APPLICATIONS
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The utility of Deep-Water Agglutinated Foraminiferal acmes for correlating Eocene to Oligocene abyssal sediments in the North Atlantic and Western Tethys

(Figs 1, 2)

Abstract. Quantitative analysis of Deep-water Agglutinated Foraminifera (DWAF) assemblages from key ODP sites in the North Atlantic reveal the presence of stratigraphically-significant abundance maxima, that may be useful for correlating sedimentary sequences deposited beneath the CCD. The DWAF record from ODP Hole 647A in the Labrador Sea was re-studied and abundances were recalculated by excluding calcareous benthic foraminifera. This hole is a key locality, as it provides direct calibration of the DWAF biostratigraphy to the standard chronostratigraphy. Eight DWAF acmes are recognised in the Eocene to lower Oligocene at Site 647 and at other North Atlantic and Norwegian Sea sites. These are: The Paleocene–Eocene Thermal Maximum (PETM) *Glomospira* Acme, a lower Eocene *N. excelsa* acme, an early/middle Eocene *Glomospira* Acme, a *Karrerulina* acme, a middle Eocene *Reticulophragmium amplectens* acme, a middle/late Eocene *Spiroplecta-mmina* acme, a latest Eocene–early Oligocene *Ammodiscus latus* acme, and an early Oligocene *Spirosigmoilinella* acme. Some of these acmes can be correlated with similar events occurring at onshore localities in the Western Tethys (northern Spain, Moroccan Rif, Italian Appenines, Western Carpathians). The occurrence of these DWAF acmes is caused by variations in the trophic continuum which is a consequence of the profound climatic and oceanographic changes that took place in the deep ocean during the Eocene and early Oligocene.

Key words: Agglutinated Foraminifera, Eocene, Biostratigraphy, Atlantic Ocean.

INTRODUCTION

Deep-water agglutinated foraminifera have been used for stratigraphic correlation for well over a hundred years (Grzybowski, 1898). A number of zonal schemes using DWAF have been proposed for the Paleogene of the Carpathian flysch deposits (e.g., Grzybowski, 1898; Jurkiewicz, 1967; Geroch & Nowak, 1984;

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Olszewska, 1997). Some of the zonations are based on the first and last occurrences of index taxa (Geroch & Nowak, 1984), while other zonations make use of a combination of first and last occurrences as well as abundance maxima (e.g., Olszewska, 1997). While the stratigraphic schemes based on DWAF are undoubtedly useful for local stratigraphical correlation, the lack of calcareous microfossils and magnetostratigraphy in the Carpathian sections makes it difficult to link the zonal schemes to the standard low-latitude planktonic foraminiferal and calcareous nannofossil zonations, and thence to the standard geological time scale.

Since the establishment of the Geroch & Nowak zonation, some of the Carpathian DWAF zones have been recognised in other areas outside the Carpathians. Figure 1 gives an overview of the foraminiferal assemblages reported from sites in the North Atlantic – western Tethyan region. In the North Sea area, Gradstein *et al.* (1988) were the first to use the "*Cyclammina amplectens* Zone". Elements of the Geroch & Nowak Zonation can be also found in turbidite sequences from northern Morocco (Kaminski *et al.*, 1996) and northern Spain (Kuhnt & Kaminski, 1997). The recovery of DWAF assemblages of Paleogene age from the Iberian ODP Sites in the eastern North Atlantic (Kuhnt & Collins, 1996; Kuhnt & Urquhart, 2001), provides another link to the Carpathian zonations. Even though some elements of the Geroch & Nowak zonation were found in the eastern Atlantic ODP Sites, unfortunately the same problem of establishing a precise age model for the cores was encountered at the sub-CCD sites on the Iberian Abyssal Plain (Kuhnt & Collins, 1996). Fortunately, two of the more recent sites drilled during ODP Leg 173 recovered calcareous claystones of Paleocene to middle Eocene age at Sites 1067 and 1068. The DWAF biostratigraphy of these two sites was studied by Kuhnt & Urquhart (2001).

