Controls on the distribution of calcareous Foraminifera in the Lower Carboniferous of Ireland

Stephen J. Gallagher

Geology Department, University College Dublin, Belfield, Dublin 4, Ireland

Received 12 May 1997; revised version received 4 February 1998; accepted 6 February 1998

Abstract

Microfacies analyses of thin sections from over 650 samples of Asbian and Brigantian (late Viséan) platform carbonates from Ireland shows that foraminiferal assemblages are controlled by the relative abundance of echinoderms (mainly crinoids), bryozoans and calcareous algae: Koninckopora, Ungdarella and palaeoberesellids. Archaediscidae, Valvulinella and Tetrataxidae thrived in algal-poor crinoid and bryozoan thickets at or below fair-weather wavebase. Late Viséan algal limestones contain abundant Endothyridae and Palaeotextulariidae, and are interpreted to have been deposited at depths between 5 and 10 m. The morphology of the Foraminifera studied is related closely to their facies distribution. Many taxa inhabited high energy shallow marine algal meadow facies, these include: Bibradya, Cribrospira, Nevillella and Bradyina with cribrate apertures and other specialised test features that protected the protoplasm from damage, Gigasbia, Omphalotis, Globoendothyra and Pseudoendothyra with large, rotund or keeled, multilayered tests and Forschiidae with large thick-walled tests. Infaunal taxa such as the Lituotubella, Nevillella, Gigasbia and the palaeotextulariids are recorded from algal facies and appear to have been unable to survive on bryozoan and crinoidal substrates. Pseudoammodiscus and Earlandia, characterized by simple morphologies and single layered walls, and Endothyranopsis, Endothyra and Eostaffella, planispirally coiled with multilayered micritic tests, are regarded as the least facies-controlled of the taxa studied. The encrusting nature of Pseudolituotuba and Scalebrina ensured survival in a wide range of platformal palaeoenvironments, though algal meadows were not generally suitable substrates for the Pseudolituotubidae. The secondary deposits in the umbilical region of the Asteroarchaediscinae may have been an adaptation for survival in the dense crinoidal bryozoan thickets where they lived. Delicate Planoarchaediscus occurs in algal-poor packstone facies typical of low energy palaeoenvironments possibly at depths below 20 m. Howchinia, which occurs with Fasciella (a probable alga) in intraclastic packstone facies may also have lived in water deeper than 20 m. Major changes in foraminiferal assemblages through the Asbian and Brigantian stages of the late Viséan are attributed to changes in associated biotic constituents. Early Asbian endothyrid and forschiid dominated assemblages were controlled by the relative abundance of bryozoans, Koninckopora and palaeoberesellids. By the late Asbian, the foraminiferal assemblages were controlled by the presence or absence of palaeoberesellids, Ungdarella and to a lesser extent bryozoans. Asbian assemblages were similar, although foraminifers such as bradyinids, Cribrospira and Globoendothyra became abundant in the late Asbian. A switch to predominantly echinoderm (mainly crinoid) and bryozoan substrates in the Brigantian may...
have caused the major change from late Asbian endothyrid and palaeotextulariid assemblages to archaediscid and tetrataxid dominated assemblages. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: foraminifera; lower carboniferous; Ireland; calcareous; algae; microfacies; bryozoans; crinoids

1. Introduction

Calcareous Foraminifera are a significant biotic component of Lower Carboniferous platform carbonates. They have been used for biostratigraphic studies in the Tethyan Realm from the former Soviet Union to northwest Europe (Rauzer-Chernousova et al., 1948; Reytlinger, 1958; Fewtrell et al., 1981; Conil et al., 1990; Gallagher, 1994; Jones and Somerville, 1996). While it is well known that these benthonic foraminifers are facies controlled (Cummings, 1961; Skipp, 1969; Mamet, 1970, 1977; Brenckle et al., 1987), few authors have described in detail the palaeoenvironmental significance of their morphologies and their facies distribution. This paper: (1) summarises the biotic controls over their distribution in the late Viséan of Ireland, (2) outlines the facies control of common foraminiferal taxa and (3) discusses the significance of morphological adaptations.

2. Previous studies

Cummings (1961) discussed the effect of facies and size sorting on Lower Carboniferous Foraminifera. He observed that tetrataxids were most abundant in sandy limestones and that ammodiscids (now pseudoammodiscids) were most common in argillaceous limestones. Cummings suggested high sedimentation rates, severe environmental conditions or diagenesis caused low diversity faunas in limestones with abundant coral, crinoids and bryozoans.

Ferguson (1963) described the distribution of foraminifers in a Dinantian shale in Scotland. He interpreted the presence of abundant Endothyra, Tetrataxis, Palaeotextularia and Earlantia to indicate open marine, subtidal, photic deposition, and the presence of abundant Glomospira (= Pseudoammodiscus) indicates a restricted intertidal or very shallow water environments.

Henbest (1963) reviewed the biology, mineralogy and diagenesis of Carboniferous sedentary foraminifers. He inferred that the cone shaped foraminifers Tetrataxis, Monotaxis and Polytaxis (= Howchinia and Vissariotaxis) could have attached to seaweed or plankton, and suggested that the morphology of Cibicides is a modern analogue to these Carboniferous forms.

Skipp (1969) discussed “environmental associations” of Lower Carboniferous foraminifers in the Redwall Limestone, Arizona. She considered all Lower Carboniferous foraminifers to have been benthonic and thrived in moderately high-energy warm shallow marine environments. Skipp also observed that: Endothyrids and forskhids were most abundant in oolitic, skeletal and peloidal carbonates, with species of Endothyra (= Spinoendothyra) and Tuberendothyra occurring in oolitic and bioclastic limestones.

Mamet (1970) described the distribution of Lower Carboniferous microfacies in eastern Canada. He outlined three main foraminiferal associations; (1) an open-marine association with abundant foraminifers, (2) an algal bank (Koninckopora) and oolitic association with abundant foraminifers; Biseriammina, Tetrataxis and Pseudoglomospira? (= Pseudolituitubata); and (3) intertidal/supratidal flats and supersaturated lagoons with rare foraminifers Earlantia, Endothyra and Pseudoglomospira? (= Pseudolituitubata).

Mamet (1977) suggested that Lower Carboniferous foraminifers were all benthic and flourished in shallow marine environments associated with dasyycladacean or cyanolithic algae. He observed that Carboniferous foraminifers are found in order of decreasing abundance in: bioclast and algal-rich packstone/wackestones; peloidal and pseudoolitic grainstones; brachiopod/crinoid/algal banks; peloidal lagoonal wackestones/mudstones with algae; palaeoberesellid packstone/wackestones with brachiopods; rare to absent in crinoid and fenestellid-rich packstones and wackestones, spicule rich packstone/wackestone/mudstones.

Haynes (1981) summarised the palaeoecology of
Lower Carboniferous foraminifers, and using a morphological approach, he outlined three coiling strategies. The most common was compressed planispiral to plectogyral coiling, e.g. the Endothyridae. The next type was uncoiled planispiral forms that are uniserial to biserial; these were inferred to have been infaunal. The least common was trochoid coiling; Haynes inferred that a fixed or temporarily attached lifestyle was not well developed during the Carboniferous. The occurrences of secondary deposits in the Endothyridae were thought to stabilize the test in turbulent environments (Haynes, 1981).

