.g., Bernhard, 1986; Murray, 1991; Kaiho, 1994, 1999) or via distributions along ecological gradients back to Paleogene (e.g., Speijer & Schmitz, 1998) or even Mesozoic strata (e.g., Gebhardt et al., 2004). A detailed analysis of the most frequent benthic taxa at Shagamu (Text-Fig. 7) shows distinct changes in assemblage composition.

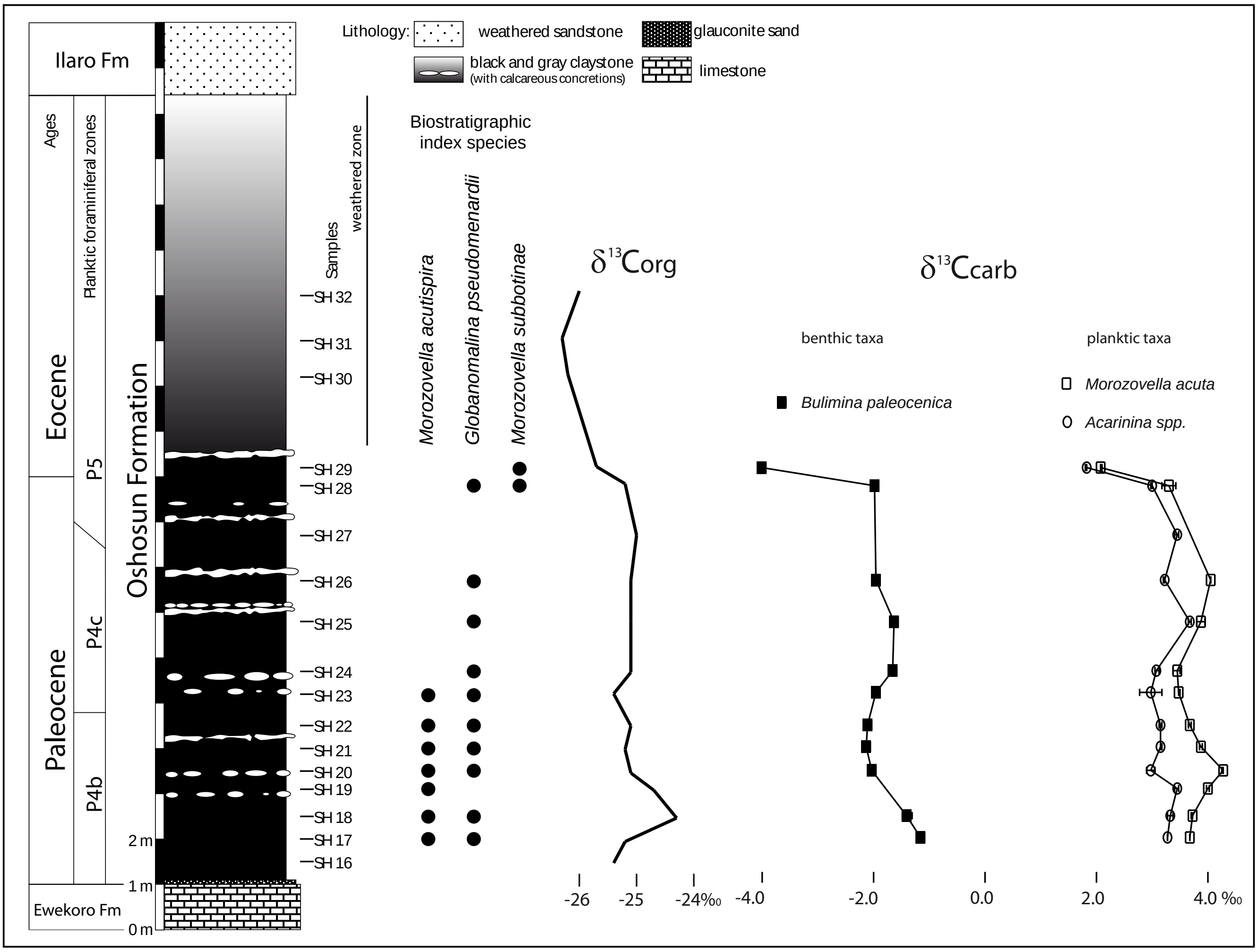
Agglutinated (arenaceous) taxa only form a significant proportion during the early, shallow water phase of deposition and probably only indicate the low water depth. With increasing paleo-water depth, calcareous taxa are the only important components.

