16. CENOZOIC BIOSTRATIGRAPHY AND PALEOECOLOGY OF SITES 403 TO 406 BASED ON THE FORAMINIFERS

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ABSTRACT

Sites 403 and 404, situated on the rifted margin of Rockall Plateau, have an incomplete Tertiary succession. Late Paleocene to Eocene clastic and volcaniclastic sediments were deposited in inner shelf, brackish to marine, and mid-shelf marine environments. By middle Eocene times the water had deepened to outer shelf or upper bathyal. The upper Eocene sediments at Site 403 were deposited in upper bathyal depths. Following a long stratigraphic break to late Miocene time, sedimentation resumed in a water depth of 2200 to 2600 meters. The record from then until the present day appears to be continuous.

Sites 405 and 406, situated south of the transform fault that bounds the southern margin of Rockall Plateau, also have an incomplete Cenozoic record. Upper Paleocene to Eocene sediments accumulated in about 1000 meters water depth. In late Miocene to Recent time the depth was 2200 to 2500 meters at Site 406 and 1800 to 3000 meters at Site 405.

Planktonic foraminifers are rare in Paleogene sediments of Sites 403 and 404; at Sites 405 and 406 they are more common but not diverse, and short-ranging stratigraphic marker species are rare. Neogene planktonic assemblages are moderately diverse, but are temperate assemblages often lacking the stratigraphic markers so valuable in tropical zonal schemes.

Benthic foraminifers show great variety in the Paleogene successions because of the changing depositional environments. Those of the Neogene were of deep water habitat and are much more uniform; most belong to the *Planulina wuellerstorfi* association characteristic of the bathyal zone.

INTRODUCTION AND OBJECTIVES

Sites 403 and 404 were drilled on the rifted margin of Rockall Plateau (Figure 1). They provide a record of events during rifting and the subsequent opening of the North Atlantic between Rockall Plateau and Greenland.

Sites 405 and 406 were drilled south of the transform fault that bounds the southern margin of Rockall Plateau. They provide a record of the evolution of a transform margin.

The main objective of this study was to investigate the benthic foraminiferal assemblages in the Cenozoic sediments for the purpose of interpreting the subsidence history and the concomitant environmental changes. A further objective was to date the assemblages using the planktonic foraminifers.

MATERIALS AND METHODS OF STUDY

Shipboard scientists selected samples that represented intervals of approximately 1 m.y. (Table 1). Most of the Neogene sediments were soft and easily processed. Those that were hard were soaked in water or in a dilute solution of sodium hexametaphosphate. All samples were washed on a 240 mesh (63 μm) sieve and the residue dried at room temperature. When dry, the > 120 fraction was separated by sieving, spread on a picking tray and benthic foraminifers were picked until at least 100 had been collected; this was not possible in all cases. No attempt was made to pick assemblages of planktonic forms; instead, representative species were mounted.
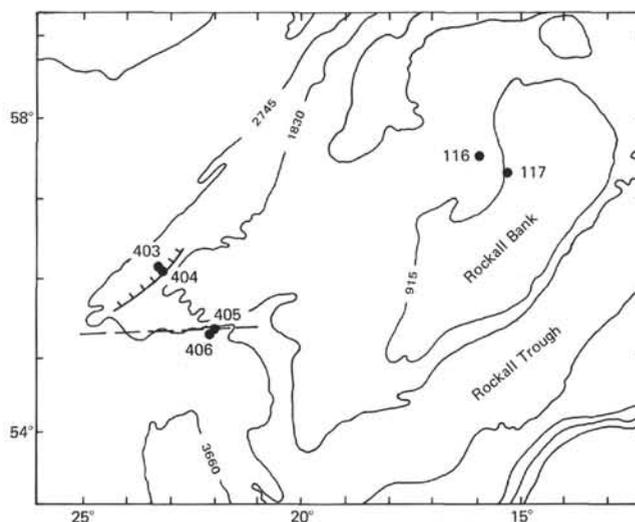
Figure 1. *Location of Sites 403 to 406.*

The large number of species and the limited time available for study has meant that not all species could be identified; many have been left in open nomenclature. In some figures i.e., 12, 14, 16, 18 and 21 to 24) the species plotted are those present in excess of 4% in one or more core assemblages. Those present in less than 4% overall abundance have not been plotted and are not included in the faunal reference list.

TABLE 1
List of Samples Studied

Site 403	Site 404	Site 405	Site 406
1-2, 141-143	1-2	1-1, 5-7	1-1, 30-32
3-3, 11-13	2, CC	3-2, 86-88	2, CC
7, CC	3, CC	6-1, 126-128	3-1, 85-87
8-6, 58-80	4, CC	7-1, 38-40	4-2, 56-58
11, CC	5, CC	8-3, 72-74	5, CC
16, CC	6, CC	12-4, 70-74	7-4, 70-74
18-2, 73-75	7, CC	14-2, 64-67	9-1, 112-116
	8-2, 37-37		
23, CC	9, CC	16-3, 108-112	12, CC
25, CC	10, CC	18-1, 55-58	20, CC
26, CC	11, CC	25-1, 60-63	27, CC
27, CC	16-2	27, CC	32, CC
28-1, 63-70	17, CC	28, CC	37-5, 32-35
28, CC	18-1, 81-87	31-2, 50-53	42, CC
29-2, 30-37	21-2, 40-46		46-3, 68-71
30-1, 27-31	22-2, 61-68		51, CC
33-1, 34-40	23-3, 90-97		
34-2, 34-43	25-1, 60-66		
35-3, 62-68			
36-2, 0-7			
37-4, 57-65			
38-4, 38-45			
39-3, 43-54			
40-3, 35-42			
42-1, 49-57			
42-3, 37-46			
43-1, 81-90			

Note: Sequence of numbers is core-section-position; CC = core catcher; in the text samples are generally referred to by site and core number only.

BIOSTRATIGRAPHY AND PLANKTONIC FORAMINIFERS

Paleogene

Paleogene sediments were cored in the North Atlantic on DSDP Leg 12 and a provisional multiple zonation was proposed by Berggren (1972b). It has not been possible, however, to apply his zonation here because many of the diagnostic species have not been recorded from Sites 403 to 406.

Identification of species has been made with reference to Stainforth et al. (1975), Postuma (1971), and Loeblich et al. (1957). The Paleogene assemblages are of low diversity, and few in numbers and size. Stratigraphically useful forms are uncommon and the resultant dates are imprecise. There is however, reasonable agreement between the dates shown herein and those determined by the shipboard scientists.

Site 403 (Figure 2)

Planktonic foraminifers are rare in Cores 42 to 34 and are mainly of the *Globigerina linaperta* group. Because Core 29 contains *Globorotalia esnaensis* and *G. pentacamerata*, of early Eocene (P 8) age, the sediments in Cores 42 to 34 are considered to be late Paleocene to early Eocene (P5-8) age.

Cores 28, 27, and 26 are dated as mid Eocene (P10-12) on the presence of *Globorotalia bullbrooki* which occurs together with the *Globigerina linaperta* group and *Pseudohastigerina wilcoxensis*. However, Core 28 may be of early Eocene age (see the section on Paleogene benthic forms). Core 25 yielded *Catapsydrax dissimilis* and *Globigerapsis index* which give an overlapping range of middle Eocene (P13) to lower Oligocene (P18). Berggren (1972b) consi-

Core	*Catapsydrax dissimilis*	*Catapsydrax* sp.	*Chiloguembelina* sp.	*Globigerapsis index*	*Globigerina linaperta* group	*Globigerina triangularis*	*Globorotalia bullbrooki*	*Globorotalia esnaensis*	*Globorotalia pentacamerata*	*Pseudohastigerina wilcoxensis*	Age
25	x			x							P.13-18 Eocene/Oligocene
26		x			x		x				P.10-12
27		x	x		x		x			x	P.10-12
28-1					x		?				P.10-12 Middle Eocene
28, CC					x	x					P.10-12
29					x			x	x		P.8 Early Eocene
34					x	x					P.5-8
35					x						P.5-8 Late Paleocene
39					x						P.5-8 to early Eocene
42					x						P.5-8

Figure 2. *Occurrence of planktonic foraminifers in the Paleogene at Site 403.*

dered that *G. index* might be a useful upper Eocene marker in high latitudes. He also found *C. dissimilis* to be a dominant form in Oligocene assemblages. Thus, this assemblage may be indicative of the Eocene/Oligocene boundary, and if so, the succession between Cores 26 and 25 is either condensed or else contains a hiatus.

Site 404 (Figure 3)

Cores 23, 22, and 18 contain a sparse planktonic assemblage of the *Globigerina linaperta* group assigned to the upper Paleocene-lower Eocene (P5-8).

Cores 17, 16, 11 and 9 contain *Globigerina linaperta* group together with *Pseudohastigerina wilcoxensis, Globorotalia esnaensis,* and *Globigerina triangularis* (which may be a variant of the *G. linaperta* group). This part of the succession is of latest Paleocene or early Eocene age (P5-8). *Truncorotaloides rohri,* of middle Eocene age, appears in Cores 8 and 7.

Site 405 (Figure 4)

The lower part of the succession is of late Paleocene to early Eocene (P5-8) age, based on the presence of the *Globigerina linaperta* group with one or more of *Globigerina triangularis, Globorotalia esnaensis,* or *Pseudohastigerina wilcoxensis* (Cores 31, 28, 27, 25, 18, 16, and 14). Core 12 contains only *G. linaperta.* Core 8 yielded a somewhat different assemblage consisting of *Globigerina boweri, Globorotalia pentacamerata,* and *Pseudohastigerina wilcoxensis;* it is early to middle Eocene (P8-12) in age.