Haynes (1965) and Brenckle et al. (1987) thought that the calcareous prismatic wall of archaediscids facilitated algal symbiosis. The characteristic test shape of these foraminifers promoted stability in turbulent environments. Cossey and Mundy (1990) and Poncet (1982) suggested that *Tetrataxis* was a loosely attached limpet-like foram, which was a mobile vagrant and phytal form living on a variety of substrate types.

Bourque et al. (1995) and Madi et al. (1996) summarise the distribution of foram/algal facies on a Carboniferous ramp in Western Algeria. They infer the facies for three bathymetric zones: aphotic zone facies with no calcareous algae and rare Foraminifera; dysphotic zone facies with common smaller Foraminifera, red algae and no green algae; and photic zone facies with abundant large Foraminifera, red algae and green algae.

3. Palaeoenvironmental and stratigraphic setting

During the late Viséan in Ireland a thick carbonate succession (Fig. 1; Gallagher, 1996) was deposited on a shallow marine tropical platform that spanned the equator (Rowley et al., 1985). These Asbian to Brigantian sediments consist of a series of minor shallowing upward cycles that are interpreted to have formed by periodic transgressions and regressions punctuated by emergent events caused by (glacio-) eustatic events (Fig. 1). Thick bedded limestones in these successions were probably deposited at or below fair-weather wavebase at depths between 5 and 20 m (Gallagher, 1996). thinly bedded cherty facies probably were deposited below fair-weather wave base but above storm wavebase at depths over 20 m. Allochems in the carbonates are dominated by calcareous algae and foraminifers and/or bryozoans and echinoderms (Gallagher, 1996).

4. Materials and methods

Foraminifera, microproblematica and calcareous algae in 685 standard 5 × 1 cm thin sections were documented from two successions of Lower Carboniferous platform limestones in Ireland (Fig. 1). The data were split into two sets for quantitative analyses and for binary presence/absence studies. The ranges of four common algal taxa and 27 foraminiferal taxa were compiled (Fig. 2). The relative abundances of major carbonate contributing bioclasts were estimated semi-quantitatively in each sample (Fig. 3a). The abundance of archaediscids, tetrataxids, *Valvulinella*, endothyrids and palaeotextulariids was point-counted in 91 thin sections from carbonates of the North Cork succession (Fig. 1) and the distributional data presented as a series of triangular plots (Figs. 4 and 5). Fig. 4 shows the percentage of each of the five families associated with the presence or absence of common to abundant echinoderms (mainly crinoids) and bryozoans in each sample. Fig. 5 illustrates the family distribution associated with the presence of abundant palaeoberesellids, *Ungdarella* and *Konicopora*. Binary presence/absence microfaunal and microfloral data were compiled from the other 594 thin sections for biostratigraphic and statistical analyses. The facies and relative abundance of selected bioclast types in each sample were correlated with the occurrence of foraminifers and an average score was derived for each taxon (Figs. 6 and 7).

5. Factors controlling Lower Carboniferous foraminiferal distribution

Based on data analyses presented in Figs. 4 and 5, the distribution of Lower Carboniferous Foraminifera were associated with two primary factors: (1) the relative abundance of echinoderm and bryozoan material and (2) the presence or absence of common algal types.
5.1. Influence of echinoderm and bryozoan abundance on foraminiferal distribution

5.1.1. Lithofacies and foraminiferal distribution

Echinoderm fragments (mainly crinoids) are common to abundant in over 56% of the carbonate thin sections (Fig. 3a: Fig. 8). Echinoderms were rare in the remaining, mostly Brigantian, samples (Fig. 2). Palaeotextulariids are relatively rare (ca. 20%) in crinoidal facies (Fig. 4a), where assemblages may comprise up to 50% archaeidiscids, tetrataxids and *Valvulinella*. Endothyrids dominate where less than 20% tetrataxids and *Valvulinella* and less than 50% archaeidiscids occur in samples.

Bryozoans are common to abundant in 31% of the samples and rare in the remainder (Fig. 3a and...
Fig. 2. The stratigraphic range of important limestone contributing bioclasts, calcareous algae and foraminifers in the late Viséan successions of southern and western Ireland. The key to the stratigraphic log is the same as that on Fig. 1, although it is not to scale. The thicker bars denote intervals typified by an abundance of a particular bioclast, calcareous algae or foraminiferal type. *Pseudo.* = Pseudoendothyrinae.
Fig. 3. (a) The relative abundance of echinoderms (mainly crinoids), bryozoans and calcareous algae in the 685 thin sections examined. Note over half of the samples have packstone to grainstone lithofacies. (b) The abundance of the 12 most common foraminiferal families in the 685 thin sections studied. *Pseudoend. = Pseudoendothyridae and Eostaffell. = Eostaffellidae.*

Fig. 8). Bryozoans are common in Ashbian to Brigantian cherty facies and are the dominant bioclast in algal-poor wackestones (Fig. 2). Bryozoans are also common to abundant in Brigantian packstone to grainstone microfacies. Tetrataxids, *Valvulinella* and archaediscids dominate bryozoan-rich facies, whereas endothyrids and palaeotextulariids are relatively rare (Fig. 4b). The latter two families of foraminifers dominate assemblages where bryozoans are absent (Fig. 4c). Bryozoan and crinoidal pack-
Fig. 4. Tetrahedron plots of the absolute abundance of significant foraminiferal families in Irish late Viséan carbonates based on quantitative analyses of 91 thin sections from north Co. Cork (locality A; Fig. 1). The tetrahedron was constructed by combining two triangular plots of quantitative data. Note: \( n \) = number of samples with or without the selected bioclast out of the 91 samples included in the quantitative analyses.

Fig. 5. Tetrahedron plots of the absolute abundance of families of Lower Carboniferous foraminifers based on the presence of calcareous algae in the samples from north Co. Cork (locality A; Fig. 1). Note: \( n \) = the number of samples with the selected bioclast out of the 91 samples included in the quantitative analyses.

stones to grainstones yield low diversity and sparse foraminiferal assemblages.