In the northwestern Atlantic, there is only one ODP site where DWAF occur in a well-dated, continuous stratigraphic succession. ODP Hole 647A in the southern Labrador Sea contains a continuous record of DWAF from the Lower Eocene to the Lower Oligocene (Kaminski *et al.* 1989). At this locality, DWAF can be tied directly to the standard time scale by means of magnetostratigraphy and calcareous nannofossils (Baldauf *et al.*, 1989). The calcareous and agglutinated benthic foraminifera from this locality were studied for the *ODP Initial Results* volume, and the foraminiferal biostratigraphy was established using both groups of foraminifera (Kaminski *et al.* 1989). However, if we wish to compare this record with the noncalcareous successions of the Eastern Atlantic and Western Tethys, it is necessary to first eliminate the "noise" created by the calcareous benthic taxa that dominate the assemblages in some samples, to reveal the structure of the residual agglutinated foraminifera assemblage. Only then, can we compare the North Atlantic DWAF record with that of the sub-CCD setting of the Outer Carpathians

METHODS

The methods used in this study are akin to the approach taken by Alve &Murray (1995), who discovered that by acidifying samples collected for the study of mod-

ern benthic foraminifera, a useful amount of ecological information was retained by the residual agglutinated foraminiferal assemblages. Often there was more structure in the residual data set by physically removing the dominant calcareous taxa from the samples. This approach of studying DWAF in acid residues is used routinely in studies of strongly lithified deep-water limestones such as those from Gubbio (e.g., Kuhnt & Kaminski, 1996, Galeotti *et al.*, 2004). With this in mind, I believed it would be instructive to remove the calcareous taxa from the published data matrix of benthic foraminifera from Hole 647A (Kaminski, 1988) and re-calculate the agglutinated foraminifera as closed sum percentages. I simply removed from the data matrix all the calcareous benthic species as well as any calcareous agglutinated forms such as *Clavulinoides* and *Karreriella*, which are not normally found in sub-CCD oceanic deposits such as those from the Iberian Abyssal Plain (Kuhnt & Collins, 1996). When the non-calcareous DWAF percentages were recalculated, the downcore plots revealed distinct acmes. The purpose of this review is to establish the timing of these DWAF acmes in the Labrador Sea, and compare their occurrences in other areas of the Atlantic and Tethys where noncalcareous sediments are found.

STUDY AREA

ODP Site 647 was drilled at a water depth of 3869 m at 53°19.8'N, 46°15.7'W on the Gloria sediment drift, situated oceanic crust of Anomaly 24 age in the southern Labrador Sea (Fig. 1). The site is located ca. 90 km SE of DSDP Site 112, which was studied by Miller *et al.* (1982). Hole 647A penetrated 580 m of Paleogene sediments, the chronostratigraphy of which was determined using calcareous nannofossils and magnetostratigraphy (Baldauf *et al.* 1989). Importantly, this hole recovered a complete section across the Eocene/Oligocene boundary at 290 mbsf. It is thus the only well-dated reference section for this interval in the North Atlantic, since at most locations this boundary is present as a hiatus.

BIOSTRATIGRAPHY

The calcareous nannofossil biostratigraphy of Hole 647A was published by Firth (1989) and summarised into a chronostratigraphic framework by Baldauf *et al.* (1989). Foraminiferal studies at Site 647 were based on quantitative analysis of 124 samples, yielding 58 species and higher taxonomical groups of DWAF. Based on the stratigraphical ranges of index taxa, Kaminski *et al.* (1989) subdivided the faunal succession into the following assemblages (in some cases the generic names of the DWAF taxa have been revised according to modern usage):

Nothia excelsa – Abyssammina assemblage (Lower Eocene)

