

Biostratigraphic zonation and correlation of Mississippian rocks in Western Europe: some case studies in the late Viséan/Serpukhovian

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In the Mississippian in Western Europe, biostratigraphic zonation and correlation of sequences has been refined using a combination of faunal and floral groups. In deep-water basins and on shelves advances have been made in recognizing evolutionary lineages of conodonts, particularly in the early Viséan to Serpukhovian, for example the *Gnathodus praebilineatus* - *G. bilineatus bilineatus* - *G. bilineatus bollandensis* lineage, which is closely tied to ammonoid zones in the Culm facies of Western and Central Europe, and the *Lochriea saharae* - *L. commutata* - *L. nodosa* - *L. ziegleri* lineage. Moreover, progress has been made in recognizing the Upper Viséan/Serpukhovian boundary, based on the first appearance datum (FAD) of *Lochriea ziegleri*.

Greater precision in the dating and correlation of shallow-water platform facies has been achieved using foraminiferans. Although evolutionary developments in the Archæodiscidae are still of major importance in terms of biostratigraphic dating, alternative lineages have been proposed recently for the late Asbian/Brigantian (late Viséan) interval, involving the *Criborespira* - *Bradyina* - *Parajanischewskina* - *Janischewskina* lineage. These large cribrate complexed-walled forms are widely recognized throughout Western Europe. The base of the Viséan has recently been defined in South China using foraminiferans with the FAD of *Eoparastaffella simplex* in the lineage *Eoparastaffella ovalis* - *E. simplex*. The same criterion has been used to define the base of the Viséan (base of emended Moliniacian) in Belgium.

Recent studies in Britain, Ireland, France, Spain and Poland have demonstrated that in the Upper Viséan many calcareous algal taxa and problematica are widespread in their distribution throughout the western Palaeotethys Realm. Moreover, five algal assemblages can be distinguished, based either on the first appearance of certain taxa or their acme developments, such as *Falsocalcifolium punctatum* and *Calcifolium okense*. In addition, there have been new discoveries in the Brigantian and Serpukhovian of algal taxa and problematica such as *Archæolithophyllum*, *Paraepimastopora* and *Claracrusta* that were regarded previously as being restricted to the Pennsylvanian-Permian interval.

Advances in rugose coral biostratigraphy have also been made in the upper Tournaisian and Upper Viséan, particularly using dissepimented taxa which occur in shallow-water platforms. The presence of uraliniids and *Keyserlingophyllum* in the upper Tournaisian of Western Europe (Belgium) are also recognized in South China and Siberia. In the Upper Viséan, refinements in zonation have been made using well-defined colonial and solitary species and species groups belonging to the families Lithostrotionidae and Axophyllidae and solitary taxa of the families Aulophyllidae and Cyathopsidae which are recognized throughout the western Palaeotethys. Copyright © 2008 John Wiley & Sons, Ltd.

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1. INTRODUCTION

1.1. Subdivisions of the Carboniferous

The current subdivision of the Carboniferous System, as followed by the Subcommittee on Carboniferous Stratigraphy (SCCS) of the International Commission on Stratigraphy (ICS) and ratified by the International Union of Geological Sciences (IUGS) in 2004, is for two subsystems: the Mississippian and Pennsylvanian subsystems

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(Heckel and Clayton 2006). The Mississippian Subsystem is further subdivided into the Tournaisian, Viséan and Serpukhovian stages (Figure 1). According to Gradstein *et al.* (2004) the Carboniferous spans *c.* 60 Ma (359–299 Ma) and the Mississippian Subsystem approximately 41 Ma (359–318 Ma), that is just over two-thirds of the duration of the Carboniferous. In the Menning *et al.* (2006) time scale the Carboniferous is 62 Ma

Chronostratigraphy				Foraminiferal zones				Conodont zones				Rugose coral zones			Spore zones														
				Poty <i>et al.</i> 2006		Conil <i>et al.</i> 1991	Mamet 1974	Varker & Sev.1985; Jones & Som.1996 Poty <i>et al.</i> 2006; Herbig & Stoppel 2006		Poty <i>et al.</i> 2006	Mitchell 1989	Clayton <i>et al.</i> 1977																	
MISSISSIPPIAN	TOURNAISIAN	S.	B & I Bel.		Arns.	Arns.	MFZ16	Cf7		17-19	boll.	<i>Ad. unicornis</i> <i>Gn. bilin.bollandensis</i>	boll.	RC9		SO													
					Pend.	Pend.										TK													
			Brig.		Warnantian		MFZ15	Cf6	δ	16s	bilineatus	<i>Lochriea nodosa</i>	nod.	RC8	J-K H-I	NC													
			Asbian				MFZ14		γ	16i		<i>M. bipluti</i>					bilin.												
							MFZ13		α-β	15		<i>Gn. bilineatus bilineatus</i>	L. commutata	RC7	β	G		NM											
												<i>Gn. praebilineatus</i>																	
		Hol.		Liv.		MFZ12	Cf5		14 13	homo. ~ T. transatlanticus	Taphrognathus transatlanticus	L. commutata	RC6	E	TC														
		Arundian		Moliniacian		MFZ11	Cf4	γ-δ	12							M. praebeckmanni	homo.	RC5	D	TS									
						MFZ10		β	11 10				Scaliofnathus anchoralis	anchoralis	RC4						β2	C B							
		Cha.				MFZ9		α2	9														Doliognathus latus Do. bouckaerti Polygnathus mehli	carina	P. mehl	A	Pu		
						MFZ8		α1																				8	Ps. multistriatus
						MFZ7	Cf3									7	Gnathodus typicus	P.i.	RC2	β1									
					MFZ6	Cf2							6	P. inornatus isosticha-upper crenulata P. spicatus lower crenulata sandbergi upper duplicata lower duplicata sulcata	P.s.						RC1	α							
					MFZ5				Cf1														5	Siphonodella					
					MFZ4			α																				pre-7	
					MFZ3																								
					MFZ2																								
					MFZ1																								
					DFZ8																								
																								</					

(358–296 Ma). The approximate time span intervals of the Mississippian are: Tournaisian (14 Ma), Viséan (19 Ma) and Serpukhovian (8 Ma). The various stratigraphic subdivisions of these stages which have been designated in different regions of the world (e.g. North America, Western Europe, Eastern Europe (Russia and Donets) and South China) are now referred to as regional substages (see Gradstein *et al.* 2004, figure 15.2; Heckel and Clayton 2006).

The base of the Carboniferous (*Mississippian* Subsystem) and the base of the *Tournaisian* Stage are at La Serre, a hill near the village of Cabrières, Montagne Noire, southern France (Paproth *et al.* 1991). The Global Standard Stratotype and Point (GSSP) marking the Devonian/Carboniferous boundary was defined at the base of Bed 89, at the first appearance of the conodont *Siphonodella sulcata* related to the evolutionary lineage *S. praesulcata* - *S. sulcata* (Figure 1). It also coincides with the first appearance of the ammonoid *Gattendorfia* (Kullmann *et al.* 1991), and the first appearance datum (FAD) of the foraminiferal species *Chernyshinella glomiformis* and *Tournayellina beata* (Conil *et al.* 1991). New conodont data from the La Serre section (Kaiser *et al.* 2006), however, have suggested that the first appearance of the conodont *Siphonodella sulcata* could be at a lower level, within Bed 85, and as a consequence, they have proposed that the base of the Tournaisian and the Mississippian should be moved down to a lower horizon, between Beds 84 and 85. Significantly, it has long been recognized that this section contains reworked conodont associations and transported near-shore oolitic sediment (Flajs and Feist 1988; Girard 1994; Feist *et al.* 2000; Casier *et al.* 2002). Thus, the possibility exists that *S. sulcata* may be discovered in the future at lower levels below Bed 85, assuming that it can be readily distinguished from *S. praesulcata*.

The base of the *Viséan* Stage is defined in the Pengchong section, Guangxi, South China (Devuyst *et al.* 2003). The GSSP is defined at the base of Bed 85, at the first appearance of the foraminiferan *Eoparastaffella simplex* in the lineage *Eoparastaffella ovalis* - *E. simplex*. Interestingly, this taxon represents the first formal benthic marker within the entire Palaeozoic (Davydov *et al.* 2004). However, this lineage is not recognized in North America, but can be identified in Belgium and the Czech Republic (Devuyst and Kalvoda 2007). In the Pengchong section the conodont *Gnathodus homopunctatus* first appears in Bed 86 and the last appearance of the conodont *Scaliognathus anchoralis europensis* is below Bed 85 (Devuyst *et al.* 2003) (Figure 1).

The base of the *Serpukhovian* Stage is still to be formally defined, but work is in progress (see Davydov *et al.* 2004; Richards 2007). Currently, the conodont species *Lochriea cruciformis* and *Lochriea zieglerei* are used to recognize the Viséan/Serpukhovian boundary (Skompski *et al.* 1995; Nemyrovska 2005), although the latter species is now preferred (see Subsection 3.2). In the Moscow Basin the base of the Serpukhovian has been referred for a long time to the base of the Foraminifera Zone *Pseudoendothyra globosa-Neoarchaediscus postrugosus* (=Cf7 Foraminifera Zone of Conil *et al.* 1991 in the Franco-Belgian basins) (Figure 1), although both species are difficult to identify precisely. New studies by Kulagina *et al.* (2003) and Nikolaeva *et al.* (2003) have improved the foraminiferal zonation in the Moscow Basin and correlated it with the conodont zonation. Because of the absence of much of the lower Namurian (Pendleian) in Northern France and Belgium (see Poty *et al.* 2006 for a recent synopsis), sections in Britain were utilized for defining the younger Mississippian foraminiferal biozones in NW Europe (see Conil *et al.* 1980, 1991).

The *Mississippian/Pennsylvanian* subsystem boundary is defined within the transition from *Gnathodus girtyi simplex* to *Declinognathodus noduliferus s.l.* (Lane *et al.* 1999). The GSSP is defined in Arrow Canyon, Great Basin, Nevada, USA. Beds below the Mid-Carboniferous boundary contain abundant archaeodiscids dominated by '*Eosigmoilina robertsoni*' (= *E. explicata* auctorum) and *Brenckleina rugosa* (Davydov *et al.* 2004). Interestingly, *Gnathodus girtyi simplex* has recently been reported in the early Serpukhovian for the first time, in the Cantabrian Mountains, N. Spain (Nemyrovska 2005).

1.2. Mississippian sedimentation and palaeogeographic setting

At the end of the Caledonian Orogeny (and temporal equivalents, e.g. Acadian) and throughout the Mississippian Subsystem, North America (Laurentia) and Western Europe (Baltica and Avalonia) were united as the Laurussia land mass, and much of Western Europe had drifted northwards towards the equator from a subequatorial position (Scotese and McKerrow 1990; Scotese 2000). In early Mississippian times much of eastern North America, Western Europe and North Africa experienced a major transgression and drowning of the low-lying coastal plains

and fluvial valleys and interior basins in which the late Devonian sediments accumulated. As a result, there was widespread development of shallow-water ramps and platforms, which initially, in the early Tournaisian, had mixed siliciclastics and carbonates, but in the late Tournaisian gave way to thick carbonates. However, in southern Europe (Spain) and North Africa the transgression did not arrive until later in the Viséan. The deepening-upward trend in the late Tournaisian and early Viséan is often highlighted by formation of mud-mounds of the Waulsortian facies (Lees and Miller 1995; Somerville 2003) which are recorded from southwest North America to Afghanistan (see Vachard 1980) and possibly South China (personal communication, Hance L, 2007). In much of the early Viséan shallow-water shelf carbonates are developed in NW Europe, and these were maintained as extensive platforms in the mid to late Viséan, where they are rich in crinoids, corals, bryozoans, brachiopods, foraminiferans and algae. To the south of Britain and Ireland (Cope *et al.* 1992) and southeast of the Brabant Massif in Germany (Paproth 1969; Franke *et al.* 1975, 1995; Gursky 2006), there was the coeval development of deeper-water basinal facies (Culm). However, even within the shallow-water platform areas, separate provinces can be distinguished, separated either by tectonic events or palaeogeographic features. These provinces can often include both shallow-water and deep-water sediments juxtaposed, for example the Askrigg Block and Craven (Bowland) Basin in the Pennine Province in northern England, north of the Wales-London-Brabant Massif, and the Balbriggan Block and Kingscourt Platform, north of the Dublin Basin (Figure 2). Much of this region in northern Britain, and in eastern and northern Ireland, shows influences of syn-sedimentary faulting (Gawthorpe *et al.* 1989; Nolan 1989; Fraser and Gawthorpe 1990). This extensional phase resulting from back-arc rifting north of the Variscan subduction zone in central France (Massif Central area) produced grabens and half-grabens (Leeder 1988; Nolan 1989; Guion *et al.* 2000). The late Viséan/Serpukhovian epoch saw the change to siliciclastic sedimentation with thin carbonates, culminating in the siliciclastic-dominated suite of Pennsylvanian cyclothems from the Appalachian belt through to Western and Eastern Europe.