5.1.2. Palaeoenvironmental interpretation
Bryozoan and crinoidal packstones to grainstones are interpreted to have formed in an open-marine subtidal palaeoenvironment, where crinoidal and bryozoan thickets were continually reworked by currents, storm action and bioturbation at or below fair-weather wave base (Gallagher, 1996; Madi et al., 1996). Such an environment would be inimical to all but the most robust foraminifers. Brenckle et al. (1987) suggested that the lenticular test of archaediscids ensured greater hydrodynamic stability. The morphology of the Archaediscidae therefore allowed test survival in crinoid and bryozoan-rich packstone to grainstone lithofacies where more delicate foraminifers would have been broken up.
Fig. 6. A list of 27 Lower Carboniferous calcareous foraminiferal taxa and their facies distribution. The column on the right hand side lists the number of sample occurrences of a particular taxon out of the 594 samples studied ($N = 594$). The scores for each foraminiferal type were calculated as follows: the relative abundance of bryozoans and echinoderms (mainly crinoids) were estimated in each of the 594 samples using the semi-quantitative scores, 0 = absent, 1 = rare and 2 = common to abundant (see Fig. 3(a) for further details); an average bioclast score was calculated for each taxon and plotted as a bar graph (for example the average echinoderm score obtained for the 146 occurrences of *Omphalotis* was 1 = rare). The vertical dotted line is the average of the scores obtained for the 27 taxa documented, therefore above average scores imply that a particular taxon has a relatively high affinity towards a particular bioclast, conversely a below average score suggests no particular bioclast affinity with a selected taxon.
Fig. 7. The calculated scores for the 27 selected foraminiferal taxa based on the relative abundance of the calcareous algae, palaeoberesellids, *Ungdarella, Fasciella* and *Koninckopora* in each sample. Note: the method for calculating the scores is outlined in the caption for Fig. 6.

*Tetratexis* is inferred to have been a loosely attached mobile sea floor browser (Cossey and Mundy, 1990). The authors suggested that the trochoid morphology of this foraminifers, allowed it to attach itself to a substrate. The umbilical positioning of the aperture on tetrataxids led Cossey and Mundy...
(1990) to believe that these foraminifers were not permanently attached but browsed on the substrate and responded to environmental stresses by attaching onto substrates like limpets when disturbed. The morphology of tetrataxids therefore allowed their test to survive transportation around dense crinoid and bryozoan thickets.

Endothyrid foraminifers occur in 86% of the samples studied (Fig. 3b). These multilocular foraminifers are most common where bryozoans are rare or absent, although some species are present in crinoid facies. Most endothyrid foraminifers have multilayered walls and well-developed secondary deposits at the base of chambers. These test strengthening adaptations would have ensured test survival in high energy environments (Haynes, 1981) such as algal shoals and banks (see Section 5.2). Their lack of association (as a family) with bryozoans is problematical, although this may be due their inability to co-exist with zooids on bryozoan fronds.

Foraminifera that may have been infaunal such as the palaeotextulariids could not tolerate coarse-grained substrates found in bryozoan and crinoidal packstones to grainstones and therefore they are rare in this facies (Fig. 4). Palaeotextulariids are also rare in algal-poor wackestone facies but flourished in algal-rich facies (see Section 5.2).

Bryozoan-rich, algal-poor wackestones were probably deposited in low energy palaeoenvironments at depths of at least 20 m, a depth inferred for Dinantian bioclastic wackestone to mudstone lithofacies in the Asbian of the Lake District in England (Horbury and Adams, 1996). The presence of tetrataxids and archaediscids and relative absence of palaeotextulariids and endothyrids in this wackestones facies suggests a depth control on Lower Carboniferous Foraminifera (this will be discussed in Section 5.2).

5.2. Influence of algal types on foraminiferal distribution

The three most abundant algal types (Fig. 3a) preserved in the samples are palaeoberesellids (present in 52% of the samples), Ungdarella (26%) and Koninckopora (37%). The presence of these algal taxa influenced the distribution of many of the foraminifers studied. A particular foraminiferal association with Fasciella confined to the Brigantian stage is discussed in Section 5.10.

5.2.1. Palaeoberesellid associations

Palaeoberesellids are small cylindrical scalariform calcareous algae (Fig. 8). They are one of the most abundant constituents of the carbonates studied and often comprise over 80% of the allochems in a thin section (Adams et al., 1992; Gallagher, 1996). Palaeoberesellids occur in abundance in wackestones, packstones and grainstones, or samples with mixed packstone to grainstone textures. Horbury and Adams (1996) suggested that the stabilisation of shallow marine substrates by this algal type may have excluded abundant foraminifers, although Horbury (1992) found abundant foraminifers in palaeoberesellid-rich buildup facies. In the present study palaeoberesellid-rich limestones generally yield diverse foraminiferal assemblages containing abundant endothyrids and palaeotextulariids (Fig. 5a). Tetrataxids and Valvilunella occur in low amounts (<20%) and archaediscids never exceed 75% of the foraminiferal fauna recorded.

Palaeoberesellids are dasycladacean algae, which thrived in water depths of around 10 m (Adams et al., 1992; Horbury and Adams, 1996) and formed extensive algal meadows in Ireland during the late Visean (Gallagher, 1996). The baffling properties of the palaeoberesellids have been mentioned by Horbury (1992), who described micritic material trapped between algal thalli in transported intraclasts of
Kamaenella bafflestone. Many thin sections in the present study have a patchy distribution of micrite between the thalli, suggesting that they acted as baffles on the sea bed (Horbury and Adams, 1996). Nutrients may have been abundant in such environments and foraminifers could thrive and be sheltered in meadows of these algae. Therefore, the palaeoberesellids may have supported distinctive communities of foraminifers as sea grass does in modern environments (Brasier, 1975) and the optimum environment for the Endothyridae was shallow marine algal meadows. The micritic fine grained substrate created by the baffling palaeoberesellid algae, may have been similarly suitable for the infaunal Palaeotextulariidae. The relatively low percentage of tetrataxids in the palaeoberesellid-rich facies may be due to the predominance of opportunistic taxa such as certain genera of endothyrid, pseudoendothyrid, eostaffellid and forschid families that thrived in such environments (see Section 6 below). This pattern may also be due to the preference of tetrataxids and Valvulinella for the substrates offered by crinoidal and bryozoan facies over palaeoberesellid-rich substrates. Unlike the tetrataxids and Valvulinella many genera of endothyrids, pseudoendothyrids, eostaffellids and forschids seemed unable to tolerate bryozoan or crinoidal palaeoenvironments (see below).

5.2.2. Ungdarella associations

Ungdarella has an erect cylindrical branching thallus up to 200 mm wide and 1 cm long, that internally has a fibrous tufted appearance (Fig. 8.5). The affinity of this alga is thought to be a rhodophyte (Wray, 1977a; Skompski, 1986, Madi et al., 1996). This alga may have occupied a similar niche to the palaeoberesellid in the latest part of the Viséan, since it associates with and locally replaces the palaeoberesellids as the predominant allochem in the latest Asbian carbonates (Gallagher, 1996; Horbury and Adams, 1996). This alga occurs most commonly in packstones to grainstones towards the top of shallowing upward cycles, typically slightly above palaeoberesellids that may occur throughout the full thickness of these cycles but dominate the mid-cycle (Gallagher, 1996; Horbury and Adams, 1996). Similar to palaeoberesellid-rich facies, Ungdarella dominated limestones yield a high percentage of Endothyridae and Palaeotextulariidae (Fig. 5b). The archaediscids, tetrataxids and valvulinellids are rare in Ungdarella dominated facies, although a few samples yield over 50% Archaediscidae (Fig. 5b).

Ungdarella may have grown in depths of around 10 m, although modern red algae may inhabit depths to 250 m, they are most abundant above 100 m (Wray, 1977b). Unlike the palaeoberesellids they probably flourished in much higher energy environments, existing as meadows on the sea bed above fair-weather wave base where they would have been subject to transportation. The thalli may have supported and sheltered a variety of endothyrid and palaeotextulariid taxa (see Section 6). Archaediscidae may have found niches in this environment or may have been transported in from other environments.