Deep infaunal, oxygen depletion tolerant *Bulimina* (tapered morphogroup; Bernhard, 1986) shows the highest proportions during three periods: middle P4b, middle P4c, and during IETM. The first period however is characterized by strong fluctuations.

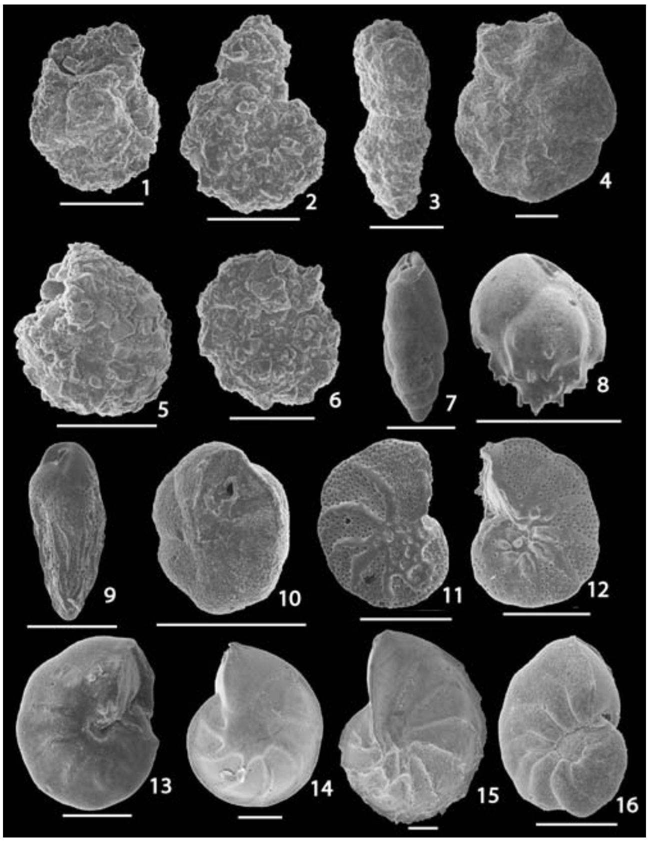
The infaunal, oxygen depletion tolerant *Nonionella* (flattened planispiral morphogroup; Bernhard, 1986) is very rare in the lower part of the section but becomes more frequent in the upper part, i.e., together with a marked increase in *Bulimina* and productivity related *Gavelinella*. The latter genus is also rather rare in the lower part of the section but becomes even dominant shortly before the IETM. Small *Gavelinella*'s followed an opportunistic life strategy and exploited increased food availability during Paleocene/Eocene (e.g., Speijer et al., 1996) or Late Cretaceous intervals (e.g., Leckie et al., 1998; Gebhardt et al., 2004).

Gyroidinoides and *Lenticulina* are epifaunal, oxic genera (planoconvex or lenticular morphogroups; Bernhard, 1986). Their dominance or frequent occurrences indicate oxic bottom water conditions. This is further confirmed by the negative correlation of *Lenticulina* and *Bulimina* (dysoxic). *Gyroidinoides* even disappears during the lower Zone P4c, exactly at the point in time when productivity related and dysoxic taxa became more frequent (see below). Therefore, high oxygen levels in the bottom water were interpreted for the P4c/P4c-transition and around the P4/P5 boundary.