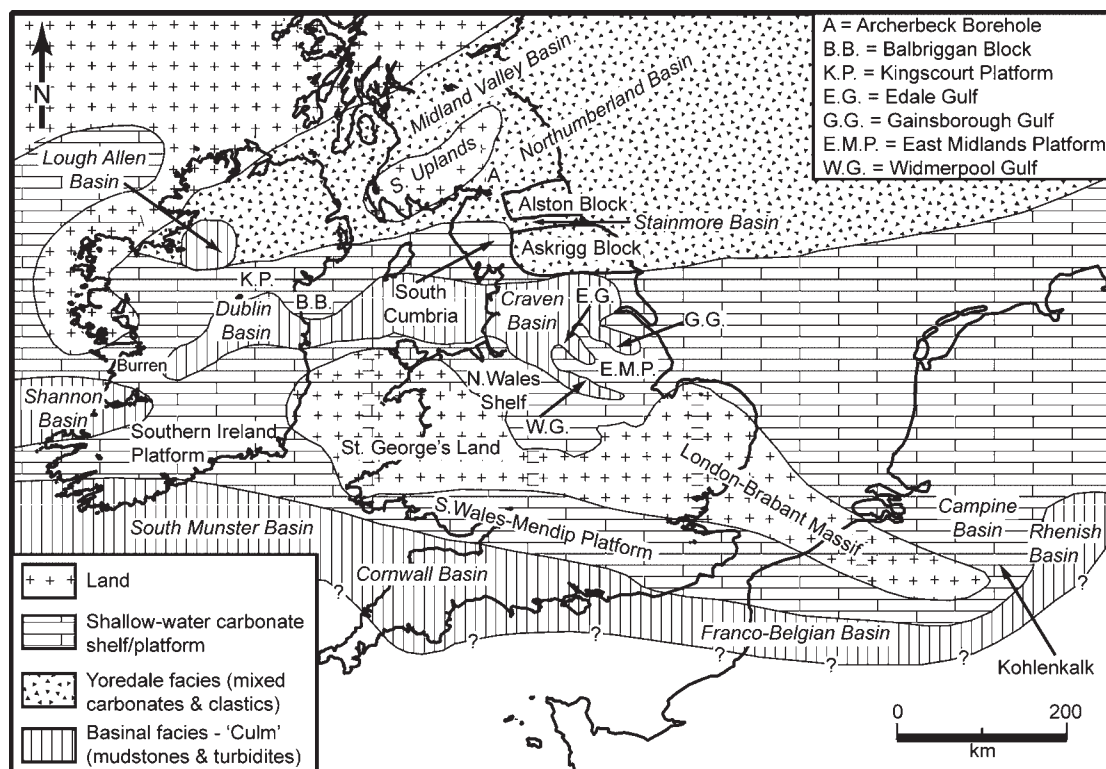


Figure 2. Palaeogeographical map of NW Europe in the Upper Viséan showing major platforms and basins (modified from Walkden 1987; Cope *et al.* 1992).

There is a major transition from the predominantly shallow-water platform limestones of Britain and Ireland southwards to deep-water basinal facies in SW England and southern Ireland, respectively (as there is, similarly, in Belgium and Germany, from the Brabant Massif (Kohlenkalk) south and east into the Culm; Gursky 2006). Also, within the major platform areas in northern Britain and Ireland there are intraplatform deeper-water shelves and basins. Thus, in central England, north of St. George's Land, the Derbyshire Platform is surrounded by deep-water basinal facies of the Edale Gulf/Craven Basin to the north, Gainsborough Gulf to the northeast and Widmerpool Gulf to the south (Strank 1987; Walkden 1987; Cope *et al.* 1992; Figure 2). In northern England the Stainmore Trough (a narrow gulf containing a thicker and more complete Mississippian succession) resides between the mostly Upper Viséan shallower-water platform limestone rocks of the Alston and Askrigg Blocks (Burgess and Mitchell 1976; Walkden 1987; Cózar and Somerville 2004). Further to the north, the Northumberland Basin is situated between the Alston Block and Southern Uplands Massif (Figure 2). In Ireland, apart from the Dublin Basin mentioned above, there are also deep-water shelf and basinal facies, particularly in the Viséan, in the Shannon Basin region in western Ireland and in the Lough Allen Basin in NW Ireland (Somerville and Strogon 1992; MacDermot *et al.* 1996; Strogon *et al.* 1996; Sleeman and Pracht 1999; Sevastopulo and Wyse Jackson 2001; Gallagher and Somerville 2003; Cózar *et al.* 2006).

A similar block and basin structural setting is known north of the Brabant Massif in Belgium (Poty 1997; Aretz *et al.* 2006), and recent investigations in the Netherlands north of the London-Brabant Massif have inferred the presence of Mississippian carbonate platforms affected by synsedimentary faulting (Van Hulten and Poty 2008).

2. REGIONAL CORRELATION AND DISCONTINUITIES

It has long been recognized in Carboniferous successions showing marked lateral facies variation, that correlations can be achieved both within and between basins using distinctive lithological marker horizons, for example ash bands (cinerites), bentonitic clays and coal seams. Moreover, many of the volcanoclastic beds can act as isochronous surfaces. On a more local scale, particular faunal features may be identified as having potential correlative value, for example storm event beds, coquinas, coral biostromes or 'algal' oncoid beds, such as the '*Girvanella* nodular bed' in northern England (cf. Garwood and Goodyear 1924; Burgess and Mitchell 1976). In addition, within carbonate-dominated sequences, unconformities (disconformities) now often identified as sequence boundaries (see below; Hance *et al.* 2002; Poty *et al.* 2002, 2006, 2007) are used to identify individual sequences that can be correlated over hundreds of kilometres, for example in the North American Kentucky and Illinois basins (Al-Tawil and Read 2003; Al-Tawil *et al.* 2003). These North American examples have been recognized utilizing both surface exposures (road-cuts and large quarries) and subsurface boreholes, in an integrated manner, to map out regional surfaces separating unconformity-bounded depositional sequences. In the shallow-water Mississippian successions in North America and Europe these disconformities (palaeokarsts) are often marked by the presence of overlying palaeosols (e.g. the thick palaeosol 'Banc d'Or de Bachant' in the Franco-Belgian Basin) comprising non-marine bentonitic clays, silts and coals, with calcareous breccias and laminar caliche often developed below karstic surfaces (see Walkden 1974, 1987; Walls *et al.* 1975; Harrison and Steinen 1978; Somerville 1979a, 1979b; Wright 1982; Esteban and Klappa 1983; Vanstone 1996; Smith and Read 2000; Al-Tawil and Read 2003). The subaerial exposure may have been prolonged to enable vegetation to establish in a soil, as identified by the development of rootlets in the terrestrial accumulates, or as pedogenic tubes in the underlying lithified limestone host. Changes in climate through the Mississippian may be detected by the differences in the character and composition of the palaeosols, from a semi-arid early Mississippian climate to alternating semi-arid and seasonally wet climate in the late Mississippian (see below; Wright and Vanstone 2001; Al-Tawil and Read 2003). The caliche forms laminated micritic crusts which coats the irregular exposed limestone surface that would probably have developed below the palaeosol, in a similar manner to modern crusts in Florida and Barbados (Multer and Hoffmeister 1968; Harrison and Steinen 1978). *In situ* brecciation of the limestone and circumgranular cracking around large peloids and grains is a characteristic feature of subaerial emergence and lithification of Mississippian carbonates (Wright 1982).

2.1. Glacio-eustatic influences and sequence stratigraphy

Sequence stratigraphy is widely applicable to the Carboniferous cyclic sequences because they are generally considered to be glacio-eustatic and therefore global in distribution (Ramsbottom 1977; Ross and Ross 1987, 1988, 1995; Veevers and Powell 1987; Smith and Read 2000; Davydov *et al.* 2004). Many of the evolutionary changes in the marine faunal and floral realms, particularly in the mid to late Mississippian, can be related to possible early phases of glacio-eustatically controlled transgressions and regressions on carbonate platforms and in adjacent basinal settings, in response to Gondwana glaciations (see Wright and Vanstone 2001). Many of the limestones in cyclothemic sequences (e.g. Yoredale facies in northern England and the Midland Valley of Scotland) contain distinctive macro- and microfossil assemblages which can be used for biostratigraphic correlation between platforms and basins (Holliday *et al.* 1975; Burgess and Mitchell 1976; Johnson and Nudds 1996; C  zar and Somerville 2004). The limestone component of siliciclastic-dominated cyclothem usually represents the initial transgressive phase of the cycle (TST) when there is widespread carbonate sedimentation with attendant new biota. Many stage and substage boundaries appear associated with major hiatuses during prolonged periods of lowered sea levels (Ross and Ross 1988). It has been suggested that the Mid-Carboniferous (Serpukhovian/Bashkirian) boundary coincided with a major global regression and sea-level fall associated with the Gondwana glaciation (Saunders and Ramsbottom 1986; Veevers and Powell 1987; Veevers 2004) leading to mass extinction events and faunal turnovers (Walliser 1995; Kossovaya 1996; Wang *et al.* 2006).

The base of the Serpukhovian (Namurian) (= Pendleian Substage in Britain) has been suggested as an important chronostratigraphic boundary and recognized in Western Europe as a widespread marine flooding surface (Ramsbottom 1977), but many recent investigations in sequence stratigraphy (Poty *et al.* 2006) have contested this claim. In the Timan-Pechora region of northern Russia the Vis  an/Serpukhovian boundary coincides with a flooding surface (Kossovaya *et al.* 2001) but, perhaps, this could be also interpreted as an event following the regression. However, in the Moscow Basin, because of severe restrictions to Palaeotethys seaways, the marine biota shows some evidence of endemism (Makhlina *et al.* 1993; Makhlina 1996).

3. HIGH RESOLUTION BIOSTRATIGRAPHY

In the Lower Carboniferous (Mississippian), many fossil groups have been used to date and correlate successions. Traditionally, macrofaunal invertebrates have been used, notably ammonoids for deep-water basinal facies (e.g. Bisat 1924, 1928; Ramsbottom and Saunders 1985; Korn 1990, 1996, 2006; Kullmann *et al.* 1991), especially in the Upper Vis  an, where 17 goniatite zones have been defined in the Culm facies of Germany (Korn 1996). On the other hand, corals (e.g. Poty 1985; Mitchell 1989; Poty and Xu 1996; Hecker 2001) and brachiopods (Pattison 1981; Legrand-Blain 1991) have been used in shallow-water platform facies. Higher precision has been achieved in the last three or four decades by using microfossil groups, notably conodonts (Lane *et al.* 1980; Metcalfe 1981; Belka 1985; Varker and Sevastopulo 1985; Higgins 1985; Wang 1991; Perret 1993; Perret and Weyant 1994; Nemirovskaya *et al.* 1994; Skompski *et al.* 1995; Nemyrovska 2005, 2006; Nemyrovska *et al.* 2006) and foraminiferans (Mamet and Skipp 1970; Mamet 1974; Vachard 1977; Conil *et al.* 1980, 1991; Jones and Somerville 1996; Vdovenko 2001; C  zar and Somerville 2006; Poty *et al.* 2006). In nearshore and marginal marine facies palynomorphs are necessary to use, often in the absence of other microfossil groups (Neves *et al.* 1972, 1973; Streel 1972; Neves and Ioannides 1974; Clayton *et al.* 1977; Higgs 1984; Clayton 1985; Higgs *et al.* 1988a, 1988b; Turnau *et al.* 1997; Clayton *et al.* 2003; Utting and Giles 2004). Recent investigations (Clayton *et al.* 2003; personal communication Clayton. G 2004) have proposed the erection of five new miospore subzones in the Mississippian: three in the Vis  an (two in the Asbian and one in the Brigantian substages) and two in the Serpukhovian (one in each of the Pendleian and Arnsbergian substages). More recently, studies on calcareous algae have highlighted the growing importance of this group for biostratigraphic dating and especially recognizing palaeobiogeographic provinces (Vachard and Berkhli 1992; C  zar and Somerville 2004, 2005b, 2005c; Vachard *et al.* 2004; Vachard and Aretz 2004).