5.2.3. Koninckopora associations

Koninckopora occurs as large fragments (up to 500 mm) in many of the samples. The thallus of this genus consists of a series of polygonal “cells” that are two-layered (Fig. 8). This taxon is considered a dasycladacean by some (Wray, 1977a; Skompski, 1986; Madi et al., 1996). Koninckopora is often found as scattered broken thalli in well-washed grainstone facies associated with abundant micritized bioclasts (Gallagher, 1992). These algae occur at the top of shallowing upward minor cycles in low amounts. Samples with Koninckopora yield high percentages of endothyrids and palaeotextulariids (Fig. 5c) and are reworked. In contrast to the palaeoberesellid and Ungdarella-rich facies described above, in most samples less than 50% Archaediscidae occurs in Koninckopora-rich facies. This facies also yields a low percentage of Tetrataxidae.

Wood (1940) suggested that Koninckopora grew in “closely packed under-water prairies”. Wray (1977a) observed that modern dasycladacean algae inhabits depths to 30 m, but most often above 5 m. Chlorophytes also may occur down to depths between 60 and 70 m (Madi et al., 1996). In this study, the presence of scattered Koninckopora in well-washed facies with micritisation features suggests shallow depths (ca. 5 m). Shallow water may well have been a limiting factor in the occurrence of the Archaediscidae, since this family occurs in relatively low numbers even though their elliptical morphology would have helped their tests to survive...
in such high energy environments. Similar to the Ungdarella-rich facies endothyrid and palaeotextulariids probably found sheltered niches between the thalli of Koninckopora.

5.2.4. Depth control on Lower Carboniferous foraminiferal distribution

Depth and substrate may have been factors limiting the abundance of the Tetrataxidae and Valvulinella since assemblages associated with the three algal types (above) all yield less than 20% tetrataxids and valvulinellids, whereas facies without algae (i.e. the crinoidal and bryozoan-rich facies) commonly yield over 20% of these two families.

6. Facies distribution of Lower Carboniferous Foraminifera

Presence/absence data of foraminifera collected from 594 thin sections provided the basic information for facies studies. Family subdivisions and generic identifications (Fig. 2) are adapted from Rauzer-Chernoussova et al. (1948), Reytinger (1958), Conil et al. (1980) and Loeblich and Tappan (1987). An example of each foraminiferal type is illustrated on Plates I and II. The lithology of each sample was documented; 60% of the samples were packstones to grainstones, the remainder were packstones to wackestones (Fig. 3a). The lithological distribution for each taxon was plotted (left side of Fig. 6). The relative abundance of echinoderm and bryozoan material was observed for each sample and an abundance score was calculated for each foraminiferal type based on this data (right side of Fig. 6). Similarly, an abundance score was calculated on the relative abundance of palaeoberesellids, Ungdarella, Fasciella and Koninckopora in each sample (Fig. 7). These score, together with morphological observations, permit the following observations on the facies and palaeoenvironmental distribution of the foraminifers.

6.1. Family Bradyinidae

The bradyinids are rare (Fig. 3b). The two identified genera Bibradya and Bradyina are characterized by involute globose tests and cribrate apertures. Bibradya has bifurcating septae and a thin simple wall (Plate I) whereas Bradyina is a large foraminifer (>400 μm) and has a thick wall characterized by a series of septal fold and pits (Plate I). Both foraminifers occur in peloidal packstone to grainstone facies with few bryozoans and crinoids (Fig. 6). The association of Bibradya with Cribrospira is so strong that their facies distribution will be discussed together under the Family Endothyridae. Bradyina rarely co-occurs with palaeoberesellids and commonly with Ungdarella and Koninckopora (Fig. 7) in high energy shallow marine environments of 5 to 10 m depth. Its thick wall, globose shape and cribrate aperture protected its protoplasm from damage. Haynes (1981) suggested that this genus with its septal folds and pits might have possessed symbiotic algae further supporting a shallow water habitat for this taxon.

6.2. Family Endothyridae (sensu lato)

Endothyrids are the second most abundant group in this study (Fig. 3b). Five facies controlled genera were documented: Cribrospira, Globoendothyra, Omphalotis, Endothyranopsis and Endothyra.

6.2.1. Cribrospira

The distribution of Cribrospira and Bibradya are very similar. Cribrospira is characterized by a large planispiral test, a microgranular wall and a cribrate aperture (Plate I). Bibradya and Cribrospira are common in packstones to grainstones with few echinoderms and bryozoans (Fig. 6). Cribrospira and Bibradya occur in well-washed Ungdarella palaeoberesellid grainstone facies at or near the top of shallowing upward cycles (Gallagher, 1992). They rarely occur with Koninckopora.

Cribrospira and Bibradya were well adapted to a high energy environment. The two taxa whose morphologies resemble that of Bradyina and thrived in shallow open-marine algal meadows at depths above 10 m (see Section 5). Their rarity in the samples studied, may reflect adaptation to a turbulent lifestyle that might have limited their distribution.

6.2.2. Globoendothyra and Omphalotis

Globoendothyra and Omphalotis are large robust foraminifers with globose plectogyral tests, multilay-
ered walls and pronounced secondary basal deposits (Plate I). The wall of *Globoendothyra* consists of three layers: an outer tectum, a clear diaphanotheca and a darker inner layer (Frewtrill et al., 1981), it shows biotic associations very similar to *Pseudoendothyra* (see below). These three taxa occur in packstones to grainstones with rare bryozoan fragments and common to rare echinoderms (Fig. 6). Both are found in carbonates with abundant to common palaeoberesellids and higher than average *Ungdarella* and *Koninckopora* scores (Fig. 7).

As suggested in Section 5, the secondary deposits at the base of endothyrid tests were probably an adaptation for survival in a relatively high energy palaeoenvironment. The globose shape and multi-layered test wall of these two foraminifers may be further adaptations for their survival in such palaeoenvironments. The association of these two taxa with the algae *Koninckopora*, palaeoberesellids and *Ungdarella* together with their lack of affinity with bryozoans suggest that they are shallow-water taxa (5–10 m depths), which probably did not inhabit deeper water bryozoan thickets.

6.2.3. Endothyranopsis and Endothyra

*Endothyranopsis* is a globular planispiral involute genus with a microgranular/agglutinated wall (Plate I). It is commonly associated with echinoderms and bryozoans in packstone to grainstones (Fig. 6). Nearly 25% of its occurrences were in wackestones. *Endothyra* is a planispiral to streptospirally coiled genus with a microgranular layered test. This taxon is the most common endothyrid in the sample set and it occurs in crinoidal/bryozoan packstones to grainstones. Of the five endothyrids listed (Fig. 7), *Endothyranopsis* and *Endothyra* are the least associated with the three algal taxa, being found in samples with only rare palaeoberesellids, *Ungdarella* and *Koninckopora*. Although, *Endothyra* has a slightly higher affinity with *Koninckopora* than *Endothyranopsis*.