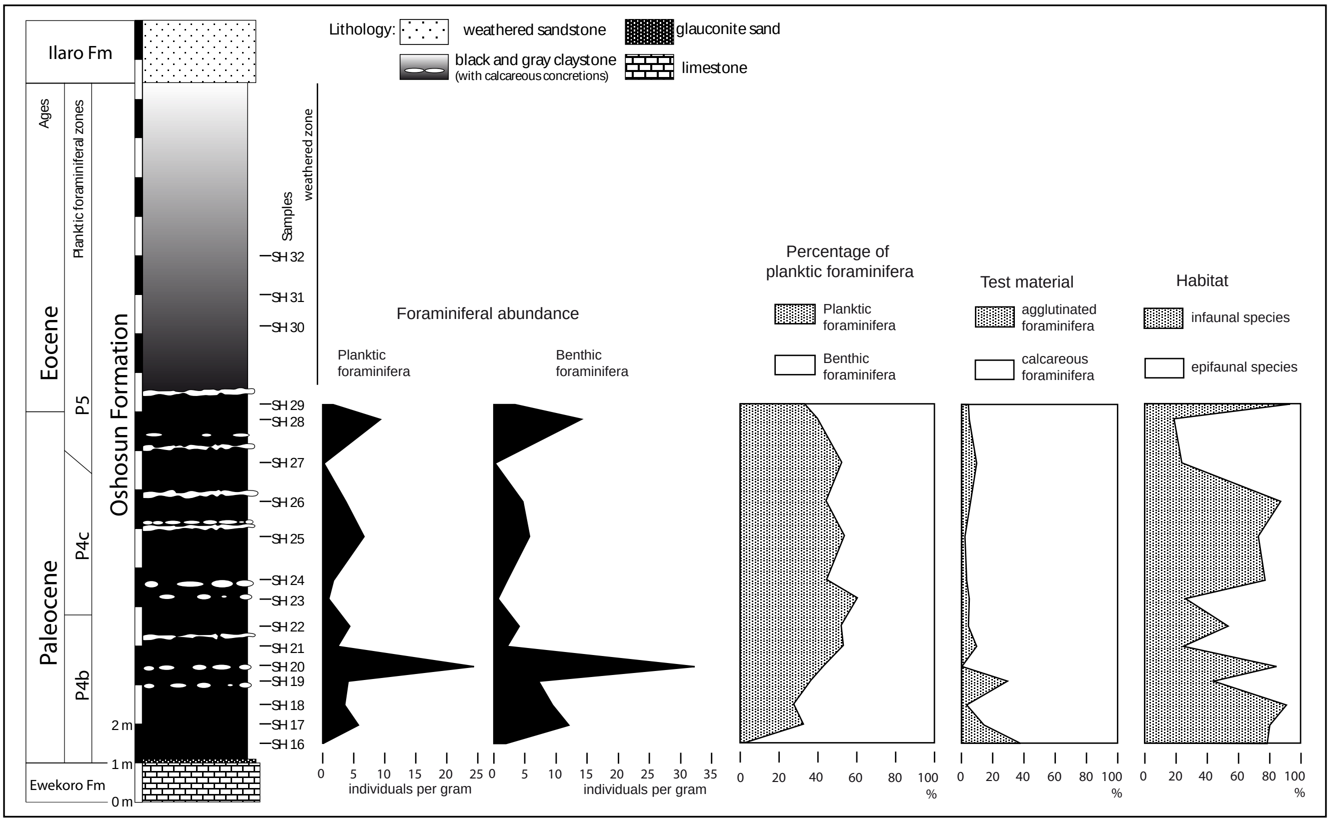
The lower Zone P4c (samples SH 23 to SH 24) is characterized by a strong increase of the low oxygen tolerant (dysoxic) genera *Bulimina* and *Nonionella*, the slight increase of the productivity indicator *Gavelinella*, a strong decrease of large (oxygen consuming) *Lenticulina* and the disappearance



Text-Fig. 4.
Stratigraphy of the Oshosun Formation at Shagamu with biostratigraphic index species (planktic foraminifera), δ^{13}C values of organic matter, and of selected foraminiferal taxa.