One of the most significant advances has been in utilizing many different fossil groups in integrated analyses (Aisenverg *et al.* 1975; Makhlina *et al.* 1993; Matyja *et al.* 2000; Somerville *et al.* 2001; C3zar *et al.* 2006; Poty *et al.* 2006), where limestones are interbedded with siliciclastic rocks. In such sequences foraminiferal, conodont, algal and coral data can be obtained from the carbonates, ammonoids from the shales and spore data from the mudstones and siltstones. Such combined studies can provide more precise age determinations for parts of sequences which were hitherto unfavourable for individual fossil groups.

In the following sections, each of the four fossil groups (foraminiferans, conodonts, calcareous algae and corals) found predominantly in carbonate rocks will be examined in turn, to highlight significant advances that have been made in the last three decades on aspects of (i) biostratigraphic dating and correlating, (ii) phylogenies and evolutionary development, (iii) recognition of new genera and species which have provided much greater precision in dating and zonation, and (iv) a better understanding of relationships between shallow-water platform biota and deep-water basal faunas and floras.

3.1. Foraminiferans

3.1.1. Foraminiferal biozonations in the Mississippian

Following on from the pioneer work of Russian foraminiferal workers in the period 1935–1966 (Mikhailov 1935, 1939; Rauser-Chernoussova *et al.* 1936, 1940; Chernysheva 1940; Rauser-Chernoussova 1948a, 1948b, 1948c; Reitlinger 1950; Schlykova 1951; Dain and Grozdilova 1953; Lipina 1955, 1963; Brazhnikova 1956; Ganelina 1956, 1966; Rozkovskaya 1963) (summarized in Rauser-Chernoussova *et al.* 1996 and Vdovenko 2001), important developments in foraminiferal biostratigraphy, taxonomy and phylogeny in the western Palaeotethys were the publications of Conil and Lys (1964, 1977), Pirlet and Conil (1974) and Conil *et al.* (1980, 1991). In these studies Conil and co-workers defined seven Foraminiferal Zones (Cf1–Cf7) within the Tournaisian, Vis3an and lower Namurian (Pendleian and Arnsbergian substages combined = most of the Serpukhovian). Several of these zones were further divided into subzones, notably the Cf4 and Cf6 Zones (Figure 1). Mamet (1974) had independently also used foraminiferans to zone the Belgian Lower Carboniferous sequence which had been used successfully earlier in North American and involved 19 zones (Mamet and Skipp 1970). Recently, Poty *et al.* (2006) have refined some parts of the Conil *et al.* (1991) zonation. Most of the new Mississippian Zones (MFZ1–16) equate with the former zones and subzones of Conil *et al.* (1991), especially in the Vis3an (see Figure 1), as well as showing close correspondence with the zonal scheme of Mamet (1974), notably in the Vis3an.

Further refinements have been achieved in Ireland in the biozonation of the late Asbian (Cf6 γ Subzone of Conil *et al.* 1991). This has been divided into two divisions: Cf6 γ 1 and Cf6 γ 2 (Gallagher 1996; Jones and Somerville 1996; Gallagher and Somerville 1997). The guides for the lower subdivision (Cf6 γ 1) are the first appearance of *Cribrostomum lecomptei* and *Bibradya grandis* (Figure 3); guides for the upper subdivision (Cf6 γ 2) are the first appearance of *Bradyina rotula*, *Neoarchaediscus stellatus*, *Neoarchaediscus incertus*, *Saccaminopsis* sp., *Howchinia bradyana* (rare, and only near the top), along with the alga *Koninckopora* sp. B (see Subsection 3.3). These divisions (with minor variations) have been recognized in several discrete platform successions in Ireland; in the Burren in western Ireland (Gallagher and Somerville 1997; Gallagher *et al.* 2006); in Carlow, Kilkenny and north Cork, south and southeast Ireland (Somerville and C3zar 2005; C3zar and Somerville 2005a); and in the Kingscourt Platform in north central Ireland (Strogen *et al.* 1995; Figure 2). A similar division was recognized in the coeval late Asbian rocks of the Montagne Noire (Vachard 1977) with a lower and upper V3b γ Subzones (=MFZ14 Zone of Poty *et al.* 2006).

3.1.2. Basal Vis3an stratotype section

The base of the Vis3an Stage in the Pengchong section in South China has been defined on the FAD of *Eoparastaffella simplex* (Devuyst *et al.* 2003). This species is characterized by having an outer subangular morphology (morphotype 2), which evolved from *E. ovalis*, the latter having a more rounded periphery (morphotype 1), within the evolving lineage *Eoparastaffella ovalis* - *E. simplex*. Other morphological criteria to distinguish the two species are: the thinner microgranular wall and umbilicate form of the advanced *E. simplex*, in

AGE		ZONE	DIAGNOSTIC TAXA (FAD) Cozar & Somerville (2004, 2005a, 2006) Somerville & Cozar (2005) Gallagher <i>et al.</i> (2006)	PREVIOUSLY PROPOSED TAXA Conil <i>et al.</i> (1977, 1980, 1991) Fewtrell <i>et al.</i> (1981) Laloux (1988); Riley (1993)
Serp.	Arnsbergian	Cf7	<i>Loeblichia minima</i>	<i>Eosigmoilina</i> ; <i>Brenckleina</i> <i>Monotaxinoides</i> <i>Bradyina cribrostomata</i> <i>Loeblichia minima</i>
	Pendleian			
Upper Viséan	Late Brigantian	Cf6δ	<i>Archaeodiscus @ tenuis</i> stage <i>Betpakodiscus</i> <i>Pseudoglomospira</i> <i>Howchinia</i> (with pseudotubes)-[top] <i>Biseriella parva</i> <i>Endothyranopsis sphaerica</i> <i>Climacammina</i> <i>Janischewskina</i>	<i>Archaeodiscus @ tenuis</i> stage ' <i>Monotaxinoides</i> ' and <i>Howchinia</i>
	Early Brigantian		<i>Neoarchaediscus karreriformis</i> <i>Loeblichia paraammonoides</i> <i>Parajanischewskina</i> <i>Asteroarchaediscus</i>	<i>Janischewskina</i> <i>Loeblichia paraammonoides</i> <i>Climacammina</i> ; <i>Warnantella</i> <i>Asteroarchaediscus</i>
	Late Asbian	Cf6γ2	<i>Howchinia bradyana</i> [top] <i>Euxinita efremovi</i> <i>Bradyina rotula</i>	<i>Howchinia bradyana</i> <i>Bradyina rotula</i>
		Cf6γ1	<i>Koskinobigenerina</i> <i>Bibradya grandis</i> <i>Cribrostomum lecomptei</i> <i>Neoarchaediscus</i>	<i>Koskinobigenerina</i> <i>Cribrostomum lecomptei</i>
	Early Asbian	Cf6α-β	<i>Archaeodiscus @ angulatus</i> stage <i>Vissariotaxis</i>	<i>Archaeodiscus @ angulatus</i> stage <i>Vissariotaxis</i> ; <i>Neoarchaediscus</i>

Figure 3. Diagnostic foraminiferal taxa of the middle and late Mississippian in NW Europe compared with previously proposed diagnostic taxa. (Taxa highlighted in bold are later first occurrences than previously suggested.) Abbreviation: Serp., Serpukhovian.

contrast to the thicker granular wall of the more primitive *E. ovalis* which is only slightly umbilicate. Morphometric analysis has also been utilized to demonstrate the evolving lineage across the Tournaisian/Viséan boundary (Devuyst *et al.* 2003). However, the ancestor of the genus *Eoparastaffella* is poorly known, despite the pioneer studies of Vdovenko (1954, 1971), as are several other Mississippian foraminiferal genera. Moreover, although *E. simplex* is known throughout Europe and S. China it is unknown from the USA. A recent study though (Devuyst and Kalvoda 2007) has provided more data on the evolution of the genus *Eoparastaffella*, especially primitive forms in the latest Tournaisian, recorded from several regions in Eurasia. It is worth noting here, as the latter authors have remarked, that *Eoparastaffella* is a very significant genus, as it is the ancestor of the important fusulinid group of foraminifers including *Eostaffella*, *Pseudoendothyra* and *Parastaffella* which were to dominate the mid to late Mississippian and Pennsylvanian subsystems.

3.1.3. Evolutionary developments in the Archaeodiscidae

Pirlet and Conil (1974) and Conil *et al.* (1980) also recognized that several evolutionary developments were taking place in the family Archaeodiscidae which were to have a major impact on determining the ages of assemblages and defining phylogenetic and evolutionary pathways. In particular, was the recognition and definition of the *involutus*, *concavus*, *angulatus* and *tenuis* stages of coiling with accompanying sutural developments in archaeodiscid foraminiferans in the Mississippian (early Viséan to Serpukhovian). Although this trend is part of an evolving

continuum with transitional forms and significant overlap of coiling types and sutural forms (cf. Conil *et al.* 1980, p. 35), nevertheless, there are important biostratigraphic data contained within this study which can be further utilized (see Vachard 1988). For instance, it is now recognized that *involutus* stage forms persist from the Arundian (lower Viséan) through to the Asbian (Upper Viséan) and overlap in time with *concavus* stage forms (cf. White in Johnson and Nudds 1996; Jones and Somerville 1996; Cózar and Somerville 2004, 2005a). Moreover, taxa such as *Planoarchaediscus* are known to extend into the Serpukhovian (Vdovenko 2001; Cózar 2005). Similarly, *concavus* stage forms of archaediscids which first appear in the Holkerian, survive through to the Arnsbergian (late Serpukhovian) and overlap with *tenuis* forms, for example in the Grindstone Limestone in the Woodlands Borehole, Alston Block, N. England (Cózar and Somerville, unpublished data) and overlap substantially with *angulatus* stage forms in the Asbian (e.g. White in Johnson and Nudds 1996). However, as *involutus*, *concavus* and *angulatus* stages are part of an evolving lineage it is quite inappropriate to use them as precise biostratigraphic markers to define the base of the Arundian, Holkerian and Asbian substages, respectively. Moreover, it is now recognized that 'true' *angulatus* forms did not appear at the base of the Asbian, but at higher stratigraphic levels in the Asbian, with reference to independent biostratigraphic markers such as *Vissariotaxis* (Strogen *et al.* 1990; Jones and Somerville 1996; Gallagher and Somerville 1997), that characterizes MFZ13 Zone in Belgium (Poty *et al.* 2006).

Nevertheless, even the latter taxon can be confused with the first *Howchinia* which lacks the well-defined secondary yellow fibrous layer. Further complications with archaediscids are those forms which appear to be transitional between *concavus* and *angulatus* stage sutures (cf. Jones and Somerville 1996), and additionally, *involutus* stage forms can have *concavus*-style sutures in the outer whorls. However, one of the greatest problems and an impediment in archaediscid taxonomy, currently, is the lack of agreement between foraminiferal workers on the definition of *involutus*, *concavus*, *angulatus* and *tenuis* stages of coiling. Recent proposals (Pille *et al.* 2007) though, may have created some harmonizing of taxonomy, with the renaming of the transitional 'evolutus' coiling (Vachard 1988) as 'angulo-tenuis' coiling. The universally applied Foraminiferal Zones (Cf1–Cf7) of Conil *et al.* (1980, 1991) use archaediscids to define the base of the Cf6 Zone (*Neoarchaediscus* Biozone), which equates to the base of the Asbian in Britain, Ireland and Spain (cf. Ramsbottom 1981b; Riley 1993; Gallagher and Somerville 1997; Cózar 2003) and Warnantian substage in Belgium (Conil *et al.* 1980, 1991; Laloux 1988; Poty *et al.* 2006; Figure 1), although it is now recognized in many sections that *Neoarchaediscus* is not recorded at the base of this biozone (Riley 1993; Cózar and Somerville 2004; Figure 3). Furthermore, there is still a lack of agreement on the definition of *Neoarchaediscus* (see comments in Cózar and Somerville 2006).