Site 406 (Figure 5)

Cores 51 and 46 contain an assemblage typical of the *Globorotalia pentacamerata* Zone (P9) (after Stainforth et al., 1975, p. 68), except that Core 46 contains, in addition, *Globigerinita unicava primitiva* (range P14-18). The latter species is present with *Globigerapsis index* in Core 42, representing a mid to late Eocene age. *Chiloguembelina* sp., *Catapsydrax dissimilis,* and *G. index* are present in Core 37

Core	*Globigerina linaperta* group	*Globigerina triangularis*	*Globorotalia esnaensis*	*Pseudohastigerina wilcoxensis*	*Truncorotaloides rohri*	Age	
7	x				x	P.10-14 Middle Eocene	
8	x				x	P.10-14	
9	x	x	x			P.5-8	
11	x			x		P.5-12	Early Eocene
16	x	cf.		x		P.5-8	to
17	x		cf.			P.5-8	Late Paleocene
18	x					P.5-8	
22	x					P.5-8	
23	x					P.5-8	

Figure 3. *Occurrence of planktonic foraminifers in the Paleogene at Site 404.*

Core	*Globigerina boweri*	*Globigerina linaperta* group	*Globigerina triangularis*	*Globorotalia esnaensis*	*Globorotalia pentacamerata*	*Pseudohastigerina wilcoxensis*	Age	
8	x				x	x	P8-12 Early-mid Eocene	
12		x					P.5-12	
14		x	x			x	P.5-8	
16		x	cf.			x	P.5-8	
18		x	x	cf.		x	P.5-8	Early Eocene
25		x	x			x	P.5-8	to
27		x	x				P.5-8	Paleocene
28		x	x				P.5-8	
31		x	x				P.5-8	

Figure 4. *Occurrence of planktonic foraminifers in the Paleogene at Site 405.*

again indicating middle to late Eocene dating. Cores 32 and 27 contain a sparse fauna of *Catapsydrax dissimilis* and *Globigerina venezuelana* of late Oligocene to early Miocene age.

Discussion

The Paleocene-early Eocene assemblages recorded by Berggren (1972a,b) from Site 117 are minimally diverse, small-sized forms similar to those reported here. Oligocene assemblages from Sites 116 and 117 were somewhat more diverse and include several species not seen in the few Oligocene samples discussed here (*Globigerinita pera, Globigerina ampliapertura, Globorotalia* spp.). It is clear that conditions for the preservation of the planktonic as-

Core	*Catapsydrax dissimilis*	*Globigerapsis index*	*Globigerina boweri*	*Globigerina linaperta* group	*Globigerina venezuelana*	*Globigerina* cf. *G. yeguaensis*	*Globigerinita unicava primitiva*	*Globorotalia pentacamerata*	*Pseudohastigerina wilcoxensis*	Age	
27					?					?	Early Miocene to
32	x				x					N3-6	late Oligocene
37	x	x								P.14-18	Middle-late
42		x					x	x	cf.	P.14-18	Eocene
46			cf.	x			x	x	x	P.9	Early Eocene
51				x				x	x	P.9	

Figure 5. *Occurrence of planktonic foraminifers in the Paleogene at Site 406.*

semblages were poor at Sites 405 and 406 and this may account in part for the low diversity of the assemblages.

Neogene

From a study of DSDP Sites 111 to 119 Berggren (1972b) set up a series of planktonic foraminiferal zones for the North Atlantic and showed their probable correlation with the tropical zonation of Blow (1969). Descriptions of the zones recognized at Site 116 (Hatton-Rockall Basin) were given by Poore and Berggren (1975). They did not recognize a zone equivalent to N20 in the North Atlantic. Five of their zones are interval zones and two are lineage-segment zones.

In this study it has been found most convenient to use, where appropriate, the ranges given by Blow (1969). Poore and Berggren (1975) have recorded *Globorotalia puncticulata* from sediments considered to be of N18 age (cf. top N19 as the lower limit given by Blow). They also noted the change in coiling of *Neogloboquadrina atlantica* from right to left at approximately the transition from Miocene to Pliocene time. The ranges quoted by these authors for DSDP Site 116 occurrences of *Globorotalia crassaformis* and *G. inflata* are shorter than those quoted by Blow (1969) but the latter has been followed.

In most cases shipboard scientists already had given a provisional age to the samples studied. Not all species recorded onboard were found when the author examined the material and, of course, additional species were found. *Globorotalia margaritae*, for example, was recorded by shipboard scientists from many of the upper Miocene samples, but the author found no specimens with the characteristic concavity of the umbilical side. In spite of these differences there is general agreement about the age designations of most of the cores. The Neogene assemblages show a marked contrast with those from the Paleogene, being diverse, abundant, and often of large size.

Site 403 (Figure 6)

The oldest Neogene sediments are of late Miocene age (*G. conomiozea* Zone, =N17) in Cores 23, 18, and 16. Stratigraphically important species include *Globigerina apertura*,

Core	Globigerina apertura	G. bulloides	G. praebulloides	G. quinqueloba egelida	Globigerinoides quadrilobatus	Globorotalia acostaensis	G. conoidea	G. continuosa	G. crassaformis	G. crassaformis ronda	G. hirsuta	G. inflata	G. pseudomiocenica	G. puncticulata	G. scitula	G. truncatulinoides	Hastigerina aequilateralis	Neogloboquadrina atlantica	N. pachyderma	Orbulina suturalis	O. universa	Biorbulina bilobata	Sphaeroidinellopsis subdehiscens	Age		
1		x									x	x			x	x			x		x			N.22-23	Neogloboquadrina pachyderma	Pleistocene
3		x	x									x			x		x		x					?N.21-22	G. inflata/N. pachyderma	Plio-Pleistocene
7		x									x			x	x	x					x	x		N.18	Globorotalia	Early
8		x						x						x	x	x		L	x	x	x			N.18	puncticulata	Pliocene
11		x							x					x	x					x	x	x		N.18		
16		x				x					x			x	x	x				x	x			N.17	Globorotalia	Late
18		x				x		x	x					x	x			L	x	x			x	N.17	conomiozea	Miocene
23	x	x		x		x	x							x	x								x	N.17		

Figure 6. *Occurrence of planktonic foraminifers in the Neogene at Site 403.*

G. praebulloides, Globorotalia conoidea, and *G. pseudomiocenica. Neogloboquadrina atlantica* (left coiling) is present in Core 18 which suggests that this level is high in the *G. conomiozea* Zone.

Cores 11, 8 and 7 contain *Globorotalia puncticulata*, which indicates the lower part of the *G. puncticulata* Zone (N18, early Pliocene).

Core 3 contains much clayey and silty clastic material and the planktonic fauna is characterized by abundant *Neogloboquadrina pachyderma*. Shipboard scientists recorded *Globorotalia tosaensis* but this was not confirmed by the author. The age would be N21-22 if this species is present. The topmost sample, Core 1, can be assigned to N22-23, *Neogloboquadrina pachyderma* Zone, on the presence of *Globorotalia truncatulinoides*.

Site 404 (Figure 7)

Cores 6 and 5 are dated as N16-17 (*N. acostaensis* Zone-*G. conomiozea* Zone, late Miocene), based on the overlap of *Globorotalia continuosa, G. merotumida, G. plesiotumida*, and *G. pseudomiocenica*. Core 4 is of N17 age (*G. conomiozea* Zone) based on *Globigerina praebulloides* and *Globorotalia conoides*. Core 3 contains *G. plesiotumida* (N17-18).

A number of new forms appear in Core 2 (*Globorotalia crassaformis, G. hirsuta, G. inflata, Neogloboquadrina pachyderma*) and, in addition, forms transitional between *Globorotalia tosaensis* and *G. truncatulinoides*. This suggests the level of the Pliocene/Pleistocene boundary, N21-22, *Globorotalia inflata/Neogloboquadrina pachyderma* zones. Core 1 contains a modern assemblage of the *N. pachyderma* Zone (N22-23).

Site 405 (Figure 8)

Cores 7 and 6 contain *Globorotalia pseudomiocenica* of late Miocene age (N16-18, *G. acostaensis-G. conomiozea* zones). Core 6 also contains *Neogloboquadrina atlantica* (left coiling) which suggests early Pliocene although *Globorotalia puncticulata* is absent. This level is therefore believed to be N18 or lowest *G. puncticulata* Zone.

Core	Globigerina bulloides	G. falconensis	G. nepenthes	G. parabulloides	G. praebulloides	G. quinqueloba egelida	Globigerinoides quadrilobatus	Globoquadrina altispira	G. dehiscens	Globorotalia acostaensis	G. conoidea	G. continuosa	G. crassaformis	G. crassaformis ronda	G. hirsuta	G. inflata	G. merotumida	G. plesiotumida	G. pseudomiocenica	G. scitula	G. tosaensis	G. truncatulinoides	Hastigerina aequilateralis	Neogloboquadrina pachyderma	Orbulina suturalis	O. universa	Sphaeroidinellopsis subdehiscens	Age		
1	x	x				x										x				x		x		x		x	x	N22-23	N. pachyderma	Pleistocene
2	x					x							x	x	x	x				x	x	x	x	x		x	x	N21-22	G. inflata/N. pachyderma	Plio-Pleist. boundary
3	x	x				x				x								x	x							x		N.17-18		Late
4			x	x						x	x						x											N.17	Globorotalia	Miocene
5				x				x	x	x	x	x				x									x	x		N.16-17	conomiozea	
6		x					x	x	x	x	x					x	x	x							x			N.16-17	Zone	

Figure 7. *Occurrence of planktonic foraminifers in the Neogene at Site 404.*

Taxon / Core	*Globigerina bulloides*	*G. falconensis*	*G. parabulloides*	*G. quinqueloba egelida*	*Globorotalia acostaensis*	*G. crassaformis*	*G. hirsuta*	*G. inflata*	*G. pseudomiocenica*	*G. puncticulata*	*G. scitula*	*G. truncatulinoides*	*Hastigerina aequilateralis*	*Neogloboquadrina atlantica*	*N. pachyderma*	*Orbulina universa*	Age	
1	x			x	x	x	x				x	x	x		x	x	N.22-23 *N. pachyderma*	Pleistocene
3	x			x	x	x	x			x	x	?			x	x	N.22-23	
6	x	x			x				x		x			L		x	N.18 *G. puncticulata*	Early Pliocene
7	x		x		x				x	x	x				x	x	N.16-18 *G. conomiozea- G. puncticulata*	Late Miocene

Figure 8. *Occurrence of planktonic foraminifers in the Neogene at Site 405.*

A major faunal change takes place above this as cores 3 and 1 contain a modern assemblage of the Pleistocene (N22-23. *Neogloboquadrina pachyderma* Zone). There is thus a hiatus between Cores 6 and 3 representing most of the Pliocene.