Text-Fig. 5.
Most frequent benthic foraminifera.
1: *Ammobaculites* cf. *expansus*, sample SH 16;
2: *Ammobaculites* sp., sample SH 16;
3: *Gaudryina* sp., sample SH 16;
4: *Haplophragmoides excavatus*, sample SH 19;
5: *Haplophragmoides* sp. A, sample SH 30;
6: *Haplophragmoides* sp. B, sample SH 16;
7: *Bulimina thanetensis*, sample SH 25;
8: *Bulimina midwayensis*, sample SH 18;
9: *Bulimina paleocenica*, sample SH 25;
10: *Eponides pseudoelevatus*, sample SH 25;
11, 12: *Gavelinella pachysuturalis*, sample SH 25;
13: *Gyroidinoides* cf. *soldanii*, sample SH 19;
14: *Lenticulina olokuni*, sample SH 25;
15: *Lenticulina pseudomamilligera*, sample SH 25;
16: *Nonionella panamensis*, sample SH 25.
Length of scale bars 0.1 mm.



Text-Fig. 6.
Foraminiferal abundance, percentage of planktic foraminifera, and in- to epifauna ratio.

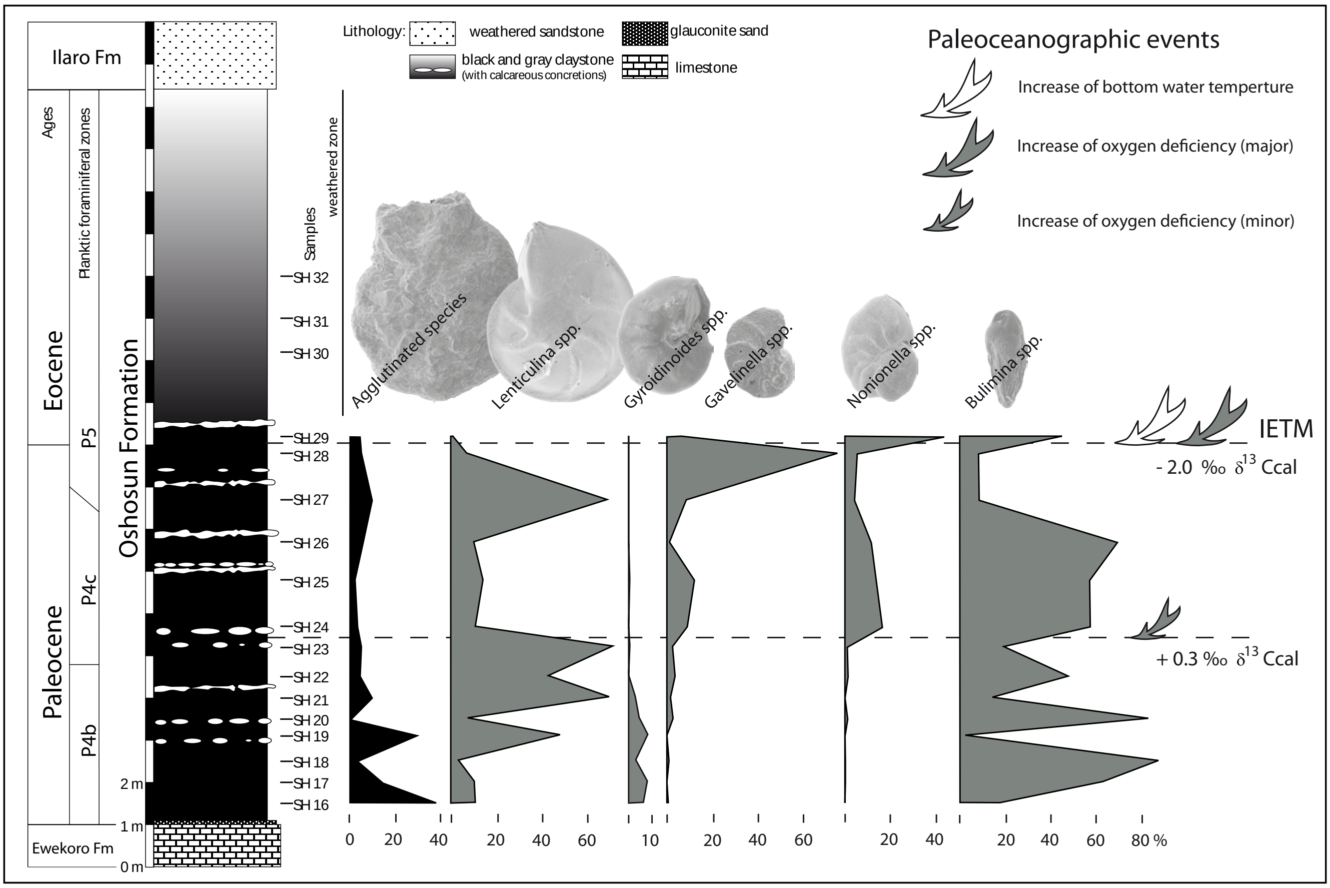
of *Gyroidinoides*. These changes coincide with a positive 0.3 ‰ δ^{13}Ccalc shift of benthic *B. paleocenica* which may point to increased water exchange (admixture of δ^{13}C-enriched surface waters) and organic matter (food) supply that lowers the oxygen level at the seafloor.