In addition, and running in parallel with this evolutionary development, is the progressive reduction in the thickness of the inner microgranular layer in the wall of archaediscids. In the Arundian, this can be very thick, and take the forms of buttresses (e.g. *Glomodiscus*). However, in the Asbian, and particularly in the Brigantian, this microgranular layer is generally very thin (e.g. in *Archaediscus s.s.*). Nevertheless, there are forms which still retain the inner microgranular layer (albeit very reduced in thickness) in the late Viséan (Asbian/Brigantian), for example in *Paraarchaediscus* and '*Leptodiscus*'. Moreover, there are archaediscids which dominate the Arundian (e.g. *Uralodiscus* and *Glomodiscus*) that 'reappear' in the late Asbian without obvious signs of having been reworked (cf. Strank in Ramsbottom 1981b; Cózar and Somerville 2004, 2005a), and yet are apparently absent from the intervening Holkerian Substage in shallow-water platform successions, but are recorded in deeper shelf facies (see below). It should be noted, however, that several foraminiferal workers (personal communication, Vachard D, 2006) do not attach much significance to the reduction of the microgranular layer after the *involutus* stage.

There is a notable increase in the number of archaediscid genera in the late Viséan, especially in the late Asbian and Brigantian (=MFZ14 and 15 Zones of Poty *et al.* 2006; Figure 4), which is closely related to the timing of major transgressions. The latter led to the formation of extensive shallow-water platform facies (during the D5b, D6a and D6b mesothems of Ramsbottom 1977, 1981a), which helped create more benthic niches for these lenticular fibrous-walled foraminiferans, especially in packstone/grainstone facies (cf. Gallagher 1998).

There is also an increase in the total number of individual archaediscid foraminiferal specimens, especially in the mid to late Viséan, with lenticular and discoidal stellate forms common in Brigantian shallow-water platforms (Strogen *et al.* 1995; Gallagher and Somerville 1997; Gallagher *et al.* 2006). On the other hand, small thin-walled

discoidal archaedisids, for example *Paraarchaediscus* can also be abundant in deeper-water shelf/basinal facies, for example in Arundian to Brigantian strata in the Lough Allen Basin, NW Ireland (Cózar *et al.* 2005b, 2006). The latter case may suggest that, in part, this is a function of hydraulic control on the dispersal and settling of foraminiferans; the fine-grained character of muddy sea-floor substrates, as well as concentration factors, which may be related to currents sweeping over the shelf floor (see Herbig and Mamet 1994).

Another significant development in the late Viséan is the trend towards large forms in the Archaediscidae. This reaches its culmination in the Brigantian, as highlighted by Conil *et al.* (1980), Cózar and Somerville (2004) and Somerville and Cózar (2005), with archaedisids at *angulatus* stage reaching diameters $>800\ \mu\text{m}$ (e.g. *Archaediscus karreri karreri* group).

Another discernible trend in the Archaediscidae is an increase in the amount of occlusion of the lumen through the mid to late Viséan, from an initial, partial occlusion, as in nodose forms in the late Arundian and Holkerian ('*Nodosarchaediscus*'), to more advanced forms with major to complete occlusion in stellate forms in the late Asbian and particularly in the Brigantian, for example *Neoarchaediscus* and *Asteroarchaediscus*. This is reflected in the higher diversity of archaedisid taxa in the Upper Viséan (14 genera recorded in the Brigantian compared with 7 in the Arundian; see below and Figure 4) (cf. Conil *et al.* 1980; Fewtrell *et al.* 1981; Vachard 1988; Cózar 2000). Moreover, studies have shown that in the Brigantian, stellate archaedisids (e.g. *Neoarchaediscus*, *Asteroarchaediscus* and *Planospirodiscus* belonging to the subfamily Asteroarchaediscinae) are more common than *Archaediscus*, without occlusion of the lumina (Cózar and Somerville 2004, 2005a; Cózar *et al.* 2005a, 2006; Somerville and Cózar 2005).

3.1.4. Other evolutionary developments

An alternative biostratigraphical scheme (used in parallel with the Archaediscidae) involves the evolution in large cribrate foraminiferans belonging to the family Bradyinidae that possess a porous wall, keriothecal septa and secondary sutural apertures. This proposed phylogenetic pathway recognizes an ancestral form in the Holkerian

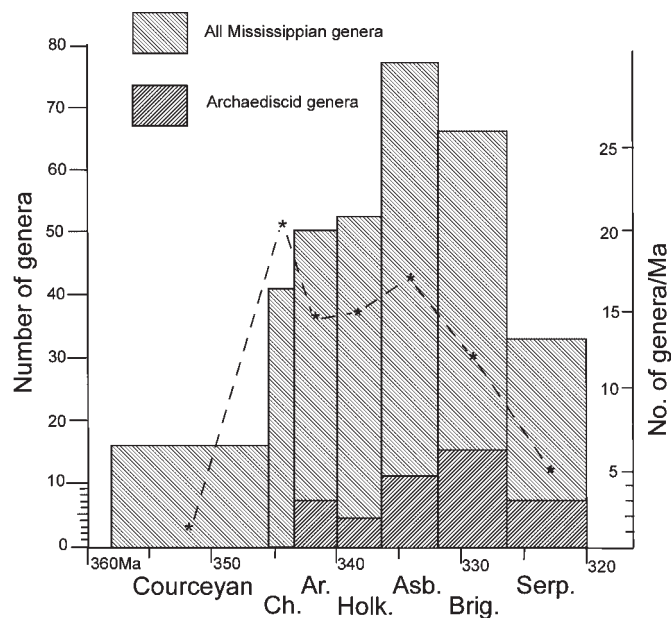


Figure 4. Histogram to show variation in all foraminiferal genera through the Mississippian, as well as those of the genera belonging to the family Archaediscidae (based on published works, including Conil and Lys 1964; Conil *et al.* 1980, 1991; Fewtrell *et al.* 1981; Strank *in* Ramsbottom 1981b; Gallagher and Somerville 1997; Cózar and Somerville 2004, 2005a, 2005b; Somerville and Cózar, 2005; Cózar *et al.* 2006; Gallagher *et al.* 2006, and in unpublished Ph.D. theses). Graph shows a plot of the variation in the number of foraminiferal genera/Ma for each substage. Abbreviations: Ch., Chadian; Ar., Arundian; Holk., Holkerian; Asb., Asbian; Brig., Brigantian; Serp., Serpukhovian (Pendleian and Arnsbergian combined). N.B. Courcayan (= Tournaisian). Mississippian time scale is that of Menning *et al.* (2006).

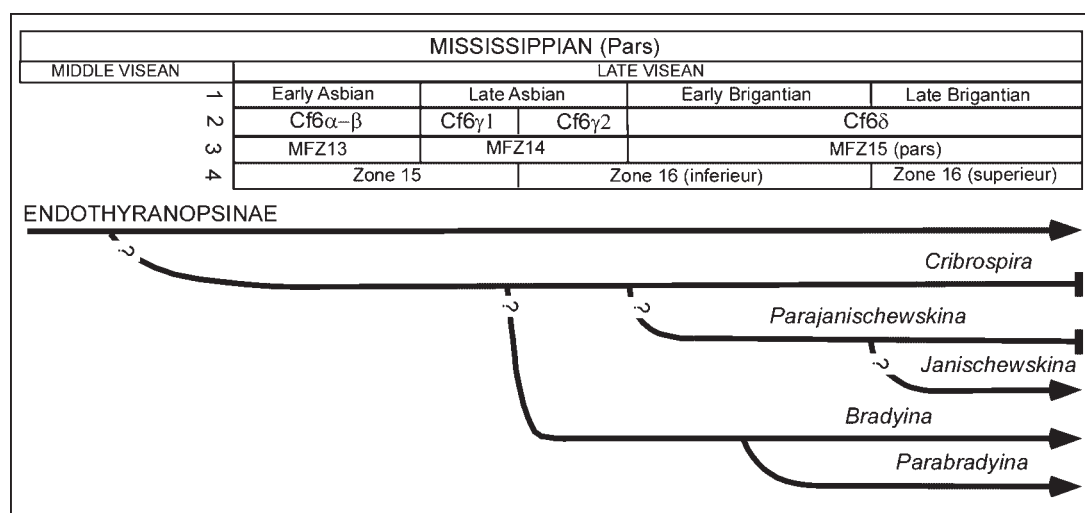


Figure 5. Evolutionary lineages of the family Bradyinidae in the Upper Viséan (modified from Cózar and Somerville 2006). 1 = Substages in Britain and Ireland (after Jones and Somerville 1996); 2 = Foraminiferal Subzones (after Conil *et al.* 1991; Jones and Somerville 1996); 3 = Mississippian Foraminiferal Zones (after Poty *et al.* 2006); 4 = Foraminiferal Zones of Mamet (1974).

(possibly *Cribrospira* or a closely related genus) from which more complex forms evolved in the late Asbian (*Bradyina*) and Brigantian (*Parabradyina*, *Parajanischewskina* and *Janischewskina*) (Cózar and Somerville 2006; Figure 5). This phylogeny has been identified in the late Viséan sequences in northern England (Stainmore Trough and Alston Block), Scotland (Midland Valley and Archerbeck Borehole) and in Ireland (Kingscourt) (located in Figure 2). The presence of *Parajanischewskina* in the basal Brigantian stratotype section in Janny Wood, Stainmore Trough has been identified as a useful early Brigantian marker and gave rise to *Janischewskina* in the late Brigantian (Cózar *et al.* 2005a; Cózar and Somerville 2006; Figure 3). Previous claims that *Janischewskina* appears first in the early Brigantian (Fewtrell *et al.* 1981; Strank 1981) have not been verified in Britain or Ireland (Cózar and Somerville 2004, 2005a; Somerville and Cózar 2005; Cózar *et al.* 2005a). Moreover, another important Brigantian taxon, *Loeblichia*, which has been used previously by many authors to identify the Brigantian Substage (Conil *et al.* 1980; Strank 1981) has only been found some distance above the base, and hence its validity as a basal Brigantian marker cannot be upheld (Cózar and Somerville 2004).

3.1.5. Foraminiferal assemblages in the Upper Viséan

Some further refinement and precision in the dating and location of substage boundaries, for example the Asbian/Brigantian boundary in N. England, has been achieved recently (Cózar and Somerville 2004). It is now recognized that the composition of foraminiferal assemblages from the Alston and Askrigg blocks differs slightly from that of the intervening Stainmore Trough, from the Janny Wood section, which has been used to define the basal Brigantian stratotype (Burgess and Mitchell 1976; George *et al.* 1976). These changes, especially the earlier first appearances of taxa at Janny Wood, may be explained by responses to subtle changes in water depth, substrate type and energy levels, as well as evolutionary biological developments. It is now proposed that the basal boundary for the Brigantian should be moved to a lower horizon, from the base of the Peghorn Limestone to the base of the Birkdale Limestone or possibly the Robinson Limestone (Cózar and Somerville 2004). The typical taxa used to recognize the Brigantian may be characterized by the first occurrence of *Asteroarchaediscus* and large *Archaediscus* at 'angulatus' stage (e.g. *A. karreri*), followed at slightly higher levels in the sequence by common *Euxinita* (= 'Pojarikovella') *efremovi*, *Howchinia bradyana*, *Neoarchaediscus* cf. *karreriiformis* and *Loeblichia paraammonoides* (Figure 3). A comparable suite of foraminifers characterizes the Brigantian Clogrennan

Formation in counties Carlow and Kilkenny (Somerville and C  zar 2005; C  zar and Somerville 2005a) and Brigantian Liscarroll Limestone Formation in North Co. Cork, Ireland (Gallagher 1992; Gallagher and Somerville 1997). Recently, Okuyucu and Vachard (2006) have reported a similar assemblage from the late Vis  an rocks of Turkey. Recent work on Brigantian assemblages in N. England and Ireland has recognized that certain foraminiferal taxa first appear in the late Brigantian, confirmed by the presence of the P_{2a} goniatite *Lusitanoceras granosus* and the conodont *Lochriea nodosa*. These include: *Climacamina*, *Endothyranopsis sphaerica*, *Janischewskina typica*, *Biseriella parva*, and in the upper part, advanced *Howchinia*, and *Tubispirodiscus* (= *Betpakodiscus*), associated with the alga *Calcifolium okense* (C  zar and Somerville 2004, 2005a, 2006; Somerville and C  zar 2005; C  zar *et al.* 2006; Figure 3). Many of these foraminiferal taxa are also characteristic of the Serpukhovian in the Donets Basin (Vdovenko 2001), the Midland Valley of Scotland (C  zar *et al.* 2007a) and Morocco (C  zar *et al.* 2007b).