This assemblage, characterised by the nominate taxa, consists of DWAF and calcareous benthics within a *Subbotina patagonica* foraminiferal ooze typical of planktonic foraminiferal Zones P7–P8. Backtracking estimates give a paleodepth
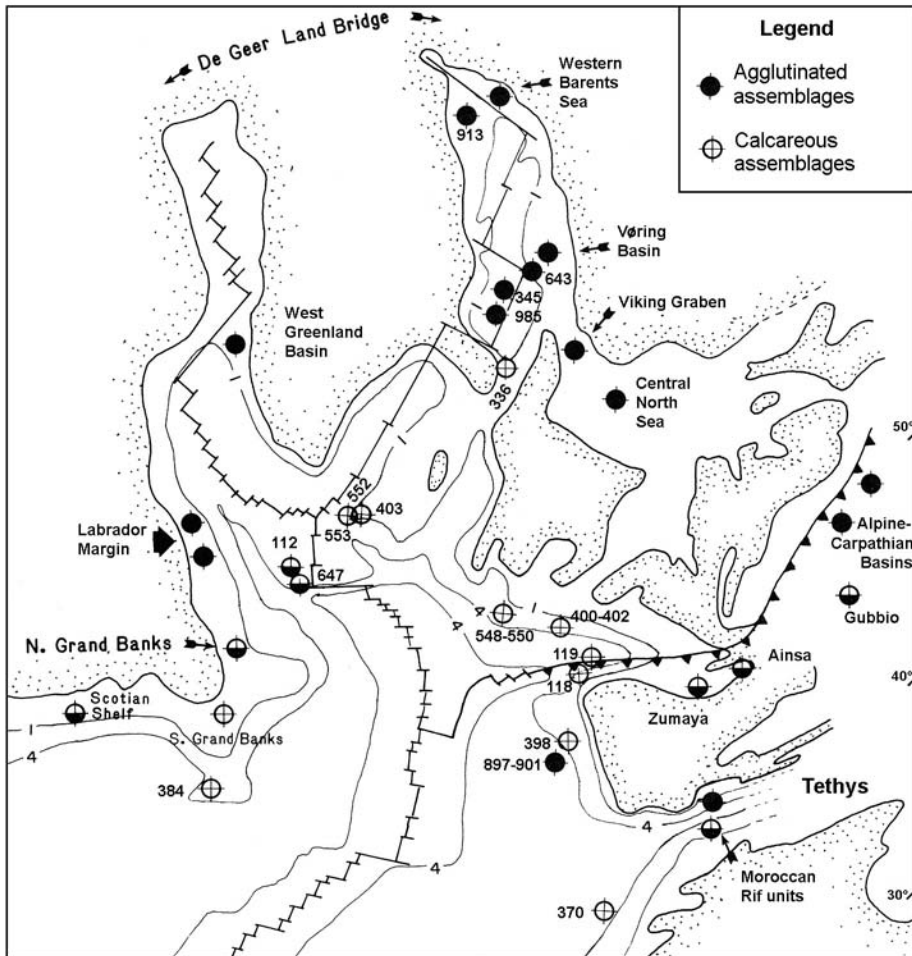
Fig. 1. Location ODP Site 647 and other localities where Eocene benthic foraminiferal assemblages have been studied. Base map is the Middle Eocene reconstruction from Tucholke & McCoy (1986)

of 1700–2000 m for this assemblage. *Nothia excelsa* (Grzybowski) dominates the agglutinated component along with other tubular forms. *Ammodiscus nagyi* Kaminski. *Subreophax scalaris*, (Grzybowski) and *Hormosinella distans* (Brady) are also common. Other characteristic species include *Caudammina ovula* (Grzybowski), *Spiroplectammina navarroana* (Cushman), and *Karrerulina coniformis* (Grzybowski) and *K. conversa* (Grzybowski).

Glomospira assemblage (Lower to Middle Eocene)

Samples from the 20-m thick interval in Cores 647A-64R and –65R are completely barren of calcareous fossils, and the DWAF are present in a *"Glomospira* fa-

cies". The most common species in this assemblage are *Glomospira irregularis* (Grzybowski), *Glomospira gordialis* (Jones and Parker), *Repmanina charoides* (Jones and Parker), and *A. cretaceus* (Reuss), which collectively comprise as much as 60% of the assemblage. Also present are *K. coniformis*, *Trochamminoides* spp., and *H. Walteri* (Grzybowski). The base of the assemblage lies within calcareous nannofossil Zone NP13, and its top is within Zone NP15.

Reticulophragmium amplectens – Nuttalides truempyi assemblage (Middle Eocene)

The assemblage in calcareous claystones in Cores 647A-63R to –47R consists of between 40 and 80% agglutinated taxa. The dominant taxa are tubular forms, with common *Recurvoides* sp. and *R. amplectens* (Grzybowski). The latter comprises up to 8% of the total fauna. Within this interval the FO of *Ammodiscus latus* (Grzybowski) and the LOs of *Spiroplectammina navarroana* and *A. nagyi* are observed. The Middle Eocene age of this interval is confirmed by the LO of *Acarinina* spp. in Sample 647A-49R-1, 118–121 cm.

Spiroplectammina spectabilis – Spirosigmoilinella compressa assemblage (Middle to Upper Eocene)

This interval is delimited by the partial range of *S. compressa* (Matsunaga), from its FO in Core 647A-46R-5 to the FO of *Duquepsammina cubensis* (Bermudez) in Core –43R-3. *Psamminopelta gradsteini* Kaminski and Geroch is also observed. The foraminiferal assemblage is characterised by the acme of *Spiroplectammina* (*S. spectabilis* (Grzybowski) and *S. trinitatensis* (Cushman and Renz)), which comprise 25–30% of the assemblage. The co-occurrence of the two species of *Spiroplectammina* in the same samples confirms that they are indeed different species. The interval corresponds to the upper part of Zone NP17. The LO of *K. conversa* was observed at the top of this interval.