Site 406 (Figure 9)

The lower-middle Miocene boundary is encountered in Core 20 which contains the stratigraphically restricted species *Globigerinoides sicanicus* and *Praeorbulina glomerosa circularis*. The absence of *Orbulina suturalis* and *O. universa* may indicate that this is early Miocene in age (N8, *Praeorbulina* spp. Zone).

Cores 12, 9, 7, and 5 yielded assemblages containing *Globorotalia acostaensis*, *G. conoides*, and *G. merotumida* or *G. pseudomiocenica*; all are of late Miocene age (N17, *Globorotalia conomiozea* Zone). Core 4 has fewer biostratigraphically important species and is considered to be late Miocene to early Pliocene in age (N17-18), *G. conomiozea* to *G. puncticulata* zones.

Core 3 contains left-coiling *Neogloboquadrina atlantica*, but lacks *Globorotalia inflata* and is dated as late Pliocene (N19-21 *Globorotalia crassaformis* Zone). Cores 2 and 1 are assigned to the Pleistocene.

Shipboard scientists recorded a hiatus between Cores 20 (early Miocene) and 19 (late Miocene); in this study it is apparent between Cores 20 and 12. The shipboard age determination of Core 3 was N19 (based on *Globortalia* cf. *cibaoensis*) whereas here it is considered to be N22 based on the presence of *G. hirsuta*. If this is correct there is a hiatus between Cores 4 and 3.

Discussion

Early Miocene sediments are rare at the four sites under discussion and only at Site 406 (Core 20) were they positively identified. The assemblage includes *Globigerina praebulloides*, *Globigerinoides quadrilobatus immaturis*, *G. sicanicus*, *Globorotalia scitula*, *G. scitula praescitula*, *G. siakensis*, and *Praeorbulina glomerosa*. This compares well with the *Praeorbulina* Zone of Berggren (1972b) and Poore and Berggren (1975).

Middle Miocene sediments were not encountered at Sites 403 to 406.

Late Miocene sediments are present at all four sites. Planktonic foraminifers are abundant and characteristic

Taxon / Core	*Globigerina apertura*	*G. bulloides*	*G. falconensis*	*G. nepenthes*	*G. parabulloides*	*G. praebulloides*	*G. quinqueloba egelida*	*Globigerinoides quadrilobatus*	*G. quadrilobatus immaturus*	*G. sicanicus*	*Globoquadrina dehiscens*	*Globorotalia acostaensis*	*G. conoidea*	*G. continuosa*	*G. crassaformis*	*G. hirsuta*	*G. inflata*	*G. merotumida*	*G. plesiotumida*	*G. pseudomiocenica*	*G. puncticulata*	*G. scitula*	*G. scitula praescitula*	*G. siakensis*	*G. truncatulinoides*	*Hastigerina aequilateralis*	*Neogloboquadrina atlantica*	*N. pachyderma*	*Orbulina suturalis*	*O. universa*	*Praeorbulina glomerosa*	*Sphaeroidinellopsis subdehiscens*	Biostratigraphic Age	
1		x	x				x								x	x						x			x			x		x			N.22-23 *Neogloboquadrina pachyderma*	Pleistocene
2		x					x							x	x						x	x						x					N.22	
3		x					x								x							x				x	L x	x		x			N.19/21 *G. crassaformis*	Late Pliocene
4		x	x									x					x										L x	x		x			N.17-18	
5	x											x	x					x	x			x						x					N.17 *Globorotalia conomiozea*	Late Miocene
7	x	x			x	x						x	x					x	x			x							x				N.17	
9					x	x						x		x								x						x					N.17	
12	x				x	x	x			x		x	x							x		x					L						N.17	
20								x	x	x	x									x	x	x										x	N.8-9 *Praeorbulina* spp.	Early Miocene

Figure 9. *Occurrence of planktonic foraminifers in the Neogene at Site 406.*

species include *Globorotalia acostaensis, G. conoides, G. merotumida, G. plesiotumida, G. pseudomiocenica*, and *Orbulina suturalis*.

Early Pliocene sediments are best developed at Site 403 where *Globorotalia puncticulata* is present with *G. pseudomiocenica, G. crassaformis*, and *Neogloboquadrina atlantica*. Late Pliocene sediments were possibly encountered at Site 404 (Core 2) where forms transitional between *Globorotalia tosaensis* and *G. truncatulinoides* are present.

The Pleistocene to Recent assemblages are composed of *Globigerina bulloides, G. quinqueloba egelida, Globorotalia hirsuta, G. inflata, G. scitula, G. truncatulinoides, Neogloboquadrina pachyderma*, and *Orbulina universa*. This is a typical temperate North Atlantic assemblage.

These assemblages are similar to those reported from the North Atlantic by Berggren (1972b) and Poore and Berggren (1975), but the Pliocene sediments are far less rich in *N. atlantica* than the above authors report from their study area.

BOLBOFORMA

Daniels and Spiegler (1974) described a new genus of incertae sedis, *Bolboforma*, from the Oligocene and Miocene of northwest Germany. The 11 species had distinct stratigraphic ranges and some of them have since been recorded from the Miocene of DSDP Site 35 off Antarctica (Rögl, 1976).

The occurrence of this genus at Sites 403, 404, and 406 (absent from 405) is shown in Figure 10. It occurs mainly in Zone N17, possibly ranging from N16-N18 where dating of samples cannot be to an individual N-zone. This group of species may be important useful biostratigraphic markers.

CRITERIA FOR THE PALEOECOLOGICAL INTERPRETATION OF THE BENTHIC ASSEMBLAGES

Paleoecological interpretation of the fossil benthic foraminiferal assemblages is not only dependent upon comparison with modern assemblages, but is also complicated by the faunal differences between Tertiary and modern assemblages.

In the past few years two reviews of the ecology and distribution of modern benthic assemblages have been published. Murray (1973) discussed living assemblages from all the major environments whereas Boltovskoy and Wright (1976) summarized the data on living, dead, and total assemblages. The relationships between living and dead assemblages and the reliability of the fossil record have been

Genus *Bolboforma*

Site		403		404				406		
Species	Core	18	23	3	4	5	6	5	7	9
aculeata			x			x				
clodiusi				x	x	x	x	x	x	x
intermedia		x			x		x	x		
laevis				x		x	x		x	
metzmacheri				x		x	x			
spiralis									x	

Figure 10. *Occurrence of species of* Bolboforma.

discussed for shelf and marginal marine assemblages by Murray (1976a). In addition, a method has been proposed for the paleoecological interpretation of fossil assemblages (Murray, 1973).

The interpreted environments of life of the Cenozoic assemblages discussed here range from shallow continental shelf to deep bathyal. The criteria for interpretation and the data used for comparison of shelf assemblages are all adequately discussed in the references cited above. This is not true of bathyal assemblages so a brief resumé is given below.

Many studies of modern benthic foraminifers have concentrated on distribution changes with increasing water depth. However, changes in depth are always accompanied by changes in other important environmental parameters such as salinity, temperature stratification, dissolved oxygen, relative solubility of carbonates, etc. (Murray, 1973). Thus, the interpretation of distribution changes cannot be made solely with reference to changes in depth. There is ample evidence of this because individual species show different depth distributions in different geographic regions.

Bandy and Chierici (1966) highlighted the problem in their comparison of the depth-temperature distribution of bathyal benthic foraminifers from the Mediterranean and from off the coast of California. They subdivided the species into isobathyal and heterobathyal groups. The former showed similar depth ranges in the two geographic areas whereas the latter group did not. Thus, it should not be expected that there is a worldwide pattern of foraminiferal depth distributions based on the same associations of species. It is more realistic to consider that the depth distributions will be different from region to region although some of the general features of assemblages and associations may be applicable over a wider area.

In two recent reviews of foraminifer distributions the following generalizations have been made (Murray, 1973; Boltovskoy and Wright, 1976): (1) forms with calcareous tests dominate the bathyal zone although they are known to live down to >6000 meters; (2) agglutinated species characterize the abyssal and hadal zones; (3) many of the species are cosmopolitan; (4) diversity is high in the deep sea because of environmental stability.

To this list may be added the observation by Belyaev (1966, p. 41) that foraminifers are more eurybathic than most metazoan groups. However, it was pointed out that two problems beset the study of benthic foraminifers in the deep sea. First, slow sedimentation gives rise to condensed deposits in which dead tests may be transported, especially downslope, thereby extending the apparent depth range.

Another generalization is the correlation of the form and structure of foraminifers with environment (Brady, 1964).

No studies of the bathymetric distribution of foraminifers in the area of Rockall Bank have yet been published. The geographically closest studies are those of Caralp, Lamy, and Pujos (1970) and Pujos-Lamy (1973a) in the Bay of Biscay, and Seiler (1975) off Portugal; in addition, there are records from the North Atlantic (Brady, 1884; and Cushman, 1918-1931). With the exception of the study by Seiler, all of these records are of dead forms only.