3.1.6. Upper Vis  an foraminiferal biofacies

It is important to bear in mind though that foraminiferans are, like many other benthic organisms, subject to substrate control and varying energy levels and water depths, and, as such, biostratigraphically significant taxa may be absent in specific lithofacies. A study by Gallagher (1998) on the distribution of Upper Vis  an foraminiferans on carbonate shelves in Ireland illustrated the effects of these influences, as well as the involvement of the associated benthos. The foraminiferal assemblages documented show variation both spatially and temporally through the Asbian and Brigantian, when major transgression events (Ramsbottom 1973, 1981a), many coincident with sequence boundaries (Hance *et al.* 2002; Poty *et al.* 2007), created new niches exploited by foraminiferans and other benthic organisms on laterally extensive shallow-water platforms. Gallagher (1998) showed that in the Asbian, foraminiferans with large, robust, thick-walled (e.g. *Omphalotis*, *Globoendothyra*) and multilayered tests, often with cribrate apertures (e.g. *Bradyina*, *Cribrospira*, *Nevillea* (= '*Haplophragmella*' auct.), *Bibradya*, forschiiids and palaeotextulariids), occurred in high-energy, shallow-water grainstones (water depths 5–10 m), often associated with calcareous algae such as moravamminids/palaeoberesellids, aoujgaliids/ungdarellids and *Koninckopora*. Many of these foraminiferal taxa may have had associations with endosymbiotic algae. On the other hand, in low-energy, quiet water environments (water depths >20 m), thin-walled lenticular archaedisks (*Planoarchaediscus*) and tetrataxids (*Tetrataxis* and *Valvulinella*) were dominant in wackestones rich in crinoids and bryozoans. This latter assemblage was also common in Brigantian limestones. In addition, shallow-water crinoid/bryozoan grainstones in the Brigantian often contain abundant small stellate archaedisks (Hallett 1971; Gallagher and Somerville 1997; Somerville and C  zar 2005; C  zar and Somerville 2005a; Gallagher *et al.* 2006). A later study (Gallagher and Somerville 2003) focused on the controls on the distribution of foraminiferans on a more regional scale (western and southern Ireland), integrating lithofacies and biota within late Asbian shallowing-upward cyclic sequences, containing individual cycles, 2–20 m thick. In this study, three types of foraminiferal biofacies were recognized, two of which were described above: Biofacies type 1, typical of low-energy wackestones and packstones (deep subtidal, >20 m), dominated by *Tetrataxis* and Archaedisks, with *Draffania* (problematicum) and encrusting taxa, associated with bryozoans and crinoids; and Biofacies type 3, characteristic of the shallowest water (5–10 m deep) high-energy grainstones with *Bradyina* and *Nevillea*, associated with ungdarellids and dasyclad algae. A third assemblage, Biofacies type 2, which occurs in algal packstones and grainstones in intermediate water depths (10–20 m) usually has the most common foraminiferans, including stratigraphically important taxa (e.g. *Vissariotaxis*, *Pseudoendothyra*, *Cribrostomum* and *Globoendothyra*). Biofacies type 3 characterizes the upper part of shallowing-upward cycles and can contain low-diversity foraminiferal assemblages. In contrast, Biofacies 2 occurs at or near the base of cycles, immediately above emergent horizons (palaeokarsts), in deeper water, and can contain new foraminiferal and algal taxa (cf. Horbury and Adams 1996; Gallagher and Somerville 1997). Biofacies 1, which occurs in deeper shelf settings, is coincident with the maximum phase of transgressions, and normally occurs in the middle of a cycle, unless the basal transgressive facies is absent. This was recognized in cycles in the northern part of the platform (Burren; Figure 2), whereas at the southern end (south Cork), the cycles and total thickness of the sequence thicken, and the lower part of each cycle is much better developed (Gallagher and Somerville 2003).

3.1.7. Foraminiferal biodiversity

Analysis of the generic diversity of foraminiferans, substage by substage, through the Mississippian in Western Europe (Britain, Ireland, Belgium and France) reveals some interesting patterns. This analysis based on published and unpublished data available primarily in Conil and Lys (1964, 1965, 1966, 1967, 1968, 1970 and 1977); Conil and Lees (1974); Conil (1976, 1980); Conil and Naum (1977); Vachard (1977, 1988); Conil *et al.* (1980, 1986); Fewtrell *et al.* (1981); Strank (1981); Ramsbottom (1981b); Brenckle *et al.* (1987); Loeblich and Tappan (1988); Vachard (1988); Strogon *et al.* (1990, 1995); Gallagher (1992); Somerville *et al.* (1992a, 1992b, 1992c); Gallagher and Somerville (1997, 2003), C3zar and Somerville (2004, 2005a); Somerville and C3zar (2005), C3zar *et al.* (2006); Gallagher *et al.* (2006) involves a database of >125 genera. The following preliminary patterns can be recognized (Figure 4):

- (i) The highest generic diversity values recorded are in the Asbian (77) and Brigantian (66), followed by the Holkerian (52) and Arundian (50).
- (ii) Lower values are recorded in the Chadian (41), with the lowest values in the Courceyan (essentially most of the Tournaisian) (16). The Serpukhovian (Pendleian and Arnsbergian combined) records 33 genera (including *Eosigmoilina* and *Brenckleina* of the Cf7 Foraminifera Zone of Conil *et al.* 1980).
- (iii) The highest generic diversity values recorded for the archaedisids are in the Brigantian (14), twice as many as in the Arundian (7) and Serpukhovian (7). The Asbian records the second highest level (11 genera). (Note that the defined genera of the Family Archaediscidae/Asteroarchaediscidae closely follows that in Brenckle *et al.* (1987), Vdovenko (2001) and Somerville and C3zar (2005).)

The nature of this type of review prevents a detailed analysis of the above data which must await more additional studies to support this interpretation. However, it must be recognized that several physical and biological factors will have had a major influence on diversity, such as: establishment of favourable shallow-water platforms throughout much of the Mississippian, connections between basins for migration of newly evolved taxa within the western Palaeotethyan region, lack of siliciclastic input into carbonate depositional settings, continuous record of sedimentation, without erosion and uplift associated with localized tectonism. Another important factor to be aware of is that the Mississippian substages are not of equal duration. According to the Menning *et al.* (2006) time scale the Courceyan substage (12.5 Ma) is three to four times longer than most Vis3an substages (*c.* 3–4 Ma). Interestingly, the Brigantian is the longest of the Vis3an substages (*c.* 5.5 Ma; Figure 4), which might help explain, in part, the highest speciation of archaedisids. Also, the Chadian which is the shortest substage has the highest number of recorded foraminiferal genera/Ma (20.5) which might be related to widespread development of shallow-water platforms in the early Vis3an creating new niches for these benthic microfossils.

3.2. Conodonts

3.2.1. Conodont biozonations in platforms and basins

There has been widespread correlation of Mississippian successions throughout Europe, China and North America, particularly in the Tournaisian, which has been facilitated by the erection of well-defined conodont zones and subzones (Rhodes *et al.* 1969; Groessens 1971, 1974; Higgins 1975, 1985; Sandberg *et al.* 1978; Lane *et al.* 1980; Metcalfe 1981; Belka 1985, 1991; Varker and Sevastopulo 1985; Wang 1991; Webster and Groessens 1991; Perret and Weyant 1994; Skompski 1996; Belka and Lehmann 1998). In Europe, much progress has been made in recognizing the different zonal schemes which have been used to date and correlate platform and basinal sequences. It has long been recognized that a major shallow-water carbonate platform in NW Europe (Kohlenkalk of Paproth 1969) passed south and east into deep-water basinal facies (Culm) representing the Rheic Ocean at the southern margin of Laurussia (Golonka *et al.* 1994). In Germany there has been a well-established tradition of dating and correlating deep-water Mississippian rocks using ‘nektonic’ conodonts which can be dated also with nektonic ammonoids occurring in the same basinal facies (Bischoff 1957; Voges 1959, 1960; Meischner 1970; Meischner and Nemyrovskaya 1999; Herbig and Stoppel 2006; Korn 2006). Thus, the basal *Siphonodella sulcata* Zone is

succeeded by the *S. duplicata*, *S. sandbergi*, *S. crenulata* (lower and upper), *Gnathodus typicus*, *Scaliognathus anchoralis-latus* and *Gnathodus* (= *Pseudognathodus*) *homopunctatus* zones and then, following an interregnum, the *Gnathodus bilineatus* Zone (Figure 1). However, the *Lochriea commutata* Zone which is developed in most platforms and other deep-water basinal sequences (e.g. Pyrenees and Cantabrian Mountains, Higgins 1981; Perret 1993) is not recognized here (summarized in Herbig and Stoppel 2006). On the other hand, the Tournaisian/Viséan boundary conodont succession in the Velbert Anticline exactly matches the GSSP in South China, with *Scaliognathus anchoralis* succeeded by *Gnathodus homopunctatus* (Herbig and Stoppel 2006).

In Belgium, in the Namur/Dinant area, a rapid change from platform/ramp to basinal facies has been recognized around Yvoir (Groessens 1971, 1974; Conil *et al.* 1977; Paproth *et al.* 1983), particularly in the Tournaisian and early Viséan. This is most apparent, passing south from the Namur Sedimentation Area to the Dinant Sedimentation Area (Hance *et al.* 2001; Poty *et al.* 2006). Similarly, in SW England, deep-water basinal Mississippian conodonts in Devon and Cornwall (Matthews 1969a, 1969b; Matthews *et al.* 1972; Matthews and Thomas 1974) give way to the northeast, to shallow-water conodonts in platform limestones of the Mendips (Butler 1973; Figure 2). This same major facies boundary can be traced in southern Ireland where deep-water conodont faunas have been reported from the South Munster Basin (Matthews and Naylor 1973). This basinal facies passes north into the equivalent shallow-water platform facies in the North Cork area with mostly shelf conodonts (Clipstone 1992).

In Ireland this lateral facies change from shallow-water to deep-water was established early in the Tournaisian associated with the Lower Carboniferous transgression and reached its climax in the late Tournaisian, coinciding with the widespread development of deep-water Waulsortian mud-mounds within the *Scaliognathus anchoralis* Zone (Sevastopulo 1982; Somerville and Jones 1985; Somerville *et al.* 1992b). Similar developments are recognized in Belgium in the Waulsort area, with the *Siphonodella*, *Polygnathus communis carina* and *Scaliognathus anchoralis* zones (Groessens 1971, 1974; Conil *et al.* 1977; Figure 1). This deepening trend continued throughout the Viséan and into the Serpukhovian (Higgins 1985). In the earliest Viséan the FAD of *Gnathodus* (= *Paragnathodus*) *homopunctatus* is recognized throughout most of Europe and North Africa (cf. Perret and Weyant 1994), and in the basal Viséan stratotype section in South China, where it first appears immediately above the first record of *Eoparastaffella simplex* and the last occurrence of *Scaliognathus anchoralis* (Devuyst *et al.* 2003). A similar relationship is recognized in Belgium (Groessens 1974; Groessens and Noël 1977; Belka and Groessens 1986; Conil *et al.* 1991; Figure 1). The deeper-water taxon *Gnathodus homopunctatus* as a basal Viséan marker is much more useful than the previous designated marker taxon *Mestognathus beckmanni*, which is a characteristic shallow-water taxon (see below) and hence often can be absent from deep-water basinal facies. As such, the former species is much more useful for global correlations because of its widespread distribution (see Perret and Weyant 1994).