Duquepsammina cubensis – Reticulophragmium amplectens assemblage (Upper Eocene)

This interval is characterised by the concurrent range of the two nominate taxa, and corresponds to the bulk of the Late Eocene. The FO of *D. cubensis* was observed in Core 647A-43R-3 at approximately the same level as the Last Common Occurrence of *S. spectabilis*. Within this interval, there is a gradual transition from a DWAF-dominated assemblage to a calcareous-dominated assemblage in the Oligocene, and the diversity of DWAF declines throughout the interval. This is particularly evident in Cores 647A-32R and –31R, which contain the LO's of 10 agglutinated taxa. The age model for Hole 647A places the Eocene/Oligocene boundary at approximately 290 mbsf, within Core 647A-31R. This core contains the LOs of *Conglophragmium irregularis* (White), *Glomospira serpens* (Grzybowski), *Saccammina grzybowskii* (Schubert), *Subreophax scalaris*, *Ammolagena clavata*

(Jones and Parker), *Spiroplectammina spectabilis*, *R. amplectens*, and *Recurvoides* spp. The highest occurrence of the Late Eocene calcareous nannofossil *Discoaster barbadiensis* was found in Core 647A-30,CC.

Ammodiscus latus – *Turrilina alsatica* assemblage (lowermost Oligocene)

The interval from Core 647A-31-1 to -27R-1 contains the concurrent range of the nominate taxa. The FO of *T. alsatica* coincides with the LO of *R. amplectens* in Sample –31R-1, 133–135 cm. The assemblage is characterised by just a few remaining DWAF, such as *R.charoides, G. irregularis, Bathysiphon* sp., *A. cretaceus*, *Reophax* sp., and *D. cubensis.* Most of the specimens show a notable reduction in size. The LO of *A. latus* is observed at the top of this interval. The LO of the planktonic foraminifer *Globigerina ampliapertura* was found in Sample 647A-27R-1, 78–83 cm, indicating the top of planktonic foraminiferal Zone P20.

Turrilina alsatica – *Spirosigmoilinella* assemblage (Lower Oligocene).

Above Core 647A-27R, the assemblages are depauperate, and washed residues contain mainly biosiliceous debris. The most characteristic species in this assemblage is *Spirosigmoilinella compressa* and *Psamminopelta gradsteini* accompanied by *Cribrostomoides subglobosus* (Brady), and *Rhabdammina* sp.

RESULTS

With the calcareous benthic foraminifera removed from the data set, the acmes of the DWAF in Hole 647A become more prominent. Figure 2 presents the relative abundance of species that display acmes within the Eocene and Lower Oligocene in Hole 647A. We compare these acmes with the published data sets of Kuhnt & Collins (1996) and Kuhnt & Urquhart (2001) for the Eocene of the Eastern Atlantic, Kaminski *et al.*, (1996) for the Moroccan Rif, Galeotti *et al.*, (2004) for the Palaeocene–Eocene transition at Gubbio, Italy, and Kaminski & Austin (1999) for the Oligocene of ODP Site 985 on the Iceland Plateau, and the recent work of Bąk (2004) from the Dukla Unit of the Polish Carpathians. The following acmes are observed in the Eocene of the abyssal North Atlantic and westernmost Tethys:

1. The PETM *Glomospira* acme
Age: earliest Eocene
A brief maximum in the relative abundance of *Glomospira* is observed immediately above the Paleocene/Eocene boundary at Gubbio (Galeotti *et al.* 2004). The *Glomospira* maximum at Gubbio occurs within a double "dissolution horizon" within the normally pink limestone of the Scaglia Rossa Formation. Its position just above the Paleocene/Eocene boundary in Gubbio has been determined magnetostratigraphically, biostratigraphically, and by the carbon isotope record (Galeotti *et al.* 2004). The acme occurs just above the "Benthic Extinction Event" observed in
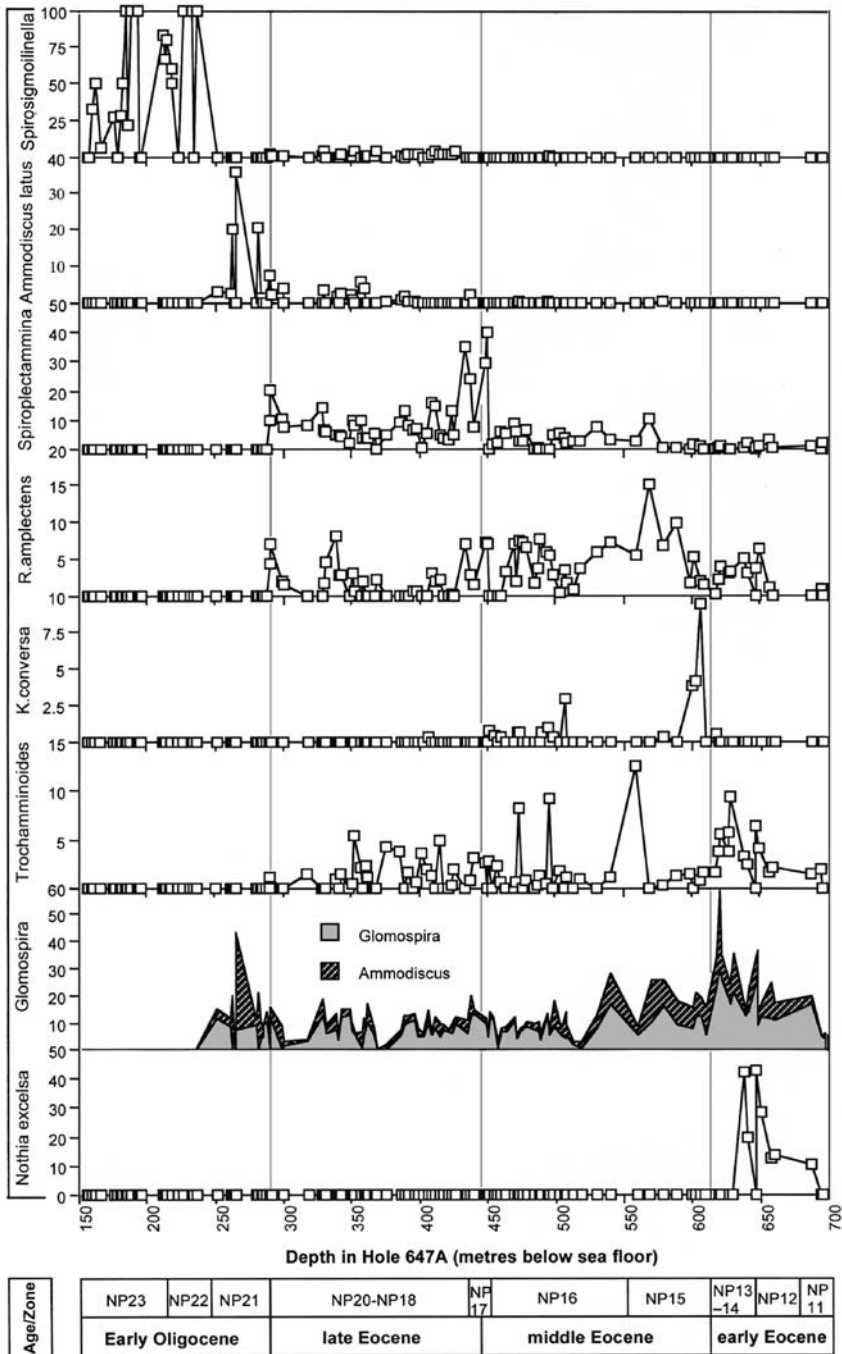
Fig. 2.   Relative abundances of characteristic taxa in the Eocene to Lower Oligocene of ODP Hole 647A in the southern Labrador Sea. Percentages are expressed as a closed sum of the agglutinated foraminiferal taxa only (calcareous benthics were excluded from the sum). Data from Kaminski (1988)

the calcareous benthic foraminiferal assemblages. The most abundant species is *Repmanina charoides* (Jones & Parker), which is often of very small dimensions.

The acme of *Repmanina charoides* seems to be of use for stratigraphic correlation across the P/E transition in deep-water settings. Although not accurately dated, this is probably the same event that is present over a 12-m interval in ODP Hole 900A, and over a 3-m interval in Hole 897C off Iberia (see: Kuhnt & Collins, 1996). Although the base of the Eocene was not recovered at Site 1067, a maximum in *Glomospira* is found in cores 1067A-11R and –12R, which is dated as Early Eocene (Zones NP11-12). A remarkable bloom of *R. charoides* occurs in the Trabakua Pass section in the Basque basin, Spain, where it forms 50% of the assemblage in the lowermost Eocene (Coccioni *et al.*, 1995; Orue-Extebarria *et al.*, 1996). The *Glomospira–Ammodiscus* assemblage reported by Kaminski *et al.* (1996) from the Paleocene–Eocene Talaa Lakrah section in Northern Morocco might be coeval. In the Polish Carpathians, the event is widely distributed and it constitutes the basal Eocene zone in the DWAF zonation of Olszewska (1997). Bąk (2004) distinguished a Glomospira biofacies within the lower part of the Hieroglyphic Beds in the Dulka Unit, where *R. charoides* and *G. gordialis* comprise up to 70% of the fauna in sediments assigned to the lower part of the Lower Eocene.