Both the Portuguese offshore area and the Bay of Biscay are under the influence of the Mediterranean outflow current

which flows along the upper slope in a northerly direction. This water mass is characterized by a salinity $>36^o/oo$, temperature $>1'1°C$, and relatively low dissolved oxygen (<4.5 ml/1) near Cape Vicente although these values undergo change with passage north. The salinity maximum is at a depth of 1100-1300 meters off Cape Vicente and ~1000 meters off Cape Finistere.

Seiler (1975) records the following six genera as common: *Bolivina* (including *Brizalina*), *Bulimina*, *Cassidulina* (including *Globocassidulina*), *Epistominella*, *Trifarina*, and *Uvigerina*. In the Bay of Biscay, genera common in the depth range 180 to 1700 meters are (Caralp et al., 1970) *Ehrenbergina*, *Trifarina*, and *Uvigerina;* from 1700 to 2500 meters *Loxostomum*, *Bulimina*, and *Uvigerina;* and from 2500 to 3000 meters *Pullenia*, *Planulina*, *Eponides*, *Epistominella*, and *Melonis* (given as *Nonion pompilioides*).

Pujos-Lamy (1972) notes that in the upper bathyal zone (180-1700 m) agglutinated foraminifers (Textulariina) form 1-2 per cent of the total assemblage, in the lower bathyal zone (1700-4000 m) 5-24 per cent, at depths greater than 4000 meters >30 per cent.

Diversity is an important measure of assemblages and the α index of Fisher et al. (1942; and see Murray, 1973) has been used here. Seiler (1975) gives data for the living assemblages off Portugal whereas Caralp et al. (1970) give data for the total assemblages of the Bay of Biscay. Their results are summarized in Figure 11, using the bathymetric divisions of Pujos-Lamy (1973a). The majority of the assemblages studied come from the epibathyal zone, and only one has been studied from the infrabathyal zone so this may account for the different ranges of variability. In all these depth zones the values of α are generally >10 whereas on continental shelves such high values are not common.

Walton (1964) introduced the concept of faunal dominance, the highest percentage occurrence of any one species in each assemblage. Data from Seiler (1975) and Caralp et al.

Figure 11. *Summary of modern benthic foraminifers depth distribution off Portugal and the Bay of Biscay.*

have been summarized in Figure 11. The problem of sampling is the same here as for diversity. In general one would expect per cent faunal dominance to be low when the diversity is high and vice versa. It is therefore surprising that in the epibathyal zone faunal dominance ranges from 8 to 55 per cent. Walton (1964, p. 217) stated that all faunas whose dominant species constitute over 35 per cent of the entire fauna occur shallower than 10 fathoms! Clearly this does not apply in this case.

Along the European seaboard the majority of benthic species shows no restricted depth distribution. Those that do have been plotted on Figure 11 (data from Brady, 1884; Cushman, 1918-1931; Caralp et al., 1970; Pujos-Lamy, 1973a; Murray, 1971).

Brouwer (1973) introduced the concept of the *Planulina wuellerstorfi* fauna which he believes to be present throughout the Atlantic Ocean in the depth range 1350 to 5084 meters. This fauna is recognized on the co-occurrence of any of the following species which together make up >5 per cent of the total fauna: *Eggerella bradyi*, *Pullenia bulloides*, *Globocassidulina subglobosa*, *Epistominella exigua*, *Oridorsalis umbonatus*, *Nuttallides umboniferus*, *Planulina wuellerstorfi*, and *Melonis pompilioides*. This is a useful concept and it has particular application to the interpretation of the Neogene assemblages.

However, Streeter (1973) demonstrated that variations in the specific composition of deep water benthic assemblages in the North Atlantic could be correlated with the water masses more readily than with depth alone. He recognized three main assemblages characterized by ?*Epistominella umbonifera* (>4000 m $<2.0°C$ potential temperature), *Cibicides (= Planulina) wuellerstorfi - Epistominella exigua* (4000-2500 m 2.0-3.0°C potential temperature), and *Nummoloculina irregularis - Cibicides kullenbergi* (<2500 m 3.0-4.0°C potential temperature). In addition he found that *Uvigerina hollicki* is dominant at a depth of ~1200 meters and a temperature of about 4°C. Both Streeter (1973) and Schnitker (1974) have used changes in benthic foraminifer assemblages in late glacial sediments to infer changes in bottom water mass circulation. Lack of detailed data on species distributions in both these papers has meant that it is difficult to apply the results to the interpretation of Cores 403 to 406.

The ratio of planktonic to benthic foraminifers is commonly used as a guide to water depth. In a recent review of data from modern sediments Murray (1976b) demonstrated that this ratio varies not only with water depth, but also with distance from the source of supply of planktonic tests. When planktonic forms are transported from an oceanic water mass onto and across a continental shelf, where the environment is not favorable for the existence of these forms, the tests become progressively smaller the further the distance from source. It is therefore worth measuring the size of the largest planktonic individual in each assemblage. These have been plotted on Figures 12 to 24.

BENTHIC FORAMINIFERAL PALEOECOLOGY
Paleogene
Site 403 (Figures 12, 13)

The deepest fossiliferous Core is 42 (Section 1, 49-57 cm). The assemblage has a high diversity ($\propto = 12$) and is domi-

Core	Alabamina cf. A. obtusa	Alabamina wilcoxensis	Anomalinoides howelli	Anomalinoides nobilis	Bulimina sp.	Cibicidoides spp.	Dentalina spp.	Epistominella vitrea	Florilus elongatum	Globocassidulina subglobosa	Gyroidina angustiumbilicata	Gyroidina neosoldanii	Gyroidina sp.	Gyroidinoides complanata	Lagena sp.	Lenticulina sp.	Melonis affine	Nonion cf. N. olssoni	Nodosarians	Oridorsalis ecuadorensis	Osangularia expansa	Pararotalia calvezae	Protelphidium sp.	Pullenia bulloides	Pullenia quinqueloba	Pulsiphonina prima	Spiroplectammina spectabilis	Textularia spp.	Turrilina brevispira	α index	planktonic:benthic ratio (%)	maximum diameter of planktonics (μm)	Inferred Depth (m) and Environment	Age
25			x	14								6		12	x		9	x	14					11	6		x			12	93	520	∿600 epibathyal	Eocene/Oligocene
26				4								x	x	12	6	x	x	x	42					x	11		x			8	99	460		
27			x									6		7		x	6	x	45						x	5	x			12	97	500	∿250 epibathyal	Middle Eocene
28-1	16	13				17	x					9	4	5		4		x	5	5	x	x		4						10	61	500	100–180 outer shelf	
28, CC						4						11	7	10		5			4	16				x	x				x	10	41	400		
29		4	15	7							7					7	x		7	x	x	x		6	4			10	9	12	30	330	<100 mid-inner shelf	Early Eocene
34			23	x				10	13							6	x		x			16	15			x				5	3	240	<10 inner shelf, near a river	
35			x												x	x	x	x								x				–	–	–		Late Paleocene
37	x	x	x								x							x												–	–	–		to early Eocene
38																		x	x											–	–	–		
39			x						x									x								x				–	–	–		
40	x	x							x																					–	–	–		
42-1	11	23	9			10	x							5				7	11			x					x			12	1	240	<100 mid-inner shelf	

Figure 12. *Occurrence of benthic foraminifers (>4%) in the Paleogene at Site 403 (values in %, x = <4%; Cores 30, 33, 36, 42, 43, and 44 were barren).*
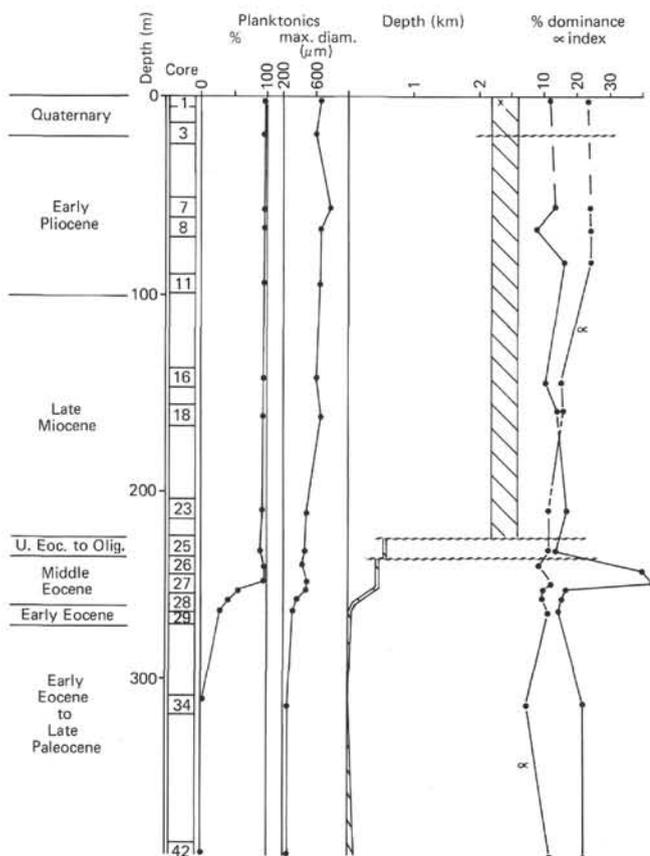
Figure 13. *Summary log of Site 403 (R = rare foraminifers).*

nated by *Anomalinoides howelli*, *Alabamina wilcoxensis*, nodosarians, and *Cibicidoides* spp. From its high diversity it is interpreted as normal marine. The species suggest mid to inner shelf and this is supported by the low planktonic-benthic ratio and the small size of the planktonic individuals.

Poor faunas were recovered from Core 42 to Core 34 and it is not possible to determine the paleoecology.