*Endothyranopsis* did not thrive in algal meadows. It seems to have tolerated crinoidal facies and is associated with bryozoans often in wackestones. The data suggest that *Endothyranopsis* may have inhabited slightly deeper palaeoenvironments than the other endothyrids (between 10 and 20 m), below the threshold of abundant algal growth and in many cases below fair-weather wave base. The presence of *Endothyra* in many samples suggests that this taxon tolerated a wide range of deep to shallow water environmental extremes, for example, crinoid thickets. Its affinity with *Koninckopora* suggests that some species inhabited shallow-water environments.

6.3. Family Palaeotextulariidae

Foraminifera of the family Palaeotextulariidae occur in more than half of the samples studied (Fig. 3b). They are biserial or biserial to uniserial foraminifers that may have simple or cribrate apertures (Plate I). The test may contain a single layered micritic wall, or have an additional fibrous layer. Single-walled genera documented in this study include the monolayered Koskinotextulariinae: *Consobrinella*, *Koskinotextularia* and *Koskinoglobigerina*. Bilayered Palaeotextulariinae include species of *Palaeotextularia* and *Cribrostomum*. Bi- and monolayered palaeotextulariids typify packstones to grainstones with relatively low crinoidal and bryozoan contents (Fig. 6). Bilayered forms seem to have an high affinity with *Ungdarella* and palaeoberesellids, whereas samples with monolayered taxa are often found with palaeoberesellid, *Ungdarella* and *Koninckopora* (Fig. 7). Monolayered palaeotextulariids occur throughout the early Asbian to Brigantian succession (Fig. 1) and are especially abundant in the *Koninckopora*-rich facies in the early Asbian Burren

---

Plate I

Plate II

succession. The first appearance in Ireland of bilayered palaeotextulariids coincides with the onset of late Asbian palaeoberesellid/Ungdarella meadows in early Asbian time and both bilayered forms existed in palaeoberesellid meadows in late Asbian time.

6.4. Family Forschiidae

Forschiidae occur in almost half of the samples studied (Fig. 3b). Forschiidae identified in this study are very robust planispiral to uncoiled foraminifers with septate and pseudoseptate chambers and granular walls that may be agglutinated (Plate I). *Bogushella, Lituotubella* and the *Forschia* are large (>400 μm) thick-walled robust foraminifers. *Nevillella* and *Lituotubella* have an elongate terminal chambers with cribrate apertures. Forschiidae predominate in packstones to grainstones with rare bryozoans and occasional echinoderms (Fig. 6). *Lituotubella* occurs in grainstones with common palaeoberesellids and echinoderms in crinoid-algal meadows in shallow marine palaeoenvironments. *Nevillella* has a similar distribution to *Bibradya* and *Cribrospira* and thrived in high-energy shallow open-marine palaeoberesellid meadows at depths shallower than 10 m (see Section 5). Forschiid-rich facies are associated with palaeoberesellids and *Ungdarella* where *Globoendothyra* and *Omphalotis* are common (Fig. 7). Forschiidae show the highest affinity with *Koninkcokopora* of all the families studied.

Their thick robust walls and association with the dasycladacean alga *Koninkcokopora* suggests that forsschiids favoured quite shallow turbulent marine palaeoenvironments above fair-weather wave base at depths between 5 and 10 m.

Morphologically, modern agglutinating foraminifers with similar shapes to the *Forschia* and *Bogushella* are epifaunal active herbivores, detritivores and omnivores (Jones and Charnock, 1985). Elongate Recent agglutinated foraminifers similar in morphology to *Nevillella* and *Lituotubella* are infaunal detrital or bacterial scavengers (Jones and Charnock, 1985).

6.5. Families Pseudoendothyridae and Eostaffellidae

Foraminifer of the Family Pseudoendothyridae and Eostaffellidae occur in 63% of the samples studied (Fig. 3). In this study, the two most common genera identified are *Pseudoendothyra* and *Eostaffella*.

These foraminifers have involute, planispiral coiling with biumbilicate tests (Plate II). The tests of *Eostaffella* and *Pseudoendothyra* range from >200 μm in diameter. *Eostaffella* has a microgranular layered wall with a differentiated tectum and tectorium and occurs in over half of the samples analysed. *Pseudoendothyra* has a wall structure that consists of four layers, a tectum, diaphanotheca, an inner and outer tectoria (Loeblich and Tappan, 1987). Both foraminifers often are keeled and occur in packstones to grainstones with average crinoid scores (Fig. 6). The two taxa are rarely associated with bryozoans. *Eostaffella* exhibits a slightly higher bryozoan score than *Pseudoendothyra* (Fig. 6). *Pseudoendothyra* is highly associated with palaeoberesellids and is also strongly associated with *Ungdarella* and *Koninkcokopora* (Fig. 7). Its associations are very similar to *Globoendothyra*. In contrast, *Eostaffella* shows no affinity with *Koninkcokopora* or the palaeoberesellids (Fig. 7), although it is associated with *Ungdarella*. *Eostaffella* occurs in abundance in calcisphere-rich peloidal grainstones which lack stenohaline indicators such as echinoderms and brachiopods (Gallagher, 1992).

The relative abundance and apparent lack of affinity of *Eostaffella* with diagnostic algal types suggest this genus prevailed in a wide range of palaeoenvironments at depths range between 10 and 20 m. *Eostaffella* did not thrive in the algal thicket palaeoenvironments typified by its multilayered relative *Pseudoendothyra*. Some species of *Eostaffella* may have been adapted to live in lagoonal restricted environments that may have been
slightly hypersaline. The high affinity of *Pseudoendothyra* with palaeoberesellids, *Koninckopora*, *Globoendothyra* and *Omphalotis* suggests that it was a shallow-water taxon. It may have existed in algal meadows at depths between 5 and 10 m above fair-weather wave base. Furthermore, the multiwalled nature of *Pseudoendothyra* would have enhanced its test strength, and the diaphanotheca could have harboured symbionts.

Modern foraminifers with bilaterally symmetrical planispiral tests similar to *Pseudoendothyra* and *Eostaffella* are adapted to an extremely mobile mode of life (Banner, 1978) as browsers on weeds and deposit feeders on soft substrates (Haynes, 1981). Morphologically, *Pseudoendothyra* is quite similar to the modern *Elphidium macellum*, the spinose keel of which helps this foraminifer to lodge in algal fronds (Haynes, 1981). The keel in such modern planispiral lenticular foraminiferans was thought by Haynes (1981) to have also helped stabilise the test on soft substrates.

6.6. Families Earlandiidae and Pseudoammodiscidae

Earlandiids and pseudoammodiscids are relatively common, each occurring in 46% of the samples studied (Fig. 3b). The distribution of *Earlandia* and *Pseudoammodiscus* are very similar (Figs. 3 and 4) and therefore they will be described together.