The widespread occurrence of a diminuative *Glomospira* biofacies in the earliest Eocene can be interpreted in terms of ocean-wide oligotrophy, as also suggested by the calcareous nannofossil record (Bralower *et al.*, 2002). In a study of modern benthic foraminifera along a productivity gradient in the Mediterranean, De Rijk et al. (2000) found that *Repmanina charoides* characterises the deepest, most oligotrophic sector of the Eastern Mediterranean. In Gubbio, the facies is preceded by a decrease in the relative abundance of deep-infaunal forms, suggesting the a decrease in the carbon flux to the sea-floor (Galeotti *et al.* 2004). While the duration of the earliest Eocene dissolution facies caused by the release of methane hydrates is only on the order of 200,000 years (Dickens, 2000), I expect that the duration of the "PETM *Glomospira* acme" might vary from place to place according to the trophic conditions. It is conceivable that the event represents a longer period of time at deeper, more oligotrophic sites because of the more severe oligotrophy generally found at deep-sea localities.

2. *Nothia excelsa* acme
Age: Early Eocene (NP11–NP13)

In Hole 647A, the species *N. excelsa* (Grzybowski) comprises a maximum of 42% of the DWAF assemblage at a depth of 646.9 mbsf. In the eastern Atlantic, Kuhnt & Collins (1996) reported a maximum of this species in one sample dated as Lower Eocene at Site 897 (Sample 897D-3,CC). It is also present in elevated numbers in the "Lower Eocene" at Site 900, where it occurs in Core 900A-72, approximately 30 m above the "PETM *Glomospira* acme"; and in Hole 1068A in the same relative position (5–10 m above the *Glomospira* acme). I also observed high proportions of *N. excelsa* in samples from the Lower Eocene of the Contessa Road section in Italy (Galeotti *et al.*, 2004).

Nothia excelsa is a surface-dwelling detritivore that builds a branching network of tubes on the sea floor (Geroch & Kaminski, 1992). Its acme in Lower Eocene likely represents a return to somewhat more eutrophic conditions following the PETM.

3. The Lower/Middle Eocene *Glomospira* acme
Age: NP13–NP14

The occurrence of glomospirid-dominated biofacies is not unique. These events are well-known from the Cretaceous, where they have been termed "Biofacies-B" by Kuhnt & Kaminski (1989). In Hole 647, the *Glomospira-Repmanina* group comprises a maximum of 30% of the assemblage at 619.6 mbsf. In this hole, the occurrence of *Ammodiscus* seems to weakly covary with that of the glomospirids (r^2=0.28), and this genus makes up 28% of the assemblage at this level. In the Labrador Sea, this E/M Eocene *Glomospira* assemblage is present within a 20-m thick dissolution horizon containing red and green variegated claystones. This is the only interval in Hole 647A that contains horizons of red clays. Backtracking indicates the CCD in the Labrador Sea had risen to a level above 2,500 m during the deposition of this *"Glomospira* facies". I suspect that this second *Glomospira* assemblage may be in some way linked to the Early Eocene Climatic Optimum.

This second *Glomospira* acme is clearly present in the data from Hole 900A, where it is the most abundant non-tubular taxon in Sample 900A-70R-2, 57–59 cm (Kuhnt & Collins, 1996). This sample coincides with the FO of *Reticulophragmium amplectens* at this locality.

4. *Karrerulina* acme
Age: lower part of NP15

A sharp peak in *Karrerulina conversa* (Grzybowski) is observed at the top of the *"Glomospira* assemblage" in Hole 647A. The species comprises 9.5% of the DWAF assemblage at 605.8 mbsf. At Site 900, the event is observed 1.5 metres above the second *Glomospira* acme, in the next higher sample (900A–70R-1, 69–72 cm). At Site 1067, *Karrerulina conversa* and *Karrerulina coniformis* (Grzybowski, 1898) together comprise an acme in Cores 1067A-5R and –6R. The acme begins at the base of Zone NN15 (subzone CP13a) and persists to the lower part of subzone CP13b). This event is curious, as we have also observed an acme in *K. conversa* in the upper part of the Lower Eocene in the North Sea (Gradstein *et al.*, 1994), and in Morocco (Kaminski *et al.*, 1996) in more or less the same relative position. However, in the latter areas the chronology of this event is not as well constrained. In Moravia, where planktonic foraminifera have been reported from the Carpathian deposits, Hanzlíková (1983) noted an acme of *Karrerulina* within the M. formosa–M. aragonensis Zones (undifferentiated) in the Magura Basin. Most recently, Bąk (2004) reported an acme of *Karrerulina* in the Lower Eocene of the Dukla basin, where it may comprise 50% of the assemblage. This acme was reported from variegated shales of the Hieroglyphic beds occurring directly above the lowermost Eocene *Glomospira* acme, and was assigned an Early Eocene age. If this

is the case, the acme is diachronous between the Carpathians and the North Atlantic. I have also observed elevated proportions of *Karrerulina conversa* in Lower Eocene variegated claystones from the Silesian Unit near Biecz. The stratigraphical occurrence of *Karrerulina* species may be controlled by palaeoceanographic factors such as changes in organic matter flux, since modern representatives of this group live infaunally in abyssal clays (Kuhnt *et al.*, 2000).