We therefore interpret Zone P4b to be well oxygenized with intermittent short dysoxic phases. A first sharp drop in bottom water oxygenation together with slightly increased food supply occurred during the lower P4c. This phase lasted until the P4/P5 transition, when a short period with increased oxygen supply took place.

The immediate phase before the onset of the IETM (sample SH 28) is characterized by the strong dominance of productivity related *Gavelinella*, increased benthic and planktic foraminiferal abundance and a reduction of *Lenticulina*, thus indicating a surface production pulse. The IETM onset (sample SH 29) goes along with a negative 2.0 ‰ δ^{13}Ccalc shift among planktic and benthic foraminifera and a global warming event (Zachos et al., 2003; Sluijs et al., 2007). The benthic IETM-assemblage at Shagamu shows a strong increase and dominance of dysoxic *Bulimina* and *Nonionella*, together with strongly reduced planktic and benthic foraminiferal abundance. This indicates reduced surface productivity and dysoxic bottom water condition. Both phenomena were possibly caused by reduced vertical mixing and/or increased stratification of the water column.

Conclusions

1. Three planktic foraminiferal zones (P4b to P5) were recognized in the lower part of the exposed Oshosun Formation at Shagamu. The onset of the CIE at the Paleocene-Eocene boundary is well expressed by a negative 2.0 ‰ δ^{13}C shift within foraminiferal shells, or by a 1.2 ‰ δ^{13}C shift of organic matter.
2. Foraminiferal abundance varies strongly between 0.05 and 24.35 ind/g for planktic and between 0.20 and 32.32 ind/g for benthic taxa and is very low compared with oceanic settings. Phases of high abundances are interpreted as periods of increased surface productivity.
3. Proportions of planktic foraminifera vary between 3 and 60 % and point to paleo-water depth increase from less than 50 m (middle neritic) to ca 300 m (shelf break) and a decrease afterwards to ca 120 m.
4. Based on benthic foraminiferal assemblages, we interpret Zone P4b to be well oxygenized *(Lenticulina-Gyroidinoides* dominated) with intermittent short dysoxic phases *(Bulimina* dominated). A first sharp drop in bottom water oxygenation together with slightly increased food supply occurred during the lower P4c and lasted until the P4/P5 transition with increased oxygen supply.
5. The immediate phase before the onset of the IETM is characterized by strong dominance of productivity indicators *(Gavelinella)* and increased benthic and planktic foraminiferal abundance. The benthic IETM-assemblage shows the dominance of dysoxic *Bulimina* and *Nonionella* and strongly reduced planktic and benthic foraminiferal abundance. This indicates reduced surface productivity and dysoxic bottom water conditions, possibly caused by reduced vertical mixing and/or increased stratification of the water column.