3.2.2. Conodont evolutionary lineages

Within the deeper-water conodont faunas, evolutionary lineages have been proposed within the *Gnathodus* and *Lochriea* genus groups (Sweet 1988). For example the cosmopolitan unornamented *Lochriea commutata* in the mid-Viséan is considered to have been derived in the early Viséan probably from the simple unornamented *Lochriea saharae* (Nemyrovskaya 2005; Nemyrovskaya *et al.* 2006) or possibly *L. cracoviensis* (Belka 1985) with *Bispathodus stabilis* as the ancestor (Figure 6). *L. commutata* in turn gave way to the ornamented *L. nodosa* and *L. mononodosa* in the late Viséan throughout Europe and Asia (Skompski *et al.* 1995; Wang and Qui 2003; Figure 6) and the more geographically restricted *L. multinodosa* in southern Europe (Pyrenees and Cantabrian Mountains) (Higgins 1981; Perret 1993; Skompski *et al.* 1995). However, in the Mississippi shelf area of the USA, only the unornamented *L. commutata* is recorded (Higgins 1981). More ornamented forms such as *L. ziegleri*, *L. cruciformis* and *L. senckenbergica* evolved from *L. nodosa* and appeared at or just above the Viséan/Serpukhovian boundary (Belka 1985; Nemyrovskaya *et al.* 1994; Skompski *et al.* 1995; Skompski 1996; Nemyrovskaya 2005; Figure 6). However, although *L. cruciformis* is currently used to recognize the base of the Serpukhovian (cf. Gradstein *et al.* 2004), recent work by Nemyrovskaya (2005, 2006) in the Triollo section, Cantabrian Mountains, N. Spain and elsewhere, has proposed that *L. ziegleri* might be a better zonal taxon to use for biostratigraphical correlations, and to define the Viséan/Serpukhovian boundary, because it is more geographically widespread and

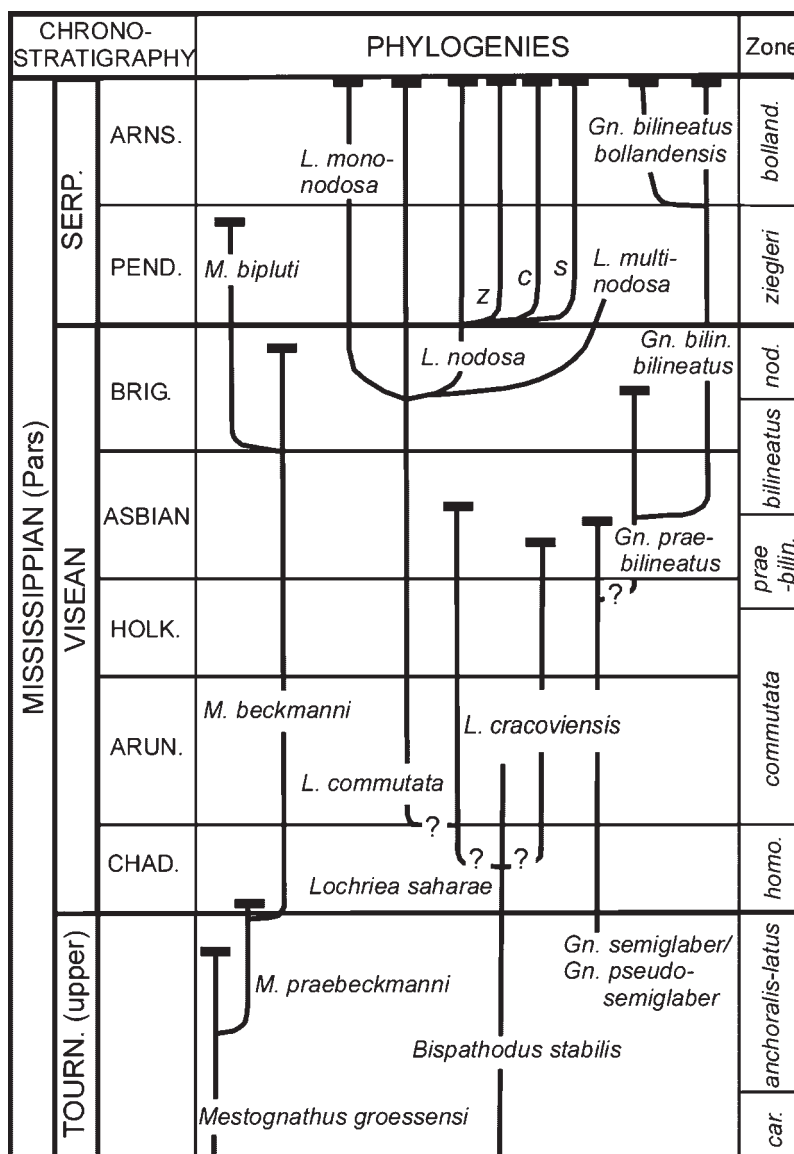


Figure 6. Summary of selected proposed Mississippian conodont phylogenies based mainly on European data (Higgins 1981, 1985; Metcalfe 1981; Belka 1983, 1985; Varker and Sevastopulo 1985; von Bitter *et al.* 1986; Skompski *et al.* 1989, 1995; Conil *et al.* 1991; Riley 1993; Nemirovskaya *et al.* 1994; Jones and Somerville 1996; Skompski 1996; Belka and Lehmann 1998; Meischner and Nemyrovska 1999; Somerville and Somerville 1999; Nemyrovska 2005; Nemyrovska *et al.* 2006). The conodont zonal scheme is a composite biozonation based on Belka (1985), Perret and Weyant (1994), Meischner and Nemyrovska (1999), Nemyrovska (2005) and Nemyrovska *et al.* (2006). Abbreviations: Tourn., Tournaisian; Chad., Chadian; Arun., Arundian; Holk., Holkerian; Brig., Brigantian; Pend., Pendleian; Arns., Arnsbergian; car., carina; M., *Mestognathus*; Gn., *Gnathodus*; homo., *homopunctatus*; L., *Lochriea*; prae-bilin., *prae-bilineatus*; bilin., *bilineatus*; nod., *nodosa*; z., *Lochriea ziegleri*; c., *Lochriea cruciformis*; s., *Lochriea senckenbergica*; bolland., *bollandensis*. (See also Figure 1.)

occurs in larger numbers than *L. cruciformis* (see also Menning *et al.* 2006), and is part of the evolving *L. nodosa* - *L. ziegleri* lineage (Figure 6). The genus *Lochriea* extends to the top of the Mississippian where it is replaced in the early Pennsylvanian by the genera *Declinognathodus*, *Idiognathodus* and *Idiognathoides* (Higgins 1985; Sanz-López *et al.* 2004). It is considered that the ancestor of these taxa is *Gnathodus bilineatus* because of the similarity of the Pb elements (Grayson *et al.* 1990). Also, these same authors suggested that *Gnathodus girtyi* was

the ancestor of *Neognathodus* at the Mississippian/Pennsylvanian boundary, based on similar Pa morphological characteristics.

Another important lineage recognized in the Upper Viséan/Serpukhovian is *Gnathodus prebilineatus* - *Gnathodus bilineatus bilineatus* - *G. bilineatus bollandensis* (Belka 1985; Meischner and Nemyrovskaya 1999; Figure 6) which has been closely tied to ammonoid zones in Poland, Germany, Spain (Sanz-López *et al.* 2004) and Austria (Bošič 1999). The base of the *G. bilineatus* Zone lies within the *Beyrichoceras* B₂ Subzone, and the younger *Lochriea nodosa* Zone lies within the P_{2b} Subzone. Skompski's (1996) zonal scheme in the Lublin Basin extends that of Belka (1985) in the Moravia/Silesia Basin, for the interval between the top of the *bilineatus* Zone to the *bollandensis* Zone in the Serpukhovian (base of the Arnsbergian; Figure 6).

3.2.3. *Conodont biofacies*

In the early to late Tournaisian in Ireland, conodonts have been recognized as exhibiting two coeval parallel assemblages; a deep-water outer shelf/basin assemblage comprising the *Siphonodella*, *Polygnathus communis carina* and *Scaliognathus anchoralis* zones, and a shallow-water shelf assemblage composed of the *Polygnathus spicatus*, *Polygnathus inornatus*, *Pseudopolygnathus multistriatus* and *Polygnathus mehli* zones (Somerville and Jones 1985; Varker and Sevastopulo 1985; Somerville *et al.* 1992b; Jones and Somerville 1996; Figure 1). In the Brigantian, shallow-water taxa, for example *Mestognathus bipluti* co-occur with deeper-shelf, basinal faunas dominated by *Lochriea nodosa* or *L. mononodosa*. Both species of *Lochriea* often first appear together in Brigantian sections in Europe (Somerville and Somerville 1999; Nemyrovskaya 2005; Figure 6). There are unusual first appearances of *L. nodosa* and *M. bipluti* in the Lough Allen Basin of NW Ireland (Kelly 1989; see Jones and Somerville 1996; Figure 2). These taxa are recorded near the base of the early Brigantian Meenymore Formation (Cózar *et al.* 2006), that was formerly regarded as being Asbian in age (George *et al.* 1976; Brandon and Hodson 1984; MacDermot *et al.* 1996). Their earlier occurrence may reflect the adaptation of pioneer conodont-bearing animals in stressful environments (the presence of evaporites in the Formation probably indicate the development of hypersaline conditions in the Lough Allen Basin). *M. bipluti* first occurs at the Asbian/Brigantian boundary in Ireland and always precedes the first appearance of *Lochriea nodosa* (Figures 1, 6). It has been defined informally as a shallow-water facies zone in the upper part of the *bilineatus* Zone (Jones and Somerville 1996).

In shallow-water platforms, conodont faunas are characterized by large robust forms, for example *Patrognathus*, *Cavusgnathus*, *Clydagnathus*, *Syncladognathus* and *Mestognathus* (Austin 1976; Higgins 1981; Rexroad and Varker 1992; Somerville and Somerville 1999). Many closely related genera have occupied this niche throughout the Tournaisian and Viséan and clearly show adaptation to a particularly high-energy, nearshore turbulent facies (oolitic and coated grainstones). Moreover, *Mestognathus* shows an evolutionary lineage from *M. groessensi* first appearing in the late Tournaisian, through *M. praebeckmanni* and *M. beckmanni* first appearing in the latest Tournaisian to early Viséan, to *M. bipluti* which is first recorded in the late Viséan (Brigantian) (Belka 1983; von Bitter *et al.* 1986; Jones and Somerville 1996; Figure 6). This evolutionary trend is highlighted morphologically by a progressive reduction in the size of the basal cavity in adult forms, from *M. groessensi* (largest) to *M. bipluti* (smallest) and an increase in the number of denticles on the inner parapet; absent in *M. groessensi*, 1 in *M. beckmanni*, and 3–6 in *M. bipluti* (Belka 1983; von Bitter *et al.* 1986).

Although these shallow-water platform and deep-water basinal genera may be restricted to one or other facies, some genera appear to be less facies controlled and can occur in both environmental settings. This might be related to a change in life style of the conodont animal (i.e. less nekto-benthic and more pelagic), or it might coincide with a major change in sedimentation, for example a drowning of a shallow-water platform during a transgression introducing deep-water basinal faunas (delicate small gnathodids and lochrieids) into a shallower-water environment such as an outer shelf. Examples of the latter scenario have been well documented on the Kingscourt Platform north of the Dublin Basin (Somerville 1999; Somerville and Somerville 1999), and in the southern margin of the Askrigg Block (Davies 1980; Davies *et al.* 1994) (Figure 2). In both cases *Gnathodus bilineatus* and *Lochriea nodosa* are recorded in the shallower-water platform facies in the Brigantian.