Core 34 yielded a distinctive assemblage of low diversity ($\alpha = 5$). The dominant species include *Anomalinoides howelli*, *Pararotalia calvezae*, *Protelphidium* sp., *Florilus elongatum*, and *Epistominella vitrea*. The latter species is a dominant form in the deltaic marine environments of the Mississippi and Ebro deltas (see Murray, 1973, p. 77, 80, for a summary). It lives in waters of normal salinity, at a depth of >10 meters in turbid waters. *Protelphidium* lives in brackish to marine waters especially in estuaries and lagoons. Thus this assemblage is thought to represent shallow inner shelf close to a river.

The next fossiliferous level (Core 29) yielded an assemblage dominated by *Anomalinoides howelli* with several common accessory species (see Figure 12). The diversity is high and the proportion and size of the planktonic forms shows an increase over those below. These features suggest a deepening of the water to <100 meters, mid to inner shelf.

A significant faunal change takes place above this level. The dominant forms in Cores 28, CC and 28-1 include *Cibicidoides* spp., *Gyroidina* sp., *Gyroidinoides complanata*, and *Osangularia expansa*; *Oridorsalis ecuadorensis* also appears. The planktonic-benthic ratio increases to 61 per cent and the planktonic size increases to 500 μm. This evidence points to an outer shelf environment, with a depth of 100 to 180 meters. The assemblage includes *Pulsiphonina*

prima as well as *O. expansa* and *A. noblis*, which suggest an early Eocene age (P9). This would not conflict with the evidence from the planktonic foraminifers as the known range of *Globorotalia bullbrooki* is P9-13.

Cores 27 and 26 have similar assemblages dominated by *Oridorsalis ecuadorensis* with common accessory *Gyroidinoides complanata* and less common *Gyroidina neosoldanii*, *Lenticulina* sp., *Nonion* cf. *N. olssoni*, *Pullenia quinqueloba*, and *Spiroplectammina spectabilis*. Rare species include *Nuttallides truempyi*, *Pleurostomella* sp., and *Cyclammina* sp. The assemblage is thought to represent the upper part of the epibathyal zone (~250 m). The planktonic-benthic ratios are high (97-99%) and the maximum size of the planktonic individuals is 460-500 μm.

There is probably a hiatus between Cores 26 and 25. The assemblages are, however, similar in several respects and differ mainly in the lesser abundance of *Oridorsalis ecuadorensis* in Core 25. New rare species include *Bulimina striata*, *Eggerella bradyi*, *Epistominella pulchella*, and *Cassidulina laevigata*. The upper depth limit of *E. bradyi* is ~600 meters and this may represent the depth of deposition of this assemblage.

Site 404 (Figures 14 and 15)

The oldest core (23) yielded a sparse assemblage dominated by *Florilus elongatum* and *Protelphidium* sp. Core 22 has a richer assemblage in which these two dominant species are joined by *Anomalinoides howelli* and *Elphidium hiltermanni*. The assemblage in Core 21 is similar but lacks *Florilus elongatum* and *Protelphidium* sp. forms 72 per cent of the total. In these cores planktonic foraminifers are rare. The α index is low, especially in Core 21. The assemblages

are indicative of shallow, marginal marine environments which, in the case of Core 21, was probably brackish.

The rest of the late Paleocene to early Eocene assemblages are dominated by *Anomalinoides howelli*. The morphology of this species suggests that it lived clinging to a firm substrate such as shells or seaweeds. Common accessory species are *Alabamina wilcoxensis* and *Osangularia expansa*. Other accessory species which are sometimes common include *Globocassidulina subglobosa*, *Gyroidina angustiumbilicata*, *Lenticulina* sp., and *Pulsiphonina prima*. With the probable exception of *Anomalinoides howelli* these species are muddy substrate forms, typical of continental shelves.

The diversity values are in the range α 9 to 12 which suggests a fully marine environment. The per cent faunal dominance is high (33-54%, mainly *Anomalinoides howelli*). The planktonic:benthic ratio ranges from 7 per cent in Core 18 to 80 per cent in Core 16 and intermediate values in Cores 11 and 9 (50 and 58%). The planktonic individuals may have undergone some solution as juveniles are not common, but even the largest individuals only range from 320 to 380 μm. The small size and low to moderate abundance of planktonic individuals suggest a continental shelf environment some distance away from the open ocean (see Murray, 1976b). The assemblages of Cores 18 and 17 are of inner shelf type with a depth of <75 meters. Cores 16 to 9 have assemblages indicative of middle to outer shelf depths (75-150 m). The middle Eocene assemblages (Cores 8 and 7) are likewise dominated by *Anomalinoides howelli*. Many of the other benthic species are different from those of the early Eocene. The planktonic:benthic ratio is 66 to 87 per cent and the planktonic forms are marginally larger (maximum diameter 320-400 μm). Nevertheless, this is still a shelf assemblage, probably outer shelf, in the depth range 100 to 180 meters.

Taxon / Core	Alabamina wilcoxensis	Anomalinoides howelli	Anomalinoides nobilis	Cancris auriculus primituvus	Cibicidina cf. C. walli	Cibicidoides alleni	Cibicidoides succedens	Cibicidoides sp.	Elphidium hiltermanni	Florilus elongatum	Globocassidulina subglobosa	Gyroidina angustiumbilicata	Gyroidina neosoldanii	Lenticulina sp.	Oridorsalis ecuadorensis	Osangularia expansa	Protelphidium sp.	Pulsiphonina prima	α index	planktonic:benthic ratio (%)	maximum diameter of planktonics (μm)	Inferred Depth (m) and Environment	Age
7		57							x	x									12	87	400	100-180 normal marine,	
8	9	21	5								8	4	7						14	66	320	100-180 outer shelf	Middle Eocene
9	x	54					x	x		x		13							10	58	320	75-150 normal marine, middle	
11	8	33			4		x	x		x		22		x					9	50	300	75-150 to outer shelf	Late Paleocene
16	x	34					x	4		5		6		x					12	80	380	75-150	to
17	8	35		4	6			7		4				9					9	6	340	<75 normal marine,	
18		13			19	24								8					10	7	260	<75 inner shelf	Early Eocene
21		16					4							72					2	0	-	<10 brackish, marginal	
22		18	5	x			12	14				x		40					6	1	220	<10 marginal marine	
23						D								D					-	2	400	<10 marine	

Figure 14. *Occurrence of benthic foraminifers (>4%) in the Paleogene at Site 404 (values in %, x = <4%; Core 23 yielded a small assemblage, D = dominant species).*
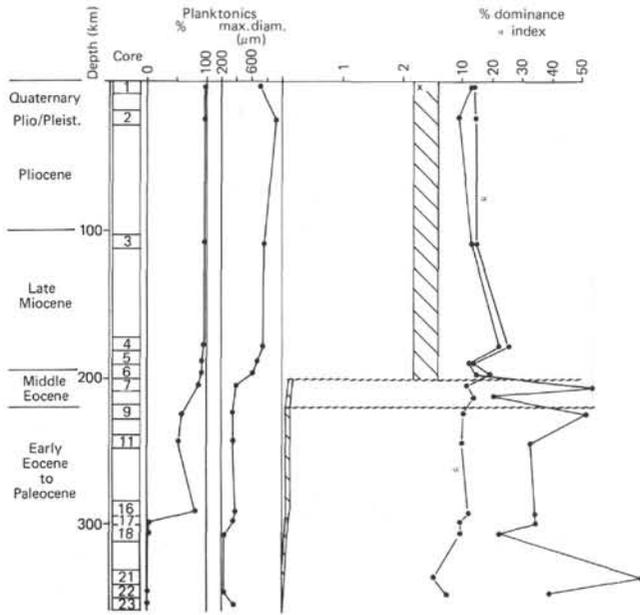
Figure 15. *Summary log of Site 404 (R = rare foraminifers).*

Site 405 (Figures 16 and 17)

In general the recovery of benthic foraminifers from the Paleogene was poor due mainly to their low abundance and the small size of the samples. The oldest sample yielding an adequate fauna is Core 27. The assemblage has high diversity ($\alpha = 18$). The dominant species include *Nodosaria* spp. and *Cyclammina* sp., with accessory *Cibicidoides hercegovinensis*, *Globocassidulina subglobosa*, *Nonion* cf. *N. olssoni*, *Nuttallides truempyi*, and *Oridorsalis ecuadorensis*. This is interpreted as epibathyal (<1000 m) because of the forms typical of deeper water (*Stilostomella*, *Pleurostomella*, *Nuttallides truempyi*—see Berggren and Aubert, 1976) only the

former is common. The planktonic-benthic ratio is low for such a depth and this is not due to dissolution because juvenile planktonics are present in abundance. Two possible explanations are that conditions were unfavorable for planktonic forms at this time or that conditions were especially favorable for benthic production.

Core 8 yielded a similar assemblage of benthic forms dominated by *Stilostomella* spp., *Dentalina* sp., and *Nodosaria* spp. and with accessory *Globocassidulina subglobosa*, *Nonion* cf. *N. olssoni*, and *Pleurostomella* sp. This is likewise believed to represent epibathyal (<1000 m) depths. The planktonic:benthic ratio is high and the maximum diameter of the planktonic individuals is high for Eocene assemblages.

These assemblages include forms likely to have been derived from shallower water: *Anomalinoides howelli*, *A. nobilis*, *Pulsiphonina prima*, and *Alabamina wilcoxensis*.

Site 406 (Figures 18 and 19)

Only one core yielded an adequate assemblage (Core 42). The dominant species is *Stilostomella* spp., with accessory *Gyroidinoides complanata*, *Gyroidinoides* sp., *Nuttallides truempyi*, and *Siphotextularia* sp. The diversity is high. This is interpreted as epibathyal (~1000 m).