Text-Fig. 7.
Distribution of paleoecologically indicative benthic taxa and paleoceanographic events.

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Stefan Schouten (Nederlands Instituut voor Onderzoek der Zee, Texel, Netherlands) kindly provided δ¹³C values of organic matter and Nils Andersen (Leibniz Laboratory for Radiometric Dating and Stable Isotope Research, Kiel) is thanked for δ¹³C data from foraminifera shells. Helga Priewalder (Geologische Bundesanstalt, Wien) is thanked for the introduction to the SEM and her unlimited patience. Fieldwork in Nigeria was founded by VW-Foundation (AZ.: I/77 620).

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Appendix A: Faunal Reference List

1. Planktic Foraminifera

Acarinina cf. *coalingensis* (Cushman & Hanna, 1927)
Acarinina cf. *mckannai* (White, 1928)
Acarinina nitida (Martin, 1943)
Acarinina soldadoensis (Brönnimann, 1952)
Chiloguembelina crinita (Glaessner, 1937)
Chiloguembelina midwayensis (Cushman & Ponton, 1932)
Globanomalina chapmani (Parr, 1938)
Globanomalina pseudomenardii (Bolli, 1957)
Igorina albeari (Cushman & Bermúdez, 1949)
Igorina tadjikistanensis (Bykova, 1953)
Morozovella acuta (Toulmin, 1941)
Morozovella acutispira (Bolli & Cita, 1960)
Morozovella aequa (Cushman & Renz, 1942)
Morozovella apanthesma (Loeblich & Tappan, 1957)
Morozovella subbotinae (Morozova, 1939)
Morozovella velascoensis (Cushman, 1925)
Parasubbotina varianta (Subbotina, 1953)
Subbotina cancellata Blow, 1979
Subbotina triangularis (White, 1928)
Subbotina velascoensis (Cushman, 1925)

2. Benthic Foraminifera

Ammobaculites cf. *expansus* Plummer, 1933
Ammobaculites sp.
Bulimina midwayensis Cushman & Parker, 1936
Bulimina paleocenica Brotzen, 1948 (= *Bulimina asperoaculeata* Brotzen, 1948)
Bulimina thanetensis Cushman & Parker, 1947
Cibicidoides succedens (Brotzen, 1948)
?*Cibicidoides* sp.
?*Dentalina* sp.
Epistominella minuta (Olsson, 1960)
Eponides pseudoelevatus Graham, DeKlasz & Rérat, 1965
?*Eponides* sp.
Gaudryina sp.
Gavelinella pachysuturalis Graham, DeKlasz & Rérat, 1965
Gyroidinoides cf. *soldanii* (D'Orbigny, 1826)
Haplophragmoides excavates Cushman & Waters, 1927
Haplophragmoides glabra Cushman & Waters, 1927
Haplophragmoides sp. A
Haplophragmoides sp. B
Lenticulina olokuni Reyment, 1966
Lenticulina pseudomamilligera (Plummer, 1926)
Lenticulina sp.
Nonionella panamensis Cushman, 1918
Osangularia plummerae Brotzen, 1940
?*Recurvoides* sp.
Saccammina sp.
Siphogenerinoides eleganta (Plummer, 1926)
Stilostomella cf. *midwayensis* (Cushman & Todd, 1946)
Stilostomella cf. *plummerae* (Cushman, 1940)
Tappanina selmensis (Cushman, 1933)
Textularia cf. *midwayana* Lalicker, 1935
Trochammina globigeriniformis (Parker & Jones, 1865)

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