Some multielement conodont taxa (e.g. *Mestognathus bipluti*, aff. *Taphrognathus atlanticus*, *Vogelgnathus campbelli* and *V. postcampbelli*) are recorded in both eastern Canada (Nova Scotia and Maritime Provinces) and

Western Europe (von Bitter *et al.* 1986, 2007; Purnell and von Bitter 1992; Somerville 1999) in the late Viséan, highlighting the close affinity between the two regions and emphasizing the western extension of the Palaeotethys Realm, that can be identified also using rugose corals (Fedorowski 1981; Poty 2002), gigantoproductid brachiopods (Pattison 1981; Legrand-Blain 2006; von Bitter and Legrand-Blain 2007), calcareous algae (Wood 1942) and palynomorphs (Utting and Giles 2004; von Bitter *et al.* 2007). Indeed, the recent discovery of a dasyclad algal species very similar to the North American algal genus *Albertaporella* in the early Viséan in Ireland (Cózar and Somerville 2005d) provides further supporting evidence for marine connections.

3.2.4. *Conodont biodiversity*

Variation in biodiversity and abundance of conodonts in the Mississippian show a cyclic pattern (Ziegler and Lane 1987), with two recognized cycles, each characterized by a major rise in diversity, one episode in the late Tournaisian and the other in the late Viséan, each coinciding with major transgressive events (Ramsbottom 1973, 1977). The highest peak in diversity is in the late Tournaisian (*anchoralis* Zone), with >40 pectiniform (Pa) species and subspecies recorded (cf. Conil *et al.* 1977; Varker and Sevastopulo 1985; Belka and Groessens 1986), but the second peak in the late Viséan is much lower (*c.* 27 species). In the early Viséan, there is a marked decline in diversity and in the number of Pa elements, which coincides not only with a widespread regression, but also a period of tectonic instability, with the break up of ramps which dominated the late Tournaisian and the subsequent formation of shallow-water platforms (Nolan 1989; Strogon *et al.* 1996). It is noticeable that in the early Viséan (Chadian and Arundian), conodonts are often sparse and of low diversity (cf. Austin 1987; Stone 1991; Poty *et al.* 2006). This constitutes the initial low-diversity episode preceding the high-diversity episode which developed innovative and radiation phases. However, it should be noted that this low-diversity episode is valid only for shallow-water platforms. For instance, further to the south in the Cantabrian Mountains of northern Spain, diversity can be much higher in the griotte nodular limestones (Alba Formation), where deeper-water taxa predominate (Higgins and Wagner-Gentis 1982). A similar situation occurs in the deep-water limestones of the Pyrenees (Perret 1993). The higher diversity and numbers of individual species rise in the late Asbian (*bilineatus* Zone) and especially in the Brigantian (*nodosa* Zone), and continues into the Serpukhovian (Higgins 1981, 1985). This rise in diversity in the second cycle in the Mississippian (from the mid-Viséan) in tropical shallow-water environments was due to eustatic transgressions, but in mid-latitude regions (such as the North Urals) it was related to climatic warming (Zhuravlev 2003). At the end of the Mississippian, at the Mid-Carboniferous boundary, a significant depletion at generic and species level is recorded (Lane and Manger 1985).

3.3. *Calcareous algae/problematica*

Calcareous algae have been generally ignored for biostratigraphic studies, mainly because most taxa are considered to be long ranging and/or have palaeoecological limitations. However, the recent but progressive improvement in the knowledge of this microfloral group is shown by more refined and precise stratigraphic ranges of algal taxa and problematica in Europe and North Africa (e.g. Vachard 1977; Skompski *et al.* 1989; Mamet 1991, 2002; Vachard *et al.* 1991, 2001; Sebbar and Mamet 1996, 1999; Krainer and Vachard 2002). Detailed investigations of sequences in Upper Viséan rocks in Ireland, for example (Cózar and Somerville 2004, 2005a, 2005b, 2005c) suggest a distinct relay of algal genera throughout the Asbian and Brigantian substages, with some new taxa appearing at the Asbian/Brigantian boundary and others later in the Brigantian. Similar assemblages of algae occurring in the same stratigraphic intervals are recognized in northern England (Figure 7; see below).

Despite the long-established and well-documented data on the late Viséan stratigraphy in Britain and Ireland (e.g. George *et al.* 1976; Ramsbottom 1981b), the knowledge of the algal content of these rocks is scarce. Moreover, although there are several studies in which algal genera are occasionally documented (e.g. Hallett 1971; Conil *et al.* 1980; Somerville and Strank 1984; Somerville *et al.* 1992a, 1992b, 1992c; Johnson and Nudds 1996; Gallagher and Somerville 1997), they do not provide any additional data on their biostratigraphical range. Of special interest are the works of Mamet and Roux (1974, 1975a, 1975b, 1977) and Mamet (1991), who revised many Carboniferous

AGE		ZONE	IMPORTANT ALGAL TAXA	ASS.
Upper Viséan	Late Brigantian	Cf6 δ	<i>Calcifolium okense</i> (FAD) <i>Archaeolithophyllum</i> (FAD) (very rare)	E
	Early Brigantian		<i>Falsocalcifolium punctatum</i> (FAD) <i>Coelosporrella</i> spp. (common) <i>Paraepimastopora</i> (FAD) <i>Windsoporella</i> (FAD) ' <i>Velebitella</i> ' (FAD) <i>Neoprincipia tethysiana</i> (FAD) <i>Fasciella crustosa</i> (FAD) <i>Claracrusta catenoides</i> (FAD)	D
	Late Asbian	Cf6 γ 2	<i>Coelosporrella</i> spp. (FAD) (common) - [top] <i>Koninckopora</i> sp. B (FAD) - [top] <i>Palepimastoporella</i> (FAD) <i>Ungdarella uralica</i> (common)	C
		Cf6 γ 1	<i>Koninckopora</i> spp. (common) <i>Fasciella kizilia</i> (FAD) <i>Kulikia sphaerica</i> (FAD) <i>Cabrieropora pokorny</i> (FAD) <i>Ungdarella uralica</i> (FAD)	B
	Early Asbian	Cf6 α - β	<i>Epistacheoides</i> spp. <i>Fourstonella</i> <i>Kamaenella</i> <i>Kamaena</i> <i>Koninckopora</i> spp. (common)	A

Figure 7. Algal assemblages (ASS.) in the late Viséan in Britain and Ireland (from data in Gallagher and Somerville 1997; Cózar and Somerville 2004, 2005a, 2005b, 2005c; Cózar *et al.* 2005a, 2005b, 2005c; Gallagher *et al.* 2006).

calcareous algal genera, and described new genera and species, as well as documenting numerous stratigraphic ranges and palaeogeographic distribution of algal taxa.

3.3.1. Biostratigraphically important taxa in the Mississippian

It has long been recognized (Garwood 1913; Wood 1963; Mamet and Rudloff 1972; Mamet 1991) that many algae or problematical algal taxa are known to range throughout the Mississippian and into the Pennsylvanian, for example the cyanobacteria *Girvanella* and *Ortonella* and the problematicum *Kamaena*, whereas others range from the Tournaisian to Serpukhovian (e.g. the dasyclad *Nanopora*), and others through much of the Viséan (e.g. the problematical dasyclad *Koninckopora*) (Wood 1942, 1964; Mamet 1991). Several genera, however, are now known to be restricted to, or first appear in, the late Viséan and Serpukhovian (e.g. *Ungdarella*, *Kulikia*, *Neoprincipia*, *Falsocalcifolium* and *Calcifolium* (Burgess 1965; Conil *et al.* 1980; Mamet *et al.*, 1980; Vachard and Tahiri 1991; Cózar and Vachard 2003; Vachard and Cózar 2005; Cózar and Somerville, 2005b, 2005c)). On the other hand, recent studies have revealed that some algae and problematica which were previously considered to occur only in the Pennsylvanian and Permian are now known to first appear in the Mississippian. For instance, the rhodophyte genus *Archaeolithophyllum* has been recorded from the Brigantian of Kingscourt, Ireland, Scotland (Somerville *et al.* 1996; Cózar and Somerville 2005c; Cózar *et al.* 2005c), and in the Serpukhovian of the Lublin Basin, Poland (Skompski 1996), Montagne Noire, France (Vachard and Aretz 2004) and Spain (Cózar 2005). It had been considered that *Archaeolithophyllum* evolved from *Neoprincipia* in the Serpukhovian (Vachard and Aretz 2004),

but the recent discoveries of *Archaeolithophyllum* in the Brigantian would suggest that this lineage probably evolved slightly earlier (Figure 8). Also, the tubular septate problematicum *Claracrusta* is now known from the early Brigantian of Britain and Ireland (Cózar and Somerville 2004, 2005a, 2005b, 2005c; Figure 7), Algeria, North Africa (Sebbar and Mamet 1996, 1999) and in the Asbian of the Guadiato area of SW Spain (Cózar 2004). In addition, the genus *Paraepimastopora*, which was once considered as being of Pennsylvanian to Permian age, with several species present in North America, has been identified recently in the Brigantian of Britain and Ireland (Cózar and Somerville 2004, 2005a, 2005b, 2005c; Cózar *et al.* 2005c; Figure 7), Spain (Cózar *et al.* 2005c), and Morocco (Sebbar and Mamet 1996), and in the Serpukhovian of Austria (Krainer and Vachard 2002), France (Vachard and Aretz 2004), Algeria (Sebbar and Mamet 1996) and Spain (Cózar 2005).

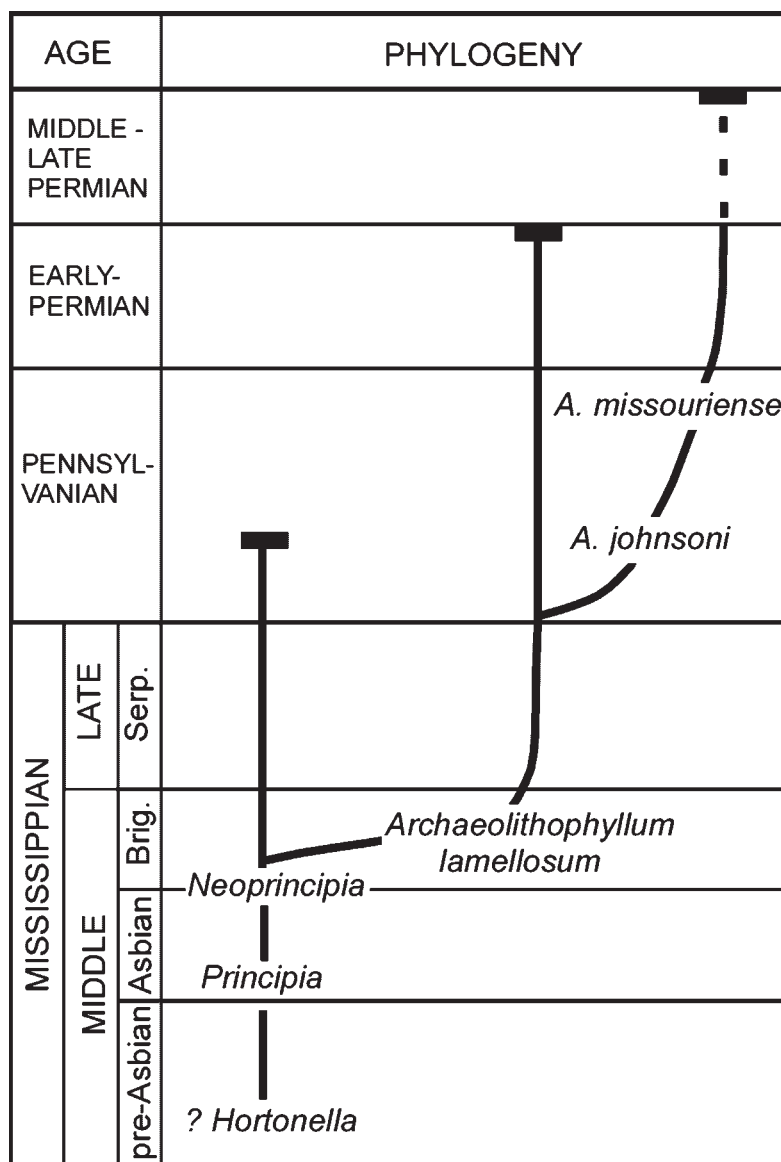


Figure 8. Revised evolutionary lineage of *Archaeolithophyllum* (modified from Vachard and Aretz 2004; Cózar *et al.* 2005c). Abbreviations: Brig., Brigantian; Serp., Serpukhovian; A., *Archaeolithophyllum*.