The planktonic:benthic ratio of this core is lower than that of the other Paleogene cores, and this is partly why an assemblage count was possible.

Discussion

Paleogene benthic assemblages have been described from the North Atlantic by Berggren (1972a, b). Further details of the faunas from Rockall Bank and Hatton-Rockall Basin have been provided by Berggren (1974) and Berggren and Aubert (1976). Figure 20 shows diagrammatically the stratigraphic extent of the deposits at Sites 116 and 117 and also at Sites 403 to 406. It shows that there is only partial

Taxon / Core	*Alabamina wilcoxensis*	*Bulimina trigonalis*	*Cibicidoides hercegovinensis*	*Cyclammina* sp.	*Dentalina* sp.	*Globocassidulina subglobosa*	*Gyroidinoides* sp.	*Nodosaria* spp.	*Nonion* cf. *N. olssoni*	*Nuttallides truempyi*	*Oridorsalis ecuadorensis*	*Pleurostomella* sp.	*Stilostomella* spp.	α index	planktonic:benthic ratio (%)	maximum diameter of planktonics (μm)	Inferred Depth (m) and Environment	Age
8			14	7	x	10	5			4			15	30	96	600		Early-middle Eocene
14						D									94	360	epibathyal <1000	
18	D														88	300		Early Eocene to late Paleocene
27		5	9		5	4	13	8	4	7			10	18	58	300		
28	D							D							81	320		
31								D							59	300		

Figure 16. *Occurrence of benthic foraminifers (>4%) in the Paleogene at Site 405 values in %, x = <4%; Cores 12, 16, and 25 yielded few benthic forms; Cores 14, 18, 28, and 31 yielded <100 benthic forms, and D = dominant species in these assemblages).*
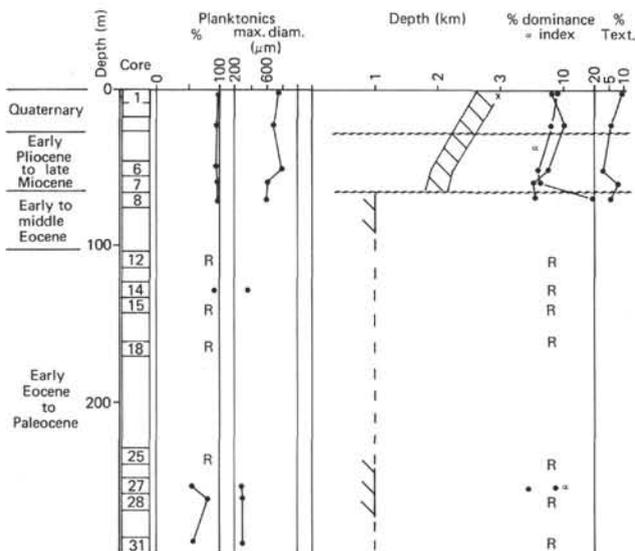
Figure 17. *Summary log of Site 405 (R = rare foraminifers).*

overlap in time between the holes of Leg 12 and those of Leg 48. There are also facies differences between different sites.

Sites 403 and 404 were drilled close to one another and between them they provide a record of most of the Eocene. At Site 403 deposition commenced in mid to inner shelf depths (< 100 m) in waters of normal salinity. A shallowing took place to a depth of <10 meters on the inner shelf close to a river as shown by brackish elements in the fauna. Thereafter, the water deepened to mid-inner shelf (<100 m) and normal marine conditions prevailed. In the middle Eocene it deepened to outer shelf then upper slope (~250 m) and finally to ~600 meters in late Eocene-Oligocene times.

Thus, with the exception of the early Eocene shallowing (Core 34) subsidence exceeded the rate of sedimentation.

At Site 404 deposition started in depths of <10 meters, initially normal marine and then brackish, and this was followed by normal marine conditions with a slow increase in water depth to 75 to 150 meters in the early Eocene and 100 to 180 meters in the middle Eocene.

The inner shelf assemblages recorded here are quite different from those recorded by Berggren (1974) as faunal assemblage 1 from Site 117; none of the characteristic species listed by Berggren are present at Sites 403 and 404. Some of the species present are found in the Hampshire Basin (England) and the Paris Basin (France) (see Murray and Wright, 1974), but there are no great faunal similarities.

In a general sense there is similarity between the mid-shelf early Eocene assemblages and faunal assemblage 2 of Berggren (1974) in the presence of *Osangularia expansa* and *Cibicidoides succedens* but there are also many differences, especially the dominance of *Anomalinoides howelli*. There are also major differences with the early Eocene of the Hampshire and Paris basins (see Murray and Wright, 1974). Middle Eocene is not represented at Sites 116 and 117 but the assemblages recorded here from Site 404 have some similarity with Berggren's faunal assemblage 3 (presence of *Oridorsalis ecuadorensis*).

Sites 406 and 405 differ from Sites 403 and 404 in representing deeper water, epibathyal environments. They also differ from the late Eocene-Oligocene assemblages of Sites 116 and 117 in the nature of the dominant species. This may be partly due to age differences as well as differences of environment of accumulation.

Neogene

Sites 403 and 404 (Figures 13, 15, 21, and 22)

Inspection of Figures 21 and 22 reveals that 15 species which form >4 per cent of the assemblage are present at both sites. Among these are *Pullenia bulloides, Planulina wuel-*

Taxon / Core	*Bulimina trigonalis*	*Globocassidulina subglobosa*	*Gyroidinoides complanata*	*Gyroidinoides* sp.	*Melonis affine*	*Nuttallides truempyi*	*Oridorsalis ecuadorensis*	*Siphotextularia* spp.	*Stilostomella* spp.	∝ index	planktonic:benthic ratio (%)	maximum diameter of planktonics (µm)	Inferred Depth (m) and Environment	Age
27											98	500		Early Miocene to late Oligocene
32			D		D						97	520		
37	D										98	600		Middle to late Eocene
42		x	5	7	x	5		4	19	25	86	640	∿1000 epibathyal	
46		D									94	440		
51	D										96	380		Early Eocene

Figure 18. *Occurrence of benthic foraminifers (>4%) in the Paleogene at Site 406 (values in %, x = <4%; Cores 27, 39, 37, 46, and 51 yielded small assemblages, D = dominant species).*
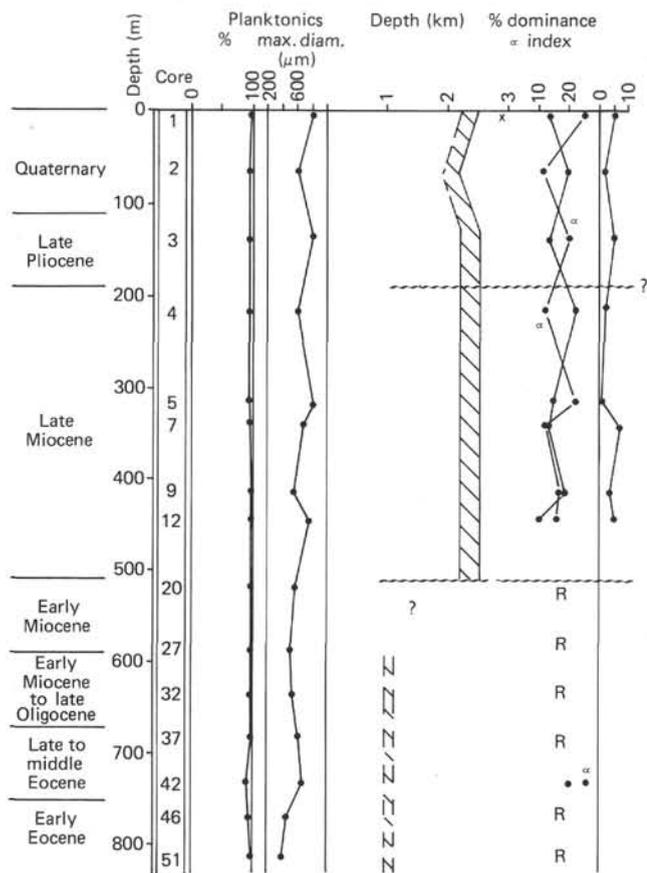
Figure 19. *Summary log of Site 406 (R = rare foraminifers).*

lerstorfi, and *Oridorsalis umbonatus*, all part of the *Planulina wuellerstorfi* fauna which, according to Brouwer (1973), extends from 1350 to 5084 meters. At these sites *Bulimina striata* and *Uvigerina peregrina* (lower depth limit ~2200 m) and *Cibicidoides robertsonianus* (upper depth limit ~2600 m) are generally absent or present only in very low abundance. Thus, the depth range may be in the range ~2200 (lower limit of the former) to ~2600 meters (upper limit of the latter). Some check is provided by the top cores as both holes are known to have been drilled in ~2300 meters of water. The whole of the late Miocene to Recent record suggests a similar depth of deposition.

Sites 405 and 406 (Figures 17, 19, 23, 24)

The *Planulina wuellerstorfi* fauna is present throughout the Neogene of Site 405. *Uvigerina peregrina* is a common species in Cores 7 and 6 (late Miocene-early Pliocene) which suggests a depth <2260 meters. *Cibicidoides robertsonianus* is absent here too, but appears in low abundance in Core 3 and in moderate abundance in Core 1 (Pleistocene). This may indicate a deepening to >2600 meters (the hole was drilled in 2958 m). An upper depth limit of ~1800 meters in Cores 7 and 6 is suggested by the abundance of Textulariina (compare Figures 17 and 11).