5. *Reticulophragmium amplectens* acme
Age: NP15 to a lower part of NP16

The species *Reticulophragmium amplectens* (Grzybowski) was one of the taxa originally used by Grzybowski (1898) in his zonation of the Potok Oil Field, near Krosno, Poland. The species is very widely distributed throughout the Western Tethys and North Atlantic.

In Poland and the North Sea, *R. amplectens* tends to be most abundant in the early part of its range. This trend is confirmed at Site 647, although the relative abundance of this species is much lower in the abyssal Labrador Sea than it is on the continental margin, where it can dominate the assemblage. A broad maximum in *R. amplectens* is observed between 588.4 and 518.8 mbsf in Hole 647A, with a maximum abundance of 15% recorded at 569.1 mbsf. At this site, its FO is observed in the lower part of Lower Eocene Zone NP11, and its LO is exactly at the level of the Eocene/Oligocene boundary as determined by calcareous nannofossil biostratigraphy. At Site 900 on the Iberian Abyssal Plain, the *R. amplectens* acme was observed 10 m above the *Karrerulina* acme, in Core 900A-69R-1. At this level it was the dominant species (Kuhnt & Collins, 1996). At Site 1067, it begins in Core 1067A-5R, immediately above the *Karrerulina* acme (Kuhnt & Urquhart, 2001).

Reticulophragmium amplectens is one of the most well-known species described from the Carpathian flysch, and has been reported from Poland, Slovakia, Moravia, the Ukraine, and Romania by numerous authors. *Reticulophragmium amplectens* figures prominently in most zonal schemes using agglutinated foraminifera, both within the Carpathians and in other regions. In Poland, its first appearance was reported in the Early Eocene (Zone NP12) by Olszewska & Smagowicz (1977). Its total range in the Polish Carpathians was given as Early to Late Eocene by Morgiel & Olszewska (1981), and its partial range and peak occurrence characterises the Middle Eocene *Cyclammina amplectens* Zone of Geroch & Nowak (1984). In Moravia, the first appearance of abundant *R. amplectens* as was reported by Hanzlíková from Zone P10 based on the occurrence of *Acarinina densa, A. pentacamerata*, and *M. aragonensis*. In the central North Sea, King (1989) used the LCO (last consistent occurrence) of *R. amplectens* to define the upper limit of his Zone NSA4 (*R. amplectens* Zone), which he regarded as Early to Middle Eocene.

The onset of the *R. amplectens* acme is usually associated with a change from variegated clays to greenish clays. Because of its abundance and its placement in the shallow infaunal morphogroup, it is likely that the acme signals a return to generally more eutrophic conditions in the early Middle Eocene.

6. *Spiroplectammina* acme
Age: NP17

The species *Spiroplectammina spectabilis* (Grzybowski, 1898) is present throughout the Eocene at Site 647, but its relative abundance increases abruptly to 40% of the assemblage at 450.1 m. The abundance acme continues to 434.4 m, where its abundance is still 34%. Higher in the Hole 647A, its abundance is lower, but it still reaches 15% in some samples. Its LO correlates exactly with the level of the Eocene/Oligocene boundary in Hole 647A. The *"Spiroplectammina* acme" in Hole 647A also includes the somewhat larger species *S. trinitatensis* (Cushman & Renz, 1946), which co-occurs with *S. spectabilis* in the younger (Upper Eocene) part of the section.

The stratigraphical significance *Spiroplectammina spectabilis* is not unequivocal, because as is the case with *Glomospira*, the occurrence of this species seems to be linked with the trophic continuum. *Spiroplectammina* is absent from the highly oligotrophic abyssal sites in the eastern Atlantic. Kuhnt & Collins (1996) did not record a single specimen of this species from the Iberian ODP sites, and Kuhnt & Urquhart (2001) reported rare specimens only from the Paleocene at Site 1068. It was also absent from our samples from the Paleocene–Eocene Talaa Lakrah section in Northern Morocco. However, it can be very common in the Middle Eocene of the Silesian Unit in the samples from Biecz.