3.3.2. Algal biofacies

Recent studies on algae in the late Viséan in Britain and Ireland (Cózar and Somerville 2004, Cózar and Somerville 2005a, 2005b, 2005c; Gallagher *et al.* 2006 and unpublished data) have recognized the presence of five assemblages (three in the Asbian and two in the Brigantian), that are characterized by the first appearance of diagnostic taxa and/or the acmes of certain species (Figure 7). *Koninckopora*, *Kamaena*, *Kamaenella* and *Epistacheoides* dominate the first assemblage (A) in the early to late Asbian, followed by assemblage B which marks the first appearance of *Ungdarella uralica* along with new dasyclads, such as *Kulikia sphaerica* and *Cabrieropora pokornyi* in the lower late Asbian (Cf6γ1). *Ungdarella* reaches its acme in the third assemblage (C) together with the first appearance of *Koninckopora* sp. B and *Palepimastoporella* in the upper late Asbian (Cf6γ2). In the early Brigantian several dasyclads (*Coelosporella*, *Windsoporella* and *Cabrieropora*) reach their acme and this fourth assemblage (D) is characterized also by the first appearance of the rhodophyte *Neoprincipia tethysiana* and the problematica *Fasciella crustosa* and *Claracrusta catenoides*. *F. crustosa* is a newly defined species (Vachard *et al.* 2004) that is characteristic of the early Brigantian. It evolved from *F. kizilia*, a species which first appears in the Arundian with its first acme in the Asbian, and is distinguished by its larger size and frequently occurring encrusting clasts. The tubular septate *Claracrusta* is also characterized by an encrusting mode of life (Homann 1972; Vachard 1980; Cózar and Somerville 2004, 2005a, 2005b, 2005c) and often present in 'Osagia'-type oncoids in the Brigantian. The first appearance and acme of *Falsocalcifolium punctatum* in the upper early Brigantian and continuing into the lower late Brigantian is one of the key taxa in assemblage D. This is replaced in importance by the first appearance of *Calcifolium okense* (assemblage E) which characterizes the upper late Brigantian and continues into the early Serpukhovian. This last assemblage is also marked by a generally low abundance of individual algal specimens and diversity. Many of the key taxa from these assemblages are known from other platform sequences in Poland (Skompski 1981, 1986, 1987), Spain (Cózar 2004) and North Africa (Sebbar and Mamet 1996, 1999; Sebbar 1998). Some dasyclad genera, for example *Evelebitella* in the Brigantian are endemic and confined to southern France, Pyrenees and SE Spain (Mamet and Herbig 1990; Cózar *et al.* 2008).

There is a close correspondence between the distribution of calcareous algae in shallow-water platforms and the energy levels on the platform. This is particularly significant in shallowing-upward sequences in late Asbian platforms, which show a cyclic pattern of deep-water low-energy fine-grained wackestones and packstones, passing up into shallower-water high-energy coarser-grained packstones and grainstones, for example in the Urswick Limestone Formation in South Cumbria, northern England (Horbury and Adams 1996); the Burren Formation, western Ireland, and Ballyadams and Ballyclogh formations in southern Ireland (Gallagher 1996, 1998; Gallagher and Somerville 1997, 2003; Gallagher *et al.* 2006). Dasyclads such as *Kulikia* and *Coelosporella* occur in the finer-grained deeper-water shelf lithofacies in the lower parts of cycles, whereas red algae (*Ungdarella*) and problematica (palaeoberesellids such as *Kamaena* and *Kamaenella*) and the problematical dasyclad, *Koninckopora*, are common in the middle to upper part of cycles in the coarser-grained shallower-water lithofacies.

3.4. Rugose corals

The use of rugose corals for biostratigraphic correlation and zonations has experienced similar problems as calcareous algae, mainly related to difficulties in identification (for instance the presence of morphotypes), and overemphasis on facies control on coral distribution. However, recent studies have shown that the former problem can be resolved by using only well-defined and well-documented species and genera, and by using the species group concept (see Poty in Poty *et al.* 2006; Rodríguez and Somerville 2007). In the Upper Viséan (Asbian and Brigantian) approximately 35 species have been considered important for coral biostratigraphy in terms of their broad geographical distribution within the Western Palaeotethys, their occurrence in shallow-water platform facies and their continuous distribution in the Upper Viséan. Detailed analysis of rugose coral faunas from the Upper Viséan in Ireland and Spain has revealed similar patterns with high correspondence of taxa present in both regions. This pattern is consistent with other regions in the Western Palaeotethys (cf. Fedorowski 1981), for example in Belgium (Poty 1981, 1983, 1985), Britain (Mitchell 1989), France (Poty 1994; Poty and Hannay 1994), Poland

(Fedorowski 1970, 1971; Khoa 1977) and Russia (Hecker 2001). Furthermore, many Upper Viséan taxa in Europe have been recognized in Vietnam and Thailand (Fontaine 1961; Fontaine *et al.* 1991), and South China (Fedorowski 1981; Wang *et al.* 2006), thus establishing the western and eastern Palaeotethyan marine connections. This Palaeotethyan seaway has also been recognized earlier, in the late Tournaisian (Ivorian), with the widespread development of the *Uralinia-Keyserlingophyllum-Bifossularia-Cyathoclisia* fauna in Belgium, South China (RC3 and RC4 α Coral Zones of Poty (1985); Poty and Xu (1996); Xu and Poty (1997); Poty in Conil *et al.* (1991); Poty *et al.* (2006); Poty (2007); Figure 1); the Urals (Hecker 2001) and the Omolon region of Siberia (Poty and Onoprienko 1984). This marks a global sea-level high-stand with equatorial seaways connecting west and east Palaeotethyan regions.

The Upper Viséan in Ireland comprises the same four Coral Zones as recognized in Britain (Mitchell 1989; Figure 1); zone F is early Asbian in age, Zone G is late Asbian and zones H and I are early Brigantian (the late Brigantian zones J–K are poorly represented in Ireland). Five coral assemblage zones can be recognized in Sierra Morena; zones 1 and 2 combined are early Asbian in age, zone 3 is late Asbian and zones 4 and 5 combined are Brigantian (Rodríguez and Somerville 2007). The late Brigantian zones are not developed in Spain, because there, the upper part of the Viséan sequence has been eroded. Nevertheless, the index taxa for these upper zones are present in boulders from the Marbella Formation in southern Spain (Herbig and Mamet 1985; Herbig 1986). Moreover, recent algal data (Cózar *et al.*, 2007c) have suggested that Sierra Morena and the Betic Cordillera can belong to two different palaeogeographic units during the Brigantian. Equivalent-aged biozones in the Upper Viséan have been distinguished in Belgium belonging to the RC7–RC8 Zones of Poty (in Conil *et al.* 1991 in Poty *et al.* 2006).

Pioneer work by Poty (1981, 1984, 1985, 1993) on the evolution of colonial rugose corals belonging to the Family Lithostrotionidae, for example *Lithostrotion*, *Siphonodendron*, *Solenodendron* and *Diphyphyllum*, has resulted in a well-defined phylogeny for taxa in the Asbian and Brigantian (Warnantian). Several independent lineages (trends) can be recognized through the mid to late Viséan: (i) in the *Siphonodendron* genus, two synchronous lineages can be detected; one trend showing a decrease in the tabularium diameter and septal number from the Arundian to Brigantian stages (the smallest species, *S. junceum*, first appearing in the late Asbian), whilst the other trend shows an increase in tabularium diameter and septal number (passing via *S. sociale* to the largest species, *S. scaleberense* (Nudds and Somerville 1987); (ii) in the cerioid genus *Lithostrotion*, there is a lineage from the Holkerian to the Brigantian, marked by a progressive decrease in the tabularium diameter and the number of septa (the smallest species, *L. maccoyanum*, first appearing in the late Asbian); (iii) the fasciculate genus *Solenodendron* shows a similar trend of decreasing tabularium diameter and septal number, only in this case the oldest species, *S. pillaoi*, is recorded in the late Tournaisian (Vuillemin 1990) and the smallest species, *S. furcatum*, first appears in the Asbian; (iv) the fasciculate genus *Diphyphyllum* also first appears in the Asbian, but is most abundant in the Brigantian. It is interesting to note that virtually all the species belonging to the genera *Lithostrotion* and *Siphonodendron* are recorded in the Asbian when the family Lithostrotionidae was at its most diverse (>16 species). Also, it has been suggested (Poty 1993) that the development of subcerioid colonies of *Siphonodendron* in the late Arundian formed a transitional link to the evolution of cerioid *Lithostrotion* in the Holkerian (Cf5 Foraminifera Zone) (=Livian in Belgium). This development was probably for better adaptation to more turbulent shallow-water environments. It is also worth noting that rugose corals have been used to define the base of the Asbian (*Dibunophyllum*) and Brigantian (*Actinocyathus*) substages in Britain. The same genera are used to define assemblage biozones in the Upper Viséan and Serpukhovian in the East European Platform and Urals (Hecker 2001).

4. OUTSTANDING PROBLEMS AND POTENTIAL FUTURE DEVELOPMENTS

1. It is quite apparent that several foraminiferal biozones in the Mississippian need to be redefined, based on the first appearance of diagnostic taxa at the base of those zones, as suggested earlier by Riley (1993). Current problems in biostratigraphical correlation relate to difficulties in recognizing the base of the *Neoarchaediscus*

- (Cf6) Biozone and the base of the Cf6 subzones, as the nominal taxon never appears at the base of the Cf6 Zone (Cózar and Somerville 2004; Somerville and Cózar 2005). Several refinements of the Cf6 subzones have been proposed, particularly for the late Asbian (Cf6 γ) and Brigantian (Cf6 δ) subzones (Cózar and Somerville 2004; Somerville and Cózar 2005; Cózar *et al.* 2005a, 2006), which correspond, closely, but not exactly to MFZ 14 and 15 of Poty *et al.* (2006).
2. There is a need for better integration of biozones using different faunal and floral groups in combination, for example foraminiferans, conodonts and miospores. This can be readily achieved when successions contain alternations of carbonates and siliciclastics in marginal marine and nearshore sequences, for example in Northern England (Johnson and Nudds 1996; Cózar and Somerville 2004); Midland Valley of Scotland (Neves *et al.* 1973; Neves and Ioannides, 1974; Dean 1987), NW and NE Ireland (Somerville *et al.* 2001; Cózar *et al.* 2006), NW Germany and Poland (Skompski 1996; Matyja *et al.* 2000), and the Russian Platform (Makhlina *et al.* 1993; Makhlina 1996).
 3. In many fossil groups there is a need to identify robust, well-defined taxa (species, subspecies and species groups) which are morphologically distinct and whose first appearances can be precisely located in stratotype and paratype sections, and ideally can be recognized as forming part of an evolving lineage. Although this has been achieved in many cases for conodonts, the ancestors of foraminiferal genera are often cryptic and more detailed investigations will have to be carried out to try and establish potential phylogenetic lineages. Refinements in Carboniferous palynostratigraphy in Western Europe, for example, is anticipated, with a proposal to use single index species to define the base of biozones and sub-biozones that would replace the current two-part zonal named biozonation (Clayton *et al.* 2003).
 4. There occur in many sections diagenetic and preservational problems that need to be considered. In carbonate sequences many limestones are prone to neomorphic alteration, and stylolitization, as well as replacement by silica and dolomite. These have a variable degree of impact on foraminiferans and calcareous algae, as they can mask their original wall structure and fabrics, and can effect mineralogical replacement of the primary wall composition which affects identification of taxa. This is especially notable in dasyclads and codiacean green algae, which had a presumed original aragonitic wall structure, and rhodophytes that had an original high-Mg calcite wall composition. Both algal groups are now often converted to low-Mg calcite. On the other hand, some algae are better preserved because of cyanobacterial biofilms.
 5. More investigations are required in sequences which are usually devoid of diagnostic macrofauna and often contain unfavourable facies, such as thick evaporites or dolomites, for example in the Windsor Group in Nova Scotia (cf. von Bitter *et al.* 2007), red-bed clastics or non-marine/peritidal units. In the latter environments many pioneer taxa can be located, often confined to rare thin horizons, for example the late Viséan shrimp bed at Granton, Edinburgh, Scotland, where the conodont-bearing animal was identified (Briggs *et al.* 1983).

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