The Pleistocene sample (Core 1) includes *Rupertina stabilis*, a species originally described from the "cold area" of the Faeroe Channel, at a depth of 1156 meters. This form lives attached to shells and rocks, and its presence in this
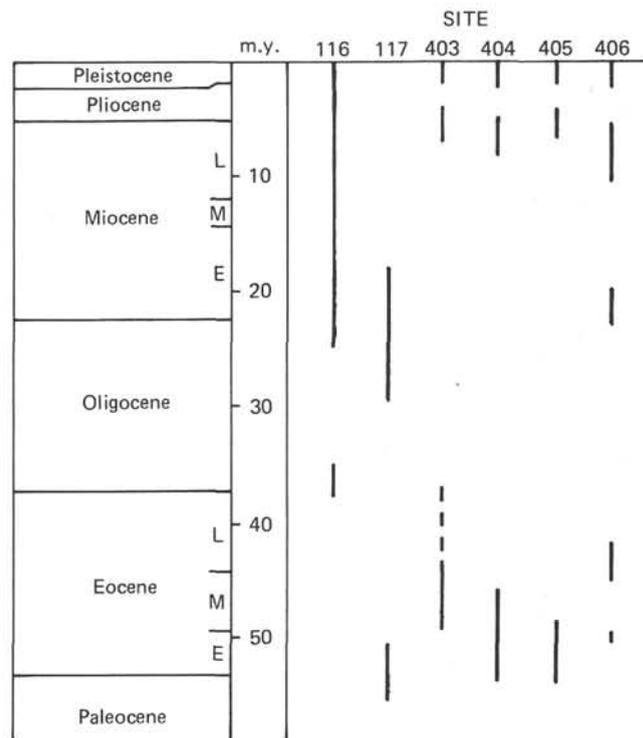
Figure 20. *Stratigraphic extent of sediments at Sites 116, 117, 403-406.*

sample indicates the nearby existence of such a firm substrate at the time of deposition.

The early Miocene sediments at Site 406 (Core 20) yielded only a small benthic assemblage from which little can be inferred. The remainder of the Neogene is characterized by the *Planulina wuellerstorfi* fauna. *Bulimina striata* is absent. *Uvigerina peregrina* is generally absent but makes up 10 per cent of the assemblage in Core 2. *Cibicidoides robertsonianus* is absent. The percentage of Textulariina is variable but reaches a maximum of 6.6 per cent.

With the exception of Core 2, depths of 2200 to 2500 meters are indicated by the above data. Core 2 indicates a depth of <2200 meters from the common *U. peregrina*. The hole was drilled in 2907 meters of water so the results from the foraminifers do not accord with the known depth at the top of the succession.

Discussion

All of the late Miocene to Pleistocene benthic assemblages have a modern appearance, being made up of species known to be living in the North Atlantic today. Berggren (1972b) suggested that the change to the modern fauna took place in the middle Miocene (not sampled here).

These Neogene assemblages are characterized by their very high diversity (α= 11-25), moderate to low per cent faunal dominance (generally <16%, rarely up to 22%), very low abundance of Miliolina (a few *Pyrgo* and *Triloculina*), low abundance of Textulariina (<10%), and predominance of Rotaliina.

It has already been stressed that changes in depth are accompanied by changes in other environmental parameters. In view of the similarity of the Neogene assemblages to those

Core	Bulimina aculeata	Bulimina alazanensis	Cassidulina laevigata	Cibicidoides kullenbergi	Cibicidoides robertsonianus	Cibicidoides sp.	Epistominella pulchella	Ehrenbergina serrata	Ehrenbergina trigona	Gyroidinoides spp.	Hyperammina? sp.	Melonis barleeanus	Nonion sp.	Oridorsalis umbonatus	Planulina wuellerstorfi	Pullenia bulloides	Pullenia quinqueloba	Pyrgo murrhina	Sigmoilopsis schlumbergeri	Siphotextularia sp.	Uvigerina hollicki	Uvigerina peregrina dirupta	α index	planktonic:benthic ratio (%)	maximum diameter of planktonics (μm)	Interpreted Depth (m) and Environment	Age
1	6	9	x	12						x		11		x	x	7	7	6	x		x		23	99	630		Pleistocene
3																								97	600		Plio-Pleist.
7		x	x	x						x	x	13		11	x	12		x	x	x		5	24	98	800	~2200 -~2600 Lower Mesobathyal	
8		x		x	x	x	4	x						x	8	4		7			x	4	24	99	640		Early
11	4	4		12	x	x	x			x		8				6			x	x	x		24	98	680		Pliocene
16	4		5	x	x	x				11		8		x	11	4	x	5	4		4	9	15	98	640		
18		7	8		4	8				15				x	12	7		x	x	x	6		16	98	700		Late
23	x		x	x		x				6				12	8	16	17	4			5		12	99	540		Miocene

Figure 21. *Occurrence of benthic foraminifers (>4%) in the Neogene at Site 403 (values in %; x = <4%; core 3 yielded only a small assemblage).*

Core	Bulimina aculeata	Bulimina alazanensis	Bulimina striata	Cassidulina laevigata	Cibicidoides kullenbergi	Eggerella bradyi	Ehrenbergina serrata	Epistominella pulchella	Globocassidulina subglobosa	Gyroidinoides spp.	Melonis barleeanus	Melonis pompilioides	Nodosaria sp.	Nonion sp.	Oridorsalis umbonatus	Planulina wuellerstorfi	Pullenia bulloides	Pullenia quinqueloba	Pyrgo murrhina	Sigmoilopsis schlumbergeri	Stilostomella antillea	Uvigerina hollicki	α index	planktonic:benthic ratio (%)	maximum diameter of planktonics (μm)	Interpreted Depth (m) and Environment	Age
1	7	x	8	5	10	x			5					x	14	9	4		x			7	14	99	720		Pleistocene
2		x		6					x	8	5			x	7	9	x	4	6			9	15	98	900	~2200-~2600 Lower mesobathyal	Plio./Pl. boundary
3	6	4		14	6		4	4	5					4	12	8	6	6		x	x	x	15	99	760		
4	x	5	7	x	5	x	x	5		x				x	22	8	11	x			4	4	25	97	740		Late
5			15	x	x					4					8	6	8	7	7		x	6	14	91	680		
6	x	x		x	x				x	5	10			x	15	5	7	15	x			5	20	93	620		Miocene

Figure 22. *Occurrence of benthic foraminifers (>4%) in the Neogene at Site 404 (values in %, x = <4%).*

of the North Atlantic at present, it seems likely that Neogene temperature and salinity at depth were no more variable than at present.

Around much of the North Atlantic, submarine canyons are well developed and downslope transport of benthic foraminifers takes place (see Pujos-Lamy, 1973a, on the Bay of Biscay). No submarine canyons exist at present on Rockall Bank (Roberts, 1975) so downslope transport is low and this seems to have been the case throughout the Neogene.

SUMMARY

The rifted northwest margin of Rockall Plateau was the site of shallow water, continental shelf, deposition of sediments in the late Paleocene-early Eocene. More rapid subsidence took place during the middle Eocene giving water depths of ~600 meters in the late Eocene-early Oligocene (Site 403). Sediments representing most of the Oligocene to middle Miocene are absent. Late Miocene sedimentation was bathyal (~ 2200 - ~ 2600 m) and these deep water conditions have continued until the present day.

The basin south of Rockall Plateau adjacent to the transform fault was already ~1000 meters deep by the early Eocene and remained so until the late Eocene (Sites 405 and 406). There is then a break in the sedimentary record until the early Miocene (few benthic foraminifers) and a further break until the late Miocene. From this time until the present this

Core	Brizalina subaenariensis	Bulimina aculeata	Bulimina alazanensis	Cibicidoides kullenbergi	Cibicidoides robertsonianus	Eggerella bradyi	Ehrenbergina trigona	Fursenkoina schreibersiana	Globobulimina subglobosa	Gyroidinoides spp.	Melonis barleeanus	Nonion sp.	Oridorsalis umbonatus	Planulina wuellerstorfi	Pullenia bulloides	Pullenia quinqueloba	Pyrgo murrhina	Rupertina stabilis	Sphaeroidina bulloides	Stilostomella sp.	Triloculina sp.	Uvigerina hollicki	Uvigerina peregrina	α index	planktonic:benthic ratio (%)	maximum diameter of planktonics (μm)	Interpreted Depth (m) and Environment	Age
1		6		9	5				x			x	4	16	6		x	7	x			5	x	18	99	760	<2600 Infrabathyal	Pleistocene
3			x	5		4					10	x			6	x	21	7				5	7	17	99	700		Early Pliocene to
6	13		16	4	x	5			x	4	4		x	x	x	x			4				13	12	95	800	1800-2200	late
7	4	x	11	4		8	x				4		10	10			6	5	x			5		6	13	96	660	mesobathyal	Miocene

Figure 23. *Occurrence of benthic foraminifers (>4%) in the Neogene at Site 405.(values in %, x = <4%).*

Core	Bolivina sp.	Cibicidoides kullenbergi	Cibicidoides sp.	Eggerella bradyi	Ehrenbergina serrata	Ehrenbergina trigona	Epistominella pulchella	Globocassidulina subglobosa	Gyroidinoides spp.	Hoeglundina elegans	Melonis barleeanus	Melonis pompilioides	Nodosaria sp.	Nonion sp.	Oridorsalis umbonatus	Planulina wuellerstorfi	Pullenia bulloides	Pullenia quinqueloba	Stilostomella sp.	Uvigerina compressa	Uvigerina hollicki	Uvigerina peregrina	α index	planktonic:benthic ratio (%)	maximum diameter of planktonics (μm)	Interpreted Depth (m) and Environment	Age
1	5	x						13	6	8	5	7			6	x	x			x		x	25	99	800	? <2200	Pleistocene
2								19	7	x				x	4	4	4	x	16	5	8	10	11	94	600		
3			x	5			x	6					x	x	10	5	5	13	x	5	x		20	97	800		Late Pliocene
4	4	22					x	x	x						5	11	x	11		x	x	x	12	97	600		
5				x				x	14	8	x			x	8	4	10	x	x	x	x	x	22	98	800	2200-2500	Late
7						5		x	8	11	x			x	12	6	13	6	9			5	12	96	660	Lower	Miocene
9	x	x	x	4					7	9			x	x	7	x	18	9	5			4	16	97	520	mesobathyal	
12	x	5	x				x	6					x	x	9	x	6	x				6	15	99	740		
20															D									97	480	?	Early Miocene

Figure 24. *Occurrence of benthic foraminifers (>4%) in the Neogene at Site 406 (values in %, x = <4%; D = dominant species in a small assemblage).*

area has been bathyal (~1800-~3000 m; note that the present water depth is ~2950 m).