The genus *Spiroplectammina* is better known to form acmes in the Paleocene rather than in the Eocene. It is known as a "disaster taxon", with the species *S. israelskyi* and *S. spectabilis* occurring in elevated proportions just above the Cretaceous/Paleogene boundary at ODP Site 959 in the equatorial Atlantic (Kuhnt *et al.*, 1998) and at Gubbio, Italy (Kuhnt & Kaminski, 1996). In the Barents Sea, a maximum in *S. spectabilis* is observed in the middle part of the Paleocene, while in the Central North Sea it is in the Upper Paleocene. Its occurrence in the deep-sea sites is most likely linked to an increase in sea-floor carbon flux. At Site 647 the biosiliceous flux increases uphole throughout the Upper Eocene (Bohrmann & Stein, 1989), suggesting increasingly more eutrophic conditions.

7. *Ammodiscus latus* acme
Age: latest NP20–NP21

The species *Ammodiscus latus* (Grzybowski, 1898) occurs in low numbers throughout the Middle and Upper Eocene at Site 647, but its relative abundance increases rapidly at 281.2 mbsf. This is just below the Eocene/Oligocene boundary as determined by the age model for Hole 647A, which places the boundary at ca. 290 mbsf within Core 647A-31R (Baldauf *et al.*, 1989). *Ammodiscus latus* can be very common and reach very large dimensions in the Lower Oligocene along the Labrador Margin-Northern Grand Banks.

In the Carpathians, The Ammodiscus latus Partial Range Zone was defined as the interval from the FO of the nominate taxon to the FO of *Reticulophragmium rotundidorsatum*. (Geroch & Nowak, 1984). *Ammodiscus latus* can be rather common in upper Middle Eocene to Upper Eocene strata in the Carpathian flysch ba-

sins. The species is also known from other localities in the North Atlantic (Trinidad, North Sea).

8. *Spirosigmoilinella/Psamminopelta* **acme**
Age: NP22–23

The diversity of agglutinated foraminifera declines abruptly across the Eocene/Oligocene boundary in Hole 647A. The Lower Oligocene at this site contains a depauperate DWAF assemblage in sediments that are increasingly biosiliceous. At 237.1 mbsf the residual assemblage is comprised only of the species *Spirosigmoilinella compressa* (Matsunaga, 1955) and *Psamminopelta gradsteini* (Kaminski & Geroch, 1997). A similar faunal change is known from the Oligocene at DSDP/ODP sites in the Central Norwegian Sea (Verdenius & van Hinte, 1983; Kaminski & Austin, 1999). This assemblage seems to be restricted to the northern North Atlantic.

DISCUSSION AND CONCLUSIONS

The biostratigraphical record of Hole 647 is exceptional because it provides the only direct calibration of the biostratigraphy of DWAF to the standard chronostratigraphy by means of a well-constrained age model. Paleobathymetrically, it was the deepest site in the northwestern Atlantic, thus giving unique insight into the nature of the abyssal biofacies. The upper Eocene portion of the record is particularly good owing to the presence of magnetostratigraphic control. Moreover, it is the only site in the northern Atlantic with a complete and well-constrained Eocene/Oligocene boundary. Our study of Hole 647A has confirmed earlier findings (e.g., Van Couvering *et al.*, 1981; Olszewska, 1984) that the Eocene/Oligocene boundary interval was a time of significant faunal turnover among agglutinated benthic foraminifera.

Even more encouraging is the fact that acmes in species such as *N. excelsa*, *Glomospira* spp., *K. conversa*, *R. amplectens*, *Spiroplectammina* spp., *A. latus* and *Spirosigmoilinella* spp. become apparent in the data set once the calcareous benthic foraminifera are excluded from the relative abundance calculations. By using this method, we can now compare the mixed calcareous/agglutinated assemblages of Hole 647A with the wholly agglutinated assemblages found in other regions. Many of the same DWAF acmes are also known from the Carpathians (Grzybowski, 1898; Jurkiewicz, 1967, Hanzlíková, 1983; Olszewska, 1997; Bąk, 2004); the Iberian Abyssal Plain (Kuhnt & Collins, 1996); the flysch units of northern Morocco (Kaminski *et al.* 1996), and the Contessa section in northern Italy (Galeotti *et al.* 2004); thus giving the potential for more detailed and precise stratigraphic correlation.

It is becoming increasingly apparent that the extreme climatic/oceanic events of the Eocene have been an important instrument of benthic faunal change in the deep ocean. The DWAF record in the deep ocean has responded to variations in the trophic continuum that have ultimately resulted from climatic and oceanographic

change. The severely oligotrophic conditions brought about by the "Greenhouse world" of the Paleocene–Eocene Thermal Maximum and the Early Eocene Climatic Optimum, or the increasingly eutrophic conditions caused by the change to more vigorous ocean circulation in an "Icehouse world" are viewed as the most likely forcing mechanisms responsible for the distinctive DWAF acmes of the Eocene.

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