*Pseudoammodiscus* and *Earlandia* are simple non-septate foraminifers with microgranular walls and simple apertures (Plate II). Both taxa are bilocular. *Pseudoammodiscus* has a planispirally coiled second chamber and *Earlandia* a straight uncoiled one. Both taxa occur in packstones to grainstones with common bryozoans and common to abundant echinoderms (Fig. 4). Their associations (Fig. 5) are extremely similar, occurring with rare palaeoberesellids, *Ungdarella*, *Koninckopora* and *Fasciella* (a probable alga). In some peloidal grainstones lacking crinoidal, algal and bryozoan material, *Earlandia* and *Pseudoammodiscus* dominate the assemblages, with few other genera of foraminifers present.

The simple morphology of these two foraminifers may have been an adaptation for survival in a wide range of subtidal environments (from low to high energy above and below fair-weather wave base), as indicated by their widespread and even representation (Figs. 4 and 5). Similar to *Endothyranopsis*, the two taxa tolerated crinoidal and bryozoan-rich environments, although some species may have found niches in palaeoberesellid meadows. The taxa that survived in wackestone facies may have been deeper water forms, tolerating low energy palaeoenvironments at or below 20 m (cf. the wackestone facies in Horbury and Adams, 1996). Samples with a high abundance of Earlandiidae and Pseudoammodiscidae without any stenohaline bioclasts (crinoids and bryozoa) may have been deposited in restricted lagoonal facies (i.e. they may represent slightly hypersaline conditions).

*Gigasbia* is a large (>250 μm in length and diameter) multilayered bilocular taxon (Plate II). It occurs in packstones with relatively low amounts of crinoidal and bryozoan material (Fig. 4).

The thick multilayered test of *Gigasbia* may have allowed it to survive in relatively high energy palaeoenvironments. The foraminifers high affinity with *Globoendothyra*, *Omphalotis* and the algae *Koninckopora*, palaeoberesellids and *Ungdarella* suggests that it is a shallow-water taxon (5–10 m depths), which avoided bryozoal thickets.

Morphologically *Gigasbia* and *Earlandia* were probably infaunal detritivores that passively fed at the sediment-water interface (Haynes, 1981; Jones and Charnock, 1985; Koutsoukos and Hart, 1990). *Pseudoammodiscus* may have been active epifaunal deposit feeder (cf. Jones and Charnock, 1985).

6.7. Family Pseudolituotubidae

Foraminifera of the family Pseudolituotubidae are found in 17% of the samples studied (Fig. 3b). *Scalebrina* (test <100 μm in diameter) and *Pseudolituotuba* (>100 μm in diameter) are encrusting foraminifers with irregular shapes (Plate II). The test of *Scalebrina* is microgranular and that of *Pseudolituotuba* is agglutinated. *Scalebrina* has a distinct bimodal distribution, occurring in both wackestone and grainstone lithologies with relatively low amounts of bryozoans and echinoderms (Fig. 6). *Pseudolituotuba* characterizes grainstones with common to abundant echinoderms and rare bryozoans.
pletely developed micritic/prismatic wall structures, the family Archaediscidae have slightly to complex micritic-prismatic wall structures, although they show a higher than average affinity with Koninckopora. Scalebrina exhibits a higher than average affinity with the problematical algal taxon Fasciella. Host substrates for Scalebrina include bryozoans, brachiopods and crinoids, in some instances they probably lived on a soft bodied substrate. The host substrates for the majority of Pseudolituotubidae are unknown, although some encrust Ungdarella (Plate II).

The robust and encrusting nature of the Pseudolituotubidae allowed these foraminifers to tolerate a wide range of environmental extremes. Pseudolituotuba tolerated high energy crinoid and bryozoan thicket environments that may have been deposited at depths below 10 m (in the case of samples lacking calcareous algae) or at depths above 10 m where it is found with Koninckopora. Pseudolituotuba is an important constituent of Viséan bryozoan-rich mudmound buildups in Ireland (Somerville et al., 1992) where its large size and thick agglutinated wall may have allowed it to encrust directly onto the sediment surface. The apparent lack of preservation of the host substrate for this taxon may be due to a preference for vegetation that does not fossilize easily (such as non-calcareous algae or other soft substrates). The small, micrite walled Scalebrina survived in high and low energy (above and below fair weather wave base) palaeoenvironments. This wide distribution may be due to the taxons’ preference for attached erect organisms such as bryozoan, brachiopods and crinoids that suspended Scalebrina above the substrate.

6.8. Family Archaediscidae

Archaediscids are the most abundant group found in this study (Fig. 5b). Genera include Planoarchaediscus, Paraarchaediscus and Archaediscus (grouped as (Para)archaediscus). The Asteroarchae- discinae include Neoarchaediscus (Neoarchaediscus), Neoarchaediscus (Asperodiscus) and Asteroarchaediscus. The distribution of the Archaediscidae will be described in three groups: Planoarchaediscus, (Para)archaediscus and stellates archaediscids. The family Archaediscidae have slightly to completely developed micritic/prismatic wall structures, a feature thought by Haynes (1965) and Brenckle et al. (1987) to have reflected the presence of algal symbionts. The thin rod-like prisms of calcite that make up the radiaxial walls of these foraminifers would have allowed light to pass directly into the interior of the test allowing algal symbionts to thrive (Brenckle et al., 1987).

6.8.1. Planoarchaediscus

Planoarchaediscus has a discoidal, skew to planispiral non-septate micritic test, with a thin layer of prismatic calcite in its umbilical area (Plate II). This taxon is rare, occurring in 10% of the samples studied. Planoarchaediscus occurs commonly with bryozoans and echinoderms in packstone to wackestone lithofacies (Fig. 6). It is absent in crinoidal and algal packstones to grainstones. This taxon has no affinity with any particular algal type, although it is often found with Howchinia in Fasciella-rich intraclastic wackestones (Fig. 7).

This taxon thrived in a low energy subtidal palaeoenvironment at depths of around 20 m, below the threshold of abundant dasycladacean algal growth. This is similar to that inferred for many of the Valvulinella and Howchinia (see Valvulinella and Howchiniidae below). Planoarchaediscus was not adapted to survive in high energy crinoidal facies.

6.8.2. (Para)archaediscus

(Para)archaediscus occur in over 70% of the samples (Figs. 6 and 7). Paraarchaediscus is a discoidal to lenticular non-septate foraminifer with an outer prismatic calcite wall and a well-developed inner micritic wall (Plate II). The morphology of Archaediscus is similar, although this genus has a greatly reduced inner micritic wall. (Para)archaediscus occurs in packstones to grainstones with rare bryozoans and occasional echinoderms (Fig. 6). Of all the archaediscids types studied, it shows the greatest affinity with calcareous algae (Fig. 7).

The relative abundance of (Para)archaediscus suggests that these archaediscids tolerated a variety of palaeoenvironments. Consequently, the scores of Figs. 6 and 7 are averaged making it difficult to draw specific palaeoenvironmental conclusions. It seems likely that species of (Para)archaediscus could have inhabited algal facies (at depths 10 m or less) as well as echinoderm and bryozoan-rich facies (at depths
greater than 10 m). Quantitative data presented in Section 5 suggest that the archaediscids probably inhabited depths greater than 5 m.