The late Miocene benthic fauna is modern in aspect and it seems likely that the temperature and salinity conditions of the Miocene bathyal zone were no more variable than those today.

ACKNOWLEDGMENTS

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APPENDIX: FAUNAL REFERENCE LIST

Paleogene Planktonic Foraminifers

Catapsydrax dissimilis (Cushman & Bermudez) = *Globigerina dissimilis* Cushman and Bermudez, 1937
Globigerapsis index (Finlay) =*Globigerinoides index* Finlay, 1939
Globigerina boweri Bolli, 1957
Globigerina linaperta Finlay, 1939, group *sensu* Stainforth et al., 1975
Globigerina triangularis White, 1928
Globigerina cf. *G. yeguaensis* Weinzierl and Applin, 1929
Globigerinita unicava (Bolli, Loeblich, and Tappan) *primitiva* Blow & Banner, 1962
Globorotalia bullbrooki Bolli, 1957
Globorotalia esnaensis (LeRoy) = *Globigerina esnaensis* LeRoy, 1953
Globorotalia pentacamerata Subbotina, 1947
Pseudohastigerina wilcoxensis (Cushman and Ponton) = *Nonion wilcoxensis* Cushman and Ponton, 1932
Truncorotaloides rohri Brönnimann and Bermudez, 1953

Paleogene Benthic Foraminifers

Alabamina cf. *A. obtusa* (Burrows and Holland) = *Pulvinulina exigua* (Brady) var. *obtusa* Burrows and Holland, 1897
Alabamina wilcoxensis Toulmin, 1940
Alabaminoides howelli (Toulmin) = *Cibicides howelli* Toulmin, 1941
Anomalinoides nobilis Brotzen, 1948
Bulimina trigonalis Ten Dam, 1944
Cancris auriculatus (Fichtel and Moll)*primitivus* Cushman and Todd, 1942
Cibicidina cf. *C. walli* Bandy, 1949
Cibicidoides alleni (Plummer) = *Truncatulina alleni* Plummer, 1927
Elphidium hiltermanni Hagn, 1952
Epistominella vitrea Parker, 1953
Florilus elongatum (d'Orbigny) = *Nonionina elongata* d'Orbigny, 1826

Globocassidulina subglobosa (Brady) = *Cassidulina subglobosa* Brady, 1881
Gyroidina angustiumbilicata Ten Dam, 1944
Gyroidina neosoldanii Brotzen, 1936
Gyroidinoides complanata (Cushman and Stainforth) = *Gyroidina complanata* Cushman and Stainforth, 1945
Melonis affine (Reuss) = *Nonion affinis* Reuss, 1851
Nonion cf. *N. olssoni* (Berry) = *Nonion olssoni* Berry, 1928
Nuttallides truempyi (Nuttall) = *Eponides truempyi* Nuttall, 1930
Oridorsalis ecuadorensis (Galloway and Morrey) = *Rotalia ecuadorensis* Galloway and Morrey, 1929
Osangularia expansa (Toulmin) = *Parrella expansa* Toulmin, 1941
Pararotalia calvezae Loeblich and Tappan, 1957
Pulsiphonina prima (Plummer) = *Siphonina prima* Plummer, 1927
Spiroplectammina spectabilis (Grzybowski) = *Spiroplecta spectabilis* Gryzbowski, 1898
Turrilina brevispira Ten Dam, 1944

Neogene Planktonic Foraminifers

Biorbulina bilobata (d'Orb) = *Globigerina bilobata* d'Orbigny, 1846
Globigerina apertura Cushman, 1918
Globigerina bulloides d'Orbigny, 1826
Globigerina falconensis Blow, 1959
Globigerina nepenthes Todd, 1957
Globigerina parabulloides Blow, 1959
Globigerina praebulloides Blow, 1959, emend, Banner and Blow, 1962
Globigerina quinqueloba Natland *egelida* Cifelli and Smith, 1970
Globigerina venezuelana Hedberg, 1937
Globigerinoides quadrilobatus (d'Orbigny) = *Globigerina quadrilobata* d'Orbigny, 1846 (see Banner and Blow, 1960)
Globigerinoides quadrilobatus (d'Orb.) *immaturus* LeRoy, 1939 = *Globigerinoides sacculiferus* (Brady *immaturus* LeRoy, 1939
Globigerinoides sicanicus de Stefani, 1950
Globoquadrina altispira (Cushman and Jarvis) = *Globigerina altispira* Cushman and Jarvis, 1936
Globoquadrina dehiscens (Chapman, Parr, and Collins) = *Globorotalia dehiscens* Chapman, Parr, and Collins, 1934.
Globorotalia acostaensis Blow, 1959
Globorotalia conoidea Walters = *Globorotalia miozea* Finlay *conoidea* Walters, 1965
Globorotalia continuosa Blow, 1959
Globorotalia crassaformis (Galloway and Wissler) = *Globigerina crassaformis* Galloway and Wissler, 1940
Globorotalia crassaformis (Galloway and Wissler) *ronda* Blow, 1969
Globorotalia hirsuta (d'Orb.) = *Rotalina hirsuta* d'Orbigny, 1839
Globorotalia inflata d'Orbigny, 1839
Globorotalia merotumida Blow and Banner, 1965
Globorotalia plesiotumida Blow and Banner = *Globorotalia (Globototalia) tumida* (Brady) *plesiotumida* Blow and Banner, 1965
Globorotalia pseudomiocenica Bolli and Bermudez, 1965
Globorotalia puncticulata (Deshayes) = *Globigerina puncticulata* "d'Orbigny" nobis Deshayes, 1832
Globorotalia scitula (Brady) = *Pulvinulina scitula* Brady, 1882
Globorotalia scitula (Brady) *praescitula* Blow, 1959

Globorotalia siakensis LeRoy, 1939
Globorotalia tosaensis Takayanagi and Saito, 1962
Globorotalia truncatulinoides (d'Orb.) =? *Rotalina truncatulinoides* d'Orbigny, 1839
Hastigerina aequilateralis (Brady) = *Globigerina aequilateralis* Brady, 1879
Neogloboquadrina atlantica (Berggren) = *Globigerina atlantica* Berggren, 1972
Neogloboquadrina pachyderma (Ehrenberg) = *Aristerospira pachyderma* Ehrenberg, 1861
Orbulina suturalis Brönnimann, emend. Blow, 1956
Orbulina universa d'Orbigny, 1839
Praeorbulina glomerosa Blow *circularis* Blow, 1956
Sphaeroidinellopsis subdehiscens (Parker and Jones) *subdehiscens* (Blow) =*Sphaeroidinella subdehiscens* (Parker and Jones) *subdehiscens* Blow, 1959

Neogene Benthic Foraminifers

Brizalina subaenariensis (Cushman) = *Bolivina subaenariensis* Cushman, 1922
Bulimina aculeata d'Orbigny, 1826
Bulimina alazanensis Cushman, 1927
Bulimina striata d'Orbigny, 1843
Cassidulina laevigata d'Orbigny, 1826
Cibicidoides kullenbergi (Parker) = *Cibicides kullenbergi* Parker, 1953
Cibicidoides robertsonianus (Brady) = *Truncatulina robertsoniana* Brady, 1881
Eggerella bradyi (Cushman) = *Verneuilina bradyi* Cushman, 1911
Ehrenbergina serrata Reuss, 1850
Ehrenbergina trigona Göes, *Ehrenbergina serrata* Reuss *trigona*, 1896
Epistominella pulchella Husezima and Marnhasi, 1944
Fursenkoina schreibersiana (Czjzek) = *Virgulina schreibersiana* Czjzek, 1848
Globocassidulina subglobosa (Brady) = *Cassidulina subglobosa* Brady, 1881
Hoeglundina elegans (d'Orbigny) = *Rotalia elegans* d'Orbigny, 1826
Melonis barleeanus (Williamson) = *Nonionina barleeana* Williamson, 1858
Melonis pompilioides (Fichtel and Moll) = *Nautilus pompilioides* Fichtel and Moll, 1798
Oridorsalis umbonatus (Reuss) = *Rotalina umbonatus* Reuss, 1851
Planulina wuellerstorfi (Schwager) = *Anomalina wuellerstorfi* Schwager, 1866
Pullenia bulloides (d'Orbigny) = *Nonionina bulloides* d'Orbigny, 1846
Pullenia quinqueloba (Reuss) = *Nonionina quinqueloba* Reuss, 1851
Pyrgo murrhina (Schwager) = *Biloculina murrhina* Schwager, 1866
Rupertina stabilis (Wallich) = *Rupertia stabilis* Wallich, 1877
Sigmoilopsis schlumbergeri (Silvestri) = *Sigmoilina schlumbergeri* Silvestri, 1904
Sphaeroidina bulloides d'Orbigny, 1826
Stilostomella antilles (Cushman) = *Nodosaria antillea* Cushman, 1923
Uvigerina compressa Cushman, 1926
Uvigerina hollicki Thalmann, 1950
Uvigerina peregrina Cushman, 1923
Uvigerina peregrina Cushman *dirupta* Todd, 1948