6.8.3. Asteroarchaediscinae

A major change in archaediscid type and abundance occurs across the Asbian/Brigantian boundary (Fig. 2), coinciding with a major switch in the importance of other significant bioclastic components. Specifically, the change from palaeeoberesellid and Ungdarella-rich limestones (during the late Asbian) to crinoidal limestones (of the Brigantian) coincides with a change from common non-stellate (Para)archaediscus to abundant Asteroarchaediscinae. Asteroarchaediscinae have a prismatic calcite wall with a partly to completely occluded tubular chamber (Plate II). They occur in nearly 40% of the samples studied. The Asteroarchaediscinae most commonly occur in packstones to grainstones, with common to abundant echinoderms and bryozoans (Fig. 6). They show no apparent affinity with palaeeoberesellids, Ungdarella or Koninckopora (Fig. 7). Brenckle et al. (1987) concluded that a study of pebble shapes has shown that the compressed spherical shape like that of the archaediscaeces provides exceptional stability which could have been enhanced further by internal calcification; in addition, the “heavy secondary deposits were secreted to promote test stability in current-swept environments”. The hydrodynamic stability attributed to the external morphology of the archaediscs by Brenckle et al. (1987) suggest that tests of the stellates could have survived palaeeenvironmentals represented by the crinoidal limestones during the Brigantian, where thickets of crinoids were developing and continuously being reworked by current activity at or below fair-weather wave base.

Morphologically, modern foraminifers with similar lenticular shapes to these Dinantian forms, are thought to be epifaunal, active detritivores feeding on soft substrates or in weed (Haynes, 1981).

6.9. Families Tetrataxiidae and Pseudotaxidae

The families Tetrataxiidae and the Pseudotaxidae occur respectively in 66% and 21% of the samples studied (Fig. 3b). These foraminifers have trochoid conical tests with several chambers (Plate II). Three taxa are included in this study: Tetrataxis, Valvulinella and Vissariotaxis. Tetrataxis is a tetrataxid that has four chambers per whorl and a bilayered test. The pseudotaxid Valvulinella has two to three chambers per whorl (each subdivided by chamberlets) and a microgranular wall. Vissariotaxis is a pseudotaxid that has a non-septate test and a microgranular wall (Plate II), this taxon is restricted to the Asbian stage. Based on contrasting facies data, the distribution of Tetrataxis and Valvulinella will be described in Section 6.9.1 and Vissariotaxis in Section 6.9.2.

6.9.1. Tetrataxis and Valvulinella

The two genera show a high affinity with echinoid-rich facies (Section 5; Figs. 4 and 6). Tetrataxis occurs in packstones to grainstones with common bryozaons (Fig. 6). Tetrataxis and bryozaons are absent at the top of seven of the nine shallowing upward cycles in the late Asbian Burren Formation (Fig. 1). These two bioclasts are rare at the top of similar cycles in the late Asbian of Co. Cork (Fig. 1). Valvulinella has a bimodal distribution, occurring in both wackestone and grainstone lithologies with abundant bryozaons (Fig. 6). This taxon is very rare in the late Asbian cyclic limestones of the Ballyclogh and Burren Formations (Fig. 1), it occurs most commonly in the Liscarrol and Slievenaglasha Formations and early Asbian bedded dark cherty limestones (Fig. 1). Tetrataxis and Valvulinella show little association with palaeeoberesellids, Ungdarella and Koninckopora (see Section 5; Figs. 5 and 7). The two families may be preserved attached to crinoids, brachiopods and bryozaons.

The quantitative data reviewed in Section 5 together with the binary distributional data above suggest that the Tetrataxis and Valvulinella flourished in crinoid and/or bryozaon thickets below the threshold of significant algal growth. The bilayered wall of the Tetrataxis and the complex chamberlets of Valvulinella may have promoted test stability in high energy grainstone environments at fair-weather wave base where some species may have lived. The lack of Tetrataxis at the top of shallowing upward cycles suggests that this genus is depth controlled, existing only at water depths below 5 m, with an optimum water depth being below 10 m (below that of peak palaeeoberesellid growth). The absence
of *Valvulinella* in algal-dominated facies suggests that this foraminiferal type is also depth controlled, with an optimum depth similar to *Tetrataxis*. Although, the prevalence of *Valvulinella* in wackestone lithofacies suggests that species may have survived below 20 m. This is the depth inferred for bryozoan-rich wackestone to mudstone lithofacies for Asbian cyclic sediments in the Lake District by Horbury and Adams (1996).

6.9.2. *Vissariotaxis*

*Vissariotaxis* thrived in palaeoberesellid thicket packstones to wackestones below fair-weather wave base, at depths of 10 m or greater. Its limited association with *Ungdarella* and *Koninckopora* suggests that it could not survive in very shallow marine high energy grainstone lithofacies perhaps shallower than 10 m.

6.10. **Family Howchinididae**

Foraminifera of the Family Howchinididae are rare, occurring in only 8% of the samples studied (Fig. 3). *Howchinia* is a non-septate trochoid howchinid with a bilayered wall and a depressed umbilicus (Plate II). In Ireland *Howchinia* ranges from the late Asbian to the Brigantian (Fig. 2).

*Howchinia* characterizes echinoderm and bryozoan-rich packstone to wackestone lithofacies (Fig. 6). This taxon shows limited affinity with palaeoberesellids, and no affinity with *Ungdarella* or *Koninckopora* (Fig. 7). *Howchinia* is particularly associated with *Planoarchaediscus* in intraclastic limestones composed of wackestone intraclasts or bioclasts often partially coated (due to partial burial in the substrate) with *Fasciella* in Brigantian cherty sediments (Fig. 2).

*Fasciella* is a probable alga that consists of distinctive yellow hyaline fibrous sheets that encrust intraclasts and bryozoans. *Howchinia* is never observed caught up in these encrusting sheets.

The intraclastic wackestone to packstone lithofacies was deposited below fair-weather wave base but above storm wave base in a subtidal palaeoenvironment (Gallagher, 1996). The lack of possible chlorophyte algae and micritisation features, point to subphotic depths that may have been at least 20 m, the depth inferred for algal-poor wackestone to mudstone lithofacies (Horbury and Adams, 1996). The presence of wackestone intraclasts suggests reworking by a combination of storm events and bioturbation.

The trochoid morphology and umbilical aperture of the tetrataxids, howchiniids and pseudotaxids suggest that they may have had a clinging mode of life. This attachment was only temporary because most specimens are found “free” (unattached) in the sediments.

7. **Discussion**

The distribution of foraminifers in the Lower Carboniferous of Ireland was controlled by facies. The proportion of echinoderms, bryozoans and algae in the carbonates varied through time (Fig. 2). In the early Asbian *Koninckopora*, palaeoberesellids and bryozoans dominate. Late Asbian carbonates are palaeoberesellid- and *Ungdarella*-rich. Brigantian limestones are dominated by echinoderms, bryozoans and *Fasciella*.

A schematic illustration of the distribution of Irish late Viséan bioclast and foraminiferal assemblages are illustrated in Figs. 9 and 10.

During the early Asbian, shallow water packstone to grainstone assemblages (deposited at or above fair-weather wavebase) contain robust *Forschia*, *Bogushella*, *Pseudoendothyra* and *Omphalotis* (Fig. 10a). These taxa are inferred to have been mobile epifaunal foraminifers that thrived in meadows of *Koninckopora* and palaeoberesellids. The substrates created around and within the algal meadows favoured infaunal foraminifers such as *Littotubella* and monolayered palaeotextulariids. In the absence of calcareous algae, facies were often bryozoan-rich. Bryozoan carbonates in the early Asbian were characterized by *Eostaffella*, *Endothyra* and *Pseudoammodiscus*. These foraminifers are inferred to be mobile epifaunal forms that had a wide palaeoenvironmental tolerance, below and above fair-weather wavebase throughout the late Viséan. The epifaunal clinging foraminifer *Tetrataxis* and the robust discoidal *Pararchaediscus* occur most commonly associated with Asbian bryozoan limestones. Algal-poor packstone to wackestone lithofacies are characterized by *Valvulinella* and *Planoarchaediscus*. This facies is inferred to
Fig. 9. A key to Fig. 10 (not to scale). Abbreviations: Bilayered PTEX = bilayered palaeotextulariid, Monolayered PTEX = monolayered palaeotextulariid.

have been deposited at depths below 20 m, similar to the depth inferred by Horbury and Adams (1996) for bioclastic wackestone to mudstone facies for Asbian cyclic sediments in the Lake District, U.K.

Palaeoberesellid and Ungdarella-rich packstone to grainstone facies dominated Irish Platform carbonates in late Asbian time (Fig. 10b). Meadows of these two calcareous algae probably thrived at or above 10 m. Assemblages of foraminifers in these algal meadows were diverse and characterized by robust multilayered Globoendothyra in addition to the epifaunal taxa listed above for the early Asbian (Fig. 10b). The early Asbian infaunal foraminifers (listed above) which inhabited these meadows were joined in the late Asbian by bilayered palaeotextulariids and Gigasbria. Mobile epifaunal foraminifers with cribrate apertures such as Bradyina, Cribrospira and Bibradya and the infaunal Nevillella typify late Asbian grainstones; this facies may have been deposited at depths as shallow as 5 m. Late Asbian bryozaol facies are rare and typified by similar assemblages as in the early Asbian.

The switch from algal dominated carbonates in the Asbian to echinoderm (mainly crinoidal) and bryozoan limestones in the Brigantian caused a major change in foraminiferal assemblages. The multilayered epifaunal and infaunal foraminifers of the Asbian were replaced by abundant Asteroarchaediscinae and Tetrataxis (Fig. 10c). Brigantian crinoidal and bryozaol-rich packstones to grainstones formed in open-marine subtidal palaeoenvironments, where thickenets were continually reworked by currents, storm action and bioturbation at or below fair-weather wave base. The shape and the development of secondary deposits in the umbilical region of Asteroarchaediscinae are thought to have enhanced their survival in these palaeoenvironments. The prismatic calcareous wall of the aracheadiscinae may also harbour algal-symbionts indicative of shallow-water habitation (Brenckle et al., 1987). Brigantian packstones to wackestones are characterized by Valvulinella, Planoarchaediscus and Scalebrina, similar to early Asbian assemblages that are inferred to have possibly been deposited at depths below 20 m. Late Brigantian facies are typified by Fasciella-coated wackestone intraclasts in a wackestone to packstone matrix. The intraclasts were probably formed by storm activity and bioturbation. Foraminifera in the intraclast facies include Valvulinella, Planoarchaediscus, Scalebrina and common Howchinia.

8. Conclusions

A study of 685 thin section samples taken from Irish late Viséan shallow-water platform carbonates
Fig. 10. A schematic diagram (not to scale) illustrating the inferred facies and depth distribution of Lower Carboniferous Foraminifera from the early Ashbian to Brigantian stages in Ireland (see Fig. 9 for key).
have revealed that the foraminiferal distribution is linked to the relative abundance of echinoderms (mainly crinoids), bryozoans and calcareous algae. Specifically:

(1) Archaediscidae, Tetrataxidae and Valvulinella thrived in algal-poor crinoid and bryozoan thickets at or below fair-weather wavebase, below the threshold of algal growth.

(2) Endothyrids (sensu lato) and palaeotextularids are common in algal-rich limestones which may represent deposition at depth at or above 10 m, the depth inferred for optimal palaeoberesellids and Ungdarella meadow development.

(3) Taxa with cribrate apertures and robust tests such as Bibradya, Cribrospira, Nevillella and Bradyina were adapted to high energy shallow algal-rich facies, where these features would have minimized damage to the test.

(4) Large multilayered foraminifers with globose or keeled morphologies such as Gigasbia, Omphalotis, Globoendothyra and Pseudoendothyra are interpreted to have been shallow water taxa (perhaps 5–10 m depths) which thrived in algal meadows. Their shape ensured survival in current-swept palaeoenvironments.

(5) The large thick-walled forsihids were well adapted for survival in high energy palaeoenvironments. Their high association with the calcareous alga Koninckopora suggests an optimal depth for survival possibly between 5 and 10 m.

(6) Endothyranopsis, Endothyra, Eostaffella, Pseudoammodiscus and Earlandia are widely distributed and the least facies-controlled of the genera documented. Their relatively simple morphologies probably ensured their survival in a wide variety of platformal palaeoenvironments. The occurrence high numbers of Eostaffella, Earlandia and Pseudoammodiscus in facies lacking stenohaline bioclasts may suggest restricted lagoonal conditions.

(7) The encrusting habitat of the pseudolituotubellids ensured survival in a wide range of environmental extremes, although the substrate generated in palaeoberesellid and Ungdarella meadows may not have been suitable for pseudolituotubid colonization.

(8) The lenticular morphology and hyaline wall structure of the Archaediscidae ensured test survival in high energy facies. This is especially true for the stellate forms where secondary umbilical deposits greatly enhanced test strength and stability. In addition, the prismatic calcite wall of the archaediscids may have harboured algal-symbionts indicative of a photic-zone existence.

(9) Archaediscids with incomplete prismatic calcite walls, such as Planoarchaediscus, seem to be adapted to low energy subtidal palaeoenvironments, possibly below 20 m depth.

(10) Howchinia exhibits a particular adaptation to Brigantian intraclastic wackestone facies associated with Fasciella. The palaeoenvironment represented by this facies may have been at least at 20 m depth below fair-weather wavebase and above storm wavebase. The intraclasts formed by bioturbation and current action.

(11) Major changes in the facies and dominant bioclast composition have occurred in late Viséan carbonates, these are reflected by marked changes in foraminiferal assemblages. It is therefore important to understand the facies control on, and palaeoenvironmental distribution of, Lower Carboniferous benthic foraminifers before using them for detailed biostratigraphic correlations.

Acknowledgements

The research for this work was partly funded by an Eolas Basic Research Grant in Science. The author greatly appreciated the comments of Ian Somerville, Marigold White and Andrew Horbury who reviewed an earlier draught of the manuscript. The detailed reviews of Paul Brenckle and Bernard Mamet greatly improved the text. The author also would like to thank Conor MacDermot of the Geological Survey of Ireland for allowing access to unpublished data on the Burren succession in Co. Clare.

References

